STUDY ON THE USE OF BIOPESTICIDES AGAINST COTTON INSECT PESTS UNDER FIELD CONDITIONS AND THEIR COST BENEFITS

By

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ABSTRACT

Cotton (*Gossypium hirsutum* L.) is one of the essential fibre crops. However, production is affected by several factors including low yields, high input costs, pests, and weeds infestations. Biopesticides can play a vital role in the integrated programme to address the challenges that limit production and reduce the profits for cotton farmers. This thesis consists of five chapters covering different aspects of the research on farmers' survey and biological control of cotton pests. Each chapter is presented as an independent study. The focus of this research was to (1) provide the bac^{-1}round on cotton production in South Africa and major pests and their control; (2) survey the current status of pests on cotton and production practices; (3) evaluate the effect of different biological agents on the control of cotton pests under field conditions; (4) evaluate the efficacy of biopesticides in comparison with the insecticides against sucking pests; and (5) perform a cost analysis of cotton production using biological control agents under field conditions. This study would share an insight to build a foundation for management of major cotton insect pests.

A survey was done to (1) evaluate farmers' knowledge and perceptions of cotton pests; (2) examine farmers' current practices in managing cotton pests; and (3) identify challenges and intervention opportunities to develop an efficient integrated pest management programme for cotton production. One hundred and forty farmers, mainly smallholder farmers were interviewed, and most of them planted cotton in less than five hectares of land, with 96% planting under dryland. Most farmers neither practiced conservation agriculture (95%) nor conducted soil analyses (87%) and harvested their cotton by handpicking (99%). Their knowledge of insect pests was higher than of diseases, with most of the participants not aware of nematodes (88%), or disease-resistant cultivars (74%), while 91% were aware of insect-resistant cultivars. Most farmers relied on synthetic pesticides to control cotton pests, and only 7% used biological control. Dryland farmers reported a mean seed cotton yield of 700 kg.ha^{-1}, and 5 000 kg.ha^{-1} was obtained from irrigated cotton. Most respondents were only mentored and supported by extension officers (82%). Climatic conditions (98%), labour costs (88%), and insect infestations (42%) were identified as the main constraints in cotton production. The study recommends the development of alternative control methods to minimize the use of agrochemicals.

Four biopesticides (Eco-Bb®, Bb endophyte, Bolldex®, Delfin®) were compared with a pyrethroid, Karate® against cotton insect pests, particularly the African bollworm, *Helicoverpa armigera* Hübner (Lepidoptera: Noctuidae). The treatments of Karate® and Bolldex® significantly reduced the *H. armigera* population, while the treatment of Eco-Bb® had the lowest number of damaged bolls. Plots sprayed with Karate® had significantly fewer aphids and leafhoppers. Plots treated with Bolldex® and Bb endophyte exhibited the lowest number of thrips. Plots sprayed with Karate® and Eco-Bb® had a significant effect on the whiteflies, while Delfin® had the least significant number of spider mites. The treatment of Eco-Bb® exhibited a lower cotton stainer population, while the treatment of Karate® had the lowest population of leafhoppers. The highest average seed cotton yield of 6 400 kg.ha^{-1} was recorded in the plots that were treated with Bolldex®. In summary, the efficacy of different biopesticides against *H. armigera* varied significantly; however, Karate® and Bolldex® resulted in better control of the pest.

Field trials were conducted to evaluate three biopesticides, Eco-Bb®, Bb endophyte, and Eco-Noc in comparison with the insecticides Chlorpyrifos® 480 EC, Karate® EC, and Bandit® 350 SC to determine their efficacy against sucking pests, notably leafhoppers *Jacobiella facialis* Jacobi (Hemiptera: Cicadellidae), aphids *Aphis gossypii* Glover (Hemiptera, Aphididae), thrips *Thrips tabaci* Lind (Thysanoptera: Thripidae), whiteflies *Bemisia tabaci* Gennadius (Hemiptera, Aleyrodidae), red spider mite *Tetranychus urticae* Koch (Trombidiformes: Tetranychidae) and cotton stainers *Dysdercus* spp. (Hemiptera: Pyrrhocoridae). Karate® significantly reduced the leafhopper population while the biopesticides had some control of the aphids. Plots treated with Eco-Bb® and Bandit® 350 SC had the lowest number of thrips, and there were no significant differences in the populations of whiteflies. All the treatments, except for Bandit®, significantly reduced the number of spider mites. The highest average cottonseed yield of 6 395 kg.ha^{-1} was recorded in plots sprayed with Bandit®.

Cost analysis was done by conducting two field trials (bollworm and leafhopper) to evaluate the effect of biopesticides and synthetic pesticides on controlling different cotton insect pests. The cost of biopesticides was higher than synthetic pesticides. Delfin® was the most expensive treatment at R 7 980/ha, while Chlorpyrifos® 480 EC had the lowest price of R 370/ha.

The highest input cost of R 7 200/ha was recorded from labour costs incurred during weed control. The highest total costs of R 21 502/ha were incurred where Eco-Bb®, Bb endophyte and Eco-Noc were applied.

In the bollworm experiment, the lowest production costs per hectare were observed from the treatment with Karate® EC (R 19 282). The maximum seed cotton yield of 6 818 $kg.ha^{-1}$ was recorded in Bolldex® treated plots while Karate® EC treated plots had the highest net profit of up to R 19 148 per hectare and mean benefit-cost ratio of 1.8. In the leafhopper trial, the highest seed cotton yield was obtained from the Bandit® 350 SC treated plots (6 394 $kg.ha^{-1}$). Plots, where Bandit® 350 SC was applied, had the maximum net profit of R 22 686 with a benefit-cost ratio of 2.

DECLARATION

I, Lawrence Nkosikhona, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original composition.
2. The thesis has not been submitted for any other degree or professional qualification at any other university.
3. The thesis contains my data, pictures, graphs or other information unless specifically acknowledged as being sourced from other persons.
4. This thesis does not contain other persons' writing unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then their words have been re-written, but the general information attributed to them has been referenced.
5. The work presented in Chapter 1 has been published as a book chapter in IntechOpen as "Role of Microbial Biopesticides as an Alternative to Insecticides in Integrated Pest Management of Cotton Pests." by Malinga, L. N. and Laing, M. D. 10.5772/intechopen.100400
6. The work presented in Chapter 2 has been submitted for publication in South African Journal of Science as "Farmers' production practices, incidence and management of pests and diseases, extension services, and factors limiting cotton production and quality in South Africa " by L. N. Malinga and M. D. Laing.
7. The work presented in Chapter 3 has been submitted for publication in Journal of Asia-Pacific Entomology as " Efficacy of biopesticides on the management of the cotton bollworm, *Helicoverpa armigera*, (Noctuidae) under field conditions" by Lawrence N. Malinga and Mark D. Laing.
8. The work presented in Chapter 4 has been published in Crop Protection Journal as "Efficacy of biopesticides against cotton pests under field conditions in South Africa" by Lawrence N. Malinga and Mark D. Laing. https://doi.org/10.1016/j.cropro.2021.105578
9. The work presented in Chapter 5 has been submitted for publication in International Journal of Pest Management as "Cost Analysis of Biopesticides and Synthetic Pesticides: Implications for Cotton Farmers" by Lawrence N. Malinga and Mark D. Laing.

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Prof. M.D. Laing (Supervisor)

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CHAPTER 1

LITERATURE REVIEW

1.1 GENERAL INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is one of the most important fibre cash crops (Ma *et al*., 2020) that is grown for fibre in over 83 countries with tropical and subtropical climatic conditions (Hussain *et al*., 2016). The incidence of cotton pests is a significant factor that affects cotton production (Xiao *et al*., 2019). The production is severely affected by insect pests resulting in poor yields despite the growing demand for the commodity (Midega *et al*., 2012). One of the key constraints to establish effective pest management approaches for smallholder farmers is the lack of adequate information about farmers' knowledge, perceptions, and practices in pest management. Constant training and extension services based on continuous research programmes using the most appropriate technologies are required to integrate new technologies that will benefit the small-scale farmers (Matthews and Tunstall, 2006). Due to environmental safety, target-specificity, and low production inputs (Bouslama *et al*., 2020), bio-insecticide development as an alternative to chemical insecticides is also essential for enhanced cotton production in South Africa. Moreover, it is equally important to perform a comparative economic analysis of bio-insecticides vs chemical insecticides to underline the best management option with lower cost. The focus of this chapter was to provide the background on cotton production and major pests and their control.

1.2 COTTON PRODUCTION ECONOMIC IMPORTANCE

Cotton is one of the most useful materials popularly used in the clothing industry and other products such as cotton swabs and cottonseed oil (Shahbandeh, 2019). In the early 1900s, cotton contributed about 75% of world fibre use; however, today, cotton contributes less than 30% of world fibre consumption (Townsend, 2017). Synthetic fibres became the leading fibre in the mid-1990s (Dhaliwal, 2019). The decline was also due to, amongst other factors, availability of water, climate change, and pest problems (OECD and FAO, 2019). In developing countries, cotton is one of the most important cash crops, and its production has been a major economic component and driver of economic growth in Africa (Vitale, 2018).

This section summarizes the role that cotton production has played in global development, focusing on how cotton contributes to economic growth globally and particularly to the South African situation.

Cotton is produced under different environmental, climatic and political conditions that may result in various practices and impacts (ICAC and FAO, 2015). In Eastern and Southern Africa, cotton production has got a fluctuating performance despite interventions from governments and other funders (Tumusiime *et al*., 2014). While cotton contributes to economic growth, the lack of profitable investment opportunities in the industrial and service sectors limit agriculture's growth potential (Vitale, 2018). The other challenges of the sector are also social and economical, which are caused by the over-use of pesticides as well as high costs of production and unstable market prices (Textile Exchange, 2019).

1.2.1 Global status

Cotton is the main viable economic activity and a major source of employment and income that benefits more than 100 million families in the most impoverished rural communities worldwide (FAO, 2019). Worldwide, cotton fibre serves as a raw material for textile industries, with an annual economic impact of more than $600 billion (Abbas *et al*., 2020). In 2014, ICAC reported that more than 75 countries produced 25.624 million tons of cotton lint harvested from over 32 million hectares. However, by 2018 cotton was grown in 64 countries on more than 29 million hectares, equivalent to 2.1% of global arable land (Textile Exchange, 2019). OECD and FAO (2019) foresee an increase of 16% in production by 2028 due to the expansion of cotton growing area.

The major cotton-producing countries are India, USA, China, Brazil and Pakistan (Statista, 2019). These countries produce more than 75% of global production (OECD and FAO, 2019), with India and China accounting for about 50% (ICAC and FAO, 2015). Among the major producers, Brazil has significantly increased its production over the past four years (OECD and FAO, 2019). According to OECD and FAO (2019), 37% of global production is exported worldwide, with the United States being the main exporter, followed by Brazil, which has also significantly increased cotton export to South and East Asia. World cotton consumption is still less than 10% compared to when it was at its peak (Textile Exchange, 2019).

The major raw cotton consumer is China, which accounts for one-third, followed by India, while there is strong growth of cotton processing in Bangladesh, Turkey, and Vietnam (OECD and FAO, 2019). In 2016, OECD and FAO predicted that by 2025, China would have the largest demand for cotton imports, followed by Bangladesh, Vietnam, and Indonesia. Over the past 30 years, the average global yields have doubled from 400 $kg.ha^{-1}$ of cotton lint in 1980 due to new technologies and improved management practices (ICAC and FAO, 2015; OECD and FAO, 2019). The current cotton lint yields range from 180 to 2600 $kg.ha^{-1}$ (ICAC, 2020a). The lower cost of polyester production remains a challenge to the cotton sector (International Trade Centre, 2020); however, cotton prices continue to be higher than polyester (OECD and FAO, 2019). AGRA (2014) projected a decrease in international cotton prices due to pressure from synthetic fibres such as polyester.

1.2.2 Continental and local status

Over 350 million people, particularly smallholder farmers in developing countries, are supported through the cotton industry (Moyo, 2016; OECD and FAO, 2016; Fairtrade, 2017; Forum for the Future, 2020; Maiti *et al*., 2020). In Africa, smallholder farmers mainly produce cotton in small plantations (IPBO, 2017; Williams, 2017; CMiA, 2020). Cotton is mostly cultivated in family farms with intensive labour (Moyo, 2016) in more than 20 countries across Sub-Saharan Africa (IPBO, 2017) (Figure 1.1). In 2005, 10% of the world's total cotton was produced in Africa (ITC, 2013), but by 2019, the production had declined to about 8% (Amanet *et al*., 2019). Western Africa produces almost 75% of the region's cotton volume (OECD and FAO, 2020).

Cotton is an important export crop that accounts for 15% of global cotton lint exports in Sub-Saharan Africa (OECD and FAO, 2019). About 88% of the cotton produced in Africa was exported in 2019 (Cotton SA, 2018), generating $2.1 billion worth of raw cotton (Yurman, 2020), and its cotton trade share has doubled since 1980 (Organic Cotton, 2020). NEPAD reported that in 2013, less than 6% of African cotton is processed within the continent. According to ICAC (2019), if the cotton fibres were processed within Africa, the addition of up to 5.5 million jobs would be created, and this has the potential to generate export revenues of between US$30 billion and US$90 billion. They further indicated that an additional US$400 million could also be generated using cotton by-products.

In Burkina Faso, cotton accounts for up to 60% of the export revenue, while in Mali, the revenue funds half of the food import bills (Vitale, 2018). In South Africa, 70% to 90% of the locally produced cotton is exported every year (Cotton SA, 2018).

ICAC recorded that despite the global cotton lint yields of up to 2 600 $kg.ha^{-1}$, Africa still has relatively low yields ranging from 180 to 550 $kg.ha^{-1}$ (ICAC, 2020a). For more than three decades, African lint cotton yields have remained among the lowest globally, with average yields of 350$kg.ha^{-1}$ (ICAC, 2018). ICAC (2019) stated that in 2018 cotton in Africa was planted by more than 3.5 million smallholder farmers, but in eleven countries, they had the lowest average lint yields of 222 $kg.ha^{-1}$. These countries planted a total area of 2.1 million hectares of cotton and produced only 465,310 tonnes of lint. However, during the same season in South Africa, estimated average yields were 1 103 $kg.ha^{-1}$ from 44 000 hectares (Cotton SA, 2018).

In South Africa, cotton is grown by 250 commercial and more than 2 000 smallholder farmers in five provinces, namely KwaZulu-Natal, Limpopo, Mpumalanga, North West, and Northern Cape (Louw, 2020). In 2016, FAO estimated that South Africa had a total agricultural area of over 96.3 million hectares. Of the available agricultural area in South Africa, only 10.3% is arable land (World Bank, 2019). During the 2018/19 season, South Africa had an increase in land under production for both dry (42%) and irrigated (22%) cotton compared to the previous season (Louw, 2020). South Africa has been widely reported as the first country in Africa to adopt genetically modified cotton in 1998.

ISAAA (2016) reported that since 1996, there had been a substantial increase in plantings, and in 2012, genetically modified cotton delivered a net farm income of around $147 million worldwide. Bryant *et al*. (1999) compared the profits per acre of genetically modified cotton varieties to non-genetic modified varieties in Arkansas between 1996 and 1998. They reported that the net change in profit ranged from a $175 per acre decrease in 1996 to a $251 per acre increase in 1998. The change in profit was positive for 13 out of 20 observations and averaged $39 per acre. In South Africa, an average income of $33/hectare was realized between 1996 and 2012 (Brookes and Barfoot, 2014). All the cotton cultivated in South Africa is currently genetically modified cotton, with 75% of local production harvested by hand (Malinga, 2019).

The main challenge faced by the agricultural industry is the high cost of production that reduces profitability (Antonaci *et al*., 2014; Khapayi and Celliers, 2016). Most cotton-producing countries worldwide are financially subsidized by their respective governments for seed cotton production. However, subsidies may result in cotton surplus that is later sold at subsidized prices, and this negatively affects developing countries which rely on cotton exports (Gillson *et al*., 2004). In the past 25 years, cotton in the United States has been subsidized with $39.8 billion (EWG, 2020), while the Chinese government had previously provided subsidy on cottonseed to encourage farmers to increase production output (Tan *et al*., 2013). Several countries in West Africa provided subsidies for cotton inputs in 2017/18 and 2018/19, especially for fertilizers and planting seeds (ICAC, 2018). Through the subsidies, Burkina Faso ($39 million), Côte d'Ivoire ($15 million), and Mali ($35 million) have increased their production (ICAC, 2018).

In Malawi, Mozambique, Zambia, and Zimbabwe, cotton is mostly supported through a credit scheme from the private sector linked to the ginning and trading industry (Chaniwa *et al*., 2020). In South Africa, between 2012 and 2018, some cotton smallholder farmers were supported with over US$6.3 million for production inputs and mechanization (Malinga, 2019). Unfortunately, during the 2018/19 season, government support has drastically declined. As a result, Cotton SA, in collaboration with other private institutions, has developed an input credit scheme to assist the farmers.

Figure 1.1 Main cotton-producing countries in Africa

1.3 MAJOR COTTON PESTS

The incidence of pests in cotton is a significant influence that affects production resulting in low yields and poor quality (DAF, 2018). Sub-Saharan Africa has climate conditions suitable for various pests, which attack cotton and result in yield losses (Amanet *et al.*, 2019). Tay *et al.* (2013) reported that an average of 30% of seed cotton is lost in West Africa due to pests. Insect pests such as the African bollworms (Bazelet, 2020), aphids (Donovan, 2015), thrips (Timm *et al.*, 2008), whiteflies (Krüger, 2014), and leafhoppers (Donovan, 2014) are serious crop pests in South Africa. This section describes the key insect pest of cotton concerned by this study.

1.3.1 African bollworm

The African bollworm, *Helicoverpa armigera* Hübner (Lepidoptera, Noctuidae), is the most significant pest of agriculture commonly found in Africa, Asia, Oceania, Europe (CABI, 2019), and recently in South America (Reigada *et al*., 2016; Tembrock *et al*., 2019). In Africa, the pest is regarded as an indigenous species that contributes to reducing crop production (Tossou *et al*., 2019) and the only heliothine species of major economic importance (Cherry *et al*., 2003). In East Africa, *H. armigera* attacks various crops, including cotton, legumes, maize, sorghum, sunflower, tobacco, and tomato (Berg, 1993). In South Africa, cotton is one of the main crops attacked by the pest. It has been regarded as a serious pest due to feeding on a wide range of host crops (Tay *et al*., 2013), high fecundity (Karimi *et al*., 2017; Herrero *et al*., 2018), multivoltine life cycle (Sarate *et al*., 2012; Chen *et al*., 2013), great potential mobility (Reigada *et al*., 2016), damage to fruiting parts (Torres-Vila *et al*., 2003) and its resistance to chemical insecticides (Joußen *et al*., 2012). Van Hamburg and Guest (1997) listed 35 host crops of *H. armigera* plus 25 wild host plants in eastern and southern Africa, while Krinski and Godoy (2015) documented over 67 host families worldwide.

H. armigera developmental cycle goes through four stages including egg, larval, pupa, and adult (Mironidis *et al*., 2010). There can be up to five generations of bollworm per year (Bazelet, 2020), and each generation can take about four to six weeks (Nunes *et al*., 2017). *H. armigera* females prefer laying eggs on host flowers, squares, and fruit (Luong *et al*., 2016) during winter or spring (Liu *et al*., 2010; CABI, 2019). The eggs are laid over two to three days and oviposition may last up to eight days (Berg and Cock, 1993; CABI, 2019).

In South Africa, it can take up to 23 days for oviposition to occur (Bazelet, 2020). Eggs are cream to white, changing to brown before hatching (Bazelet, 2020) and up to 0.6 mm in diameter (CABI, 2019). A single female may lay up to 1500 eggs (Czepak *et al*., 2013). In South Africa, a single female moth can lay an average of 730 eggs (Bazelet, 2020). Larval colour and size vary depending on the larval instar. The larvae range in colour from yellow to brown with a cylinder-shaped body, and longitudinal stripes occur on the dorsal side (Queiroz-Santos *et al*., 2018). At the later stage, the larvae have white or yellow lines and white spiracles with black rims (EPPO, 2003; Gardner, 2009).

Pupae are round at both ends with a brown colour and are about 14-18 mm in length (Bazelet, 2020). The pupal stage occurs in the soil (Mironidis *et al*., 2010) at a depth of 3-15 cm in the soil (EPPO, 2003; CABI, 2019b). When the pest feeds on cotton, the pupal viability increases, and the pupal stage lasts for about 15 days (Czepak *et al*., 2013) (CABI, 2019b). The moth is usually brown (Hughes and Cardé, 2020; Satoh *et al*., 2016), with a broad thorax and seven to eight blackish spots on the forewings (EPPO, 2003). The hind wings have apical ends with a broad dark-brown border and yellow margins (Wubneh, 2016). *H. armigera* is a nocturnal pest (Riley *et al*., 1992) that can travel long distances due to a separation of feeding and oviposition by unfavourable habitats (CABI, 2019b). Long-range movement can also be attributed to migration, and this may have implications on the management of the pest in the various agricultural landscapes (Farrow and Duly, 1987; Jones *et al*., 2019). Lu *et al*. (1999) reported that most moths were distributed within a 720 m range when released in the field.

H. armigera damage differs by crop, and because of the migratory behaviour, the occurrence of this pest is frequently unpredictable (Burgio *et al*., 2020). The pest causes damage of more than US$2 billion to crops every year, and this excludes the environmental costs that are related to its control (Bazelet, 2020). The damage caused by *H. armigera* depends, to some extent, on the adult population numbers, the number of eggs laid, and the survival rate of larvae (Kriticos *et al*., 2015). Young larvae tend to feed on younger leaves while the older ones feed on different parts of the plants, preferably the buds, flowers, fruits, and pods (FAO, 2017). Although there may be low numbers in the field, the damage may significantly increase because the larvae tend to feed partly on one cotton boll and then move to another boll (Bazelet, 2020; CABI, 2019).

The damaged bolls ultimately drop off the plant (Agritech, 2015; Vonzun *et al*., 2019). When left untreated, *H. armigera* can cause up to 90% of boll damage in cotton. In Brazil, the pest was reported to reduce cotton yields by up to 80% (Tay *et al*., 2013). In 2014, Bueno and Sosa-Gómez reported that Brazil had crop loss estimated at US$ 0.8 billion due to the pest’s damage.

1.3.2 Aphids

The cotton aphid, *Aphis gossypii* Glover (Hemiptera, Aphididae), is an important agricultural pest due to its wide host range (Carletto *et al*., 2009; Wang *et al*., 2016). Ma *et al*. (2019) reported that the pest has over 900 hosts from 116 plant families. Although *A. gossypii* can significantly damage the crop through direct feeding, its main threat is the ability to transmit many plant viruses (Kumar, 2019; Fingu-Mabola *et al*., 2020). *A. gossypii* populations are mostly high on cotton from mid to late in the season (Cisneros and Godfrey, 2001; Lu *et al*., 2015). Before the introduction of genetically modified cotton, pesticides that were sprayed against *Helicoverpa* species, controlled aphids; however, the aphid populations increase thereafter resulting in the development of resistance to pesticide control (Herron and Wilson, 2017).

A. gossypii are small, soft-bodied insects with a pear-like shape and a pair of black cornicles (Sutherland, 2006; CABI, 2019a). They are 1 to 2 mm in length with relatively long antennae and legs (Flint, 2013; Muimba-Kankolongo, 2018). Aphids can be distinguished from other pests like mites through slower movement when disturbed (Gilkeson and Klein, 2020). Body colour varies depending on the host plant and the biological state of the individual aphid (Döring, 2014; Lu *et al*., 2016). The nymphs vary in colour from yellow to green, black, or brownish (Patterson and Ramirez, 2016; Cannon and Bunn, 2017). They often have a dark head and thorax with a dark green abdomen (Capinera, 2018; Kring, 1959). The first instar has four antennal segments, while the second instar has five (Ebert and Cartwright, 1997). The third instar can be differentiated from the fourth instar by the absence of setae on the genital plate (CABI, 2019a). The fourth-instar nymphs have developed wings, while adults are mostly wingless (Pirotte *et al*., 2018). During unfavourable environmental periods, small yellow or white aphids are observed, and they do not reproduce until conditions are favourable (Infonet, 2020). During favourable conditions, larger green forms are produced (Barbercheck, 2014). The aphids generally require at least two hosts, and the primary host is for sexual reproduction while the secondary host is for asexual reproduction (Sullivan, 2006). Females produce offspring that take about a week to develop and moult four times to become reproductive adults (Agarwala and Choudhury, 2013; Ogawa and Miura, 2014; Agropedia, 2020). The reproductive period covers 20 days, and the female can produce up to 80 offspring (Flint, 2013).

Aphids can cause more than 70 % loss in crop production (Aslam *et al*., 2007). They cause damage to the undersurface of the leaves and the stems by using sharp mouthparts and suck the sap from the tissues (Barbercheck, 2014; Cannon and Bunn, 2017; Kumar *et al*., 2019). The leaves may produce insufficient chlorophyll, initiate curling, and die prematurely (Begum *et al*., 2018). Genetically modified cotton has been reported to not affect preference and colonization by aphids (Sujii *et al*., 2012). Besides the physical damage done to the host, aphids have been widely reported to transmit various virus diseases (Shen *et al*., 2018; Wang *et al*., 2020).

Moreover, aphids produce a sugary substance called honeydew that causes stickiness (Cannon and Bunn, 2017; Liu, 2018), which interferes with the photosynthesis of the plant (Heimoana and Charlotte, 2012; Muimba-Kankolongo, 2018). When aphids feed on cotton plants, the honeydew drops onto the bolls resulting in a sticky deposit on the fibre (Wilson *et al*., 2013; Mohan *et al*., 2014). Stickiness reduces the lint quality and results in substantial price penalties to the grower (Hequet *et al*., 2007). It is a serious challenge during cotton ginning since it causes the lint to stick to machinery (Bange *et al*., 2017). Honeydew also exposes the leaves to sunburn, which results in secondary infections that inhibit the plant's functions (O'Brien and Baier, 2017).

1.3.3 Whiteflies

Whiteflies *Bemisia tabaci* Gennadius (Hemiptera, Aleyrodidae) is one of the most important agricultural and horticulture pests throughout the world (Perring *et al*., 2018). In Australia, Africa, China, the EU, and the USA, whiteflies are considered regulated quarantine species (Boykin and de Barro, 2014). Currently, 39 species differ in their host-plant range (Mugerwa *et al*., 2018), and they have more than 600 host plant species (Romba *et al*., 2018). This species is reported to transmit over 100 plant viruses (Kanakala and Ghanim, 2019).

Whiteflies undergo six different developmental stages: egg, four larval instars, and adults (Malumphy *et al*., 2017). The average developmental stage on cotton takes approximately 17 to 29 days to complete. Perring *et al*. (2018) reported that at a lower temperature of 15°C, the complete development could take up to 105 days compared to 14 days at 30°C. The eggs are approximately 0.2 mm long and elongated with a pale brown colour (Kedar *et al*., 2014; CABI, 2019e; Infonet, 2020c).

They are laid either singly or in group circles on the undersides of the leaf surface (Malumphy *et al*., 2017; Perring *et al*., 2018). Each female can lay between 60 to 300 eggs (Mau and Kessing, 2007; McAuslane, 2009; Chen *et al*., 2015), and the eggs take about five to nine days to hatch depending on the host species and humidity (Gangwar and Gangwar, 2018). Of the four larval stages, the first and second larval-instars are up to 0.6 mm in length, and the first larval-instar is the only mobile larval stage (Malumphy *et al*., 2017). The fourth instar, known as the pupa, is 0.7 mm long, oval, and lasts for about six days. (McAuslane, 2009; CABI, 2019e).

The adult emerges from the pupal case and expands its wings before powdering itself with wax from glands on the abdomen (Malumphy *et al*., 2017; Haldhar *et al*., 2018). Adults are about 1 to 2 mm long (Infonet, 2020c; Muimba-Kankolongo, 2018) with wings covered in white powder wax (Mau and Kessing, 2007). Their body is white to slightly yellowish with seven segmented antennae and one sensorial cone on the third, sixth, and seventh segments (Baig *et al*., 2015). The wings are kept above the body in a tent-like position (McAuslane, 2009), and up to 15 generations can occur annually (Onstad, 2013; Gangwar and Gangwar, 2018). Onstad (2013) stated that mating occurs several times from 12 hours after emergence, and the female may live up to 60 days while the male lives for a shorter period. Whitefly nymphs and adults can be easily identified in the crop (McAuslane, 2009).

Whiteflies can cause damage through phloem-feeding, excretion of honeydew, and transmitting viruses such as cotton leaf curl virus (Moreno-Delafuente *et al*., 2013; Czosnek *et al*., 2017; Guo *et al*., 2019; Lu *et al*., 2019). Whiteflies suck phloem-sap and cause damage to a wide range of crops, including cassava (Bellotti and Arias, 2001), cotton (Roopa *et al*., 2014), and tomato (Ramachandran, 2018). With their piercing-sucking mouthparts, they insert their stylets into the plant to feed on the phloem (Garzo *et al*., 2020). While feeding on the plant, both immature and adult stages excrete honeydew onto the leave surface and fruit (McAuslane, 2009), causing discolouration of leaves and fruit deformations (Wraight *et al*., 2017; Saad *et al*., 2019). Whiteflies have developed resistance due to the overuse of insecticides (Ahmad *et al*., 2002; Yao *et al*., 2017; Hopkinson *et al*., 2020).

1.3.4 Thrips

Thrips, *Thrips tabaci*, Lindeman (Thysanoptera, Thripidae) is a serious early-season pest of seedling cotton (Miyazaki *et al*., 2017; Vyavhare and Kerns, 2017) and vegetable crops (Gill *et al*., 2015) throughout the world. They are commonly one of the first insects found on cotton (Greenberg *et al*., 2009). Hull (2014) reported that thrips feed on a wide host range including 140 species from over 40 families of plants, while Bhonde *et al*. (2016) and Cook *et al*. (2011) reported that there are several hundred host plants. Thrips may be found on weeds and flowers growing near cotton and migrating onto cotton plants (Vyavhare and Kerns, 2017).

The life cycle of thrips has six stages: egg, two larval stages, two pronymph stages, and adult stage (Mau and Kessing, 2007). The life cycle can take between 10 and over 30 days to complete depending on the climate and the host plant (Rueda and Shelton, 1995; Bergant *et al*., 2005; Swamy and Veere Gowda, 2006; Vyavhare and Kerns, 2017; Ertunc, 2019). The reproduction is both asexual and sexual (Kobayashi *et al*., 2013; Li *et al*., 2015), producing both males and females from unfertilized eggs (Nault *et al*., 2006; Riley *et al*., 2017) and females from fertilized eggs (Chatzivassiliou *et al*., 2002; Li *et al*., 2015). The eggs are small, shiny white (IFAS, 2020), 0.2 mm in length, and 0.08 mm wide (Gill *et al*., 2015; Pal *et al*., 2019). They are laid individually inside the leaf tissues (Fiene *et al*., 2013; Li *et al*., 2014). A female can lay up to 100 eggs, which take up to six days to hatch (Das *et al*., 2017; Ghosh *et al*., 2017; Moraiet *et al*., 2017). The first instar is semi-transparent and white, while the second instar is yellow (Gill *et al*., 2015). The larvae undergo two instar stages, which last up to 10 days (Madadi *et al*., 2011; Shiberu and Mahammed, 2014). The pupae do not feed (Rueda and Shelton, 1995), and the pupal stage takes about four days to complete (Mau and Kessing, 2007).

Adult females are about 1.2 mm long, while males are smaller than 0.7 mm in length (Gill *et al*., 2015). The body colour varies from yellow to brown depending on temperature (Diaz-Montano *et al*., 2011). Adults are very active with fringed and pale wings (Alston and Drost, 2008). The antennae have seven segments, and the eyes are grey (Dara *et al*., 2018). Adults live up to about 35 days (Vyavhare and Kerns, 2017), and several generations can develop annually (Bethke *et al*., 2014).

The host plant, temperature, and humidity play a role in the development of thrips (Cook *et al*., 2011; Li *et al*., 2014). Adults may hibernate in field crops (Diaz-Montano *et al*., 2011) and overwinter in the soil (Larentzaki *et al*., 2007). Adults can fly long distances from immediate plant hosts (Smith *et al*., 2016), and flight occurs during daylight at low wind speeds (Grode, 2017). Thrips found in nearby weeds migrate onto cotton plants (Silva *et al*., 2018), and adults are attracted to white, blue, and yellow colours (Demirel and Yildirim, 2008; Devi and Roy, 2017; Pobozniak *et al*., 2020). It is sometimes impossible to control thrips with pesticides since the eggs are laid under leaf tissues (Cañas, 2015), the pupae are found in the soil or between the leaves (Bethke *et al*., 2014), and some adults may avoid control by hiding in the inner leaf spaces (Shiberu and Mahammed, 2014).

During the seedling stage, cotton growth is slow, resulting in attack by early-season insect pests such as thrips (Allen *et al*., 2018). When feeding, thrips move from the lower to the upper parts of the cotton plant as the plants increase in size (Shah, 2015). The feeding preference may be due to the pest trying to access younger leaves with thinner epidermis on the lower surface (Wardle and Simpson, 1927; Mo *et al*., 2008). Thrips feed on leaves, young leaf, and flower buds (Infonet, 2020c), causing silvering of leaves due to the loss of chlorophyll (Shiberu and Mahammed, 2014; Gill *et al*., 2015). The silvery appearance occurs after the fluids in the cell are replaced by air (Cook *et al*., 2011). Both adults and larvae feed on plant epidermal cells' contents, causing damage that results in 30-50% of lint yield (Cook *et al*., 2011). Damaged cells wrinkle, and the leaves do not develop well, causing them to twist (Cook *et al*., 2011; UMass, 2014). The damage caused by thrips can also allow secondary infection by plant pathogens (Muvea *et al*., 2018). Attique and Ahmad (1990) reported that thrips and cotton leafhoppers cause almost 40% loss in seed cotton yield. Scouting for thrips is difficult, a lens may be required (Michalak, 2014; Shiberu and Mahammed, 2014), and the population level can be determined by observing leaf damage (Attique and Ahmad, 1990). Wardle and Simpson (1927) reported no evidence of toxicity from the thrips salivary secretion. Thrips are also reported to be vectors of plant viruses (Jones, 2005; Riley *et al*., 2011). Hull (2014) stated that 17 species are reported to transmit viruses from four plant virus groups, with most of them feeding on vegetative parts of the plant and pollen.

1.3.5 Leafhoppers

Leafhoppers, *Jacobiella facialis* Jacobi (Hemiptera: Cicadellidae), commonly known as jassids, is one of the major cotton pests in Africa (Kone *et al*., 2018). The pest has a synonym called *Empoasca facialis,* and it was described from Dutch East Africa in 1912. Leafhoppers are commonly found in the tropics and subtropics (Sharma and Singh, 2002; Radcliffe and Lagnaoui, 2007). Numerous species of leafhoppers are found on cotton (Poos and Wheeler, 1943) and can feed throughout the crop cycle despite pesticide application (Kone *et al*., 2018).

Leafhoppers reproduce sexually, and the egg hatches to a nymph (Radcliffe and Lagnaoui, 2007). The nymphs look like adults but are smaller with pale yellow-green colour (Infonet, 2020; Vennila, 2002). Leafhoppers undergo five nymphal instars (Pascua and Pascua, 2002; Singh *et al*., 2018; Infonet, 2020c), and they are multivoltine with several generations every year (Nagrare *et al*., 2012). Eggs are laid on the underside of leaves, and they can hatch in about ten days (Chandel *et al*., 2013; Arora *et al*., 2020). They are elongated and range from 0.8 mm up to about 10 mm (CottonInfo, 2016). Leafhopper species are almost similar in shape but vary in colour from green to yellowish-brown (Heisswolf *et al*., 2010). They overwinter as the egg, adult, or immature forms and pass through several moults before becoming an adult (Chasen *et al*., 2014). Leafhoppers are generally found low in the canopy (CottonInfo, 2016), and when disturbed, they hop fast (Infonet, 2020c). Both the nymphs and adults may feed on the aerial parts of the same plant (Schabel, 2006), and the attack occurs throughout the crop production cycle (Murugesan and Kavitha, 2010). Both the nymphs and the adult suck the sap from the xylem and phloem tissues of the plant and young leaves from the lower surfaces (Weintraub, 2013). The damage caused by the leafhoppers is called "hopper burn" because of the brownish appearance of plants, and it is a non-contagious disease (Vennila, 2002; Ghante *et al*., 2019). Hopper burn causes the edges of the leaves to curl downwards and change to yellow and then red before drying out and falling off the stem (Atakan, 2009).

The premature reddening has been reported to be a characteristic reaction of the plant rather than the attack (Poos and Wheeler, 1943). Hopper burn occurs when there is an interaction between insect feeding stimuli and plant responses (Backus *et al*., 2005).

Heavy infestations can damage the canopy and impair cotton growth, causing a 40 to 100% reduction in the number of bolls (Malinga, 2012). Prolonged feeding also results in the shedding of leaves, squares, and young bolls and subsequently lead to significant yield losses (Vennila, 2002). The pest damage levels vary under different climatic conditions, and lower rainfall significantly increases the pest population (Sathyan *et al*., 2017; Vennila *et al*., 2018).

1.3.6 Spider mites

Spider mites, *Tetranychus urticae* Koch (Trombidiformes: Tetranychidae) are important pests of cotton (Khan *et al*., 2008; CABI, 2019c). There are many controversial reports on the taxonomic placement of the two-spotted spider mite with about 65 synonyms included under this species (Fasulo and Denmark, 2009; Auger *et al*., 2013; Brust, 2017). While numerous spider mite species attack cotton worldwide (Steinkraus *et al*., 2020), the two-spotted mite is one of the most common and important species (Leigh *et al*., 1996; O'Hara *et al*., 2008; Hazzard, 2010). This species is an early-season pest that causes significant yield losses in cotton (Attia *et al*., 2013; Gore *et al*., 2013). The growth stages of spider mites differ from one species to another (Fasulo and Denmark, 2009). However, their life cycle is short with high fecundity and haploid-diploid sexes (Macke *et al*., 2011; Martin and Latheef, 2017; Yoon *et al*., 2018). Spider mite development occurs in five to twenty days depending on temperature, and it may have overlapping generations every year (Fasulo and Denmark, 2009; Meena *et al*., 2013). The optimal reproduction usually occurs in seven days at a temperature above 30°C (Tehri, 2014). Gunning and Easton (1989) reported average development periods of 27 days at 16 °C and six days at 29°C for the females and a slightly shorter time for the males. The complete life cycle consists of the egg, larva, two nymphal or pupal stages, and the adult (Goto, 2016; Bryon *et al*., 2017; Kamala, 2020). Females lay male eggs during asexual reproduction, and in sexual reproduction, both female and male eggs are laid (Ros, 2010; Rocha *et al*., 2020). Female spider mites can lay over 100 eggs over 12 days (CABI, 2019c), and under optimal conditions, several hundred eggs are laid by each female (Fasulo and Denmark, 2009). The eggs are oval, shiny, colourless, 0.08 mm long, and 0.13 mm in diameter (Beers and Hoyt, 1993; CABI, 2019c).

The eggs are attached to a silk web (Goff *et al*., 2010; Clotuche *et al*., 2012), and their presence can be used to confirm when the plant damage is due to spider mites (Oku *et al*., 2009). The eggs hatch in three days into larvae that are 0.1 mm long (Fasulo and Denmark, 2009) with pale green colour and three pairs of legs (Capinera, 2001b; Meena *et al*., 2013). The larval stages are mainly dormant and only become active after the moulting to the nymphal stage (Laing, 1969; Ito and Chae, 2019). The larvae move slowly and develop into the nymphal stage within three days (Pundt, 2014). The two nymphs are known as protonymph and deutonymph, and they have darker markings and eight legs (Amala *et al*., 2016; Kedar *et al*., 2014; Sandeepa *et al*., 2019). Initially, the nymph is pale yellow-green and later turns to a darker green colour (CABI, 2019c). Adult females are 0.2-0.6 mm in length, elongated with long hairs on the dorsal side of the body, and translucent pale greenish-yellow to brown (Fasulo and Denmark, 2009; Meena *et al*., 2013; CABI, 2019c; Rincón *et al*., 2019; Infonet, 2020d). Adult females live for about two to four weeks (Fasulo and Denmark, 2009; Ruckert *et al*., 2015), while males can live up to nine days (Meena *et al*., 2013). The overwintering females are orange to orange-red (Suzuki *et al*., 2009; White *et al*., 2018).

Spider mites feed on the undersurface of the leaves (Bensoussan *et al*., 2016; Elsadany, 2018), where they remove the sap (He *et al*., 2018; Abo-Elmaged *et al*., 2020; Kamala, 2020). Spider mites are the mesophyll feeders because they pierce the leaf epidermis and feed mostly on mesophyll cells affecting photosynthesis in the leaves of host plants (Agut *et al*., 2018; Estrella *et al*., 2020). The damaged leaves become grey or yellow, and damage to the open flower results in a brown colour and withering of the petals (Fasulo and Denmark, 2009; Brust and Gotoh, 2017). When the pest is not controlled, complete defoliation may occur at higher population densities (Coviello and Bentley, 2009; Santamaria *et al*., 2020). Crop development is reduced on cotton by high infestation during the early developmental stage (Meena *et al*., 2013; Jimenez, 2014; Elsadany, 2018). The spider mites also transmit several viruses, including potato virus Y, tobacco mosaic virus, and tobacco ringspot virus (Brust and Gotoh, 2017).

1.3.7 Cotton stainers

Cotton stainers, *Dysdercus* species (Hemiptera: Pyrrhocoridae), are serious pests of cotton (Ishfaq and Shah, 2014; Ciesla, 2016). The Pyrrhocoridae is a small family that consists of 33 genera and approximately 340 species throughout the world (Schaefer and Ahmad, 2000). Eleven pest species are found in Africa (Rajendran *et al*., 2018), with four species occurring in South Africa. *D. fasciatus, D. nigrofasciatus, and D. intermedius* are important in Africa cotton (Marlos, 2014). Cotton stainers have a wide range of alternative hosts including wild plants (Fuseini and Kumar, 1975; Tengecho, 1994) and various hibiscus species (ARC-IIC, 2004; Donovan, 2015).

The cotton stainers have several generations a year and the complete life cycle may take one to three months depending on temperature (Mead and Fasulo, 2017). Over 100 small pale eggs are laid and incubation can take up to two weeks (Paul Donovan, 2015). The female lays eggs in the soil or plant debris (Paul Donovan, 2015; Infonet, 2020b). The emerging nymphs are initially red, and after five moults, they have the same colours as adults but lack wings (Jaleel *et al*., 2013; Yuwei and Lin, 2019; Infonet, 2020b). The last stages of nymphs and the adults have long mouthparts used when feeding on the cotton seeds inside the bolls, while younger nymphs only feed on bolls that have slightly opened (Ishfaq and Shah, 2014). Both the nymphs and adults are usually found in larger groups (Brambila and Hodges, 2006; Ciesla, 2016). The cotton stainers are similar to assassin bugs; however, adult females are bigger than males (Donovan, 2015). Adults are up to 2 cm long (Marlos, 2014) with colours that vary from a red to orange body and black stripe on the wings (Stehlík and Jindra, 2006; Infonet, 2020b). Adults are very active during the daytime and can travel long distances (Duviard, 1977; Paul Donovan, 2015). When crushed, the cotton stainers release an unpleasant odour (Vennila *et al*., 2007).

Both adults and nymphs suck the sap from the seeds with piercing mouth parts causing physical damage and shedding of young bolls (Bohmfalk *et al*., 2011; CottonInfo, 2016; Rajendran *et al*., 2018). While feeding on cotton, the pest also damages the fibres and affects the development of the bolls (Kumar and Samal, 2020).

The feeding on developing and mature cotton seed negatively affects the quality of the seed and oil content (Wilson *et al*., 2008; Sahayaraj *et al*., 2012; Sammaiah and Samatha, 2012). Cotton stainers attack cotton throughout the fruiting stage and transmit a fungus disease known as boll disease that results in hard bolls and stained lint (Infonet, 2020b). Adults are found on cotton as early as when the first bolls open, and they can remain inside the boll until harvesting (Donovan, 2015).

1.4 CONTROL STRATEGIES OF COTTON PESTS

Pests and diseases are estimated to cause 60% losses in cotton production throughout the world (UIA, 2019). A successful control strategy requires integrated pest management (IPM) that prevents or suppresses damaging populations of insect pests by applying the comprehensive and coordinated integration of multiple and compatible control tactics, including chemical, cultural and biological methodologies. Chemical control involves the use of synthetic insecticides (Chattopadhyay *et al*., 2017), while biological control includes the introduction of a natural enemy or living organisms (le Hesran *et al*., 2019) and cultural control focuses on the manipulation of the environment to reduce the pests populations (de Franca *et al*., 2013). This section provides an overview of these control strategies and their application to the control of cotton pests.

1.4.1 Chemical control

Synthetic insecticides are mainly used on cotton to provide rapid control of insect pests (Asif *et al*., 2016), and farmers opt for insecticides as the first line of defence (Kone *et al*., 2018). Since the development of synthetic insecticides after World War II, they have been extensively used in agriculture due to their efficiency in pest control and yield increment of many crops (National Research Council, 2000). Cotton has been reported to receive more chemical control than most other arable crops (Matthews, 2003). Cotton uses up to 60% of all commercialized agrochemicals globally (Yadav and Dutta, 2019). In Africa, about 50% of insecticides are used on cotton (ICAC, 2019), and South Africa has been one of the largest importers of chemical pesticides in sub-Saharan Africa (Quinn *et al*., 2011). Various insect pests and beneficial insects coexist in a cotton ecosystem; however, insecticides have reduced the impact of beneficial insects (El-Wakeil and Abdallah, 2012).

As one of the management tools for pests, synthetic insecticides can be used as part of integrated pest management to promote sustainable pest control methods (Chamuene *et al*., 2020). When synthetic insecticides such as organophosphates (1960s), carbamates (1970s), and pyrethroids (1980s) were introduced, they had an impact on agricultural pest control and resulted in high yields (Aktar *et al*., 2009). In Africa, the use of pesticides had been reported to be low compared to the rest of the world due to economic and social constraints, and the majority of pesticides are applied mostly against pests of commercial crops such as cotton (Abate *et al*., 2000). Usage of pesticides in Africa is reported at more than 1.2 $kg.ha^{-1}$, a fraction of what is used in Latin America (7.17 $kg.ha^{-1}$) (Srinivasan *et al*., 2019).

Although chemical control remains a key method to control targeted pests, a controversy has surfaced regarding the use and abuse of pesticides (Aktar *et al*., 2009). The diversity of pests found on cotton requires serious control, mostly with pesticides, which subsequently has a negative impact on natural enemies and the environment (Machado *et al*., 2019). The continuous use of synthetic chemicals to protect crops may also result in resistance to insecticides in pest populations (Kone *et al*., 2018). Combining selective chemical and biological controls is important for integrated pest management; however, this has not been entirely explored due to, among others, insufficient information on the insecticide tolerance or resistance of natural enemies (Rodrigues *et al*., 2013). The development of integrated pest management strategies is required to reduce pesticide use and maximize the impact of natural enemies. However, there is still a need to address the complexity of insect pests on cotton where control needs may conflict (Cherry *et al*., 2003). Below is a summary of the different insecticides used in this study (Chapters 3 and 4).

1.4.1.1 Pyrethroid – Lambda-cyhalothrin

Pyrethroids are non-systemic pesticides that have contact and stomach action (Barr and Buckley, 2011). Pyrethroids are insecticides that are mainly used to control insects that are leaf-eaters (Torres *et al*., 2015). In Africa, pyrethroids are the most commonly used insecticides in cotton (Javaid *et al*., 1999). They are synthetic derivatives of pyrethrins produced by chrysanthemum flowers (Mahdavian and Somashekar, 2013).

Pyrethroids differ in their vulnerability to sunlight, and they are characterized by their ability to dissolve in water with persistent compounds (Laskowski, 2002). This group of insecticides includes cypermethrin, deltamethrin, fenvalerate, lambda-cyhalothrin, and permethrin, among others. Lambda-cyhalothrin, also known as Karate®, is a non-selective insecticide commonly used to control agricultural insect pests (Machado *et al*., 2019). It is frequently used on cotton and other crops to control different insects, including lepidopterans and coleopterans (Rodrigues *et al*., 2013; Birolli *et al*., 2019). The insecticide has low vapour pressure, and it is relatively stable in water at a pH that is less than eight (He *et al*., 2008).

The effect of lambda-cyhalothrin on cotton pests and beneficial insects has been widely reported around the globe. Cole *et al*. (1997) investigated the efficacy of lambda-cyhalothrin (Karate®) in Bt cotton and reported that lambda-cyhalothrin had no major disruption of beneficial insects but significantly increased yield. Gayi *et al*. (2017) evaluated the efficacy of bio and synthetic pesticides against *H. armigera* and its natural enemies on cotton. They reported that under laboratory conditions, lambda-cyhalothrin combined with Thiamethoxam showed 100% mortality of third instar larvae of *H. armigera* after 96 hours while under field conditions, lambda-cyhalothrin combined with profenofos showed 100% mortality after 96 hours. Furthermore, it was observed that synthetic pesticides significantly reduced natural enemy populations. This is in line with the finding of Ruberson and Tillman (1999) and Riley *et al*. (2001), who recorded the reduction in the number of natural enemies after the application of Karate. Lambda-cyhalothrin has been reported to have the quickest and best control against cotton leafhopper nymphs after the first spray (Maketon *et al*., 2008). In a study comparing the efficacy of some conventional and neonicotinoid insecticides against whiteflies, leafhoppers, and thrips, Asif *et al*. (2016) observed that Karate®, when sprayed twice, had a significant reduction of the pests from one to seven days after application. Lambda-cyhalothrin showed a 57.93% reduction against leafhopper seven days after application. Zidan *et al*. (2012) found that lambda-cyhalothrin was the most efficient insecticide against bollworms and aphids, with an average reduction of 71.91% in pink bollworms and 81.61% in spiny bollworms. However, the data also revealed that this insecticide had a weak to moderate effect against leafhoppers and whiteflies and was more toxic against predators.

Javaid *et al*. (1999) recommended that the inclusion of insect growth regulators in the management of cotton insect pests on small-scale farms in Africa could eliminate the continuous use of pyrethroids.

1.4.1.2 Organophosphate – Chlorpyrifos

Organophosphates are one of the major insecticide classes that became prominent in the mid-1940s (Costa, 2018). They are the large class of compounds that are used in agriculture (Jett, 1998). Over the years, there has been a significant decline in the use of organophosphates in developed countries, but this has been offset by an increase in developing countries (Moretto, 2014; Esen and Uysal, 2018). Organophosphates are highly toxic and impact both target insect pests and non-target species and mammals, including humans (Farahat *et al*., 2011; Dewer *et al*., 2016). Chlorpyrifos is a heterocyclic organophosphate that belongs to the class of organophosphorus insecticides and has been widely used in agriculture (Ware and Whitacre, 2004; Testai *et al*., 2010). Chlorpyrifos is a non-systemic insecticide that disrupts the production of certain important enzymes of the nervous system (Testai *et al*., 2010; Vigneshwaran *et al*., 2019). It is a frequently used insecticide on a wide range of crops, including cotton (Racke, 1993), and a variety of formulations have been developed to control important insect and arthropod pests (Jepson, 2001). Chlorpyrifos is known to be persistent and toxic to non-target organisms; however, it may exhibit low persistence in the field (Koshlukova and Reed, 2014). Chlorpyrifos is one of the most effective and cheaper insecticides compared with alternative products (Testai *et al*., 2010). However, in South Africa, chlorpyrifos was banned for residential use in 2010 and is only used in the agricultural sector.

A mixture of chlorpyrifos and alphacypermethrin was tested against cotton bollworms and compared to chlorpyrifos alone (Tambe *et al*., 1997). The mixture was more effective in controlling the cotton bollworm complex and resulted in the highest seed cotton yield. Similar results were observed by Vojoudi *et al*. (2011), who reported that chlorpyrifos controlled the third larval instars of cotton bollworm and reduced longevity and fecundity of adults. Chlorpyrifos has been found to have a significant effect on the control of cotton stainers in a laboratory experiment (Saeed *et al*., 2016; Sarwar *et al*., 2018).

Chlorpyrifos has also been recorded to control *J. facialis* (Kone *et al*., 2018). Zidan *et al*. (2012) evaluated the efficacy of different pesticides against cotton bollworms and sucking insects and their associated natural enemies. It was evident from the results that chlorpyrifos was efficient against cotton bollworms and aphids but had a weak to moderate effect against whiteflies and leafhoppers. Martin *et al*. (2003) studied the synergism of pyrethroids by organophosphorus insecticides on cotton using the combination index method. They revealed that the organophosphorus insecticides significantly reduced the resistance of *H. armigera* against pyrethroids and increased the toxicity of the pyrethroids.

1.4.1.3 Neonicotinamide – Imidacloprid

Neonicotinoids, such as imidacloprid, are products of synthetic nicotinoids used to control insects and pests of different crops, including cotton (Pang *et al*., 2020). They are a newer class of insecticides developed in the late 1970s with low risk for non-target organisms and selective for insect pests (Salgado, 1999; Tomizawa, 2013; Ensley, 2018; Sobhakumari *et al*., 2018). Neonicotinoids attack the central nervous system, reducing reproduction and insect movement resulting in their death (Buszewski *et al*., 2019). Imidacloprid is the first and most-used member of the neonicotinoid family (Elbert *et al*., 1991). In the US, over 60% of cotton is planted with seed treated with the neonicotinoids imidacloprid (Allen *et al*., 2018). Imidacloprid belongs to a newer class of chloronicotinyl (Talcott, 2012), and it is registered for many agricultural uses (Sheets, 2014). Imidacloprid has been reported as a safer insecticide compared to the older classes of insecticides because, despite its high-water solubility, it has low leaching potential in the soil (Oi, 1999). However, this depends on soil type, as some soils with low organic matter content may not absorb imidacloprid well (Churchel *et al*., 2011). Imidacloprid can be applied directly onto the crops or used as a seed or soil treatment to control different pests, including leafhoppers, aphids, whiteflies, and thrips (Elbert *et al*., 1991; Li *et al*., 2018). Imidacloprid can be used to control aphid infestations of cotton plants (Conway *et al*., 2003). However, the insecticide is harmful to ladybirds (Wumuerhan *et al*., 2020) and has been found to reduce the fecundity of other natural enemies of aphids (Kang *et al*., 2018). It is, therefore, recommended that imidacloprid must only be applied during the initial stages of aphid invasion in cotton fields (Wumuerhan *et al*., 2020).

Imidacloprid has been widely reported to significantly reduce leafhopper, thrip, and whitefly infestations in cotton (Mohan and Katiyar, 2000; Shivanna *et al*., 2011; Abbas *et al*., 2012; Asif *et al*., 2018; Singh *et al*., 2018). Asif *et al*. (2016) tested different insecticides against sucking insect pests of cotton. They reported that imidacloprid exhibited a significant reduction in the populations of leafhoppers (86.92%), whiteflies (74.5%), and thrips (66.30%); and gave the highest seed cotton yield. In a study to determine the production of honeydew by whiteflies, Cameron *et al*. (2014) documented that when adult whiteflies were placed on insecticide-treated plants, imidacloprid showed a reduction in the honeydew produced by the pest. Similarly, He *et al*. (2013b) reported that imidacloprid reduced feeding, honeydew excretions, and fecundity of adult whiteflies. Afzal *et al*. (2014) compared different insecticides under field conditions and reported that imidacloprid reduced the leafhopper population up to seven days after application and gave an average of more than 90% mortality after three days of application.

1.4.2 Challenges of synthetic insecticides

Despite the duration of use of synthetic insecticides on agricultural pests, their extensive use has resulted in health hazards, environmental pollution, outbreaks of secondary pests, toxicity to natural enemies, development of resistances, and decreases in biodiversity (Kuye *et al*., 2007; Pimentel and Burgess, 2014; Dewer *et al*., 2016; Kumar *et al*., 2017; Visnupriya and Muthukrishnan, 2019).

1.4.2.1 Health hazards

Pesticide use in cotton poses a hazard to humans (Yadav and Dutta, 2019). In developing countries, the use of pesticides has been reported to account for up to 14% of work-related injuries, of which 10% of these injuries led to fatality (Bennett *et al*., 2003). In Pakistan, health problems associated with the absence of personal protective equipment were reported in cotton pickers who experienced headaches, stomach-aches, fever, skin and eye problems due to the lack of proper education and training programmes on personal protective measures (Bakhsh *et al*., 2017; Memon *et al*., 2019). In Sudan, human blood samples were analysed for organochlorine pesticide residues in areas that used pesticides intensively. The levels of organochlorine in blood samples were less in areas distant from where the heavy application of these pesticides was previously done (Elbashir *et al*., 2015).

In Benin, Agbohessi *et al*. (2015) conducted a study to determine the impact of agricultural pesticides on the health status of fish found in the water near cotton fields. It was evident that pesticides significantly reduced the health condition of fish living in the Beninese cotton basin.

1.4.2.2 Toxicity to natural enemies

In any area where cotton is grown, insect pests and natural enemies coexist. It is therefore important that while the use of insecticides reduces the pest populations, it must not have a negative impact on natural enemies. Lambda-cyhalothrin has been recorded as toxic to natural enemies of different crop pests (Tillman and Mulrooney, 2009; Fernandez, 2015). Van Hamburg and Guest (1997) noted that the variety of natural enemies in South Africa plays a vital role in controlling insect pests; however, spraying of insecticide reduces the ability of natural enemies to control cotton pests. Barros *et al*. (2018) observed that after exposure to different insecticide residues, parasitoids and some of the predator populations were reduced by lambda-cyhalothrin. D'ávila *et al*. (2018) studied the effects of imidacloprid and lambda-cyhalothrin and reported that the insecticides negatively affected the longevity of adult aphid parasitoids. In contrast, Saner *et al*. (2014) reported that lambda-cyhalothrin and imidacloprid were found to be eco-friendly towards the ladybird beetle population.

Similarly, Ahmed *et al*. (2014) conducted a study to evaluate the impact of neonicotinoids and traditional insecticides against cotton pests and their natural enemies. From the outcome of the study, it was evident that imidacloprid controlled sucking pests while it did not have an impact on the natural enemies. Tillman and Mulrooney (2009) recorded that, after spraying cotton with lambda-cyhalothrin, the number of predators of cotton aphids was found to increase as the number of cotton aphids increased, indicating that lambda-cyhalothrin did not have an impact on the predator population. Saeed *et al*. (2016) evaluated the efficacy of imidacloprid against the cotton leafhopper and its predators; and documented that when imidacloprid is applied at the manufacturer-recommended dose, there are fewer negative effects on the abundance of natural enemies (Nazir *et al*., 2017). Chlorpyrifos has been reported to cause high mortality on the natural enemies of whiteflies (Prabhaker *et al*., 2007), aphids (El-Sayed and El-Ghar, 1992), and spider mite (Al-Ne'ami, 1981) as well as the larvae of green lacewing and spiders (Dhawan, 2000).

Natural enemies also reduce cotton bollworm eggs and larvae without insecticide application (van Hamburg and Guest, 1997). Despite all the positive and negative impacts of insecticides, cases of natural enemies showing resistance to insecticides have also been recorded in some studies (Barbosa *et al*., 2016). It is recommended that selective insecticides be encouraged to control cotton pests, maintaining the natural enemies' population (Machado *et al*., 2019).

1.4.2.3 Environmental pollution

The excessive use of hazardous insecticides has a huge impact on the environment, water, and soil fertility in many countries. (Yasin *et al*., 2014; Székács *et al*., 2015). There are over 4.6 million pesticides that are applied in the environment (Ansari *et al*., 2014). Most of the insecticides are resilient towards degradation, and therefore they remain in the environment for a prolonged period (Farhan *et al*., 2014). Environmental impact due to repeated use of insecticides is categorized by different environmental compartments such as air, soil, land, and groundwater (Özkara *et al*., 2016). The soil is regarded as the main source of different pollutants and contaminants to surface water, groundwater, and air (Tao *et al*., 2008; Zhang *et al*., 2011). Pesticides can be transported from the soil through contaminated surface water and leach into groundwater resulting in damage to non-target organisms and pollution to the soil (Zhang *et al*., 2015).

The use of neonicotinoid insecticides in agriculture has been reported to contaminate the soil while their residues are transferred to the aquatic environment and reduce the abundance of aquatic insects (Sánchez-Bayo *et al*., 2016). Sumon *et al*. (2018) stated that imidacloprid might pollute aquatic ecosystems through spray drift, surface runoff, and groundwater leaching. They further conducted a study to assess the effects of imidacloprid on the freshwater and sub-tropical ecosystems in Bangladesh. It was recorded that sub-tropical ecosystems were negatively affected by imidacloprid compared to temperate regions. Lambda-cyhalothrin has also been widely used in agriculture, and its residues in runoff waters are toxic to humans and aquatic organisms (Colombo *et al*., 2018).

Imidacloprid and chlorpyrifos residues have been found to be highly contaminating in most of the soils (Rafique *et al*., 2016). A study was done in fruit orchards in the Western Cape province of South Africa to determine the effect of organophosphorus and endosulfan insecticides as a potential source of contamination in farm streams (Schulz *et al*., 2001). It was found that the level of pesticide deposition on the ground declined with increasing distance from the sprayed plants. In India, a study was conducted to determine the level of organophosphorus pesticide residues along the 85 km stretch of a river that flows near cotton plantations (Thakur *et al*., 2017). Chlorpyrifos was one of the organophosphorus pesticides that were detected in the water samples above the permissible limit.

1.4.2.4 Secondary pest outbreaks

The effect of broad-spectrum pesticides on targeted pests may reduce natural enemies and cause outbreaks of secondary pests (Johnson and Tabashnik, 1999; Gross and Rosenheim, 2011). The outbreak of secondary pests may occur after effective control of primary pests when the two pest species feed on the same plant part (Dutcher, 2007). However, secondary pest outbreaks are occasionally difficult to document as they may be due to factors other than the applied pesticides (Gross and Rosenheim, 2011). With the introduction of Bt cotton, there has been a reduction in insecticide use for bollworms. However, this led to outbreaks of secondary pests, necessitating the continuous use of synthetic insecticides (Lu *et al*., 2009; Zeilinger *et al*., 2016). This continued use of insecticides may also cause the resistance of the target pests. Harris *et al*. (1998) have demonstrated that over-spraying Karate (λ-cyhalothrin) combined with proper habitat management can control secondary pests on Bt cotton and reduce resistance development. Insecticides are highly toxic to insect predators of pink bollworm, and they are alleged to encourage the outbreaks of other cotton pests (Steenwyk *et al*., 1976). While lambda-cyhalothrin has been highly poisonous to spider mites and their natural enemies, imidacloprid has been recorded to have minimal harm to this pest but highly poisonous to the natural enemies (Schmidt-Jeffris and Beers, 2018). This may be because spider mites are initially susceptible to the pesticide and develop resistance more quickly than their natural enemies. In Australia, the application of organophosphates has been observed to disrupt beneficial insects, which may result in outbreaks of secondary pests (Hill *et al*., 2017).

Wilson *et al*. (1998) studied the effect of insecticides on cotton red spider mites and their predators, and they reported an outbreak of spider mites when insecticides significantly suppressed the predator. In South Africa, red spider mites were also recorded as a primary pest on cotton after predator suppression caused by the negative effect of pesticides (van Hamburg and Guest, 1997).

1.4.3 Cultural control

Cultural control is one of the oldest techniques used to regulate the pest populations in agriculture while encouraging crop growth. Cultural control is intended to make the environment less attractive and favourable to pests, stimulating the reduction in the pests' populations to allow natural or biological controls to take effect (Hill, 1989). The control of cotton insect pests through cultural strategies includes selecting suitable cultivars and correct agronomic practices that commence at pre-planting until post-harvest (Abd-Rabou and Simmons, 2012). This control method involves long-term planning and may control a specific pest but may not be effective against other species (Hill, 1989). Some cultural strategies such as planting time, climatic factors, post-harvest practices, resistant varieties and mixed cropping play a pivotal role in controlling some key pests of cotton when integrated with other control measures (Frank *et al*., 2018). These strategies can also decrease the application of insecticides on cotton for small-scale farmers; however, some of these strategies have not been fully explored, and further research and adoption are required (Javaid, 1995).

1.4.3.1 Timing of planting

Different cultural methods such as early planting of cotton can substitute the use of pesticides (Matthews and Turnstall, 1994); however, these methods are commonly not preferred as much as pesticides (Karavina *et al*., 2012). Early planting and early termination of crops remain two of the key methods used to control pests in crops (El-Wakeil and Abdallah, 2012). The importance of planting time on the control of pests has been studied extensively around the world. Early planting of cotton has been reported to decrease red bollworms, leafhoppers, and aphids (Karavina *et al*., 2012). The correct planting date of cotton can prevent the outbreaks of spider mites and thrips (Khan *et al*., 2008). Kerns *et al*. (2019) also indicated that early planting of cotton could potentially reduce thrips infestation.

Vyavhare and Kerns (2017) recommended that planting cotton during cool conditions reduces the population of thrips and that thrip migration to cotton may be avoided by not planting cotton near small grains and onions fields. Early planting of cotton has a positive impact on reducing late pests like red spider mites (Dippenaar, 2015). Late planting of cotton has been found to reduce the biological control efficiency of ladybirds against aphids (Ge *et al*., 2002). Saeed *et al*. (2018) evaluated planting time-based action thresholds to control cotton leafhoppers. They demonstrated that early planting of cotton required only one spray of insecticides without significant yield loss compared to 10 sprays needed for late planting. Iqbal *et al*. (2018) reported that early cotton planting had less boll retention but higher seed cotton yield. Early planting to allow time between successive crops is a useful tool to control whiteflies; however, this practice relies on the absence of weeds and other plants that may be the host of this pest (Perring *et al*., 2018).

1.4.3.2 Climate/ abiotic factors

Heavy rainfalls have been reported to reduce thrips on onion plants by washing away the pest (Waiganjo *et al*., 2008; Ibrahim and Adesiyun, 2010). Heavy rainfalls and overhead irrigation can displace or drown thrips resulting in a significant reduction of the pest population (Diaz-Montano *et al*., 2011). In a study conducted by Ashfaq *et al*. (2010) on the effectiveness of rainfall of some pests of Bt cotton, it was noted that rainfall reduced the whitefly population; however, there was no effect on the leafhopper population. Kone *et al*. (2017) observed that with the regression of the rainfall in Côte d'Ivoire, there was a significant increase in the population of leafhoppers. Different irrigation techniques and fertilizer applications have been reported to reduce the numbers of whiteflies, which results in lower virus incidence in tomato production (Perring *et al*., 2018). Higher nitrogen levels were found to decrease the population of whiteflies (Jauset *et al*., 2000; Park *et al*., 2009; Hosseini *et al*., 2015) in tomatoes, while daily drip irrigation positively influenced whitefly densities and lower incidence of virus (Abd-Rabou and Simmons, 2012). Rainfall was also reported to increase the mortality of the first and fourth aphid instars during the vegetative, flowering, and fruiting stages of cotton (Chamuene *et al*., 2020).

1.4.3.3 Mixed cropping

Plant diversification has been used to control pests in many crops (Ratnadass *et al*. 2012); however, some plant species may act as an alternative source of food and shelter for insect pests (Tonhasca and Byrne 1994). Many farmers globally practice intercropping to control pests (Kremer, 2019) and enhance beneficial insects on different crops (Jones and GIllett, 2005). Cotton intercropped with maize, sesame, and soybean has also been reported to sustain the populations of different beneficial insects that attack cotton pests (Godhani *et al*., 2010). The rotation or intercropping of cotton with wheat and maize have been reported to increase the population of predators and reduce aphids in cotton (Ouyang *et al*., 2020). Cotton has been intercropped with basil and sorghum to decrease different pests of cotton and enhance predators of cotton aphids (Parajulee *et al*., 1997; Xia, 1997; Schader *et al*., 2005). Wheat-cotton and fennel-cotton intercropping systems have been found to conserve beneficial insects and reduce cotton aphid populations (Ma *et al*., 2006; Fernandes *et al*., 2015).

Dassou *et al*. (2019) also recorded a significant abundance of beneficial insects, including ants and spiders, in mixed-cropping systems compared with mono-cropping systems. Myaka and Kabissa (1996) examined the influence of insecticide applications when cotton is intercropped with cowpea. The results demonstrated that insecticides applied to cotton also controlled the pests found on cowpea when the crops were in alternating single rows. Intercropping of cowpea in cotton has also shown a positive effect on controlling the population of thrips and whiteflies and increasing the yield (Chikte *et al*., 2008). Multiple hosts affect the behaviour of whiteflies and cause the frequent migration of the pest from one host to the other, which reduces the feeding periods on each host (Perring *et al*., 2018). Intercropping of vegetables with other crops under field conditions has a positive impact on reducing thrips populations (Diaz-Montano *et al*., 2011). Thrips populations have been reduced when onion and garlic were intercropped with tomato (Afifi and Haydar, 1990) as well as when onions were intercropped with carrots (Uvah and Coaker 1984). Onion intercropped with cotton also acts as a trap crop to reduce the thrips population (Khaliq *et al*., 2016). Due to prolonged flowering, pigeon pea can act as a refuge for cotton bollworms, thus producing as many pupae as unsprayed cotton (Baker *et al*., 2008).

Although different crops, when intercropped with cotton, have shown a good reduction of insect pests, Li *et al*. (2018) reported that there were higher spider mite populations in both systems than in the cotton mono-cropping system.

1.4.3.4 Natural enemies

Natural enemies or beneficial insects such as predators, parasitoids, and pathogens play a significant role in the population dynamics of different crop pests. They have a long history as a possible alternative for insect control in crops (Orr and Lahiri, 2014; García-Lara and Saldivar, 2015). They are more effective against insect pests when the pest populations are low as they are not as fast as synthetic pesticides (Hagstrum and Subramanyam, 2006). In fields where natural enemies were used to control cotton pests such as whitefly, leafhopper, and thrips, there were lower infestations of these pests (Mohyuddin *et al*., 1997). Although natural enemies may affect a small portion of the thrips population, many predators such as pirate bugs and spiders are effective in controlling the pest (Diaz-Montano *et al*., 2011; Vyavhare and Kerns, 2017).

With the introduction of Bt cotton, insecticide application has been reduced, which has increased the populations of natural enemies of different cotton pests (Luo *et al*., 2014). Natural enemies such as aphid parasitoids, coccinellids, and spiders are reported to suppress aphid populations during the early to middle stages of cotton growth were key natural enemies of cotton aphid (Abney *et al*., 2000; Ali *et al*., 2016). The presence of arthropod predators also plays a significant role in killing whiteflies compared to aphelinid parasitoids on cotton (Asiimwe *et al*., 2016). Prasifka *et al*. (1999) documented that when grain sorghum is planted adjacent to cotton fields, there is some evidence of the movement of natural enemies between the crops, which contributes to pest control in cotton.

1.4.3.5 Resistant varieties

Genetic improvement of cotton varieties contributes to resistance or tolerance against major pests and diseases (Rajendran *et al*., 2018). Hairy cotton varieties have been widely reported to reduce different cotton insect pests. Early season sucking pests of cotton have been found to be controlled by hairy cotton varieties (Naveed *et al*., 2011). Cotton varieties with smooth leaves are reported to be susceptible to leafhopper attacks (Matthews, 2003).

In South Africa, hairy cotton varieties for resistance to leafhoppers were started in the 1920s (Annecke and Morán, 1982). In 2014, the Agricultural Research Council registered a new hairy cotton cultivar resistant to leafhopper attacks (ARC, 2014). In 1934, Hargreaves also recorded an association between hairiness of leaves and resistance to leafhopper infestation on cotton. In Malawi, Jambawe *et al*. (2001) revealed that some cotton varieties from Zimbabwe exhibited moderate to high levels of leafhopper tolerance. The development of hairy varieties could provide good leafhopper tolerance in cotton varieties by inhibiting leafhopper feeding and multiplication (Rajendran *et al*., 2018). Most cotton varieties genetically modified for bollworm tolerance are susceptible to leafhopper damage (Rajendran *et al*., 2018). Reddall *et al*. (2011) revealed that although colonies of spider mites developed quicker on hairy cotton leaves, there was greater leaf damage on smooth cotton leaves. Cotton plants can use gossypol in tissues as a biochemical defence against various pests. Oligophagous pests are reported to adapt to the chemical, while polyphagous pests survive one or two generations and eventually relocated to other crops (Rajendran *et al*. 1999).

African bollworms were reported to migrate to pigeon pea during the flowering stage of cotton, while spiny bollworms relocate to okra after completing early generations in cotton (Rajendran *et al*., 2018). A study conducted by Khalil *et al*. (2017) on the effects of plant morphology on the incidence of cotton pests revealed that whiteflies and thrips showed a positive correlation with hair density on cotton leaves, whereas leafhoppers revealed a negative response. Leafhoppers further displayed a positive correlation with gossypol glands on the different leaf parts, while the thrips population showed a negative correlation. The pH and shape of cotton leaves have also provided some tolerance level against whiteflies (Avidov, 1956).

1.4.3.6 Tillage systems

For centuries, tillage has been one of the most important practices to clear and loosen the soil for planting crops (Ali *et al*., 2020). Since some pests can build up in crop residues, it is important to use cultural practices to control insect pests and reduce the use of pesticides (McCutcheon, 2000). Soil tillage plays a significant role in soil-inhabiting organisms, and it has an impact on predatory arthropods (Rusch *et al*., 2010).

Some tillage methods can decrease pest populations by removing weeds and other volunteer crops around the main crop (Vänninen, 2005). Conservation tillage is a method that is used to loosen soil with little disturbance, and this suppresses insect pests while inducing natural enemy populations (Knight *et al*., 2017). Conservation tillage has been found to reduce the abundance of thrips on cotton compared to conventional tillage (Parajulee *et al*., 2006; Bauer *et al*., 2010). In an experiment to evaluate the effect of different tillage systems on thrips populations, Harris *et al*. (1999) documented lower populations of thrip adults and larvae where no soil tillage was done. Gencsoylu and Yalcin (2004) reported that although different tillage systems had no negative impact on the cotton pests and their natural enemies, the highest numbers of whiteflies were observed in the conventional and strip tillage compared to the precision and ridge tillage systems. Deep ploughing has been found to play a significant role in the avoidance of pest carry-over in cotton production (Rajendran *et al*., 2018). Bowers *et al*. (2020) reported that cover crops could improve the populations of natural enemies on cotton, and they could reduce insecticide application by natural reductions in pest pressure.

1.4.4 Biological control

Pest management has significantly evolved to include integrated pest management that focuses on biological control strategies that include biopesticides. It has been widely reported that chemical pesticides have a negative impact on the environment; therefore, efforts have been made to minimize their use in controlling insect pests. Biopesticides are commonly used to manage agricultural pests through specific biological effects (Dimetry, 2014). Biopesticides are cheaper, take less time to develop (Liu *et al*., 2019) and naturally less toxic to humans and the environment (Leahy *et al*., 2014) compared with synthetic pesticides.

They are mainly categorized into three groups: biochemical, plant, and microbial pesticides (Ojha *et al*., 2018; Fathipour *et al*., 2019; Nuruzzaman *et al*., 2019). Biochemical pesticides include plant extracts, pheromones and plant and insect growth regulators that control pests by non-hazardous mechanisms (Sarwar *et al*., 2018). Plant pesticides, also known as plant-incorporated protectants, include genetically modified crops using protein from the bacterium *Bacillus thuringiensis* (Liu *et al*., 2019). Microbial pesticides consist of viruses, fungi, and bacteria (Marrone, 2019).

Biopesticides form only around 5% of the global pesticides (Seiber *et al*., 2014), while microbial pesticides account for over 75% worldwide (Leppla *et al*., 2018). In South Africa, there are over 30 microbial-based products registered, including *B. thuringiensis*, *B. bassiana*, and *H. armigera* nucleopolyhedrovirus (Hatting *et al*., 2019).

1.4.4.1 Bacillus thuringiensis

Bacillus thuringiensis subsp. kurstaki is a spore-forming gram-positive bacterium that produces poisonous insecticidal crystal proteins used on more than 3 000 different insects (Wu *et al*., 2011; Zhang *et al*., 2016). It was first isolated by Shigetane Ishiwatari in 1901 and first used commercially in the 1920s (Gorashf *et al*., 2014). *B. thuringiensis* accounts for 95% of the biopesticide market worldwide (Devi *et al*., 2019). The bacterium plays a significant role in biological control because it is the most widely used microbial control agent (Nuruzzaman *et al*., 2019). Different strains of *B. thuringiensis* have been produced with different spectrums of activity (Thorne *et al*., 1986). *B. thuringiensis* commonly attacks larval stages of different insects rather than adults or other stages (Raymond *et al*., 2010; Ring, 2017). As a target-specific pathogen, *B. thuringiensis* only attacks the target insects (Bravo *et al*., 2011) without disturbing non-target insects and natural enemies (Ring, 2017; Pujiastuti *et al*., 2019). *B. thuringiensis* does not kill the target pest on contact but through disruption of the midgut tissue of the insect (Raymond *et al*., 2010). It is therefore difficult for the pathogen to attack those insects that feed inside the plant part (Ring, 2017). *B. thuringiensis* toxins have shown well-documented toxicity against various insects, including Lepidoptera, Diptera, Hemiptera, Coleoptera, and nematodes (Dulmage, 1981; Brousseau and Masson, 1988; Acosta and Dicklow, 1993; Wei *et al*., 2003; Torres-Quintero *et al*., 2018; Fernández-Chapa *et al*., 2019).

In cotton, *B. thuringiensis* has been widely reported as a biopesticide to control various insect pests (Gorashf *et al*., 2014; Togbé *et al*., 2014; de Bortoli *et al*., 2015). Table 1.1 provides an overview of some studies conducted to control some cotton pests using *B. thuringiensis*.

Table 1.1 Control of cotton pests using *Bacillus thuringiensis*

Control	Findings	Authors
Larvicidal activity of *Bacillus thuringiensis* strains against *Bemisia tabaci*	The second instar larvae of *Bemisia tabaci* exhibited mortalities of up to 69%.	(Cabra and Fernandez, 2019)
Interaction of *Bacillus thuringiensis* and *B. bassiana* for biological control of *Bemisia tabaci*	Higher concentrations of *Bacillus thuringiensis* and *Beauveria bassiana* had above 90% mortality of *Bemisia tabaci* nymphs	(Somoza-Vargas *et al*., 2018)
Efficacy of *Bacillus thuringiensis* spray applications for the control of *Earias biplaga*	*Bacillus thuringiensis* spray provided between 77 and 88% control of *Earias biplaga* after ten days	(Fourie *et al*., 2017)
Effects of *Bacillus thuringiensis* on *Alabama argillacea* and *Aphis gossypii* of cotton	Dipel® had good control on *Alabama argillacea,* selective for *A. gossypii,* and caused an increase in cotton yield	(de Bortoli *et al*., 2015)
Evaluation of *Bacillus thuringiensis* strain when applied to *Bemisia tabaci* nymphs	*Bacillus thuringiensis* strain had 88-92% mortality of the third and fourth instar of *Bemisia tabaci* nymphs	(Salazar-Magallon *et al*., 2015)
Efficacy of biopesticides and chemical insecticide to control *Helicoverpa armigera*	*Bacillus thuringiensis* showed the highest mortality rate of *Helicoverpa armigera* larvae in the shortest period	(David *et al*., 2013)
Efficacy of *Bacillus thuringiensis* against *Helicoverpa armigera* under laboratory and field conditions	*Bacillus thuringiensis* showed 95-100% and 76% *Helicoverpa armigera* mortality under laboratory and field conditions, respectively	(Shanker *et al*., 2009)
Influences of *Bacillus thuringiensis* cotton on *Aphis gossypii*	*Bacillus thuringiensis* cotton efficiently prevented *Aphis gossypii* resurgence in response to insecticide use	(Wu and Guo, 2003)
Effects of *Bacillus thuringiensis* on larva and adult of *Bemisia tabaci*	*Bacillus thuringiensis* showed latent effects on the reproductive potential of *Bemisia tabaci*	(Al-Shayji *et al*., 1998)
Evaluation *Bacillus thuringiensis* for control of *Heliothis* spp. on cotton	Dipel exhibited higher mortality of *Heliothis* spp. larvae	(Patti and Carner, 1974)

1.4.4.2 Beauveria bassiana

Beauveria bassiana (Bals) Vuill is a fungus that grows naturally in soils. It is one of the commercial alternatives to chemical insecticides (Lopez *et al*., 2014). Its strains have been used as the active ingredient in several biopesticides to control a diversity of agricultural pests (Zanwar *et al*., 2010). The genus *Beauveria* contains at least 49 species, of which approximately 22 are considered pathogenic (Lopez and Sword, 2015). Notwithstanding its importance as a biological control agent, *B. bassiana* is also an organism used to examine fungal growth and development, such as host-pathogen interactions (Bugeme *et al*., 2014; Arthurs and Bruck, 2017). Its strains can be developed as host-specific, considering their broad-spectrum as an insect pathogen (Uma Devi *et al*., 2008). *B. bassiana* has good control by coming into contact with the insect pests (Gatarayiha, 2009). *B. bassiana* attacks its host by penetrating the exoskeleton or cuticle (Mousumi and Sabu, 2020), producing a toxin that prevents the immune response of the host (Lopez *et al*., 2014). Even though *B. bassiana* based biopesticides may reduce the application of chemical pesticides; their effectiveness requires enhanced formulation or combining them with other pesticides (Islam and Omar, 2012). *B. bassiana* is a promising pathogen against a variety of cotton pests, including spider mites (Seyed-Talebi *et al*., 2012), stainers (Vinayaga Moorthi *et al*., 2012), thrips (Abe and Ikegami, 2005), whiteflies (Lacey, 2016; Zafar *et al*., 2016), aphids and bollworms (Lopez *et al*., 2014; Lopez and Sword, 2015). Some research on the efficacy of *B. bassiana* in cotton pests is documented in Table 1.2 below.

Table 1.2 Control of cotton pests by using *Beauveria bassiana*

Control	Findings	Authors
The activity of protease and the virulence of *Beauveria bassiana* isolates against *Tetranychus urticae*	The isolate of *Beauveria bassiana* caused 15 to 70% mortality of *Tetranychus urticae*	(Elhakim *et al*., 2020)
Pathogenicity of *Beauveria bassiana* isolates against *Helicoverpa armigera* larvae	Of 22 *Beauveria bassiana* isolates, four exhibited >80% larval mortality	(Tahir *et al*., 2019)
Assessment of the effects of exposure of *Helicoverpa armigera* larvae to *Beauveria bassiana*	Pre-adult duration of *Helicoverpa armigera* was extended, and longevity and fecundity were decreased	(Kalvnadi *et al*., 2018)
Effect of isolates of *Beauveria bassiana* against different life stages of *Bemisia tabaci* on cotton	*Beauveria bassiana* isolate had the highest eggs (65.30%) and nymphs (88.82%) mortality	(Zafar *et al*., 2016)
Effect of *Beauveria bassiana* on cotton growth and control of cotton bollworm	*Beauveria bassiana* significantly reduced boll damage, increased plant dry biomass and seed cotton yield	(Lopez and Sword, 2015)
Infection of *Helicoverpa armigera* by endophytic *Beauveria bassiana* colonizing tomato plants	*Beauveria bassiana* has potential as an effective strategy to control *Helicoverpa armigera*	(Qayyum *et al*., 2015)
Susceptibility of different stages of *Tetranychus urticae* to *Beauveria bassiana* in the laboratory	*Beauveria bassiana* gave 90% mortality of *Tetranychus urticae*	(Bugeme *et al*., 2014)
Effect of *Beauveria bassiana* against *Aphis gossypii* on cotton	Plants inoculated with *Beauveria bassiana* had significantly lower numbers of *A. gossypii*	(Lopez *et al*., 2014)
Control of *Helicoverpa armigera* with *Beauveria bassiana*	The highest dose of *Beauveria bassiana* gave 76.7% mortality on the fourth instar larvae of *Helicoverpa armigera*	(Prasad *et al*., 2010)
Effect of *Beauveria bassiana* on the control of *Tetranychus urticae*	*Beauveria bassiana* had 81.8% control of *Tetranychus urticae*	(Gatarayiha, 2009)
Biological control of *Tetranychus urticae*	Two strains of *Beauveria bassiana* caused 80% mortality of *Tetranychus urticae* in the laboratory and one strain-controlled *Tetranychus urticae* in the field	(Armes *et al*., 1996)

1.4.4.3 Metarhizium rileyi

Metarhizium rileyi (Farlow) Kepler, formerly known as *Nomuraea rileyi,* is a potential agent for microbial control of insect pests that can cause considerable agricultural productivity loss (Binneck *et al*., 2019). It is an entomopathogenic fungus commonly known to infect and cause mortality in insects, particularly the lepidopterans (Kogan *et al*., 1999; Fronza *et al*., 2017; de Souza Loureiro *et al*., 2020). The fungus is host-specific and eco-friendly, making it significant in integrated pest management (Sinha *et al*., 2016). However, *M. rileyi* has been rarely developed and commercialized (Jaronski, 2013). As a result, the host range of *M. rileyi* has been reported to be only around 60 species compared to fungi such as *B. bassiana* (Fronza *et al*., 2017). As a well-known entomopathogenic fungus used in the biological control of pests, limitations include the long pathogenic process and its application is limited (Liu *et al*., 2019). On the contrary, Jaronski and Mascarin (2017) have claimed that *M. rileyi* can be more easily produced than other fungi. *M. rileyi* has been broadly studied, mainly on its efficacy against *H. armigera* (Barad *et al*., 2015; Costa *et al*., 2015; Zhong *et al*., 2017). Table 1.3 presents some research work on the control of cotton pests using *M. rileyi*.

Table 1.3 Control of cotton pests by using *Metarhizium rileyi*

Control	Findings	Authors
The potential of *Metarhizium rileyi* as a biological control agent of *Bemisia tabaci*	*Metarhizium rileyi* isolate had a high mortality rate and control efficiency against *Bemisia tabaci*	(Espinosa *et al*., 2019)
Field evaluation *Nomuraea rileyi* against *Helicoverpa armigera*	*Nomuraea rileyi* significantly reduced *Helicoverpa armigera* (74.58%) larval population	(Sharmila and Manjula, 2017)
Effect of *Nomuraea rileyi* on *Helicoverpa armigera* cellular immune responses	*Nomuraea rileyi* suppressed the cellular immune response of *Helicoverpa armigera*	(Zhong *et al*., 2017)
The occurrence of an entomopathogenic fungus on *Helicoverpa armigera* larvae	The natural occurrence of *Nomuraea rileyi* caused 33% of the total mortality of *Helicoverpa armigera* larvae	(Costa *et al*., 2015)
The effective dose of *Nomuraea rileyi* against *Helicoverpa armigera*	*Nomuraea rileyi* was effective against the developmental stages of *Helicoverpa armigera*	(Barad *et al*., 2015)
Bio-efficacy of *Nomuraea rileyi* against *Helicoverpa armigera*	*Nomuraea rileyi* revealed 30-83% mortality against different instars of *Helicoverpa armigera*	(Ingle *et al*., 2015)
The efficiency of *Nomuraea rileyi* against *Bemisia tabaci*	The percentage of infested plants with *Bemisia tabaci* significantly decreased after treatments with *Nomuraea rileyi* under the field conditions	(Matter and Sabbour, 2013)
Comparison of *Nomuraea rileyi* with *B. bassiana* and *Isaria fumosorosea* against *Helicoverpa armigera* in laboratory	*Nomuraea rileyi* performed the best with a mortality rate of 87 ± 1.4 % against *Helicoverpa armigera*.	(Hatting, 2012)
Pathogenicity of *Nomuraea rileyi* against *Helicoverpa armigera* larvae	*Nomuraea rileyi* showed 73 to 87% mortality of *Helicoverpa armigera* larvae within eight days	(Padanad and Krishnaraj, 2009)
Application of *Nomuraea rileyi* for the control of *Helicoverpa armigera*	*Nomuraea rileyi* showed an average of 95% mortality in fourth instar and fifth-instar larvae of *Helicoverpa armigera*	(Tang and Hou, 1998)
Effects of *Nomuraea rileyi* in a field population of *Helicoverpa armigera*	*Nomuraea rileyi* showed higher rates of fungal infection (37%) in *Helicoverpa armigera* found on pigeon pea	(Gopalakrishnan and Narayanan, 1989)

1.4.4.4 Nucleopolyhedrovirus

Baculoviruses belong to the family Baculoviridae, which consists of four genera, including *Alphabaculovirus* (Moscardi *et al*., 2011). Viruses from this family have been recorded since 1911, and their natural hosts include almost 700 insect species, mainly belonging to the orders Lepidoptera, Hymenoptera, and Diptera (Eroglu *et al*., 2020). Baculoviruses are host-specific (Nai *et al*., 2017; Rohrmann, 2019) and are usually limited to one or a few insect species (Cory and Myers, 2003; Haase *et al*., 2015). Because of their specificity, these viruses can form part of the resistance management strategy (Jehle *et al*., 2006), demonstrating genetic variations among species (Cory and Myers, 2003). Several members of baculoviruses that display promising results have been successfully developed into commercial biopesticides for the control of agricultural and forest insect pests worldwide (Grzywacz, 2017). However, the application of these pesticides has a limited acceptance due to marketing, slow speed of kill, and difficulties with registration and mass production (Knox *et al*., 2015). The production relies mainly on baculovirus infection and transmission in vulnerable hosts as well as harvesting and purification (Sokolenko *et al*., 2012). Although viruses can be an alternative to synthetic insecticides, they depend on integration with other management strategies (Endersby and Morgan, 1991). In South Africa, baculoviruses are used as part of integrated pest management programmes to control pests in field crops (Knox *et al*., 2015). Despite the regular use of baculoviruses as biopesticides, biological insecticides based on the bacterium *B. thuringiensis* remain the most used biopesticides (Moscardi *et al*., 2011).

Nucleopolyhedrovirus (NPV) is a naturally occurring pathogen that belongs to the group of Alphabaculovirus, and it is a lepidopteran-specific virus (Sosa-Gómez, 2017). The virus reproduces in the host cells, causing nuclear polyhedrosis disease, and the outbreak of the virus may assist in the control of the host population (Sun, 2015). The nucleopolyhedrovirus has the potential to control the target insects without harming the environment, pest predators, and parasitoids (Sharma *et al*., 2019). *Helicoverpa armigera* nucleopolyhedrovirus (HearNPV) is specifically developed to control *H. armigera,* and the formulations are commercially available throughout the world (Black, 2017). Whitlock (1974) was the first to report the virus in South Africa, and the first commercialization of HearNPV was done in China in 1993 (Sun, 2015).

It is reported to have significant potential as a biopesticide in the field (Moore *et al*., 2004; Knox *et al*., 2015). Nucleopolyhedrovirus can be used in conjunction with other insecticides to control *H. armigera* (Reddy and Manjunatha, 2000; Mtambanengwe, 2019). It is recommended that the application of HearNPV must commence when cotton starts flowering, and the pests are observed in the field (Black, 2017). However, the interaction between HearNPV and host insects remains poorly understood (Xing *et al*., 2017). Bolldex™ is one of the commercial labels currently registered as a HearNPV to control *H. armigera* (Knox *et al*., 2015). Below (Table 1.4) is a summary of some studies on the efficacy of the nucleopolyhedrovirus against cotton pests.

Table 1.4 Control of cotton pests by using nucleopolyhedrovirus

Control	Findings	Authors
Assessment of NPV and spinosad against *Helicoverpa armigera* in a controlled environment	The highest concentrations of NPV had the highest mortality of 95%	(Nawaz *et al*., 2019)
Pathogenicity of HearNPV against *Helicoverpa armigera*	HearNPV had 90-100% mortality effects on newly hatched and second instars larvae	(Ginting *et al*., 2018)
Evaluation of different HearNPV concentrations on neonate, 3rd, and 5th instars larvae of *Helicoverpa armigera*.	The highest dose of HearNPV showed 92% mortality within 14 days	(Eroglu *et al*., 2018)
The ability of HearNPV to kill each *H. zea* instar, and a second infestation	HearNPV was successful in controlling early instars of *H. zea* in five days	(Black, 2017)
The efficiency of production of HearNPV in *Helicoverpa armigera*	HearNPV exhibited 80–93% of virus-induced mortality in individualized *Helicoverpa armigera* larvae	(Arrizubieta *et al*., 2016)
Insecticidal efficacy of HearNPV on *Helicoverpa armigera*	Larval mortality of *Helicoverpa armigera* ranged from 97.9-100% at ten days post-application of HearNPV	(Arrizubieta *et al*., 2016)
Efficacy of HearNPV as a control in the cell transfection analysis	HearNPV caused paralysis, weight loss, and suppressed growth and feeding of *Helicoverpa armigera* larvae	(Yu *et al*., 2015)
Bio-efficacy of NPV against *Helicoverpa armigera*	NPV significantly reduced both larval population and boll damage	(Pugalenthi *et al*., 2013)
Field efficacy of (HaNPV) isolates and insecticide control against *Helicoverpa armigera* on cotton	HaNPV isolates significantly reduced *Helicoverpa armigera* larvae and recorded the highest yield of over 2 000 $kg.ha^{-1}$	(Jeyarani *et al*., 2010)
Evaluation of HearNPV for control of *Helicoverpa armigera* in citrus	HearNPV had a 100% reduction of *Helicoverpa armigera* larval infestation within 7-16 days	(Moore *et al*., 2004)

1.5 HOST PLANT RESISTANCE TO PESTS

Host resistance is one strategy that can decrease host susceptibility to pests (Shapiro-Ilan *et al*., 2012). Host plant resistance to insects can be caused by different characteristics, including morphological, physiological, and biochemical features of a plant that influence the selection of plant hosts by the pest (Din *et al*., 2016). It forms part of integrated pest management, and it can reduce the use of insecticides; however, it is crucial to rotate cultivars to avoid the development of resistance (Kennedy, 2008). Cotton breeders have broadly researched host plant resistance to integrate various traits such as leaf types and smoothness (Rajendran and Basu 1999). Plant secondary metabolic compounds play a vital role in plant resistance against insect pests (Guo *et al*., 2013). Gossypol is a toxic micronutrient produced by the cotton plant's pigment glands and consists of amino acids of proteins and inhibiting enzyme activities (Krempl *et al*., 2016). It is a phenolic compound found on all the cotton parts, including the leaves, seeds, and stems (Gadelha *et al*., 2014). Cottonseeds contain up to 6% of gossypol that act as plant resistance to insects (Brand *et al*., 2012). Cotton cultivars with higher levels of gossypol have been found to increase the fecundity and population of whiteflies (Guo *et al*., 2013). The resistance of cotton cultivars with high gossypol against cotton aphids has been well documented (Gao *et al*., 2008; Guo *et al*., 2013). Ma *et al*. (2014) reported that low gossypol levels in Bt cotton resulted in the decline of the generation time and an increase in the number of spider mites' eggs.

The relationship between the hairiness of the cotton plant and leafhopper infestation has been investigated, and leaf hairiness has been recorded to result in resistance to leafhoppers (Parnell *et al*., 1949). Cotton cultivars with smooth leaves developed to control bollworms are susceptible to leafhoppers, and there is ongoing research to develop resistant plants against cotton pests (Rajendran *et al*., 2018). In Sudan, Sippell *et al*. (1987) conducted an experiment on the effects of leaf-hair densities and leaf shapes on the whitefly population. They observed that low leaf-hair densities and okra leaf shapes significantly reduced the whitefly population and stickiness of lint caused by honeydew. They further noted that leaf shape also contributed to low humidity and higher temperature in the canopy. Miyazaki *et al*. (2017) observed no significant relationship between thrips abundance and the hairiness or leaf shape of cotton.

G. hirsutum cultivars with okra leaf shapes reduce populations of leafhoppers, whiteflies, and bollworms (Din *et al*., 2016; Nazir *et al*., 2019). Despite this, there are few okra leaf cotton cultivars available worldwide (Nazir *et al*., 2020). The population of sucking insect pests has been lowered by cotton growing with the okra leaf trait because of its open canopy (Ahmad *et al*., 2005).

1.6 PEST RESISTANCE TO PESTICIDES

The resistance of pests to different pesticides such as pyrethroids, neonicotinoids, and biopesticides have been extensively studied worldwide (Saeed *et al*., 2018). Insects can develop resistance to insecticides through various mechanisms such as behavioural, morphological, and physiological adaptations (Joußen and Heckel, 2016). Cotton bollworms and whiteflies have shown resistance to organophosphates, organochlorines, pyrethroids, and carbamates (Johnson *et al*., 2000; Joußen *et al*., 2012; Naveen *et al*., 2017). The development of resistance in whiteflies on cotton has been recorded for over 40 active ingredients of insecticides in several countries (Naveen *et al*., 2017). Pittendrigh *et al*. (2008) have observed resistance mechanisms of whiteflies to imidacloprid. The resistance of whiteflies to different insecticides can be reduced by alternating the insecticides with products such as biological agents (Capinera, 2001a). Using insecticides to control *H. armigera* has led to widespread resistance (Chaturvedi, 2007; O'brien *et al*., 2009; Tossou *et al*., 2019). Ochou and Martin (2002) conducted a study on pyrethroid resistance management using several non-pyrethroid insecticides to control *H. armigera* on cotton in West Africa. They found that alternating pyrethroids with endosulfan or profenofos at the vegetative stage of cotton significantly controlled *H. armigera* and increased the yields. In Côte d'Ivoire, Martin *et al*. (2000) noted that the continuous application of pyrethroids resulted in resistance of *H. armigera* populations. This led to the development of resistance management of the pest that was intended to reduce the reliance on pyrethroid by using alternative pesticides (Ochou and Martin, 2002; Djihinto *et al*., 2016). Although the resistance management strategy to control the *H. armigera* populations is effective, this often results in a significant increase of secondary pests on cotton plants (Herron and Wilson, 2017; Kone *et al*., 2018; Bouslama *et al*., 2020).

Pest resistance to pyrethroids has been noticed in cotton-producing regions around the world. In Australia, cotton bollworm resistance to pyrethroids was first identified in 1983 (Joußen *et al*., 2012), while countries such as Thailand, Egypt, and Zimbabwe reported resistance by 1985 (Sawicki and Denholm 1987). In South Africa, restrictions on pesticides were introduced in the late 1970s to avoid over-reliance on synthetic chemicals (Hatting *et al*., 2019). Cotton aphids have developed resistance against neonicotinoid insecticides despite using high rates (Ulusoy *et al*., 2018). Herron and Wilson (2017) revealed that despite the fact that aphids were effectively controlled by insecticides sprayed against cotton bollworms, after some time, aphids showed resistance to organophosphates targeted against bollworms.

Similarly, Wu and Guo (2003) reported significant resistance of cotton aphids to pyrethroid and organophosphate insecticides used to control cotton bollworms. Furthermore, Ulusoy *et al*. (2018) revealed that aphids had developed resistance to imidacloprid. Thrips have also developed resistance to pyrethroids (Toda and Morishita, 2009) and organophosphates (Nazemi *et al*., 2016). Pests with high fertility and a short life cycle can easily infest their hosts and develop resistance to insecticides (Diaz-Montano *et al*., 2011). The spider mites can quickly develop resistance to insecticides due to their short life cycle and abundant reproduction (van Leeuwen *et al*., 2010). Although cotton stainers continued to be susceptible to pyrethroids, including lambda-cyhalothrin, they may develop resistance to these insecticides (Saeed *et al*., 2018).

With the rising concern among different stakeholders regarding the negative impact of synthetic pesticide application for the control of crop pests (Knox *et al*., 2015), biopesticides can be alternated with insecticides to avoid insect resistance (Usta, 2013; Nawaz *et al*., 2019; Kranthi and Stone, 2020). The increasing pest status of *H. armigera* in South Africa has prompted renewed interest in the use of biopesticides, especially as resistance is suspected to be developing against commonly used chemical control measures. However, close to 30 insect species have been reported as resistant to *B. thuringiensis* toxins (Siegwart *et al*., 2015). The insect-resistant varieties have been used as a method of insect control; however, due to Bt resistance by non-target pests, cotton farmers are spending more money on pesticides than before the introduction of Bt cotton (Kranthi and Stone, 2020).

1.7 CHALLENGES AND OPPORTUNITIES FOR THE USE OF BIOPESTICIDES

Over-reliance on chemical control resulted in changes in the status of cotton pests and environmental pollution (El-Wakeil and Abdallah, 2012). In Sub-Saharan Africa, there are still challenges to sustain the environment for cotton production (Partzsch *et al*., 2019). Much research has focused on the advancement of pest control, and biological control agents are an important criterion for sustainable agriculture (Bale *et al*., 2008; Namasivayam and Vidyasankar, 2014). Biopesticides or biological pesticides are an eco-friendly alternative to chemical pesticides (Gupta and Dikshit, 2010). They can play a significant role in the integrated pest management of many insect pests (Usta, 2013). They are obtained from the environment to control agricultural diseases and insects (Liu *et al*., 2019). They are only about 5% of the total crop protection market; however, they are expected to surpass synthetic pesticides by 2050 (Damalas and Koutroubas, 2018). The production of biopesticides is sometimes highly labour intensive and difficult to produce at levels that are economically viable and profitable (Claus *et al*., 2012). Enhancement of biopesticides has been explored by improving different compounds to sustain their efficacy as well as the shelf life (Leggett *et al*., 2011; Ravensberg, 2011). The development of non-toxic and effective biopesticides requires a holistic approach, which will turn most of the research results into profitable business products. Although this section provides generalities, each biopesticide needs to be individually assessed to determine its impacts on pest control, humans, the environment, and other factors associated with their adoption by farmers.

The adoption of biopesticides by farmers relies on their efficacy, increased yield, lower prices, and an efficient supply (Shukla *et al*., 2019). They have been unreliable and very costly due to their limited market share (Siegwart *et al*., 2015). However, Sharma and Sharma (2019) reported that bacterial biopesticides are the most widely used and less expensive than other control measures. Biopesticides benefit the farmers due to target specificity, the ability to manage the pest rather than eradicate, and conservation of environmental balance (Gupta and Dikshit, 2010). The very high specificity of the products might be a disadvantage when a complex pest species needs to be controlled.

Baculovirus-based insecticides have been considered safe on non-target organisms and can be used as part of integrated pest management to ease the risks of synthetic insecticides (Haase *et al*., 2015). However, baculoviruses are reported to act slowly in killing the targeted pests (Islam and Omar, 2012), which has led to the development of faster killing products through genetic modifications (Moscardi *et al*., 2011; Knox *et al*., 2015). Baculoviruses are also reported to be less effective due to their high susceptibility to ultraviolet radiation, and this requires the reapplication of the virus over time (Arthurs and Lacey, 2004; Jeyarani *et al*., 2013). The activity of nucleopolyhedrovirus has been found to significantly decrease over time after the application of the virus on the plant leaves (Arrizubieta *et al*., 2016). When exposed to direct sunlight, nucleopolyhedrovirus has been reported to be inactivated within a day or two (Kranthi *et al*., 2001).

The efficiency of entomopathogens mainly relies on their ability to infect the target insect and their persistence (Patil *et al*., 2017). Microbial insecticides have low persistence in the environment, and they require accurate application because many of these pathogens are insect-specific (Bravo *et al*., 2011). Namasivayam and Vidyasankar (2014) recorded that various formulations of *M. rileyi* are persistent under different temperatures. They further recommended that the utilization of a bio gel formulation of *M. rileyi* might play a role to control pests under field conditions. The persistence of *B. bassiana* under field conditions has been found to be negatively affected due to ultraviolet light, extreme temperatures and rain (Gatarayiha, 2009). Sandhu *et al*. (1993) have reported that this pathogen can live longer at lower temperatures and relative humidity. Bouslama *et al*. (2020) demonstrated that some formulations of *B. thuringiensis* could be persistent after rain wash compared to treatment with an unformulated bacterium. Biopesticides that degrade rapidly in the environment may have a short field persistence resulting in numerous product applications (Islam and Omar, 2012). The major constraints of biopesticides are limited to, among others, environmental conditions such as solar ultraviolet radiation, temperature, humidity and their ability for spreading on the surface (Patil *et al*., 2017; Saranraj and Jayaparakash, 2017). Since biopesticides often contain living material, the products have reduced shelf lives. Temperature, moisture or humidity also plays a role in the shelf life of the biopesticides (Hong *et al*., 1997).

Due to their practical limitations, such as rapidly washing away in rain and degradation by the sunlight (Watkins *et al*., 2012), biopesticides may not be as effective as synthetic pesticides. The impact of rain on the persistence of entomopathogenic fungi is less when the conidia are in direct contact with the cuticle of leaves and larvae (Inglis *et al*., 1995). Under natural conditions, biopesticides often cause natural mortalities of insect populations (Sandhu *et al*., 1993). Inglis *et al*. (2000) noted that the influence of rain has a minimal effect on *B. bassiana* persistence; however, high rains washed away significant quantities of *B. bassiana* from leaves.

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CHAPTER 2

SURVEY ON THE CURRENT STATUS OF PESTS ON COTTON AND PRODUCTION PRACTICES IN SOUTH AFRICA

Abstract

There is no recent information on the status of incidence of the major cotton pests and diseases in South Africa. The last survey of cotton pests conducted was more than 15 years ago. To fill the gap, a study was conducted in four cotton-producing areas from three provinces: (1) to evaluate farmers' knowledge and perceptions of cotton pests; (2) to examine farmers' current practices in managing cotton pests; and (3) to identify pest management challenges and intervention opportunities to develop an efficient, integrated pest management programme for cotton production. One hundred and forty farmers, mainly smallholder farmers (farmers owning small-based plots of land on which they grow subsistence crops), were interviewed during the 2017/18 growing season using a questionnaire. Most farmers (62%) planted cotton on less than five hectares of land, with 96% planting dryland cotton varieties. Although all the farmers planted GM cotton (genetically modified by the insertion of one or more genes from a common soil bacterium, *Bacillus thuringiensis*), 34% preferred non-GM varieties. The majority of the farmers neither practised conservation agriculture (95%) nor conducted soil analysis (87%). A mean cotton seed yield of 700 $kg.ha^{-1}$ was reported by dryland farmers, while a mean yield of 5 000 $kg.ha^{-1}$ was obtained from irrigated cotton. Most of the farmers (99%) harvested their cotton by hand picking. Farmers' knowledge of pest was slightly better than their knowledge of different diseases that attacked their crop. Most of the participants were unaware of nematodes (88%), or cultivars resistant to diseases (74%), while 91% were aware of insect-resistant cultivars. Most respondents were mentored and supported by extension officers (82%), whereas the Cotton Research Institute supported only 1%. Most farmers relied on chemicals to control cotton pests (57%), and only 7% used biological control. Climatic conditions (98%), labour costs (88%) and insect infestations (42%) were identified as the main constraints to efficient cotton production. Almost two thirds (65%) of the respondents referred to weed infestation as a factor limiting high yields. This study will contribute to cotton production by identifying the gaps in the industry to increase yields, reduce pesticide use, and generate a higher gross margin.

2.1 INTRODUCTION

Cotton (*Gossypium hirsutum* L.) is an important cash crop globally (Boyer *et al.*, 2017; Tigga *et al*., 2017), particularly in the Southern African Development Community countries (Gwarazimba, 2009). Cotton is grown in more than 100 countries globally, and it accounts for about 31% of worldwide fibre production (Australian Grown Cotton Sustainability Report, 2014). However, South Africa's production is far less than the domestic demand for cotton (DAFF, 2011). Cotton production is marginally profitable, and yield losses are likely to make its production unprofitable. Cotton is susceptible to a wide range of insect pests that significantly impact the yield and quality of the fibre (Manjunath, 2004). The damage caused by these pests is most severe on cotton grown in developing countries by farmers who lack knowledge of these pests and are limited with their control options. Efficient integrated pest management (IPM) has long been proposed as being essential for efficient cotton production (Fitt *et al*., 2009). However, the concept requires interventions based on a thorough knowledge of the pests, the crop and the environment (Prudent *et al*., 2007). Although pests and diseases are not new to South African cotton farmers (DAFF, 2011), there is no recent information that reflects their current status on cotton. An important component to improve cotton production is to obtain an insight into farmers' knowledge and needs, as acceptance of any innovation must meet the needs of the farmers and their market (Norton and Mumford, 1993). With the introduction of genetically modified cultivars in South Africa, the relative importance of various pests might have changed. Hence, a survey was conducted to know more information about farmers' knowledge and perceptions of cotton production in four cotton-producing regions of South Africa. This survey also aimed to give relevant information on the farmers' agronomic activities, the status of pests and diseases, and their management.

2.2 MATERIALS AND METHODS

2.2.1 Study area description

The study was conducted in three provinces of South Africa (Figure 2.1), namely Mpumalanga (Nokaneng and Tonga), KwaZulu-Natal (Makhathini) and Limpopo (Groblersdal and Marble Hall).

Figure 2.1 Map showing the study area in three provinces in South Africa (GoogleMap)

2.2.2 Survey sampling

Information for this study was gathered from a farmers' survey conducted between April and August 2017. Farmers were selected based on the list of producers supply by the cooperatives in each area. The number of farmers interviewed in each area depended on the participation and availability of farmers. The survey was carried out on a sample of recognized cotton farmers in each region. The survey involved both electronic and conventional surveys of cotton producers, both commercial and smallholder. Each recognized cotton farmer in each area had an equal chance of participating in the study.

2.2.3 Data collection

The survey was based on a questionnaire that was developed in collaboration with Cotton SA (https://cottonsa.org.za). The questionnaire was designed to obtain information on production practices as well as the incidence and management of pests and diseases, extension services and factors limiting cotton production and quality (Table 2.1). Where required, translation was done into the language of the farmers, and then their answers were translated back into English. Before the survey, the questionnaire was tested with the personnel of Cotton SA and was modified according to their comments and suggestions. A total of 140 farmers were randomly selected. The questionnaire required approximately 10 minutes to complete, and there was no compensation for responding, nor was there any known risk to the participating farmers. All information was confidential, and no individual farmer's responses were shared with any other party or person.

Table 2.1 Overview of questions concerning farmers' knowledge and perceptions that were given to cotton farmers (table adapted from Ntow *et al*., 2006)

Data group	Description
Farm details	Area where the farm is situated; How many hectares do you plant under irrigation; How many hectares do you plant under dryland; Typical environmental conditions and soil type of your field/region (average rainfall, temperature, soil type).
Production practices	Names of varieties usually planted; Type of your favourite variety (GM/Non-GM); Do you practice conservation agriculture (yes/no); Do you make use of soil analysis (yes/no); How do you harvest your produce (handpick, machine, both); What was your average yield per hectare for the past five seasons (irrigation, dryland); Do you keep cotton seed leftover and not planted from the year before for the following year's crop
Incidence and management of pests and diseases	Resistance of the variety to diseases and insects (yes, no, don't know); Awareness, incidence and economic importance of diseases and pests (know it, occurrence, ranking damage:1-5); Which management strategies do you use to protect your cotton from damages by diseases and pests (no control, farming practices, chemical, resistance cultivars, biological control, others).
Extension service and factors limiting the yield	Who advises you on what variety to grow (yourself, farmer who is knowledgeable, seed company, chemical agents, extension officers, others); Has a researcher visited your field (yes/no); If yes, when was the last time they visited your field; Where do you get your cotton seed; which factors were the most limiting to your cotton yield (irrigation, fertilizer, labour, climate, disease, insects, weeds); Identify difficulties in controlling weeds and mention types of weeds involved; If you could choose, in which area of cotton production would you like to see the research.

2.2.4 Data analysis

Survey data from the questionnaires were summarized and conveyed using means and percentages based on the total number of farmers that responded to a particular question. Data collected at four of the localities were combined for analysis. The results were expressed in percentage.

2.3 RESULTS AND DISCUSSION

The results are based on the completed questionnaires forms that were returned. This survey covered four cotton-producing areas from three provinces, among the main cotton-producing regions of South Africa. A summary of the survey data is provided below in four primary categories.

2.3.1 Farm details

The basic information on each farm is recorded in Table 2.2. The survey was conducted on cotton farms situated in three provinces, KwaZulu-Natal (70%), Limpopo (2%), and Mpumalanga (28%), which are among the five cotton-producing regions in South Africa (Agriculture, 2015). Of the 100 farmers who specified the soil type of their cotton fields, 16%, 22%, 3%, 56%, and 3% had clay, loam, loam clay, sandy, or sandy loam soils, respectively. The overall mean rainfall during the summer season recorded by the respondents was 450 mm. KwaZulu-Natal reported a mean of 498 mm, Limpopo 500 mm and Mpumalanga 350 mm. Rain is crucial after planting or during emergence, and rainfall of 15 to 20 mm after planting promotes a good stand of cotton (Dippenaar, 2015).

The mean summer temperature was 26.7°C, which is a suitable temperature for cotton production. As cotton is a tropical crop, it prefers summer temperatures of 25°C or higher (Coleman, 2019) and is favoured by soil temperatures above 18°C during germination (Boman and Lemon, 2005). Krzyzanowski and Delouche (2011) reported that the optimal temperature for cotton germination is 28ºC to 30ºC and that the rate of germination decreases as temperatures go above 33ºC or below 20ºC. Cotton should also not be planted before the top 30 mm of the soil has maintained a temperature of 16 to 18°C or higher for approximately ten days (Dippenaar, 2015). However, Dippenaar (2015) also noted that in Limpopo, Mpumalanga, and KwaZulu-Natal, soil temperature was not a limiting factor for the planting date for cotton.

Table 2.2 Basic information of the surveyed areas in a sampling (N = 140) of cotton farms

Variables	n = 140 (%)
Area where the farm is situated	
KZN	70%
Limpopo	2%
Mpumalanga	28%
Soil type	
Clay	16%
Loam	22%
Loam clay	3%
Sandy	56%
Sandy loam	3%
Variables	**n = 140**
Mean rainfall	
KZN	498 mm
Limpopo	500 mm
Mpumalanga	350 mm
Mean temperature	
KZN	29°C
Limpopo	25°C
Mpumalanga	26°C

On average, the selected farmers grew cotton on six hectares per household. The size of each farm varied significantly across provinces, ranging from 1 ha in Mpumalanga and KwaZulu-Natal to 200 ha in Limpopo (Table 2.3). The farm that had 200 ha of cultivated cotton belonged to a commercial farmer. Most (62%) of the farms included in the survey had less than five hectares of land under cotton cultivation. Cotton SA (2017) reported that in South Africa during the 2016/17 season, 33 628 hectares were planted (irrigated 19 273 ha and dryland 14 355 ha). A total of 134 (96%) of the selected farmers planted dryland cotton, while only 13% had any irrigated cotton fields. In the South African cotton industry, most of the smallholder farmers cultivate cotton under dryland conditions.

Table 2.3 Farm size under cotton cultivation

Agro ecology	Farm size (ha)	Number of farmers*	% of Farmers
Dryland	0	6	4%
	1 - 2	29	21%
	2 - 3	26	19%
	3 - 5	31	22%
	5 - 10	36	26%
	> 10	12	8%
Irrigated	0	122	87%
	1 - 5	12	9%
	5 - 20	3	2%
	20 - 100	2	1%
	100 - 200	1	1%

*multiple responses

2.3.2 Production practices

Basic production practices of the farmers are provided in Table 2.4. Cultivar PM 3225 B2RF from Monsanto was the cotton variety that most participants (89%) planted. This cultivar has both the BGII and RR Flex genes, giving it resistance to bollworms and glyphosate herbicides. It also has hairy leaves, giving it tolerance to leafhoppers but making it unsuitable for mechanical picking. All the farmers planted GM cotton because all cotton cultivars available in South Africa are genetically modified (James, 2014; USDA, 2017). GM cotton was introduced in South Africa in 1997 as the first GM crop grown by both commercial and smallholder farmers (Thomson, 2016). Today, South Africa is one of the largest producers of GM crops globally and by far the largest in Africa, with most African farmers who have adopted GM cultivars.

Most farmers indicated that the advantages of planting GM cotton include reduced production costs, reduced insecticide use and higher yields. Gouse *et al*. (2003) noted yield increases for large-scale irrigated farmers (18.5%), large-scale dryland farmers (13.3%) and small-scale dryland farmers (45.8%) that adopted GM cotton.

Most of the respondents (95%) did not practise conservation agriculture. Thierfelder *et al*. (2016) suggested that conservation agriculture could contribute to water-conservation and sustainable cropping systems affected by the unpredictable climatic conditions and frequent droughts in southern Africa. However, currently available estimates of its adoption suggest that smallholder farmers have not adopted it widely (Brown *et al*., 2017).

Most of the interviewed farmers (87%) also indicated that they did not conduct soil analysis before planting their fields. This problem was linked to their financial constraints and a lack of knowledge. Soil analysis is crucial to optimal fertilization, which can increase yields and lower the costs of cotton farming (Harper, 2011).

Of the respondents surveyed, 99% harvested their cotton by handpicking. However, handpicking is more expensive than machine picking in South Africa. In contrast, Chaudhry (2008) reported that handpicking cotton in mainland China was cheaper than machine picking in Brazil. Although manual harvesting of cotton is labour intensive (Sandhar, 1999), major cotton-producing countries such as Egypt have not considered moving to machine picking because handpicking of cotton guarantees high quality and puts less stress on the fibres. Those farmers (1%) that harvested cotton mechanically either used a picker or a stripper. A picker harvests the cotton without causing damage to unopened bolls and is generally used only for a yield higher than 5 000 $kg.ha^{-1}$. A stripper device pulls off the entire boll, damaging the stalk, and is usually used when the yield is lower than 5 000 $kg.ha^{-1}$ (Coleman, 2019).

A mean cottonseed yield of 700 $kg.ha^{-1}$, with individual fields ranging between 120 $kg.ha^{-1}$ and 1 800 $kg.ha^{-1}$, were reported by dryland farmers, while a mean yield of 5 000 $kg.ha^{-1}$ was obtained from irrigated cotton. In 2017, the mean cotton yields in South Africa were 4 595 $kg.ha^{-1}$ and 910 $kg.ha^{-1}$ for irrigated and dryland production, respectively (Cotton SA, 2017). Global cotton yields are near the 10-year mean of 770 $kg.ha^{-1}$ (Cotton SA, 2018), a yield below which cotton production is non-profitable. The break-even point for high-quality dryland cotton in South Africa is 1 500 $kg.ha^{-1}$, compared to 3 780 $kg.ha^{-1}$ for average-quality irrigated cotton (Coleman, 2019). Many farmers bought new seeds for planting (86%), while 14% used seeds purchased in the previous season.

Table 2.4 Summary of the production practices of South African cotton farmers

Variable	Total respondents Number (n=140)	%
Cotton varieties usually planted		
18 + 12B RF	13	9%
Candia + 1541+ DP1	1	1%
DP1240B2RF	1	1%
PM 3225 B2RF	123	89%
Total	138	100%
GM status of the favourite varieties		
GM	93	66%
Non-GM	47	34%
Total	140	100%
Conservation agriculture practice		
No	131	95%
Yes	7	5%
Total	138	100%
Conduct soil analysis		
No	120	87%
Yes	18	13%
Total	138	100%
Harvesting method		
Handpicking	137	99%
Machine	2	1%
Total	139	100%
Mean yield per hectare (seed cotton)		
Irrigation	5 000 $kg.ha^{-1}$	
Dryland	700 $kg.ha^{-1}$	
Planting of seed bought from the previous year		
No	118	86%
Yes	20	14%
Total	138	100%

2.3.3 Incidence and management of pests and diseases

The incidence and management of pests and diseases are summarized in Table 2.5. The study found that farmers' knowledge of pests was slightly better than their knowledge of various diseases that attacked their crop. Li *et al*. (2011) reported that a similar trend was observed in China, where the early detection and treatment of cotton diseases are not common. They recommended guidance from experts and a diagnostic system to help cotton farmers. Those who were aware of diseases on cotton knew about *Verticillium* wilt (10%), *Fusarium* wilt (8%), boll rots (23%), virus diseases (5%), seedling diseases (9%) and bacterial blight (12%). Those farmers who were aware of *Verticillium* wilt further reported how difficult it was to control this disease and its contribution to yield loss. These observations correspond with other studies that have identified *Verticillium* wilt as one of the key reasons for low cotton yields among smallholder farmers (Mapope, 2001; Chapepa *et al*., 2015; Yuan *et al*., 2017). The control of *Verticillium* wilt is challenging because it can infect a wide host range (Trapero *et al*., 2015), and there are few registered control measures. The Agricultural Research Council-Industrial Crops has developed two cultivars resistant to *Verticillium* wilt.

Cotton bollworms were recognized by 89% of the respondents. Larvae of these species are regarded as a major pest of cotton in South Africa (Fourie *et al*., 2017). Other pests mentioned included aphids (84%), cotton stainers (96%), spider mites (91%), leafhoppers (known as jassids locally) (84%) and whiteflies (32%). Most of the participants (88%) indicated that they were not aware of nematodes on cotton in their fields. Fifty-eight farmers (41%) were aware of insect pests other than the ones listed above. Most of the participants indicated that there was a high prevalence of beneficial insects such as spiders (91%), ants or termites (87%), ladybirds (80%) and parasitic wasps (76%). Farmers that use resistance varieties to control cotton insects and diseases are categorized into those who were aware, those who had not used resistant varieties, and those who did not know about resistant varieties. While 91% of participants were aware of the resistance of some varieties to insects, only 26% knew of disease-resistant cotton varieties.Out of the 140 participants who took part in the survey, 96 (69%) responded to the nature of resistance of the GM varieties against pests and diseases.

Although most respondents relied on GM varieties to control pests, their yield was compromised when some insects developed resistance to commonly used pesticides (Kranthi *et al*., 2019). Bollworms (42%), bollworms and leafhoppers (31%), cotton stainers (1%), *Verticillium* wilt and bollworms (5%), *Verticillium* wilt and cotton stainers (2%), *Verticillium wilt* and leafhoppers (19%) were identified as the pests and diseases that the GM varieties provide resistance against. Where possible, host resistance is the most effective, natural and most affordable strategy to control *Verticillium* wilt (Klosterman *et al*., 2009; Tsror, 2011).

Most farmers used chemical sprays to control cotton pests (57%). Only 7% used biological control by relying on natural enemies . For effective control of cotton insect pests, an integrated management option taking into account multiple strategies should be recommended (Hillocks, 1995). Those who used chemical sprays to control cotton diseases were 9%, while 44% relied on resistant cultivars. The number of farmers who relied on resistant cultivars was not proportional to the 26% who knew disease-resistant cotton varieties. Chemical control (31%) was primarily used as a management strategy for the control of both pests and diseases, followed by resistant cultivars (27%) and biological control (2%). Where crop development is adversely affected by diseases, weed infestation or poor crop management, the effectiveness of chemical control cannot be realized (Hillocks, 1995). Only 1% of the respondents said that they received advice from other farmers. This confirms the observation of Midega *et al*. (2012) that mechanisms are required to train and encourage the farmer-to-farmer transfer of appropriate pest management information.

Table 2.5 Farmer's perceptions of pest and disease incidence on cotton and their management practices

Variables		No of farmers	% of farmers
Awareness of diseases	*Verticillium* wilt	No: 123	90%
		Yes: 13	10%
	Fusarium wilt	No: 124	92%
		Yes: 11	8%
	Boll rots	No: 103	77%
		Yes: 31	23%
	Virus diseases	No: 123	95%
		Yes: 7	5%
	Seedling diseases	No: 127	91%
		Yes: 12	9%
	Bacterial blight	No: 120	88%
		Yes: 17	12%
	Other	No: 82	59%
		Yes: 58	41%
Awareness of pests	Bollworms	No: 16	11%
		Yes: 124	89%
	Aphids	No: 22	16%
		Yes: 118	84%
	Cotton stainers	No: 6	4%
		Yes: 134	96%
	Spider mites	No: 13	9%
		Yes: 127	91%
	Nematodes	No: 120	88%
		Yes: 16	12%
	Leafhoppers	No: 23	16%
		Yes: 117	84%
	Whiteflies	No: 95	68%
		Yes: 45	32%
	Other	No: 82	59%
		Yes: 58	41%

Awareness of beneficial insects	Parasitic wasps	No: 34	24%
		Yes: 106	76%
	Ants/termites	No: 18	13%
		Yes: 122	87%
	Ladybirds	No: 28	20%
		Yes: 112	80%
	Spider	No: 12	9%
		Yes: 128	91%
Resistance of the variety to diseases	Yes	31	22%
	No	6	4%
	Do not know	102	74%
Resistance of the variety to insects	Yes	126	91%
	No	4	3%
	Do not know	8	6%
Type of resistance	Bollworms	40	42%
	Bollworms and leafhoppers	30	31%
	Cotton stainers	1	1%
	Verticillium wilt and bollworms	5	5%
	Verticillium wilt and stainers	2	2%
	Verticillium wilt and	18	19%
Management strategies for diseases	No control	15	11%
	Cultural practices	2	1%
	Chemical	13	9%
	Resistance cultivars	61	44%
	Biological control	7	5%
	Others	1	1%
Management strategies for insect pests	Chemical	80	57%
	Resistance cultivars	1	1%
	Biological control	10	7%
Management strategies for insect pests and diseases	Cultural practices	1	1%
	Chemical	44	31%
	Resistance cultivars	38	27%
	Biological control	3	2%

2.3.4 Extension service and factors limiting yield

Results summarized in Table 2.6 illustrate the level of farmer support, factors limiting cotton yields and the areas where more research is required. Most of the respondents (82%) received mentoring and support from the extension officers and seed companies (14%), but only 1% indicated that they had received support from the Agricultural Research Council (ARC). This highlights the importance of technology transfer that is based on research to enhance cotton production. The ARC has experts and technicians specializing in various fields of cotton research, and it is supposed to play a major role in providing farmers with the latest research results. However, only 23% of the participants had been visited by a researcher. Of those whom researchers visited, 63% were visited at least once in the previous season, with only 20% of the farmers experiencing more than one visit.

Most of the seed purchased by farmers were from seed companies. Most farmers (91%) purchased their cotton seed from the seed suppliers, while only 8% used seed bought in the previous year. Most of the respondents (98%) identified climatic conditions as the main constraint to cotton production, followed by the intensive demand for labour (88%) for the efficient production of cotton on their farms. The high number of respondents who identified climatic conditions as the main constraint may be because smallholder farmers in developing countries are more vulnerable to climate change than farmers in developed countries because their agriculture is mainly rain-fed (IPCC, 2007). Further increases in global temperature and changes in rainfall patterns will significantly reduce the yield of cotton in Africa (Diarra *et al*., 2017). Problems with insects' infestation affected 42% of the farmers, and only 8% reported a combination of different factors. However, most farmers were not aware of diseases and their impact on cotton yields. Chapepa *et al*. (2013) noted that diseases remain a major limiting factor in cotton production.

The farmers reported difficulties in controlling weeds, especially morning glory (*Ipomoea purpurea* (L.) Roth.) (33%) and nutsedge (*Cyperus esculentus* L. and *C. rotundus* L.) (21%). However, more than a third (35%) of the respondents reported that they did not experience any weed problems, possibly because they were successfully using Glyphosate to manage weeds.

Morning glory is one of the most problematic weeds due to its extended emergence period (Jha *et al*., 2006; Jha and Norsworthy, 2009) and abundant growth capabilities (Sellers *et al*., 2003; Norsworthy *et al*., 2008). Kerr (2016) described nutsedge as the world's most prolific weed, with two primary nutsedge weed species found in South Africa. There are effective chemical control methods for these weeds (Burke *et al*., 2008; Reinhardt, 2016). However, this would add to the financial burden that the farmers have to endure.

The farmers believed that the problem of low cotton yields could be resolved through research on pest control (45%), weed control (19%), soil analysis (5%) and breeding for new cotton varieties (17%). The problem related to handpicking of cotton is more of a labour issue, with some farmers concerned about the high costs involved. As reported earlier, 99% of the sampled farmers harvested their crop through handpicking. Hence, some farmers (14%) recommended mechanical harvesting as an alternative. Conservation agriculture would allow farmers to reduce labour constraints and increase yields compared to conventional methods (Grabowski and Haggblade, 2016; Thierfelder *et al*., 2016). Although many farmers cited climate issues of rainfall and heat as the factor most limiting on cotton yields, none of the farmers recommended more research on the impact of climate change.

The study was conducted to explore farmers' perceptions of the current status of pests and diseases on cotton and current production practices in South Africa. The study further sought to report on the farmers' views of extension services and factors limiting cotton yields. Despite the limited sampling area of the study and the majority of respondents being smallholder farmers, the outcomes of this survey highlight the economic importance of the pests and diseases of cotton and also of the crop management practices in South Africa. The study may be useful in developing integrated pest management practices and identifying the production practice gaps in the industry to increase yield, lower pesticide use, and increase gross margins. These results could also assist in the development of more efficient and effective agricultural extension programmes for cotton production farmers in South Africa.

Table 2.6 Summary of the extension service rendered, factors limiting cotton yields and the topics on which more research is required

Question posed to farmers		Farmers' response (%) N=140
Who advises you on what variety to grow?	ARC	1%
	Chemical agents	1%
	Extension officer	82%
	Farmer	1%
	Seed company	14%
	Other	1%
Has a researcher visited your field?	Yes	23%
	No	77%
If yes, what is the number of visits in the past season?	Visits: 0	17%
	Visits: 1	63%
	Visits: 2	20%
Where do you get your cotton seed?	Cooperative	8%
	Gin	1%
	Seed company	91%
Which factors were the most limiting to your cotton yield?	Climate	98%
	Insect	42%
	Labour	88%
	All factors	8%
Identify difficulties in controlling weeds and mention types of weeds involved	Morning glory	33%
	Nutsedge	21%
	Kweek grass	2%
	No weed problem	35%
	Other	9%
If you could choose, in which area of cotton production would you like to see research?	Mechanical harvesting	14%
	Pest control	45%
	Weed control	19%
	Soil analysis	5%
	New cultivars	17%

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CHAPTER 3

EFFICACY OF BIOLOGICAL CONTROL AGENTS ON MANAGEMENT OF KEY COTTON INSECT PESTS WITH FOCUS ON *HELICOVERPA ARMIGERA* UNDER FIELD CONDITIONS

Abstract

The study was conducted to evaluate the effect of different biological agents on the control of African bollworm, *Helicoverpa armigera* and other pests of cotton under field conditions. Field trials were conducted at the Agricultural Research Council - Industrial Crops, Rustenburg, in 2017 and 2018. Four bio-pesticides (Eco-Bb®, Bb endophyte, Bolldex®, and Delfin®) were evaluated against cotton insect pests and compared with a pyrethroid, Karate®, and untreated control. In plots sprayed with Karate® and Bolldex®, the number of *H. armigera* larvae was significantly reduced compared to the untreated control. Plots treated with Eco-Bb® had the lowest number of damaged bolls compared to the other treatments. Plots sprayed with Karate® had significantly fewer aphids on different treatments than those sprayed with Bolldex® and the untreated control in 2017. Although statistically not significant, plots treated with Bolldex® and Bb endophyte exhibited the lowest number of thrips. Plots sprayed with Karate® had a significant effect on the whiteflies in 2017, and those sprayed with Eco-Bb® performed the best in 2018. Plots where Delfin® was applied, had significantly lower numbers of spider mites in 2017, while there were no significant differences in 2018. In 2017, there were no significant differences in the cotton stainer population amongst all the treatments, while Eco-Bb® had the lowest significant population in 2018. The statistically lowest population of leafhoppers was recorded in the plots treated with Karate®. The highest mean seed cotton yield of 6 400 $kg.ha^{-1}$ was recorded in the plots that were treated with Bolldex®. In summary, the efficacy of different bio-pesticides against *H. armigera* larvae varied significantly; however, Karate® and Bolldex® performed better than other options in the control of cotton pests.

3.1 INTRODUCTION

The African bollworm, *Helicoverpa armigera* (Hübner) (Noctuidae: Lepidoptera), is an indigenous species considered to be a major pest of fibre crops in Africa (Cherry *et al*., 2003) and ranks as the most important lepidopteran pest in South Africa (Moran, 1983; Bell and McGeoch, 1996; Moore and Kirkman, 2010). Four *heliothine* species are reported as of economic importance in Africa, but *H. armigera* is the only species of major economic importance (Greathead and Girling, 1989). The pest causes damage to crops is estimated at greater than US$2 billion annually in Asia, Europe, Africa and Australasia (Tay *et al*., 2013). It has a very large range of host plants, including cotton, pepper, corn, tomato, lucerne, soybean, sorghum and tobacco (Cunningham and Zalucki, 2014; Gu *et al*., 2018). *H. armigera* is perceived as a serious pest because of its polyphagy and high voracity (Achaleke *et al*., 2005; Brévault *et al*., 2011), high fecundity (Noor-ul-Ane *et al*., 2018), high mobility (Fitt, 1989) and resistance to chemical insecticides (Chaturvedi, 2007; Pretorius, 2011; Yang *et al*., 2013).

In South Africa, cotton is a significant crop produced by commercial and small-scale farmers (Van Jaarsveld, 2003). It is mainly attacked by *H. armigera* (Li and Bouwer, 2012) in its larval stage, causing high yield losses. Because the bollworm has a habit of entering the fruit, boll or pod, the plant affords it good protection against chemical sprays, making control almost impossible (Joubert, 2012). Low economic damage thresholds in cotton require a high level of control (Cherry *et al*., 2003), which has historically resulted in reliance on synthetic insecticides (Mensah, 2002; Safna *et al*., 2018). Although chemical pest control is extensively used throughout the world, it has become environmentally undesirable (Szewczyk *et al*., 2009). Excessive use of chemicals causes not only economic restraint on farmers but also produces harmful side effects on the environment as well as vertebrates (Patel *et al*., 2015). Lately, many chemical pesticides in agriculture are under pressure to be eradicated due to their harmful effects, and farmers turn to biological pesticides (Maghsoudi and Jalali 2017; Vilas-Boas *et al*., 2007). Integrated control for *H. armigera* that seeks to minimize insecticide use and impact on non-target pests needs to be considered. One way to overcome this situation is to use eco-friendly control measures, such as biological agents. Hence, this chapter confines itself to evaluating the field efficacy of several biological agents on the control of *H. armigera* and other cotton pests.

3.2 MATERIALS AND METHODS

3.2.1 Trial site, layout, and planting

The trials were conducted at ARC – Industrial Crops (25°39.0S, 27°14.4E) in Rustenburg, North West Province. Each plot consisted of six rows, 5 m long, 1 m spacing between rows, 2 m path between replications and 20 cm spacing between plants. The treatments were replicated four times in a randomized block design. The non-GM cultivar, DeltaOPAL, was planted under irrigated conditions. Black soil (approximately 55% clay) was cultivated by a tractor to obtain a fine tilth, and the trials were hand planted. After emergence, weeds were controlled by hand hoeing and seedlings at the fourth true leaf stage were thinned out to obtain the plant population density of five plants per metre. The trials were planted on 24 October 2016 and 17 October 2017.

3.2.2 Application of treatments

The following treatments were used:

Trade name	**Active ingredient**	**Formulation**	**Concentration**
Eco-Bb®	*Beauveria bassiana*	2 x 10^9 spores/gram	300g ha^{-1} in 1 g/l water
Bb endophyte	*Beauveria bassiana*	2 x 10^9 spores/gram	300g ha^{-1} in 1 g/l water
Bolldex®	Nuclear polyhedrosis virus	7.5 x 10^{12} spores/gram	200ml ha^{-1} in water
Delfin®	*Bacillus thuringiensis*	32 000 IU/mg	1kg.ha^{-1} in 25l ha^{-1} water
Karate®	lambda-cyhalothrin	50 g/l	120ml ha^{-1} in 200l ha^{-1} water

The administration of treatments started 13 weeks after planting when target pest infestations commenced, and weekly spray applications were done until 23 weeks after planting. Ground applications were administered late afternoon due to the UV sensitivity of the biological agents (Zhang *et al*., 2016). The treatments were applied using knapsack sprayers.

3.2.3 Data collection

The efficacy of different treatments was assessed based on *in situ* counts of living *H. armigera* larvae. From 12 weeks after planting, same twelve whole plants per plot were scouted weekly for the bollworm complex (American, red and spiny bollworms) and damaged bolls. Other pests, including aphids, thrips, whiteflies, spider mites, cotton stainers and leafhoppers, were also recorded weekly during the same period. The seed cotton yields were determined at the end of the season. The trials were harvested on 22 – 23 May 2017 and 10 May 2018, when over 90% of the bolls had opened. The two middle rows were harvested per plot. Hand harvesting was done to ensure that the seed cotton was harvested and weighed accurately.

3.2.4 Analysis

The data were analyzed as a randomized complete blocks experiment (RCB). The analysis was performed using Genstat Release 18 and SAS version 9.4 statistical software (SAS, 1999). The data were subjected to appropriate analysis of variance (ANOVA). The Shapiro-Wilk test was performed on the standardized residuals to test for deviations from normality (Shapiro and Wilk, 1965). In cases where significant deviation from normality was observed and due to skewness, outliers were removed until it was normal or symmetrically distributed (Glass *et al*., 1972). Student's t-LSDs (Least Significant Differences) were calculated at a 5% significance level to compare insect numbers and yield means of significant source effects (Snedecor and Cochran, 1967). Values followed by the same letter did not differ significantly at the 5% test level according to Student's t-LSD test.

3.3 RESULTS

Plots treated with Karate® showed the lowest significant number of *H. armigera* larvae compared to untreated control and were comparable to the plots treated with Bolldex® (Figure 3.1). The control had the highest number of African bollworms, and the trend was similar for both the 2017 and 2018 seasons. All the treatments significantly reduced the number of African bollworms compared to the control during the 2018 season. The lowest significant number of spiny bollworm larvae was recorded in the plots treated with Karate® and Bolldex® in 2017 (Figure 3.2). However, no larvae were recorded in 2018. No red bollworm larvae were recorded in both 2017 and 2018.

The results shown in Figure 3.3 revealed that plots treated with Bolldex® had the lowest significant number of damaged bolls compared to Bb endophyte and the control in 2017. In 2018, plots treated with Karate® had the lowest number of damaged bolls, followed by Eco-Bb® and Bolldex®. All the treatments had a significantly lower number of damaged bolls in both seasons than the untreated control.

Although there were no differences among all the treatments in the first trial (2017), plots sprayed with Delfin® had the least number of aphids while those sprayed with Bb endophyte had the highest number of aphids (Figure 3.4). During the second trial (2018), plots sprayed with Bolldex® and Eco-Bb® had the highest number of aphids and plots sprayed with Bb endophyte had the lowest population. However, there were no significant differences amongst all the treatments. The plots that were treated with Bolldex® (2017) and Bb endophyte (2018) had the lowest population of thrips (Figure 3.5), although there were no differences among all the treatments. The plots that were treated with Delfin® exhibited the highest population of thrips in both seasons.

The results shown in Figure 3.6 indicated that the highest significant population of whiteflies was observed on plots that were sprayed with Bolldex® in 2017. However, in 2018 the highest population was observed on plots that were sprayed with Karate®. Figure 3.7 shows that there were no significant differences in the spider mite population amongst all the treatments. However, Bolldex® and Delfin® reduced the population in 2017 and 2018, respectively. Eco-Bb® also reduced the population in 2018, while in 2017, the highest spider mite populations occurred in the blocks sprayed with Eco-Eb. Plots treated with Karate® exhibited the least significant number of cotton stainers compared to Bolldex®, Eco-Bb® and the control in 2017 (Figure 3.8). There were no significant differences in the cotton stainer population amongst all the treatments in 2018. However, the plots treated with Eco-Bb® had the lowest population, and those with Bb endophyte had the highest population.

Of all the treatments evaluated, Karate® was the most effective in reducing the leafhopper population compared to the control. However, there were no significant differences amongst all the treatments in both seasons (Figure 3.9). Bb endophyte and Eco-Bb® performed the worst in 2017, while in 2018, they performed the best. Despite the higher populations of aphids, thrips, whiteflies, spider mites, cotton stainers and leafhoppers in 2018, the seed cotton yields were also higher than the previous season.

The highest seed cotton yields of 5 987 $kg.ha^{-1}$ (2017) and 6 818 $kg.ha^{-1}$ (2018) were recorded in the plots treated with Bolldex®. These yields were much higher than all the other treatments in 2017; and much higher than the untreated control in 2018 (Table 3.1). The mean seed cotton yield was higher for all treatments in 2018 than in 2017. On average, plots that were treated with Bolldex® had increased seed cotton yields (45%) compared to the untreated control, followed by Karate®. Plots treated with Karate® had earlier boll opening than the other treatments in 2017 (Figure 3.10).

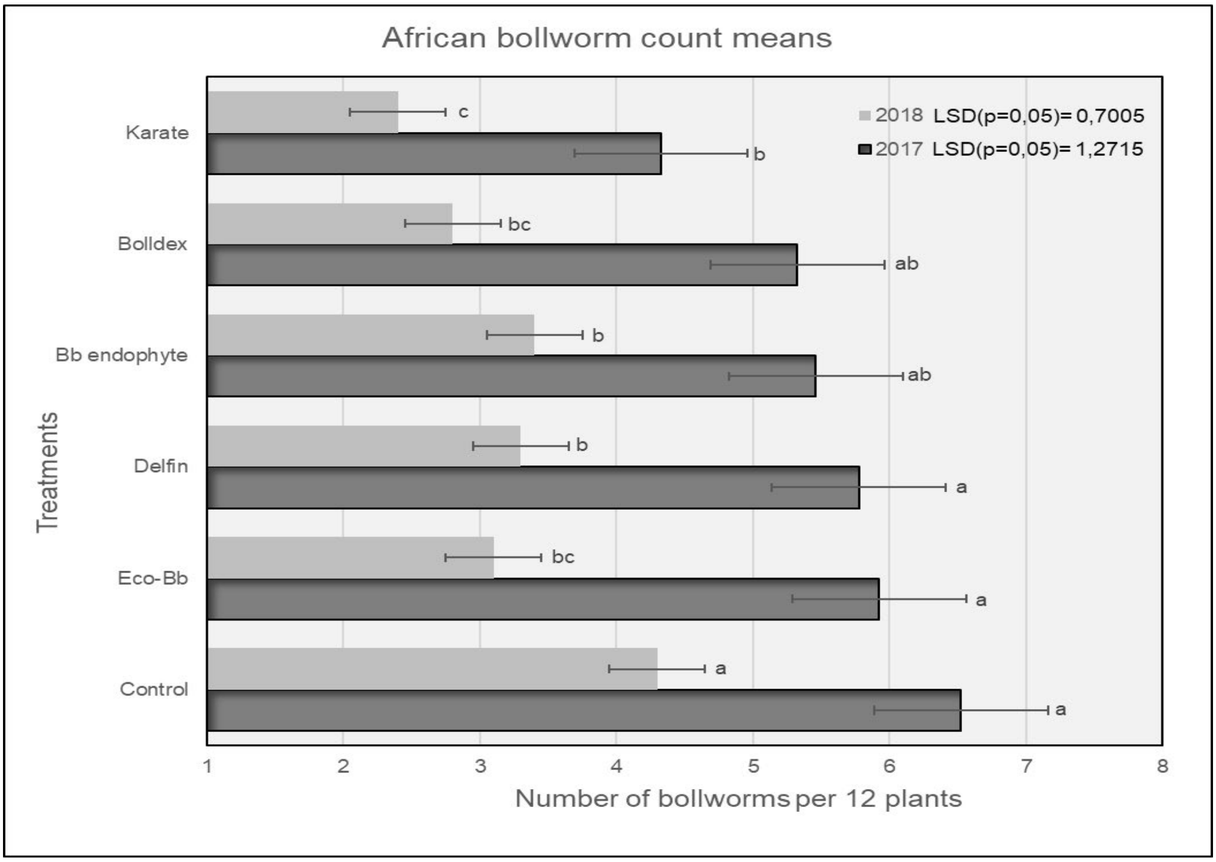

Figure 3.1 The average number of African bollworm *H. armigera* after different treatments under field conditions during the 2017 and 2018 seasons. Means with the same letter are not significantly different ($p > 0.05$)

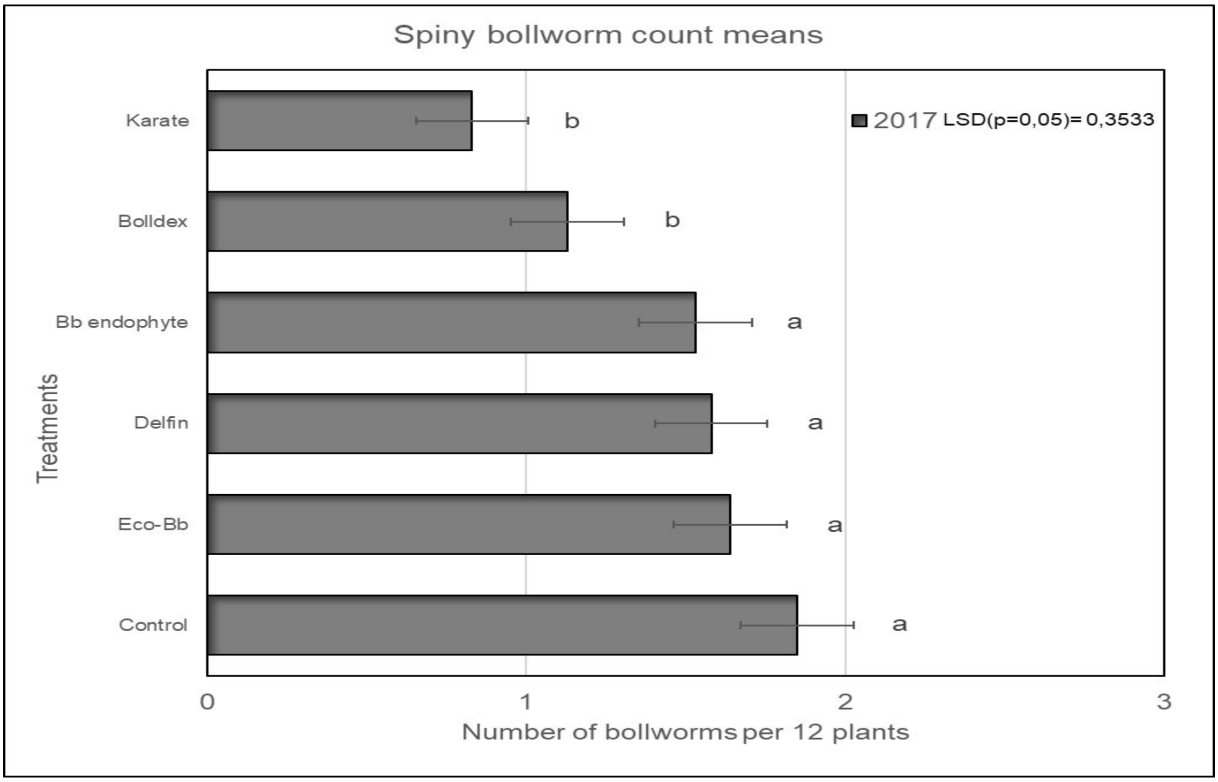

Figure 3.2 The average number of spiny bollworm *Earias insulana* after different treatments under field conditions during the 2017 season. Means with the same letter are not significantly different (p > 0.05)

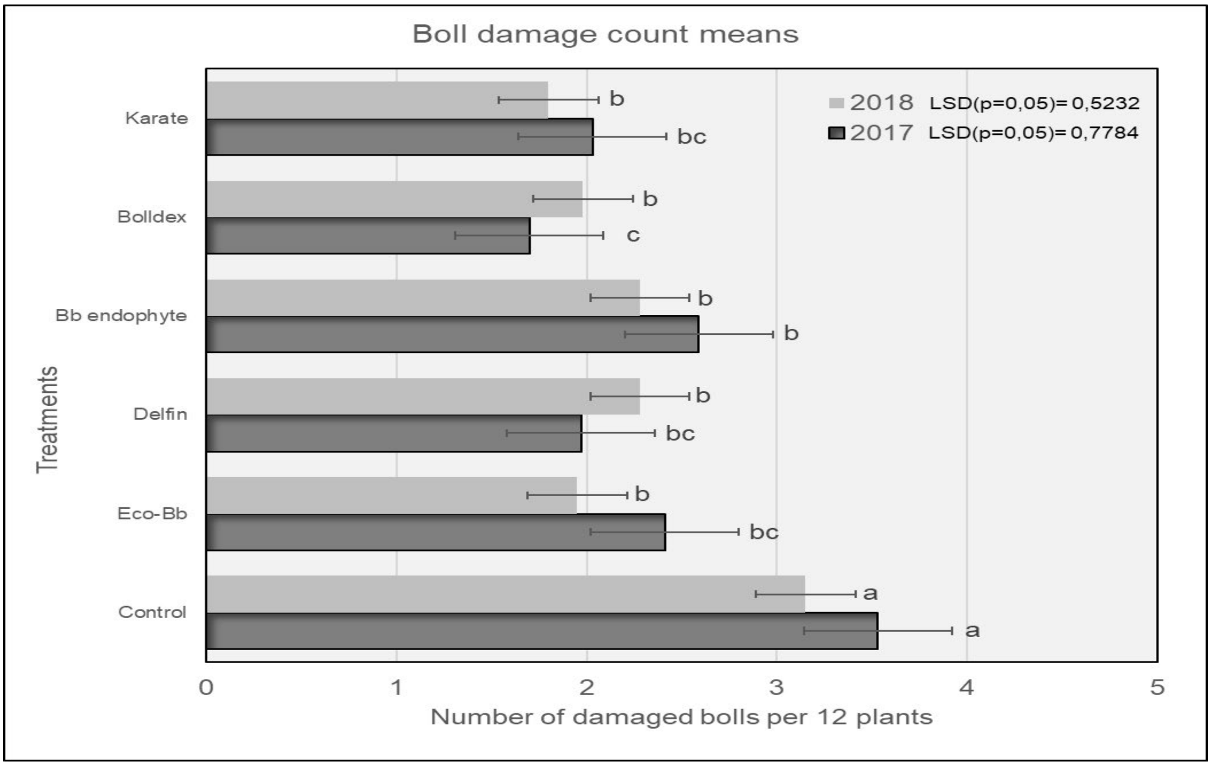

Figure 3.3 The average number of bolls damaged after different treatments under field conditions during the 2017 and 2018 seasons. Means with the same letter are not significantly different (p > 0.05)

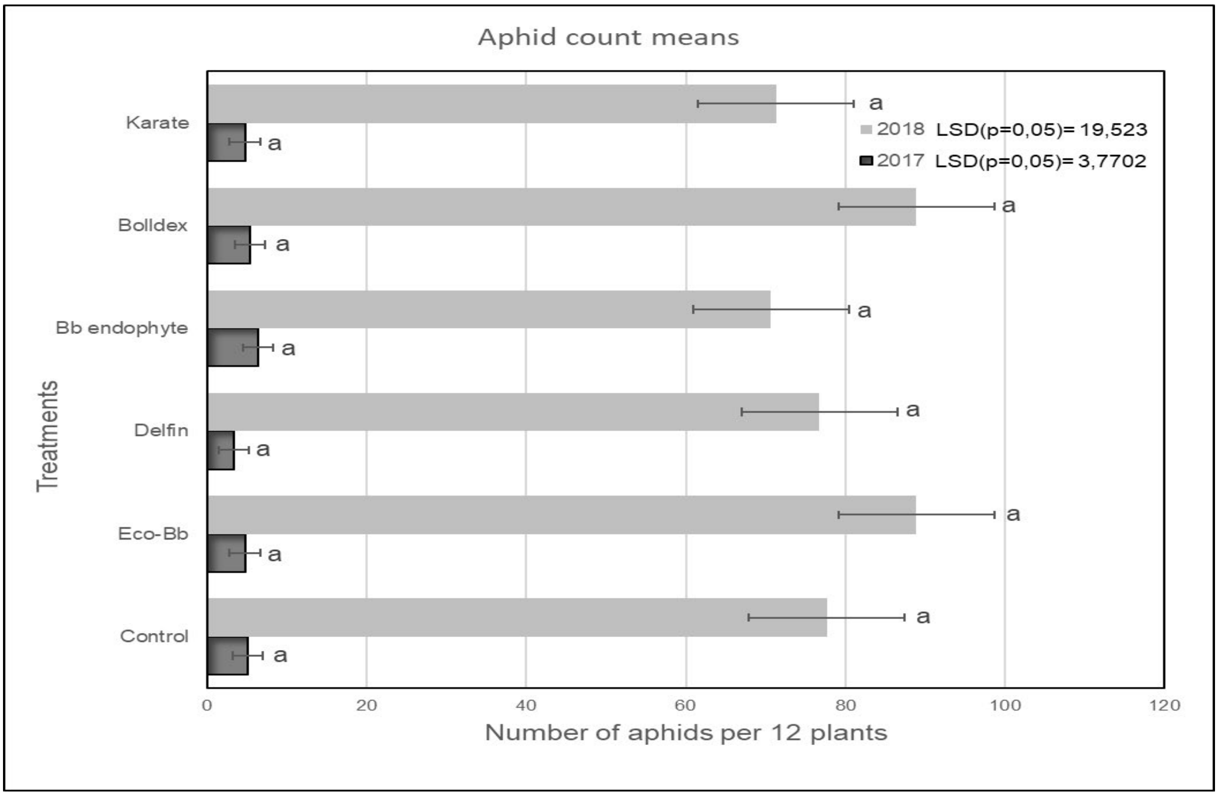

Figure 3.4 The average number of aphid *Aphis gossypii* after different treatments under field conditions during the 2017 and 2018 seasons. Means with the same letter are not significantly different (p > 0.05)

Figure 3.5 The average number of thrip *Thrips tabaci* after different treatments under field conditions during the 2017 and 2018 seasons. Means with the same letter are not significantly different (p > 0.05)

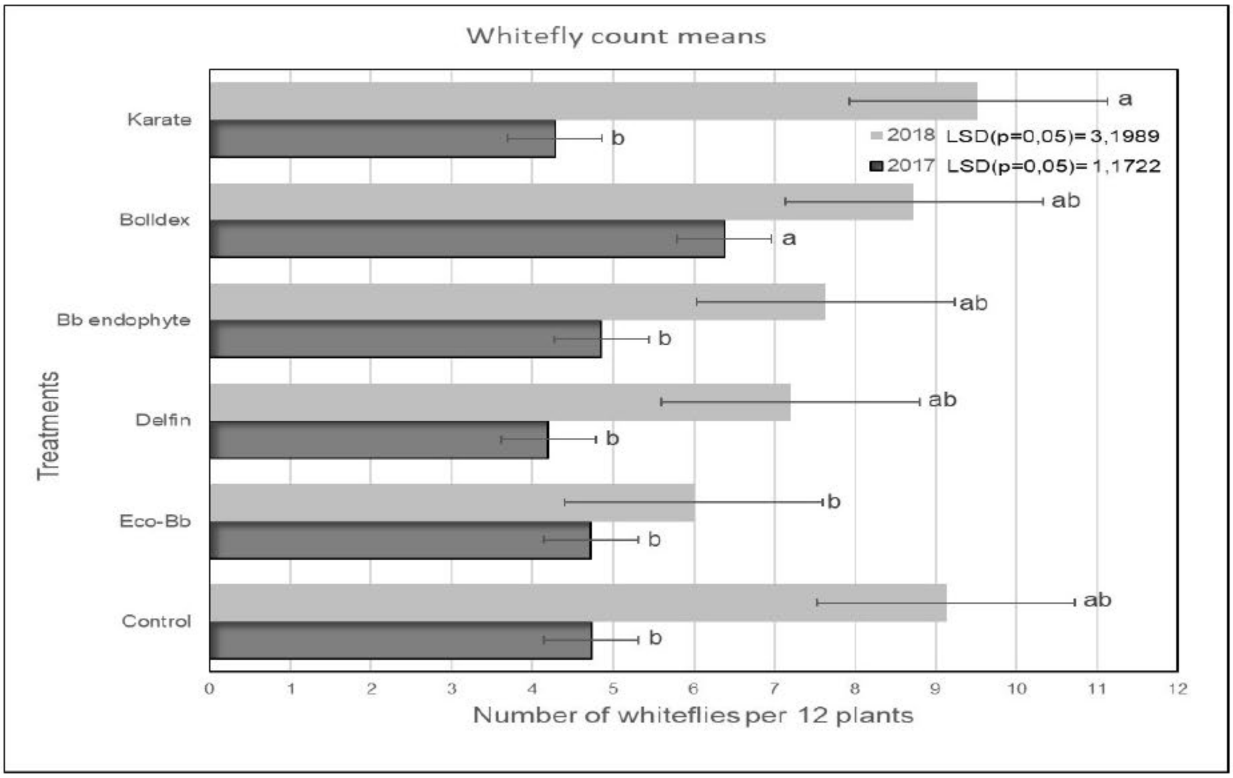

Figure 3.6 The average number of whitefly *Bemisia tabaci* after different treatments under field conditions during the 2017 and 2018 seasons. Means with the same letter are not significantly different (p > 0.05)

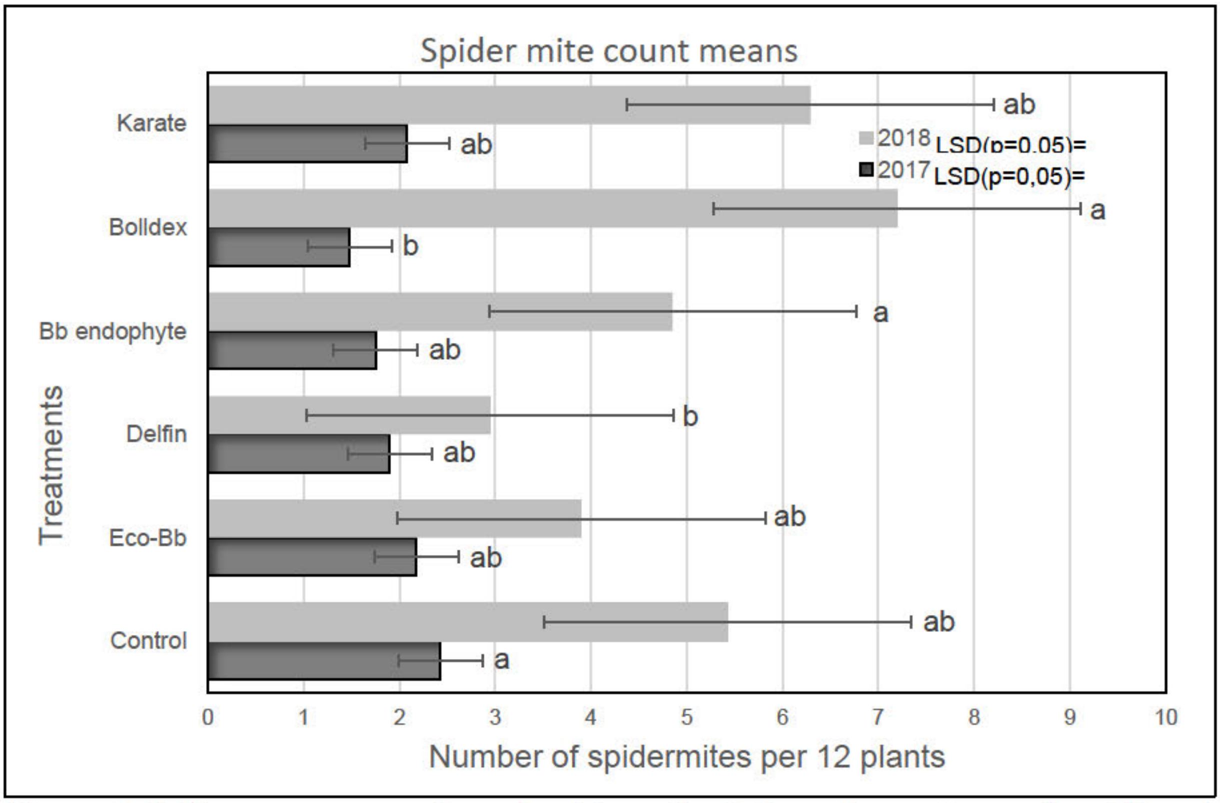

Figure 3.7 The average number of spider mite *Tetranychus urticae* after different treatments under field conditions during the 2017 and 2018 seasons. Means with the same letter are not significantly different (p > 0.05)

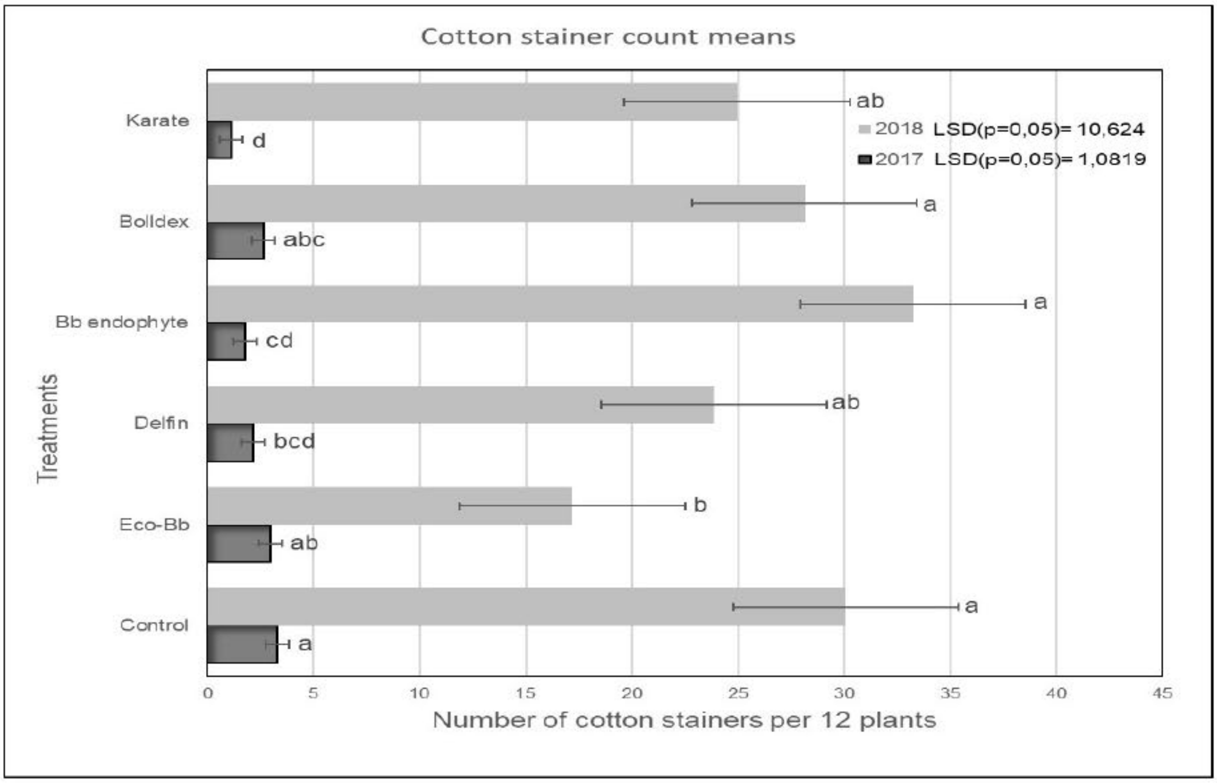

Figure 3.8 The average number of cotton stainer *Dysdercus* sp. after different treatments under field conditions during the 2017 and 2018 seasons. Means with the same letter are not significantly different (p > 0.05)

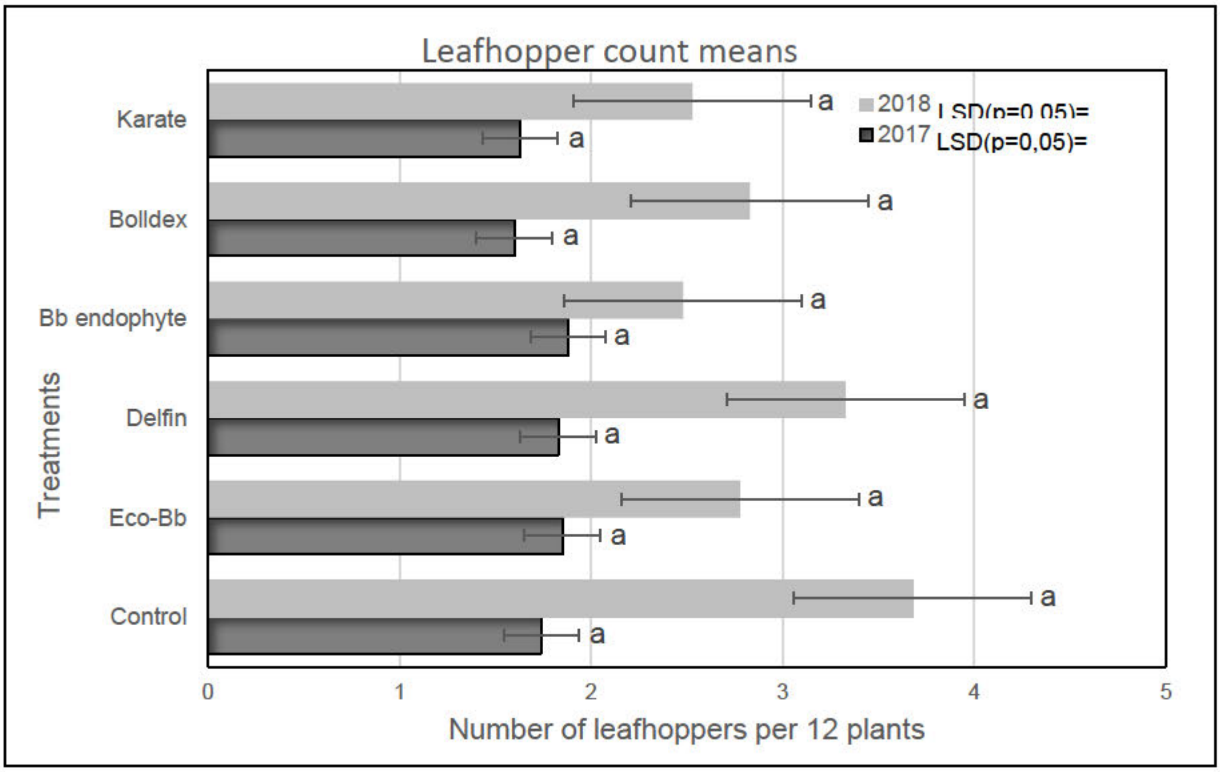

Figure 3.9 The average number of leafhopper *Jacobiella facialis* after different treatments under field conditions during the 2017 and 2018 seasons. Means with the same letter are not significantly different (p > 0.05)

Table 3.1 Average seed cotton yields obtained from the different treatments under field conditions during the 2017 and 2018 seasons

Treatment	2017 ($kg.ha^{-1}$)*	2018 ($kg.ha^{-1}$)*
Eco-Bb®	3055 **b**	5961 **ab**
Bolldex®	5987 **a**	6818 **a**
Delfin®	3523 **b**	5755 **ab**
Bb endophyte	3100 **b**	6409 **a**
Karate®	5133 **ab**	6405 **a**
Untreated Control	4168 **ab**	4673 **b**
LSD (5%)	**2373.8**	**1.6178**
CV%	**37.94516**	**17.88032**
P value	**0.1216**	**0.1436**

*Means with the same letter are not significantly different ($p > 0.05$)

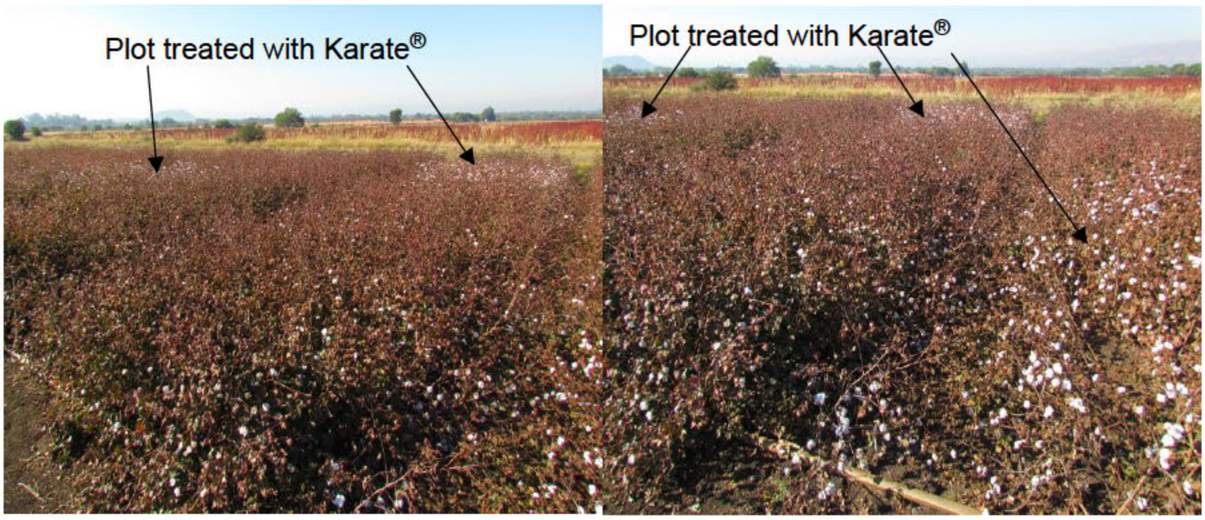

Figure 3.10 Arial view of the trial showing the rate of boll opening for the plots that were treated with Karate®

3.4 DISCUSSION

In this study, considerable control of pests and consequent increases in yield were obtained with some biological agents. However, the chemical control, Karate, provided the best overall control of the cotton pests. Contrary to greenhouse trials, with controlled conditions, field trials are affected by a range of environmental factors (Tesfagiorgis, 2008), which may influence the effectiveness of the biological agents. However, some of the tested biopesticides provided efficacy that was comparable to the insecticide. Bolldex® warrants more attention since the reduction of African bollworm larvae was very close to the used standard Karate®. These results demonstrated the potential of biopesticides to reduce cotton pests and that they can be introduced as natural reduced non-target impact in organic and commercial agriculture. This study demonstrated that both Bolldex® and Karate® significantly reduced the African bollworm populations during the two seasons. Khalique and Ahmed (2001) reported that the mortality response of *H. armigera* larvae to a combination of Karate® and *B. thuringiensis* subsp. *kurstaki* were highly compatible and synergistic. *Helicoverpa armigera* nucleopolyhedrovirus (HaNPV) has been used in several countries and introduced in South Africa for use on several crops (Joubert, 2012; Madumbi Sustainable Agriculture, 2014).

Karate® gave better control of spiny bollworm than all other treatments, followed by Bolldex® in 2017. However, there were no larvae recorded in 2018. These findings are similar to the findings by Khan *et al*. (2012), who reported that plots treated with Karate® showed minimum infestation compared to other insecticides. Zidan *et al*. (2012) also recorded that under field evaluation of different pesticides against cotton bollworms, Karate® caused a reduction of above 80% in spiny bollworm populations. Delfin® may have reduced the larval population of *H. armigera* compared to the control in 2018, but there were no significant differences in 2017. Biopesticides may effectively reduce the larval population of *H. armigera* when combined with nuclear polyhedrosis virus and parasitoids (Sharma *et al*., 2008). While considering the economic injury levels of the different bollworms (ARC, 2004), the results show that *H. armigera* larvae exceeded the threshold level of five bollworms per hectare for all the treatments except for the Karate® treatment in 2017 with less than 4 bollworms for all the treatments except for the untreated control in 2018.

The least number of damaged bolls was observed in plots treated with Bolldex®, Karate®, and Eco-Bb®. The effect of Bolldex® and Karate® on the reduction of boll damage corresponded with the decrease in the bollworms on the plots where these treatments were applied. These results are also in concordance with the observation by Li *et al*. (2006), who found that more than 60% of parasitism of African bollworm decreased boll damage by 80% compared with the control. Joubert (2012) reported that a trial was conducted to control African bollworm on peaches, and Bolldex® yielded 99% scar-free fruit.

Although there were no significant differences amongst the treatments, Delfin® caused some control of aphids. This is in line with several studies showing the efficacy of *B. thuringiensis* strains against aphids (Melatti *et al*., 2010; Rajashekhar *et al*., 2017; Rajashekhar *et al*., 2018). Bb endophyte provided no control of aphids in 2017, while in 2018, it had the lowest population of aphids. Sarwar (2016) reported that selected *B. bassiana* strains are important entomopathogens of *Aphis gossypii*. Although Karate® did not reduce the population of aphids, Atanasova *et al*. (2018) reported Karate Zeon® (Lambda-cyhalothrin) as a standard chemical for the control of aphids. Slosser *et al*. (2001) reported that the application of lambda-cyhalothrin, consistently resulted in high aphid numbers when cotton bolls are opening. Chamuene *et al*. (2018), reported that high rainfall could reduce the aphid population in cotton fields. Leite *et al*. (2006) and Karim *et al*. (2001) also reported that climatic conditions, including rainfall, are inversely proportional to the aphid population. Numerous studies have also observed that higher temperatures and rainfall usually cause the mortality of aphids (Walker *et al*., 1984; Nakata, 1995; Picanço *et al*., 1997). Plots that were sprayed with Bolldex® had the highest aphid populations. However, this was expected because the virus is highly specific to some members of the Lepidoptera, especially bollworm species (Xia, 1997; Hegde *et al*., 2011).

Bb endophyte reduced the population of thrips. This is in line with Annamalai *et al*. (2016), who reported that *B. bassiana* caused 80.90 % mortality of thrips under greenhouse and field conditions. Bharani *et al*. (2015) also evaluated the effect of biopesticides and insecticides against the thrips population. They observed that *B. bassiana* had higher efficacy than the other biopesticides in controlling thrips.

However, Bharani *et al*. (2015) reported that, although the effectiveness of *B. bassiana* was significantly superior over the untreated control in reducing the thrips population, the insecticide treatments were superior over the biopesticides. In the current study, the plots that were treated with Delfin® exhibited the highest population of thrips in both seasons. This is in line with the study by Cui and Xia (2000), who reported that *B. thuringiensis* subsp. *kurstaki* had no effect on the thrips population. Again, this result is not unexpected because this strain of Bt is highly specific to Lepidoptera.

Similar to other studies (Santiago-Álvarez *et al*., 2006; Anderson and Gugerty, 2013; Mascarin and Jaronski, 2016; Zafar *et al*., 2016; Hatting *et al*., 2018), Eco-Bb® significantly reduced the number of whiteflies during the 2018 season. In an experiment conducted by Jat and Jeyakumar (2006), *B. bassiana* reduced the whitefly population by 39.7 to 72.6% in cotton. The highest significant number of whiteflies on plots sprayed with Karate® may have resulted from the insect's resistance. Whiteflies have previously been reported to build up resistance against lambda-cyhalothrin (Abou-Yousef *et al*., 2010; Yao *et al*., 2017; Dângelo *et al*., 2018). Due to the indiscriminate use of insecticides, whiteflies have developed resistance against various insecticide groups (Zafar *et al*., 2016).

There were no significant differences in the spider mite populations. However, Bolldex® reduced the population in 2017 but performed poorly in 2018. Delfin® significantly reduced the population in 2018, a surprising result. However, Vargas *et al*. (2001) demonstrated similar results for the efficacy of *B. thuringiensis* on the larvae of *Tetranychus* species. In contrast, one paper reported that *B. thuringiensis* isolates against *Tetranychus* nymphs caused mortality between 16% and 30% (Alper *et al*., 2013). There were no significant differences in the population of spider mites in the plots that were treated with Bb endophyte and EcoBb®. However, in 2017, EcoBb® had the second-highest number of spider mites, while in 2018, the population was the second lowest. Bb endophyte provided little control of the spider mites during both seasons. The limited control of spider mites in the plots treated with Bb endophyte and EcoBb® may have been due to the inadequate contact of *B. bassiana* inoculum with the target pest. Gatarayiha (2009) stated that *B. bassiana* controls pests by contact, and therefore, it is important that emerging mites pick up a lethal dose of conidial inoculum deposited on leaf surfaces.

Gatarayiha *et al*. (2011) further recommended the repeated application of *B. bassiana* as being essential for the control of spider mites. In the field experiments, the persistence of *B. bassiana* has been a concern because of environmental conditions such as ultraviolet light (Daoust and Pereira, 1986; Inglis *et al*., 1993), extreme temperatures (Inglis *et al*., 1997) and rain (Wraight and Ramos, 2002).

Karate® significantly reduced the number of cotton stainers in 2017. However, in 2018 plots that were sprayed with Eco-Bb® had the lowest population. In contrast, Bb endophyte was the second best at controlling the cotton stainers in the first trial and was inferior in the second trial. The reduction of stainers by Eco-Bb® and Bb endophyte was in accordance with the study by Moorthi *et al*. (2012), who reported that *B. bassiana* isolates caused significant mortality of cotton stainers. *B. bassiana* has been reported as naturally occurring in cotton (Jones, 1994). Similar to the aphid populations; the lowest cotton stainer populations were observed in 2017.

Although there were no significant differences amongst all the treatments, Karate® was the most effective treatment against leafhoppers. Ahmad *et al*. (1999) conducted a study on the toxicity of pyrethroids against cotton leafhopper and reported very low resistance to lambda-cyhalothrin. The efficacy of different insecticides was evaluated by Kone *et al*. (2018) in Côte d'Ivoire on the basis of leafhopper mortality. They reported that lambda-cyhalothrin had a significant effect on leafhoppers mortality as compared to the control. Bb endophyte and Eco-Bb® performed the worst in 2017, while in 2018, they performed the best. Some studies have confirmed that *B. bassiana* was effective against leafhoppers (Joshi and Patel, 2010; Janghel, 2015; Akramuzzaman *et al*., 2018), while other studies reported that *B. bassiana* had little or no control against the pest (Jat and Jeyakumar, 2006; Maketon *et al*., 2008; Ghelani *et al*., 2014). However, strain selection plays a significant role in the efficacy of *B. bassiana*.

Despite the higher populations of aphids, whiteflies, spider mites, cotton stainers and leafhoppers in 2018, the seed cotton yields were higher than in 2017. The data on yield revealed that a significantly higher yield of seed cotton was recorded in the treatments with Bolldex®, followed by Karate®. In 1997, Cole *et al*., (1997) reported that Karate® increased cotton yield by 12% and provided good pest control whilst maintaining beneficial populations.

This is contrary to the findings of Kumar and Stanley (2010), who reported that, although lambda-cyhalothrin enhanced seed cotton yields, it caused mortalities of both destructive and useful insect species.

Plots that were treated with Karate® had earlier boll opening than the other treatments in 2017. The additive effects were probably due to a combination of multiple mechanisms that affected the pathogens instead of the fewer control mechanisms provided by a single antagonist. Ali (2016) stated that the average number of open bolls/plants could be significantly influenced by spraying insecticides and salicylic acid.

This study showed that biopesticides caused moderate to low levels of mortality of cotton pests and thus could be used within an integrated pest management programme. As a possible replacement or in conjunction with synthetic pesticides, the development of resistance could be delayed.

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CHAPTER 4

EFFICACY OF BIOPESTICIDES AGAINST SECONDARY COTTON PESTS UNDER FIELD CONDITIONS IN SOUTH AFRICA

Abstract

Cotton is a major fibre crop grown in South Africa; and is subjected to pest attacks, which reduce its yield and profitability for farmers. Field trials were conducted in 2017 and 2018 at the Agricultural Research Council - Industrial Crops, Rustenburg. Three biopesticides, namely Eco-Bb®, Bb endophyte and *Metarhizium rileyi*, Eco-Noc (Kepler, Rehner and Humber), were evaluated in comparison with the insecticides Chlorpyrifos® 480 EC, Karate® EC and Bandit® 350 SC, and untreated control. The objective was to determine their efficacy against sucking pests, leafhoppers *Jacobiella facialis* (Hemiptera: Cicadellidae), aphids *Aphis gossypii* (Hemiptera: Aphididae), thrips *Thrips tabaci* (Thysanoptera: Thripidae), whiteflies *Bemisia tabaci* (Hemiptera: Aleyrodidae), two-spotted mite *Tetranychus urticae* (Trombidiformes: Tetranychidae) and cotton stainers *Dysdercus* spp. (Hemiptera: Pyrrhocoridae). Karate® significantly reduced the leafhopper population and outperformed all the other treatments. Eco-Bb® and Bb endophyte did not control aphids in 2017. However, in 2018 the best aphid control resulted from the biopesticides used. In 2017 plots treated with Eco-Bb® developed the lowest number of thrips, while in 2018, plots treated with Bandit® developed the fewest thrips, followed by treatments with Eco-Noc and Karate®. There were no significant differences in the populations of whiteflies; however, the three insecticides were more effective than the biocontrol agents in reducing the numbers of this pest. All the treatments, except for Bandit®, significantly reduced spider mites compared to the untreated control in 2017. Applications of Eco-Bb® and Bb endophyte significantly reduced spider mites in 2017, while in 2018, plots treated with Karate®, followed by Eco-Noc, resulted in the lowest number of spider mites. The use of Chlorpyrifos® and Karate® resulted in the lowest number of cotton stainers, but Bb endophyte also significantly reduced the population in 2017. The highest mean yields of cotton seed of 6 395 kg.ha^{-1}, 6 295 kg.ha^{-1} and 6 141 kg.ha^{-1} were recorded in plots sprayed with Bandit®, Bb endophyte, and Eco-Bb®, respectively. Biopesticides and chemical insecticides can be combined or alternated for future IPM programmes to control cotton pests.

4.1 INTRODUCTION

Cotton, *Gossypium hirsutum* L., plays a significant role in the economies of many countries in the sub-Saharan region. Despite the fact that cotton is not edible, it could improve food security by providing farmers with cash to purchase food. The majority of cotton producers in the sub-Saharan region are small-scale farmers who rely on cultural practices to control insect pests. Adopting a holistic approach to farming could impact food security by stabilising food and cash crops yields within the region. Sub-Saharan Africa has a climate favourable for pest growth, resulting in severe attacks on cotton and subsequent yield losses (Amanet *et al*., 2019). Cotton is attacked by a wide range of pests (Qaim and De Janvry, 2005), which causes a reduction in cotton yield and quality (Williams, 2004; Din *et al*., 2016; Sarwar and Sattar, 2016). The cotton pest complex includes bollworms, two-spotted mite (*T. urticae*), cotton stainers (*Dysdercus* spp.) and some of lesser importance such as thrips (*T. tabaci*), leafhoppers (*J. facialis*), whiteflies (*B. tabaci*), and aphids (*A. gossypii*) (Van Hamburg and Guest, 1997). The increase in the development of synthetic insecticides has enabled crop production worldwide to more than double in the last third of the 20th century (Krebs *et al*., 1999; Catarino *et al*., 2015). However, misuse of insecticides may result in (i) the killing of beneficial, non-target organisms (Pimentel, 1995; Abudulai *et al*., 2018); (ii) rapid multiplication of secondary pests (Zeilinger *et al*., 2016); (iii) the development of pesticide resistance (Kranthi *et al*., 2002); and (iv) food and environmental contamination (Bennett *et al*., 2004). Pyrethroids and organophosphorus insecticides are among the most commonly used pesticides on cotton (Jiménez-Jiménez, *et al*., 2019).

South Africa has only 31 biopesticides currently registered, of which 23 are imported (Srinivasan *et al*., 2019). There is a lack of experience and data regarding the use and efficacy of these biopesticides on cotton. Given that biopesticides have the potential to replace pesticides for pest management (Bateman *et al*., 2018), they are a promising tool for integrated pest management. When used in conjunction with good crop management, biopesticides can assist in cotton pest control and reduction in the use of agrochemical pesticides. Therefore, the goal of this study was to quantify the efficacy of biopesticides versus current insecticides for the control of primary and secondary pests of cotton.

4.2 MATERIALS AND METHODS

4.2.1 Study area

The trials were planted over two years on 15 November 2016 and 19 October 2017. The trials were conducted at the ARC – Industrial Crops Research Station (25°39.0S, 27°14.4E), located in Rustenburg, North West Province, South Africa. The cotton crops were harvested on 19 – 23 June 2017 and 21 May 2018.

4.2.2 Trial layout and preparation

The plot sizes were five metres long with six rows that were one metre apart. The spacing between plants was 20 centimetres, and the distance between replications was two metres. Each treatment was replicated four times in a randomized block design. The trials were planted in black soil with 55% clay, and sprinkler irrigation was used. The conventional cotton cultivar, DeltaOPAL was used. Land preparation was done using a tractor. The trials were hand planted, with two seeds planted at each station, and each row consisted of 25 plants, with a plant population of 50 000 plants per hectare. Three weeks after emergence, seedlings were thinned to ensure a population density of five plants per metre. Weeds were controlled by hand hoeing.

4.2.3 Treatments and application

The study examined the effects of three biopesticides Eco-Bb® (*Beauveria bassiana* Vuill. Strain R444 (www.plant-health.co.za), an experimental *B. bassiana* endophyte and a novel strain of Eco-Noc (*Metarhizium rileyi* Kepler, Rehner and Humber) (www.plant-health.co.za) compared to three synthetic pesticides (Chlorpyrifos® 480 EC, Karate® EC, Bandit® 350 SC) and untreated control against the pests that were abundant in the cotton field (Table 4.1). A fourth viral biopesticide, Bolldex® (www.andermattbiocontrol.com), was applied to all the plots to eliminate the populations of the bollworm complex because this pest tends to outcompete other pests, and this would mask the outcomes of the trial against the secondary pests. The treatments were applied weekly from nine weeks after planting for ten weeks. The products were applied early in the morning when the temperature was above 10°C and below 30°C (O'Neill and Gwynn, 2014; Zhang *et al*., 2016). Ground applications were done using a GARDENA knapsack pressure sprayer with nickeled brass spray nozzle.

4.2.4 Data collection

Evaluation of pest populations was conducted weekly from eight weeks after planting when target pest infestations commenced. Counts for aphids, thrips, whiteflies, leafhoppers, two-spotted mites, and cotton stainers were recorded for all the plots. The pests were recorded from ten randomly selected plants in each plot. At harvest, seed cotton yield ($kg.ha^{-1}$) was determined by handpicking all opened bolls from the four middle rows.

4.2.5 Statistical procedure

The data were analysed as a randomized complete blocks design. The data was analysed using Genstat Release 18 statistical software and SAS version 9.4 (SAS, 1999). The data were subjected to an Analysis of Variance (ANOVA). The Shapiro-Wilk test was performed on the standardized residuals to test for deviations from normality (Shapiro and Wilk 1965). In cases where significant deviation from normality was observed and due to skewness, outliers were removed until the data set was normal or symmetrically distributed (Glass *et al*., 1972). The Student's t-LSDs (Least significant differences) were calculated at a 5% significance level to compare means (Snedecor and Cochran, 1967).

Table 4.1 Pesticide formulations that were tested against cotton pests in the field trials

Chemical family	Trade name	Active ingredient	Formulation	Dose of usage	Cost/item	Manufacturer
Biopesticide	Eco-Bb®	*Beauveria bassiana*	2 x 10^9 spores $gram^{-1}$	300g ha^{-1} or 1 g l^{-1}	R 300/300g	Plant Health Products
Biopesticide	Bb endophyte	*Beauveria bassiana*		300g ha^{-1} or 1 g l^{-1}	R 300/300g	Plant Health Products
Biopesticide	Eco-Noc	*Metarhizium rileyi*	1 x 10^9 spores $gram^{-1}$	300g ha^{-1} or 1 g l^{-1}	R 300/300g	Plant Health Products
Biopesticide	Bolldex®	Nuclear polyhedrosis virus	7.5 x 10^{12} particles $gram^{-1}$	200ml ha^{-1} in water	R 1 642/500ml	Andermatt Biocontrol
Organophosphorus	Chlorpyrifos® 480 EC	Chlorpyrifos	480 g l^{-1}	150 to 200 ml / 100 l water in 30 l ha^{-1}	R 185/l	Universal Crop Protection
Pyrethroid	Karate® EC	Lambda-cyhalothrin	50 g l^{-1}	120ml ha^{-1} in 200l ha^{-1} water	R 650/l	Syngenta
Neonicotinamide	Bandit® 350 SC	Imidacloprid	350 g l^{-1}	200 ml 100 l^{-1}	R 310/l	ARYSTA LifeScience

4.3 RESULTS

Three biopesticides were evaluated for their efficacy against the secondary cotton insect pest complex (leafhoppers, aphids, thrips, whiteflies, spider mites, and cotton stainers) based on infestation and yield, in comparison with three conventional insecticides. All the treatments significantly reduced the leafhopper population in 2017, and although there were no significant differences in 2018, all the treatments recorded a lower population than the untreated control (Figure 4.1). The highest number of leafhoppers was found on the untreated plots in both seasons. Although the populations were lower during both seasons, the use of Karate® resulted in the best overall performance. Chlorpyrifos® significantly reduced the leafhopper population in 2017; however, it did not control the pest in 2018. Similarly, Eco-Noc performed the best in 2018 while it was the worst in 2017.

Control of aphids by the different treatments is displayed in Figure 4.2. The number of aphids in 2018 doubled that of 2017. Eco-Bb® and Bb endophyte did not reduce the aphid population in 2017, while in 2018, Eco-Bb® was the second-best treatment. All the biopesticides were effective treatments in 2018, but only Eco-Noc performed well in 2017. Plots treated with Bandit® recorded the lowest aphid population, followed by the plots treated with Chlorpyrifos®, in the first trial.

The thrips populations were very low during the first season. A mean of less than one thrip per plot was recorded on plots treated with Eco-Bb® in 2017, and more than two were recorded in 2018. Plots where Eco-Bb® was applied had the lowest number of thrips in 2017, while in 2018, Eco-Bb® performed poorly compared to the other treatments. During the second season, all the treatments significantly reduced the thrips populations compared to the untreated control. Bandit® provided the most control of thrips in 2018. Eco-Noc gave the second-best control in both seasons and was on a par with Karate®. There were no significant differences in the populations of whiteflies as a result of the treatments (Figure 4.4). In 2017, plots where Eco-Bb® was applied recorded the lowest whitefly populations. Karate® was the second-best treatment against whiteflies over the two seasons.

The results on the effect of different treatments against spider mite are presented in Figure 4.5. Besides Bandit®, all the treatments significantly reduced the number of spider mite in 2017. Eco-Bb® and Bb endophyte were the most effective treatments for reducing spider mite numbers in 2017, while Karate® gave the best control in 2018, followed by Eco-Noc, although the difference was not significant. Bandit® was the worst-performing treatment against spider mites.

Figure 4.6 summarizes the effect of different treatments against cotton stainers. The observations recorded after the first season indicated that all the treatments reduced cotton stainer populations significantly relative to the untreated control. In general, the use of Chlorpyrifos® and Karate® resulted in the lowest number of cotton stainers. However, there were no significant differences among all the treatments in 2018. The cotton stainer population increased in 2018 when there was relatively little rainfall. Bb endophyte significantly reduced the cotton stainer population in 2017; however, it did not differ from the untreated control during the following season.

The seed cotton yield of the different treatments is shown in Figure 4.7. In the 2017 trial, the highest seed cotton yield of 5 983 $kg.ha^{-1}$ was recorded on the plots treated with Karate®, which was not significantly different from the plots treated with Eco-Bb® (5 963 $kg.ha^{-1}$). In plots treated with Chlorpyrifos®, the lowest yield of 5 021 $kg.ha^{-1}$ after the untreated control (4 808 $kg.ha^{-1}$) was recorded. In 2018 treatments with Bandit® and Bb endophyte resulted in the highest yields of 6 968 and 6 763 $kg.ha^{-1}$, respectively. The lowest yield was from the plots treated with Karate® (5 340 $kg.ha^{-1}$), which was not significantly different from the yields of the untreated control plots (5 090 $kg.ha^{-1}$). Overall, plots that were treated with Bandit® had the highest seed cotton yield, followed by Bb endophyte and Eco-Bb®. The yields were slightly higher during the 2018 season when there was less rainfall than in the 2017 season.

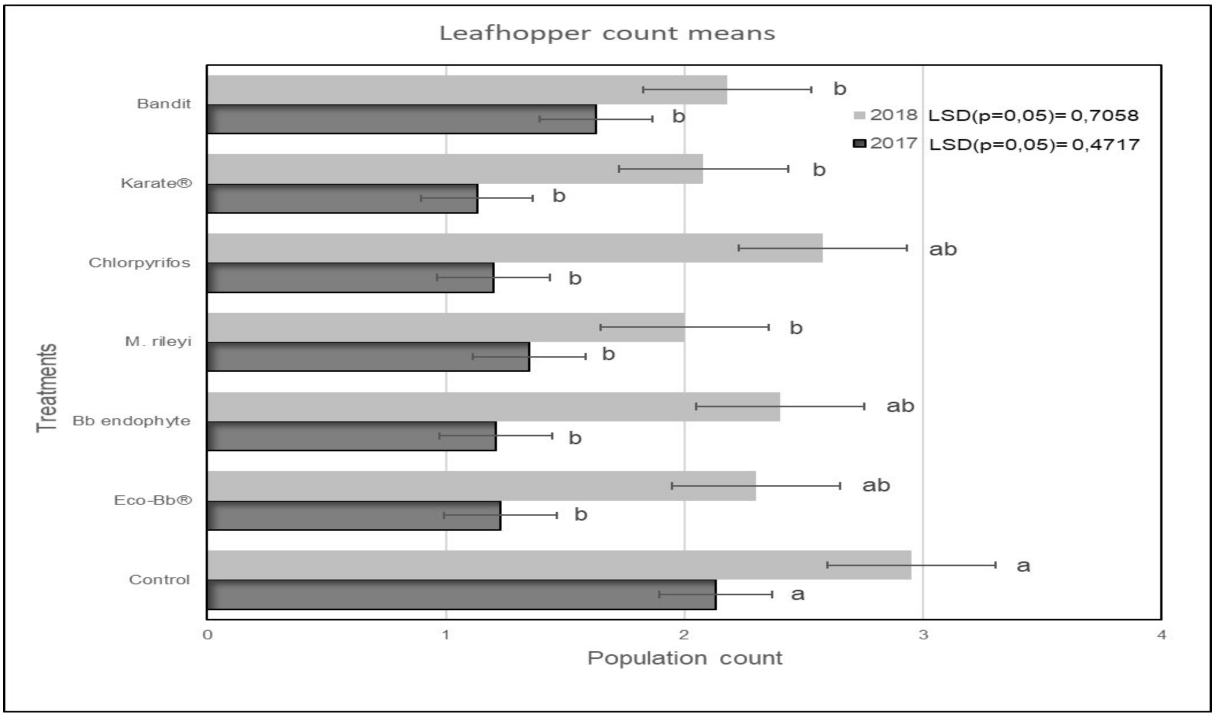

Figure 4.1 Comparison of various treatments against the population of cotton leafhoppers *Jacobiella facialis* under field conditions during the 2017 and 2018 seasons

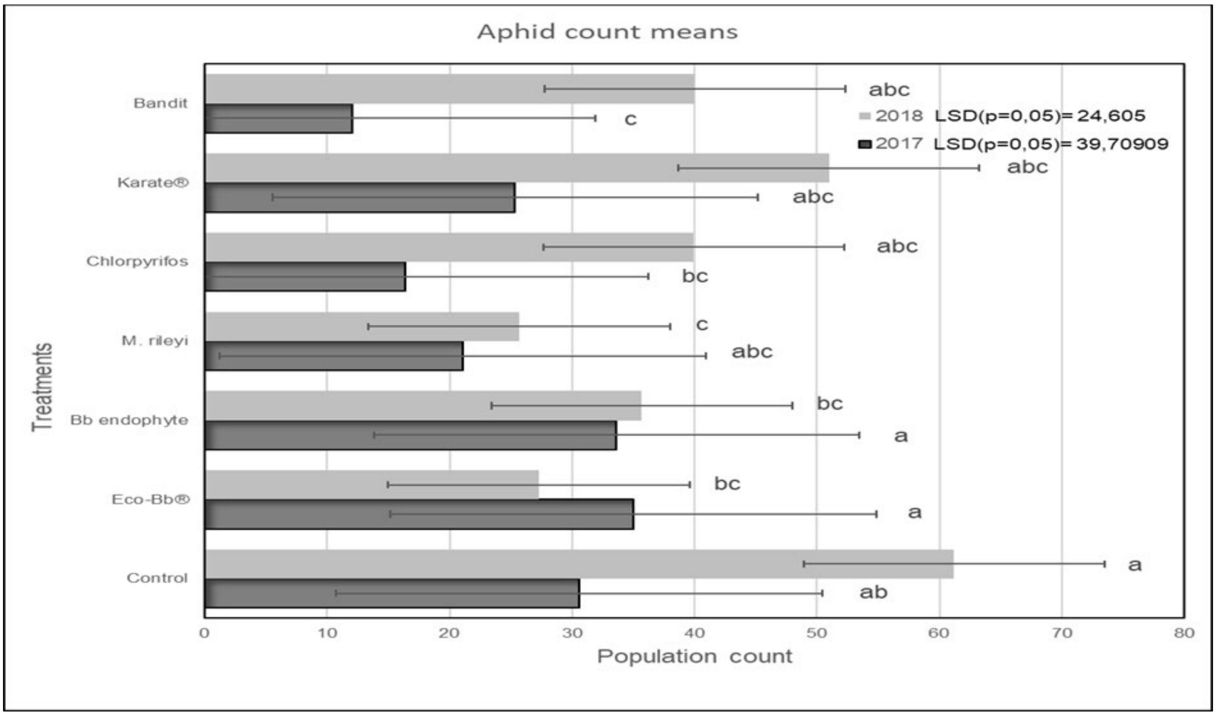

Figure 4.2 Comparison of various treatments against the population of cotton aphids *Aphis gossypii* under field conditions during the 2017 and 2018 seasons

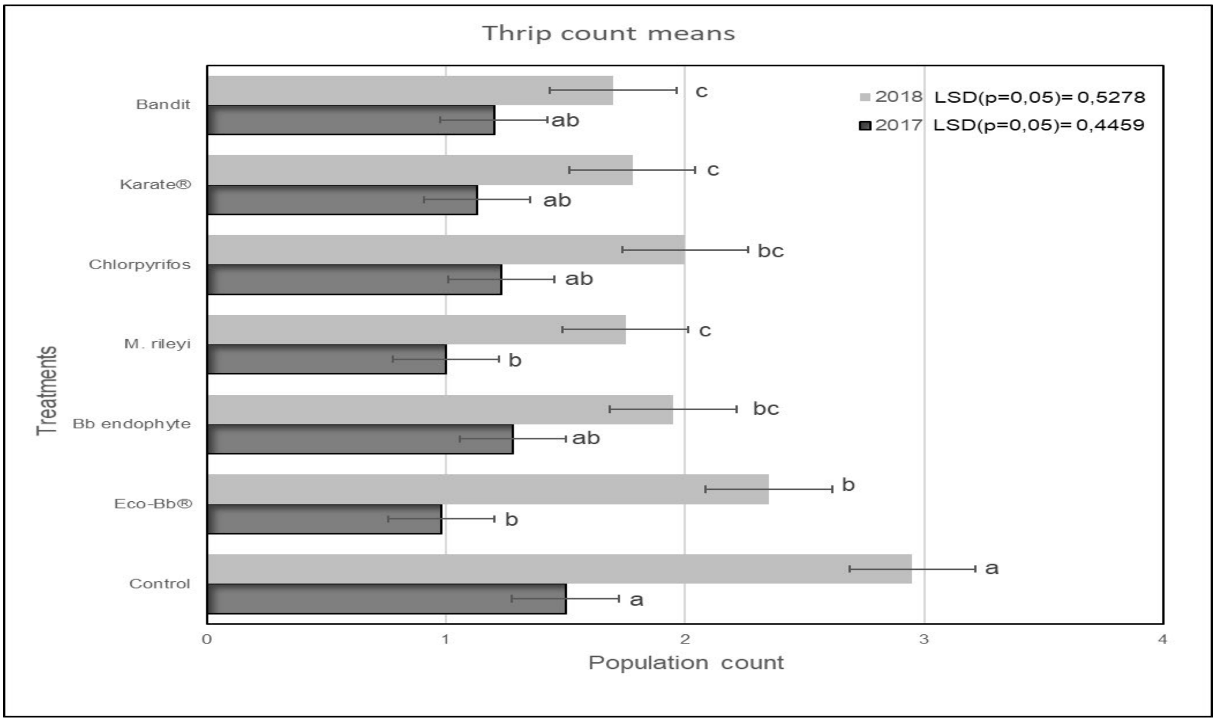

Figure 4.3 Comparison of various treatments against the population of cotton thrips *Thrips tabaci* under field conditions during the 2017 and 2018 seasons

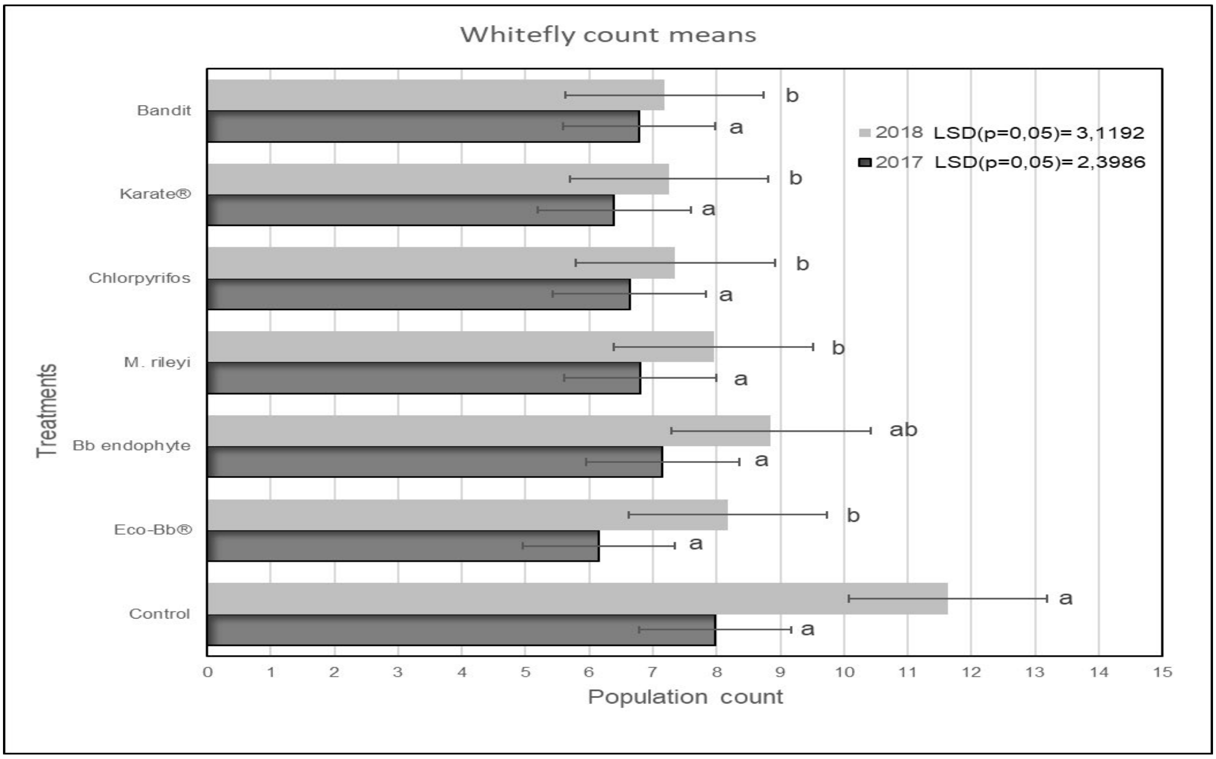

Figure 4.4 Comparison of various treatments against the population of cotton whiteflies *Bemisia tabaci* under field conditions during the 2017 and 2018 seasons

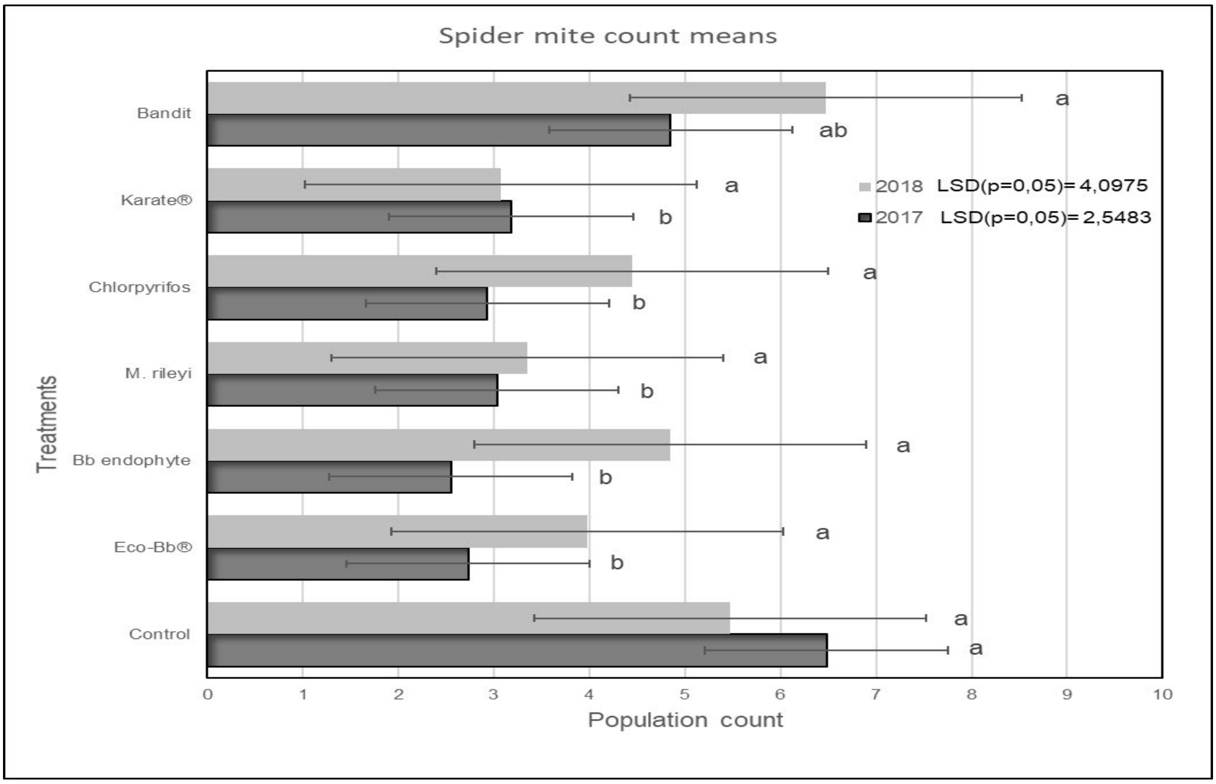

Figure 4.5 Comparison of various treatments against the population of cotton spider mites *Tetranychus urticae* under field conditions during the 2017 and 2018 seasons

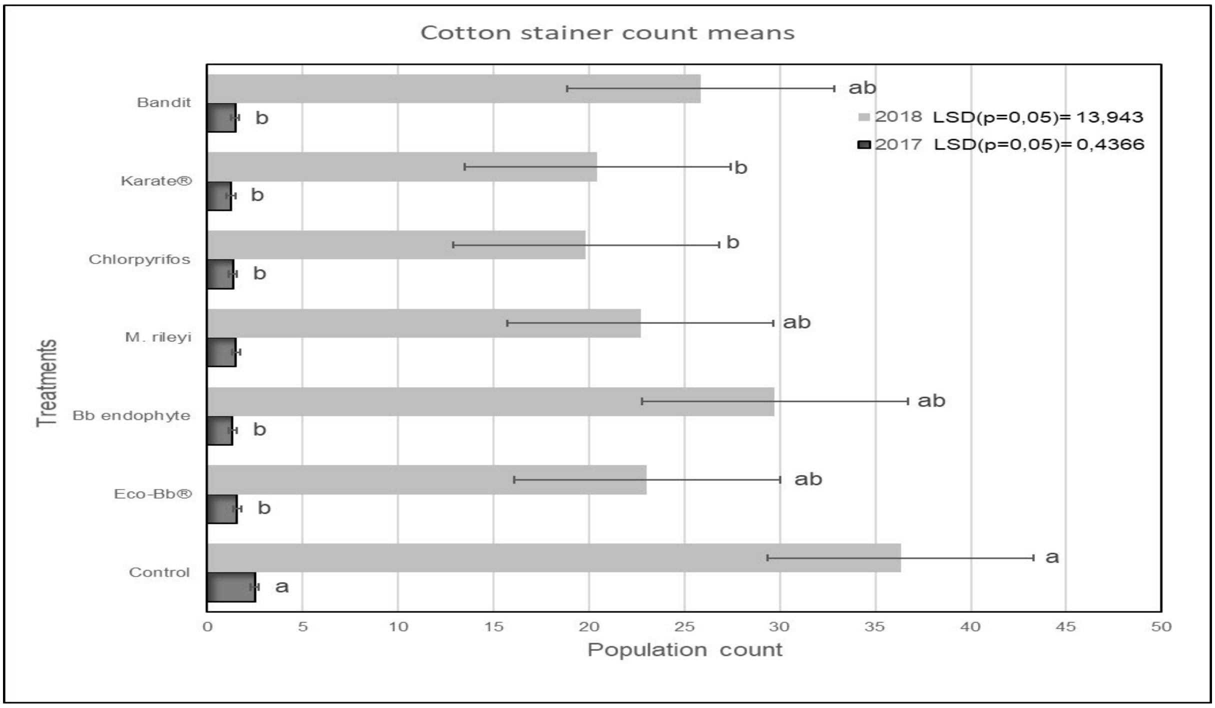

Figure 4.6 Comparison of various treatments against the population of cotton stainers *Dysdercus* sp. under field conditions during the 2017 and 2018 seasons

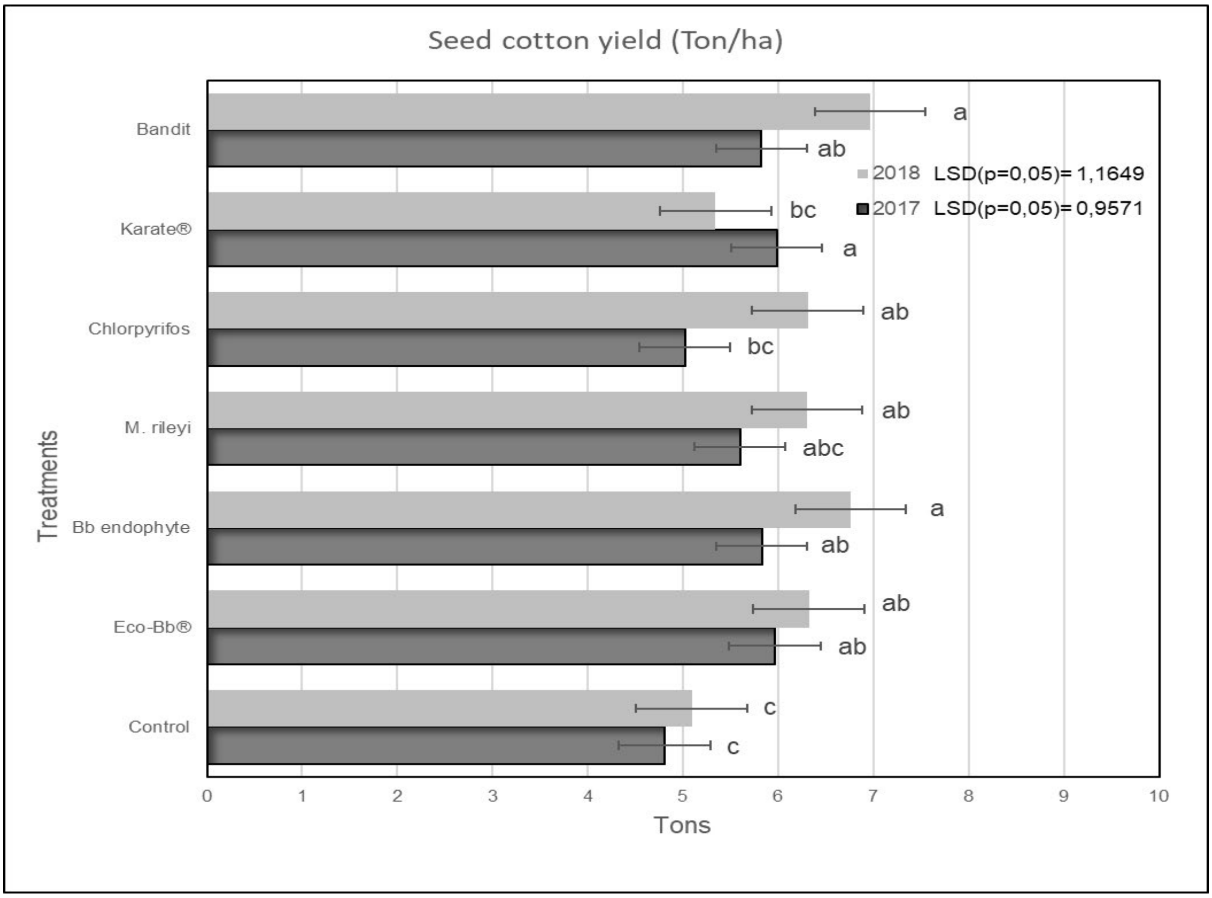

Figure 4.7 Seed cotton yields obtained from the different treatments under field conditions during the 2017 and 2018 seasons

4.4 DISCUSSION

The biopesticides tested in this study provided control against some of the cotton pests. Karate® outperformed the other treatments in controlling leafhopper. Asif *et al*. (2016) have documented the efficacy of Karate® against leafhopper, where Karate® caused a 57.93% reduction of the pest. In an experiment conducted by Javaid *et al*. (2000), the use of Karate® resulted in the highest cotton yield; however, it did not significantly control the leafhoppers. In contrast to the findings in this study, the lambda-cyhalothrin was less effective than the other six ingredients. Zidan *et al*. (2012) also evaluated various pesticides against cotton insects and reported that lambda-cyhalothrin and chlorpyrifos had a weak to moderate effect on leafhoppers.

Chlorpyrifos® significantly reduced the leafhopper population in 2017. Kone *et al*. (2018) conducted susceptibility tests of ten active ingredients against cotton leafhopper. They reported that chlorpyrifos-ethyl and imidacloprid were amongst the most toxic to leafhoppers. Although the efficacy of Eco-Bb® and Bb endophyte was on par with the Chlorpyrifos®, Mandage *et al*. (2015) reported that a strain of *B. bassiana* provided the least control of leafhoppers under laboratory conditions. Similarly, Eco-Noc performed the best in 2018 while it was the worst in 2017. There is very limited literature on the effect of *M. rileyi* on cotton pests. Fronza *et al*. (2017) reported that the host range of *M. rileyi* is quite narrow and mostly limited to lepidopteran larvae. Rainfall plays a significant role in the incidence, development, and population fluctuations of sucking insect pests on cotton crops (Mohapatra, 2008). However, Majeed *et al*. (2016) found no significant influence of rainfall on the cotton leafhopper population. Parnell (1925) reported that more leafhopper damage occurs during wet seasons than in dry ones in South Africa.

Eco-Bb® and Bb endophyte did not control aphids during the first season in 2017. The development of dormant forms and infection of the fungus *B. bassiana* requires several days of high humidity, which is dependent on the movement of aphids to come into contact with their conidia (Kim *et al*., 2001). In contrast, in 2018, Eco-Bb® was the second-best treatment for the control of aphids, all the biopesticides being effective treatments against aphids in 2018. The fungus *B. bassiana* has previously been reported to reduce aphids on cotton (Kim and Je, 2010; Kim *et al*., 2010; Gurulingappa *et al*., 2011). Manjula *et al*. (2017) conducted field experiments to investigate the control of cotton aphids using *P. fluorescens* compared to *B. bassiana* and imidacloprid on non-Bt cotton. Their results revealed that *B. bassiana* was among the bio-inoculants that caused the greatest reduction in aphid populations with soil and foliar application. The effect of *B. bassiana* against cotton aphid reproduction under field conditions was also investigated by Lopez *et al*. (2014). They reported that plants inoculated with *B. bassiana* displayed significantly reduced numbers of aphids.

Plots that were treated with Bandit® recorded the lowest aphid populations in 2017. Imidacloprid has been used widely for the control of aphids (Wang *et al*., 2002). No resistance to imidacloprid has been found in field-derived populations of aphids (Nauen *et al*., 1998; Nauen and Elbert, 2003). More than 70% reduction of aphid populations with the treatment of imidacloprid was reported by Ghelani *et al*. (2006). Imidacloprid has been previously found to be relatively non-toxic to coccinellids and spider populations (Ghosal *et al*., 2018), which are the key natural enemies of cotton aphid (Ali *et al*., 2016). Chlorpyrifos® also reduced the aphid population by almost half in comparison to the untreated control, Bb endophyte and Eco Bb®. This is in line with the findings of Irshaid and Hassan (2011), who found that chlorpyrifos caused 100% mortality of aphids and a long period of plant protection against aphid infestation. The pest infestation numbers doubled in 2018 when compared with the previous season. Even though there were no significant differences as a result of the various treatments, aphids seemed to be affected by the climatic conditions. Several authors have cited high temperatures and rainfall as the cause of aphid mortality in the field (Walker *et al*., 1984; Nakata, 1995; Picanço *et al*., 1997; Leite *et al*., 2006).

The thrips populations were very low during the first season when the rainfall was higher. Rainfall and mean daily temperatures below 10°C have been reported to reduce thrips movements; however, heavy infestations may result from build-up in the field (Harding, 1961). Lower thrips population may be attributed to higher rainfall in 2017 (Khan *et al*., 2008), while the increased thrips population in 2018 may have been due to less rainfall, causing thrips to concentrate in cotton (Wilson and Bauer, 1993). Eco-Bb®-treated plots recorded the lowest number of thrips in 2017, while they performed poorly in 2018. During the second season, all the treatments significantly reduced the thrips populations compared to the untreated control. Boricha *et al*. (2010) stated that the combination of biopesticides with synthetic pesticides was superior to biopesticides alone against cotton thrips. Bharani *et al*. (2015) studied the efficacy of biopesticides and insecticides against thrips. They concluded that insecticides were superior to biopesticides.

Bandit® produced the most significant control of thrips in 2018, which is in accordance with the study conducted by Bharani *et al*. (2015). Despite *M. rileyi* being highly sensitive to environmental conditions (Grijalba *et al*., 2018; Binneck *et al*., 2019) and difficult to produce in large quantities (Fronza *et al*., 2017), plots that were treated with Eco-Noc performed as well as Bandit® and Karate® in controlling the thrips.

The symptoms of whitefly attack on cotton are similar to the cotton leaf curl virus disease, making it difficult for farmers to identify the pest at the early stages of plant development (Farooq *et al*., 2014). There were no significant differences in the populations of whiteflies; as a result of the six treatments, however, Bandit®, Karate® and Chlorpyrifos® were more effective in reducing the pest numbers. Avicor *et al*. (2014) reported that whiteflies were susceptible to Karate® on cassava, okra, and tomato. These findings more or less matched the present findings. In 2017 comparatively few whiteflies were found in plots treated with Eco-Bb®. Although Karate® was effective against whiteflies, Watson *et al*. (1994) reported that insecticide combinations proved to be the most effective treatments against whitefly infestation. In contrast to the findings of this study, some studies found whiteflies to be resistant towards lambda-cyhalothrin and imidacloprid (Cahill *et al*., 1996; Prabhaker *et al*., 1997; Elbert and Nauen, 2000; Wang *et al*., 2002; Khan, 2011). These studies are contrary to reports that imidacloprid offered excellent control of aphids, whiteflies and other insects worldwide (Mullins 1993, Wang *et al*. 1995, Torres and Ruberson, 2004; Kar, 2017).

All the treatments used, except for Bandit®, significantly reduced the number of spider mites compared to the untreated control in 2017. The application of imidacloprid has been found to cause secondary outbreaks of spider mites (Szczepaniec *et al*., 2011). Szczepaniec (2009) attributed this to the eradication of beneficial insects, stimulation of spider mite fecundity and changes in plant defence pathways. Eco-Bb® and Bb endophyte caused high levels of mortality of spider mites in 2017. This confirmed the findings of previous research by Shi *et al*. (2008) on the use of *B. bassiana* formulations to control cotton spider mites, which significantly controlled the pest.

Plots treated with Karate® had the lowest number of spider mites, followed by those treated with Eco-Noc. Although Chlorpyrifos® treated plots had significantly reduced numbers of spider mites in 2017, Shi *et al*. (2008) did not observe any field efficacy against spider mites when treated with Chlorpyrifos®. They further suggested that the overuse of pesticides against major cotton pests results in outbreaks of spider mites. Yousuf *et al*. (2012) evaluated the comparative toxicity of Chlorpyrifos® and lambda-cyhalothrin against the adults of two-spotted mites. They found that the overall efficacy of Chlorpyrifos® and lambda-cyhalothrin against fecundity, and survivorship of the spider mites was superior to a neem extract.

Late-season pests like cotton stainers can cause considerable cotton yield losses when outbreaks are not controlled (Kuklinski and Borgemeister, 2002). It was evident from the results that in 2017 all the treatments were significantly effective against cotton stainers. Chlorpyrifos® and Karate® were the most effective treatments against cotton stainers. Sarwar *et al*. (2018) studied the effect of various conventional insecticides on haemocytes of cotton stainers and observed that chlorpyrifos was more effective and significantly altered the total haemocyte counts. Bb endophyte significantly reduced the cotton stainer population in 2017. Moorthi *et al*. (2012) reported a 100% mortality of red cotton stainer after treatment with *B. bassiana* isolates, which conformed with the results found in this study.

During this investigation, the highest mean seed cotton yields for both seasons were registered in the plots that were treated with Bandit® (6 395 $kg.ha^{-1}$), Bb endophyte (6 295 $kg.ha^{-1}$) and Eco-Bb® (6 141 $kg.ha^{-1}$). Previous studies have shown that imidacloprid increased cotton yields (Gonias *et al*., 2008; Kalyan *et al*., 2012; Bharpoda *et al*., 2014; Asif *et al*., 2018; Meena, 2018), as did *B. bassiana* (Ramesh *et al*., 1999; Togbé *et al*., 2015). The results of this study are also in agreement with those reported by Hossain *et al*. (2012) and Asif *et al*. (2016), who found that plots treated with imidacloprid produced greater seed cotton yields. It was evident from the data that treatment with Chlorpyrifos® resulted in the lowest yield of 5 021 $kg.ha^{-1}$, which was not significantly different from the untreated control (4 808 $kg.ha^{-1}$).

Harris (2015) studied the effect of chlorpyrifos application at different growth stages on tomato, but in contrast, it caused significantly increased yields in tomato. These findings are not in agreement with the findings of this study. Although in 2017 treated plots were found to be non-significantly different from each other, the highest seed cotton yield was recorded in the plots that were treated with Karate® according to what was observed in Figure 4.7. Karate® has been previously found to significantly increase cotton yield compared to untreated control (Asif *et al*., 2016). These findings were contrary to the results obtained in 2018, where plots treated with Karate® developed the lowest seed cotton yield after the untreated control. The yields were slightly higher during the 2018 season when there was less rainfall than in the 2017 season. Togbé *et al*. (2015) noted that excessive rainfall could cause a reduction in yields in cotton production.

The results from the present study indicate that the biopesticides the biopesticides were as effective as the chemical insecticides against some cotton pests. The plots treated with these biopesticides also produced comparative seed cotton yields as some of those treated with insecticides and the untreated control. The trials demonstrated that the chemical insecticides were most effective against targeted pests, while the biopesticides produced a moderate reduction of some pests. Bb endophyte and Eco-Bb® significantly increased seed cotton yield among the biopesticides, and Bandit® significantly increased seed cotton yield among the chemical insecticides. Integration of chemical and biological control strategies remain a viable option in an IPM programme for the control of cotton pests.

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CHAPTER 5

BENEFIT-COST ANALYSIS OF BIOPESTICIDES AND SYNTHETIC PESTICIDES: IMPLICATIONS FOR COTTON FARMERS

Abstract

Cotton (*Gossypium hirsutum* L.) remains one of the crucial sources of income in Sub-Saharan Africa. However, production is constrained by biotic losses and high input costs that result in profit losses. Two field trials were conducted in 2017 and 2018 to evaluate the effect of biopesticides and synthetic pesticides on the control of various cotton insect pests. Based on the outcomes of these experiments, a cost analysis of each treatment was done. The highest cost of pesticide applications was recorded with Delfin® (R 7 980/$602.32), followed by the Bolldex® (R 6 568/$495.74), while the lowest cost was from the use of Chlorpyrifos® 480 EC (R 370/$27.93). Other input costs were R 18 502/$1 396.50 per hectare, with the highest cost of R 7 200/$543.45 being recorded for labour costs for weed control. Overall, the lowest total production costs per hectare in the bollworm experiment was observed from the treatment with Karate® EC (R 19 282/$1 455.38) while the treatment with Delfin® (R 26 482/$1 998.82) recorded the highest costs of treatment. In the bollworm trial, the maximum seed cotton yield of 5 987 kg.ha^{-1} (2017) and 6 818 kg.ha^{-1} (2018) were recorded in the Bolldex® treated plots. The maximum net profit of up to R 19 148/$1 445.26 per hectare was recorded in Karate® EC treated plots, with the highest mean benefit-cost ratio of 1.8. In the leafhopper trial, the mean highest seed cotton yield of 6 394 kg.ha^{-1} was obtained from the Bandit® 350 SC treated plots, followed by Bb endophyte with 6 297 kg.ha^{-1}. During the 2016/17 season, plots where Karate® EC was applied had the highest net profit of R 16 598/$1 712.31, while during the 2017/18 season, the plots treated with Bandit® 350 SC recorded the highest net income of R 22 686/$1 252.79. However, the benefit-cost ratios showed that the treatment of Bandit® 350 SC had the highest mean benefit-cost ratio of 2. Overall, the cost of biopesticides was higher than the synthetic pesticides. However, they were all financially viable and can be adopted by the cotton farmers as part of a profitable IPM programme.

5.1 INTRODUCTION

Cotton, *Gossypium hirsutum* L. (Malvaceae), remains the most commercially important fibre crop worldwide (Haider *et al*., 2016). Africa contributes approximately 8% of the global cotton production (Amanet *et al*., 2019), mainly from smallholder farmers (IPBO, 2017). Despite this, cotton yields and fibre quality are affected by a wide range of insect pests (Sabesh and Prakash, 2018). Synthetic pesticides are commonly utilized because they are readily available and most effective depending on when and where a pest encounters them (Bolzonella *et al*., 2019). However, pesticides have a negative impact on water quality (Herrero-Hernández *et al*., 2017), human health (Nicolopoulou-Stamati *et al*., 2016) and the environment (Amaraneni, 2018; Hassaan and El Nemr, 2020). The misuse of pesticides also results in the development of resistance and adverse effects on non-targeted organisms (Benelli, 2018). The use of biopesticides in cotton reduces the application of synthetic pesticides while decreasing insect resistance and increasing yields (Sharma *et al*., 2018). However, in developing countries, the technology is not well explored, particularly for smallholder farmers (Gayi *et al*., 2017). The delay in adopting biopesticides includes incorrect testing without considering their modes of action and incorrect perceptions of cost and efficacy (Marrone, 2008). The demand for biopesticides is expected to surpass synthetic pesticides, with annual growth rates of more than 15% (Marrone, 2014). In 2014, biopesticides represented about $3 billion of the $56 billion pesticide market, and by 2019 approximately $4 billion of the US$61.3 billion pesticide market (Marrone, 2019). The global market for synthetic pesticides and biopesticides is expected to reach $79.3 billion by 2022 (BCC Research, 2018).

The cotton production process involves various inputs, from inputs and land preparation to harvesting and marketing. Smallholder cotton farmers continuously struggle to access better-quality seed, fertilizers and pesticides to improve their production (IPBO, 2017). Over time, the prices of these inputs have increased, resulting in a higher cost of production and reduced net profits.

In Africa, cotton production can be improved by increasing agricultural research and seed availability, reducing input costs, and adopting a capacity-building strategy to enable the farmers to increase profits from cotton (Amanet *et al*., 2019). South Africa was the first country on the African continent to adopt Bt cotton for commercial production in 1998. Although there was initially a rise in yields due to reduced pest damage (Gouse *et al*., 2003; Kathage and Qaim, 2012), it also increased costs due to the need to control secondary pests (Catarino *et al*., 2015). Furthermore, the Bt cotton seed has cost farmers more than non-Bt varieties due to royalty costs (Gouse *et al*., 2003; Pschorn-Strauss, 2005).

While the cotton price, input costs and weather have a great influence on cotton production, the increasing cost of cotton production per hectare has gradually reduced the profit share for cotton farmers (Ali *et al*., 2012). With each input playing a significant role in cotton production, plant protection is key to increased yields and profit margins. In order to identify the influence of these inputs, the present study was undertaken. Furthermore, farmers need to understand the financial viability of biopesticides on the market to make profitable decisions. In Chapters 3 and 4, research experiments were conducted to determine the impact of different biopesticides compared with popular synthetic pesticides against some cotton pests. Therefore, this chapter aimed to estimate the cost of inputs and the gross profits in cotton production associated with the use of various pest control agents. The study undertook a benefit-cost analysis of biopesticides and synthetic pesticides on cotton production to determine the best economical options for farmers.

5.2 MATERIALS AND METHODS

5.2.1 Trials site

The costs of cotton production using biopesticides and synthetic pesticides were recorded from two field experiments (bollworm and leafhopper) conducted during the 2016/17 season and repeated during the 2017/18 season at the Agricultural Research Council – Industrial Crops, Rustenburg, South Africa.

5.2.2 Seed and pesticides

The non-GM cottonseed, DeltaOpal (Monsanto: Sandton, South Africa), was planted. The commercially available pesticides Karate® EC (Syngenta: Centurion, South Africa), Chlorpyrifos® 480 EC (Villa Crop Protection: Kempton Park, South Africa), and Bandit® 350 SC (Arysta LifeScience: Durban, South Africa) were applied. The commercially available biopesticides, Eco-Bb® (Plant Health Products: Midlands, South Africa), Bolldex® and Delfin® (Madumbi Sustainable Agriculture: Hilton, South Africa), and the experimental biopesticides, Bb endophyte (University of KwaZulu-Natal: Pietermaritzburg, South Africa) and Eco-Noc (Plant Health Products: Midlands, South Africa), were also applied. The costs of the seed and pesticides were obtained by multiplying the total quantity (kg or litre) of the respective item required (per hectare application) with the market price that was obtained from the suppliers. The cost of pesticide application per hectare is based on the ten sprays administered in each experiment. As the Eco-Noc and Bb endophyte are experimental biopesticides, for this analysis, their prices were equated to the market price of Eco-Bb®.

5.2.3 Treatment application

In both the experiments, there were ten treatment applications administered in each trial per season. This frequency of application was used to give comparability with common practice in the use of synthetic and biological pesticides. The spray applications of treatments were administrated for 10 weeks.

5.2.4 Labourer wages and other production inputs

Two research assistants administer the treatments in a day at the prescribed wage rate of $10.87/day based on the National Minimum Wage Act of 2018. A total of 20 days of labour per season was costed for the application of treatments per hectare. This is based on two labourers per day per ten applications. Hand hoeing was costed at five labourers per day for ten days. Table 5.2 summarizes the list and costs of the seed and other inputs required to produce a hectare of cotton.

5.2.5 Benefit-cost analysis

The benefit-cost analysis was based on variables that included the costs of seed and pesticides, land preparation, and trial maintenance. The cost and return were calculated at Rand per hectare. The externalities such as potential impacts on the environment, natural enemies, farmworker, and consumer safety associated with each treatment were not considered in the analysis. The data required for doing the benefit-cost analysis were based on the expenses incurred during the experiments. The prices for treatments and seed were obtained from suppliers, while the selling price/kg of the seed cotton was based on the selling price at the ginnery.

The net return was calculated by subtracting the total cost of production from the revenue based on a formula by Ali *et al*. (2012):

Net Benefit = Total revenue earned – Total cost of production

The net return refers to the profit made after deducting the input costs, while the total revenue refers to the amount received after selling seed cotton to the ginnery.

5.2.6 Benefit-cost ratio

The benefit-cost ratio was calculated from the seed cotton yield of each treatment and the cost of insecticide treatments. The benefit-cost analysis cost ratio of the pesticides was calculated based on the formula adopted from Gayi *et al*. (2017):

Benefit-Cost Ratio = Total income earned ÷ Total cost of production

The total revenue earned represents the income that may be received from the sale of seed cotton, while the total cost of production represents all the costs incurred to produce the seed cotton yield in each season. The benefit-cost ratio was interpreted using the following index: When the benefit-cost ratio is greater than 1, the seed cotton yield was financially viable, while the benefit-cost ratio of less than 1 implies that the seed cotton yield was not financially viable. A benefit-cost ratio of 1 implies breakeven.

5.3 RESULTS

5.3.1 Cost of pesticides

The cost of each treatment per hectare is provided in Table 5.1. The highest cost of pest control treatment was recorded with Delfin® (R 7 980) followed by the Bolldex® (R 6 568), while the lowest cost was obtained from the Chlorpyrifos® 480 EC (R 370). The cost of the other treatments ranged between R 620 and R 3 000.

Table 5.1 Application rates and prices of biopesticides and synthetic pesticides that were used in the experiments

Trade name	Active ingredient	Application	Unit Price	Amount*
Eco-Bb®	*Beauveria bassiana*	300g ha^{-1}	R 300/300g	R 3 000/$226.44
Bolldex®	Nucleopolyhedrovirus	200ml ha^{-1}	R 1 642/500ml	R 6 568/$495.74
Delfin®	*Bacillus thuringiensis*	1kg.ha^{-1}	R 798/kg	R 7 980/$602.32
Bb endophyte	*Beauveria bassiana*	300g ha^{-1}	R 300/300g	R 3 000/$226.44
Eco-Noc	*Metarhizium rileyi*	300g ha^{-1}	R 300/300g	R 3 000/$226.44
Karate® EC	Lambda-cyhalothrin	120ml ha^{-1}	R 650/l	R 780/$58.87
Chlorpyrifos® 480	Chlorpyrifos	200ml ha^{-1}	R 185/l	R 370/$27.93
Bandit® 350 SC	Imidacloprid	200ml ha^{-1}	R 310/l	R 620/$46.80

*The amount is based on ten sprays per hectare at the application rate.

5.3.2 Production costs

Over and above the costs incurred from the procurement of the pesticides, other production costs amounted to R 18 502 per hectare (Table 5.2). These costs included seed, land preparation, planting, weeding, application of pesticides and harvesting. The highest cost of R 7 200 was recorded for the manual control of the weeds, followed by harvesting (R 4 780). The total production costs for each treatment are reflected in Tables 5.3–5.6. Overall, the lowest total production costs per hectare in the bollworm experiment was observed from the treatment with Karate® EC (R 19 282), while the treatment with Delfin® (R 26 482) recorded the highest costs of production.

In the leafhopper experiment, the lowest total production costs were obtained from all the plots treated with synthetic pesticides. Plots that were treated with Chlorpyrifos® 480 EC (R 18 872) had the lowest costs, followed by Bandit® 350 SC (R 19 122) and Karate® EC (R 19 282). The highest costs of R 21 502 were incurred where Eco-Bb®, Bb endophyte and Eco-Noc were applied.

Table 5.2 Costs of the other inputs that were used in the experiments

Input	Quantity	Cost/ha
Seed	8kg/ha	R 1 035/$78.12
Ripping	Tractor hire/ha	R 1 117/$84.31
Discing	Tractor hire/ha	R 745/$56.23
Planting	Tractor hire/ha	R 745/$56.23
Hand hoeing	5 workers/day for 10 days @ $10.87	R 7 200/$543.45
Spraying of pesticides	2 workers/day for 10 days @ $10.87	R 2 880/$543.45
Harvesting	Tractor hire/ha	R 4 780/$360.79
Total		**R 18 502/$1 396.50**

5.3.3 Seed cotton yield

5.3.3.1 Bollworm experiment

Tables 5.3 and 5.4 summarize the benefit-cost analysis of the pesticides in the cotton bollworm experiments conducted during the 2016/17 and 2017/18 seasons. The seed cotton yields were higher during the 2017/18 season. In both seasons, the highest seed cotton yield of 5 987 kg.ha^{-1} (2017) and 6 818 kg.ha^{-1} (2018) were recorded in the plots treated with Bolldex®. Plots that were treated with Bolldex® increased the seed cotton yield by 45% compared to the control.

5.3.3.2 Leafhopper experiment

Accordingly, all the treatments had higher seed cotton yields than the control, which resulted in net benefits that exceeded production costs (Tables 5.5 and 5.6). During the 2016/17 season, the highest seed cotton yield was obtained with treatment of Karate® EC (5 983 $kg.ha^{-1}$) followed by Eco-Bb® (5 963 $kg.ha^{-1}$). The lowest yield was obtained from plots treated with Chlorpyrifos® 480 EC (5 021 $kg.ha^{-1}$). During the 2017/18 season, the yields were higher than the previous season. Plots treated with Bandit® 350 SC had the highest seed cotton yield of 6 968 ha^{-1}, followed by Bb endophyte with 6 763 $kg.ha^{-1}$. The lowest seed cotton yield was obtained from the plots treated with Karate® EC (5 340 $kg.ha^{-1}$). On average, plots that were treated with Bandit® 350 SC had the highest seed cotton yield.

5.3.4 Gross income

5.3.4.1 Bollworm experiment

Based on a mean rate of R 6/kg, the highest gross income was obtained with the treatment of Bolldex® (R 35 922 and R 40 908) in both seasons.

During the 2016/17 season, the plots treated with Eco-Bb® and Bb endophyte had the lowest gross income of R 18 330 and R 18 600, respectively. During the 2017/18 season, the lowest gross income was recorded with the untreated control (R 28 038) followed by the treatment of Delfin® (R 34 530). The gross income of all the other treatments ranged between R 34 530 and R 40 908.

5.3.4.2 Leafhopper experiment

The highest gross income of R 35 880 was obtained from treatment of Karate® EC and closely followed by Eco-Bb® at R 35 760 during the 2016/17 season. Treatment of Chlorpyrifos® 480 EC recorded the lowest gross income of R 30 120 compared to the other treatments. Besides the control (R 28 860), all the treatments ranged between R 30 120 and R 35 880.

During the 2017/18 season, in plots where Bandit® 350 SC was applied, the highest gross income of R 41 808 was obtained, whereas, in the plots where Karate® EC was applied, the lowest gross income of R 32 040 was obtained. The gross income for the other treatments ranged from R 37 860 to R 40 578.

5.3.5 Net income

5.3.5.1 Bollworm experiment

During the 2016/17 season, the highest net income was obtained with treatment of Karate® EC (R 11 516) and lowest with Delfin® (R -5 344). Other treatments had net incomes ranging from R -3 172 to R 10 852. During 2017/18, the treatment of Karate® EC was found to have the highest net income of R 19 148 while Delfin® had the lowest net income of R 8 048. Except for the control, the other treatments had net incomes of between R 14 264 and R 16 952.

5.3.5.2 Leafhopper experiment

All the treatments exhibited higher net income than the control in both seasons (Tables 5.5 and 5.6). Plots, where Karate® EC was applied, had the highest net income of R 16 598 during the 2016/17 season, whereas the lowest net income of R 11 248 was recorded where Chlorpyrifos® 480 EC was applied. Other treatments had a net income that ranged between R 12 098 and R 15 798. During the 2017/18 season, treatment of Bandit® 350 SC resulted in the highest net income of R 22 686, followed by Bb endophyte at R 19 076. The lowest net income was recorded with the treatment of Karate® EC at R 12 758. Net incomes resulting from the other treatments ranged from R 16 298 to R 18 988.

5.3.6 Benefit-cost ratio

5.3.6.1 Bollworm experiment

The benefit-cost ratio performed for different treatments in this study indicated ratios of 1.4 for Bolldex® and untreated control, 1.6 for Karate® EC compared to 0.8 for Delfin®, 0.9 for Eco-Bb® and Bb endophyte during the 2016/17 season (Table 5.3).

During the 2017/18 season, the ratios indicated that Karate® EC (2.0) had the highest benefit-cost ratio compared to Bb endophyte (1.8), Eco-Bb® (1.7), Bolldex® (1.6), untreated control (1.5) and Delfin® (1.3). The Karate® EC treatment had the maximum benefit-cost ratio during both seasons (Table 5.4).

5.3.6.2 Leafhopper experiment

During the 2016/17 season, the highest benefit-cost ratio was registered with Karate® (1.9), while the lowest benefit-cost ratio of 1.6 was registered with Eco-Noc, Bb endophyte, Chlorpyrifos® 480 EC and the control. Other treatments had a benefit-cost ratio that ranged from 1.7 for Eco-Bb® to 1.8 for Bandit® 350 SC (Table 5.5). During the 2017/18 season, the benefit-cost ratio of different treatments increased as follows: Control (1.7), Karate® EC (1.7), Eco-Bb® (1.8), Eco-Noc (1.8), Bb endophyte (1.9), Chlorpyrifos® 480 EC (2.0), Bandit® 350 SC (2.2) (Table 5.6).

Table 5.3 Estimates of benefit-cost analysis of the synthetic and biological pesticides in the cotton bollworm experiments conducted during the 2016/17 season

Treatments	Quantity	Cost/treatment*	Other costs	Total costs	Cotton yield	Cost/kg	Income	Net benefits	Benefit-cost ratio
	ha^{-1}	(R ha^{-1})	(R)	(R)	($kg.ha^{-1}$)	(R)	(R ha^{-1})	(R ha^{-1})	
Control	0	0	18 502	18 502	4 168	6	25 008	6 506	1.4
Eco-Bb®	300g	3 000	18 502	21 502	3 055	6	18 330	-3 172	0.9
Bolldex®	200ml	6 568	18 502	25 070	5 987	6	35 922	10 852	1.4
Delfin®	1kg	7 980	18 502	26 482	3 523	6	21 138	-5 344	0.8
Bb endophyte	300g	3 000	18 502	21 502	3 100	6	18 600	-2 902	0.9
Karate® EC	120ml	780	18 502	19 282	5 133	6	30 798	11 516	1.6

*The cost per treatment is based on ten applications per season.

Table 5.4 Estimates of benefit-cost analysis of the synthetic and biological pesticides in the cotton bollworm experiment conducted during the 2017/18 season

Treatments	Quantity	Cost/treatment*	Other costs	Total costs	Cotton yield	Cost/kg	Income	Net benefits	Benefit-cost ratio
	ha^{-1}	(R ha^{-1})	(R)	(R)	($kg.ha^{-1}$)	(R)	(R ha^{-1})	(R ha^{-1})	
Control	0	0	18 502	18 502	4 673	6	28 038	9 536	1.5
Eco-Bb®	300g	3 000	18 502	21 502	5 961	6	35 766	14 264	1.7
Bolldex®	200ml	6 568	18 502	25 070	6 818	6	40 908	15 838	1.6
Delfin®	1kg	7 980	18 502	26 482	5 755	6	34 530	8 048	1.3
Bb endophyte	300g	3 000	18 502	21 502	6 409	6	38 454	16 952	1.8
Karate® EC	120ml	780	18 502	19 282	6 405	6	38 430	19 148	2.0

*The cost per treatment is based on ten applications per season.

Table 5.5 Estimates of benefit-cost analysis of the synthetic and biological pesticides in the cotton leafhopper experiment conducted during the 2016/17 season

Treatments	Quantity	Cost/treatment*	Other costs	Total costs	Cotton yield	Cost/kg	Income	Net benefits	Benefit-cost ratio
	ha^{-1}	(R ha^{-1})	(R)	(R)	(kg.ha^{-1})	(R)	(R ha^{-1})	(R ha^{-1})	
Control	0	0	18 502	18 502	4 810	6	28 860	10 358	1.6
Eco-Bb®	300g	3 000	18 502	21 502	5 960	6	35 760	14 258	1.7
Bb endophyte	300g	3 000	18 502	21 502	5 830	6	34 980	13 478	1.6
Eco-Noc	300g	3 000	18 502	21 502	5 600	6	33 600	12 098	1.6
Karate® EC	120ml	780	18 502	19 282	5 980	6	35 880	16 598	1.9
Chlorpyrifos® 480 EC	200ml	370	18 502	18 872	5 020	6	30 120	11 248	1.6
Bandit® 350 SC	200ml	620	18 502	19 122	5 820	6	34 920	15 798	1.8

*The cost per treatment is based on ten applications per season.

Table 5.6 Estimates of benefit-cost analysis of the synthetic and biological pesticides in the cotton leafhopper experiment conducted during the 2017/18 season

Treatments	Quantity	Cost/treatment*	Other costs	Total costs	Cotton yield	Cost/kg	Income	Net benefits	Benefit-cost ratio
	ha^{-1}	(R ha^{-1})	(R)	(R)	(kg.ha^{-1})	(R)	(R ha^{-1})	(R ha^{-1})	
Control	0	0	18 502	18 502	5 090	6	30 540	12 038	1.7
Eco-Bb®	300g	3 000	18 502	21 502	6 320	6	37 920	16 418	1.8
Bb endophyte	300g	3 000	18 502	21 502	6 763	6	40 578	19 076	1.9
Eco-Noc	300g	3 000	18 502	21 502	6 300	6	37 800	16 298	1.8
Karate® EC	120ml	780	18 502	19 282	5 340	6	32 040	12 758	1.7
Chlorpyrifos® 480 EC	200ml	370	18 502	18 872	6 310	6	37 860	18 988	2.0
Bandit® 350 SC	200ml	620	18 502	19 122	6 968	6	41 808	22 686	2.2

*The cost per treatment is based on ten applications per season.

5.4 DISCUSSION

In Sub-Saharan Africa, cotton production encounters challenges due to competition with other crops (IPBO, 2017). This has been caused by the decline of productivity over the years, which is related to negative financial factors such as changes in market prices and costs of production inputs. Since cotton markets are highly competitive, a reduction in input costs is as important as obtaining a higher level of productivity (Isin *et al*., 2009). The production of cotton relies mainly on the climate, availability of affordable inputs and favourable marketing conditions. The market price fluctuates because of the changes in supply and demand as well as of the global cotton market. The net incomes that were found in this study differed for each treatment based on the input costs and the yield obtained.

When comparing the cost of all the treatments from the experiments, the data demonstrate that the costs of biopesticides were higher than the synthetic pesticides. When looking solely at each pesticide use per hectare, Delfin® was the most expensive treatment at R 7 980 per 10 sprays. All synthetic pesticides that were used in the trials cost less than R 1 000 per hectare. The lower costs of synthetic pesticides may be due to fixed costs related to their use by a large part of the farming community on many crops (Chandler *et al*., 2011). However, biopesticides must compete on cost and performance. With a synthetic pesticide, provided one knows its composition, it is easy to predict what it will do, whereas, with a biological product, the farmer may have less confidence about how it fits into the ecosystem. However, excessive spending on synthetic pesticides may necessitate an increased extension into complex pest control management strategies (Wheeler and Ortmann, 1990). In Pakistan, Ali *et al*. (2012) reported an increase in input costs of pesticides over time compared to seed costs.

Bolldex® (HaNPV) was the second most expensive treatment at R 6 568 per 10 sprays. In a study conducted by Ojha *et al*. (2019) to quantify the cost of biopesticides against *H. armigera* in chickpea, HaNPV was also the most expensive treatment followed by *B. bassiana*. However, contrary to the findings of these cotton trials, they reported that the *B. thuringiensis* treatment was cheaper than HaNPV and *B. bassiana*.

This was also supported by a survey that was conducted by Constantine *et al*. (2020) in Kenya, which observed that the highest mean amount that farmers spent on biopesticides was \$131 ha^{-1} for *B. bassiana* and \$95 ha^{-1} for *B. thuringiensis*.

Although biopesticides are often much cheaper to develop (Wilson, 2020) and they provide a more sustainable solution than synthetic pesticides (Warwick, 2010), they are a segment of larger market products with low-profit potential due to high fixed costs of adoption, which may decline when the technology is broadly used (Chandler *et al*., 2011). Olson (2015) stated that it costs about \$250 million and nine years to develop and register a synthetic pesticide, while a biopesticide development requires less than \$10 million and four years. The costs of treatments rely mainly on their efficacy, and synthetic pesticides are generally perceived as more effective than biopesticides. The farmers' views on how effective a product is, are crucial when testing a new product (Constantine *et al*. 2020). This includes the cost of buying the product to the risk of that product being not effective against the pest that it is intended for. As biopesticides may not work immediately and are often found to be more effective under greenhouse conditions, farmers must acquire more knowledge on the application of biopesticides (Warwick, 2010). Constantine *et al*. (2020) conducted a survey on farmers' current use and perception of chemical pesticides and biopesticides. They documented that the low use of biopesticides by smallholders was due to, among other things, availability and affordability.

Cotton production is about combining inputs to produce an output. Some of the most important factors for competing in cotton markets include high yields and minimum production costs (Isin *et al*., 2009). Other than the costs of controlling pests on cotton, there are other expenses such as seed, cultivation and labour costs for weed control and harvesting. For the purpose of the experiments conducted, conventional cotton was used to eliminate the effect of the Bt gene on bollworms. Although Bt cotton has been reported to increase yield and profit, it had been shown that the total costs of cultivation and seed of Bt cotton is greater than the costs on conventional cotton (Qaim and de Janvry, 2003; Arora and Bansal, 2012; Noonari *et al*., 2015).

In Pakistan, inputs such as land preparation and irrigation costs have positively impacted the revenue, while pesticides and fertilizer costs negatively affected the revenue (Wei *et al*., 2020). Farmers with larger fields have the advantage to spread the costs of production over more cotton hectares and can allocate some of the costs to other crops to increase profitability (English *et al*., 2005).

Labour costs on cotton production are among the highest inputs (Sabo *et al*., 2009; Kranthi *et al*., 2018). However, to cotton farmers with limited financial support and small land sizes, the labour wages are the primary source of cash income for the household (Wheeler and Ortmann, 1990). Smallholder farmers that rely on family labour tend to limit the size of production fields based on the amount of cotton that a family can handle (Welch and Miley, 1950). In the survey conducted in Chapter 2, 88% of the farmers identified labour costs as one of the major constraints in cotton production. Alam *et al*. (2013) reported that in Nigeria, the cost of labour has the highest percentage (21%) of the total cost of cotton production. In Bangladesh, Sarker and Alam (2016) reported that labour cost on cotton amounts to 28.60% of the total cost of production. In India, labour cost has occupied up to 50% of total operational cost (Balaji and Kumar, 2016; Singh, 2018). In Turkey, labour and pesticide costs were reported to be amongst the highest cost items; however, the costs increased on large farms (Yilmaz *et al.*, 2005). China has also reported increasing production costs due to high labour costs, despite the government's strong cotton price support programme (Agbenyegah, 2013).

The control of weeds through hand hoeing had the highest cost of R 7 200 compared to the other inputs during the two seasons when the trials were conducted. Weed control in cotton remains a challenge due to differences in weed species, soil type, and rainfall, amongst other factors, which makes it difficult to develop single practices that work well in larger cotton fields (Holstun *et al*., 1960). Farmers must consider combining crop rotation, cultivation, hand hoeing, and herbicide application to control weeds in cotton production successfully (Wrona *et al*., 1997). According to Khalilian *et al*. (2017), strip-tillage systems is one of the techniques that can be used to reduce labour costs in cotton production. These strategies can reduce the labour costs that may be incurred during weed control.

Isin *et al*. (2009) has also reported that manual harvesting is one of the highest costs in cotton production, primarily due to manual labour employed during the harvest. They recommended that mechanical harvesting may play a vital role in reducing the cost of cotton production. Similarly, Feng *et al*. (2017) cited mechanization and precision seeding as key practices to reduce labour costs in cotton cultivation.

Yield is one of the significant factors that determine the gross margin and net profit in cotton production. Cotton yields change yearly due to, among other factors, climatic conditions, weeds, pests and diseases (Honnappa *et al*., 2018). The mean seed cotton yield per treatment varied from 4 500 to 6 400 $kg.ha^{-1}$ for the bollworm experiment and from 5 600 to 6 900 $kg.ha^{-1}$ for the leafhopper experiment. During the 2016/17 season, Eco-Bb®, Delfin® and Bb endophyte had the lowest seed cotton yields of less than 3 600 $kg.ha^{-1}$. During the same period, the mean yield in South Africa was at 4 411 $kg.ha^{-1}$ for irrigated cotton (Cotton SA, 2020). According to ICAC (2017) and FAO (2020), irrigated cotton has the potential to obtain seed cotton yields ranging between 4 000 and 5 000 $kg.ha^{-1}$ with 35% lint. In support of these reports, the survey conducted in Chapter 2 revealed that a mean seed cotton yield of 700 $kg.ha^{-1}$ was reported by dryland farmers and 5 000 $kg.ha^{-1}$ was obtained from irrigated cotton.

At a mean rate of R 6 per kilogram, the highest gross income of R 40 908 and R 41 808 was obtained from the bollworm and leafhopper experiments, respectively. The lowest gross income of R 18 330 was obtained in the bollworm experiment, while the leafhopper experiment had the lowest gross income of R 30 120. The very low income of the bollworm experiment was due to the low yields of less than 3 600 $kg.ha^{-1}$ that were obtained during the 2016/17 season. When harvested mechanically, irrigated cotton in South Africa can provide an income of almost R40 000 per hectare at R7,50/kg with the yield estimates of 5 000 $kg.ha^{-1}$ (Coleman, 2019). The estimated break-even point is 3 780 $kg.ha^{-1}$ when harvesting is mechanical. In India, Reddy (2018) reported a mean gross income of R 14 460 per hectare during 2010-15 while net income was R 1 829 per hectare.

DAFF (2017) reported that in 2017, the mean gross value of agricultural production in South Africa was estimated at R273 344 million, with the gross income from cotton production increasing by 29,3% to R298 million. DAFF further stated that the seed cotton price for 2017 was R 8/kg, while the price for 2018 was R 7.45/kg. In South Africa, the seasonal price of cotton matches the international price projections; however, different ginners have their pricing depending on the grading of the cotton lint. This is almost similar to the case in Zimbabwe, where prices are negotiated between ginners and farmers (Chisoko, 2011).

After deducting the total production costs from the output revenues, it was evident that the overall net income from the treatments of Karate® EC was higher than the other treatments. This was due to the high seed cotton yields and low cost of the product. The efficacy of Karate® EC on cotton pests was observed by Cole *et al*. (1997), and they reported that Karate® EC gave a 12% increase without any significant disruption of season-long predator to pest ratios. Mink *et al*. (1997) also reported that timely applications of Karate® provided higher yields compared to untreated Bt cotton. Similarly, in Mozambique, Javaid *et al*. (2000) found that Karate® gave a significantly higher yield of cotton.

It is essential that producers select production inputs to increase the benefit-cost ratio and maximise profit (Moradi and Darmian, 2016). The benefit-cost ratio provides the farmers with an indicator of the comparative economic performance of the inputs that they select (Aziz *et al*., 2012). It further considers the amount of profit gained through economic activities, and the greater the benefit-cost ratio, the better the return in investment for the farmers (GhafoorAwan *et al*., 2015). In this study, benefit-cost ratios above one indicated that the treatment was economically viable and had a return on investment. Considering the benefit-cost ratios for the treatments used in this study, the synthetic pesticides Karate® EC, Chlorpyrifos® 480 EC and Bandit® 350 SC had highly significant financial viability ratios than found with biopesticides. The high costs of the biopesticides had a significant negative impact on the benefit-cost ratio of those treatments.

Due to the low seed cotton yields of Eco-Bb®, Delfin® and Bb endophyte in the bollworm experiment during the 2016/17 season, their benefit-cost ratios were less than one, which reflected a net loss of up to R 5 344 per hectare. Karate® EC consistently gave a better benefit-cost ratio than the other treatments, while a minimum benefit-cost ratio was observed on the treatments of Delfin®. This study agrees with Patel and Das (2010) who recorded the highest benefit-cost ratio in cotton field plots treated with lambda-cyhalothrin. Based on the cost benefits, treatments with lambda-cyhalothrin have been reported to be financially viable and adopted by the cotton farmers in Uganda (Gayi *et al*., 2017).

Lambda-cyhalothrin has also been reported to have high benefit-cost ratios in crops such as chickpea (Sood and Mondal, 2005; Ameta and Swami, 2017; Chaudhari *et al*., 2018), pigeon pea (Chandrakar and Shrivastava, 2002) and mung bean (Malappa *et al*., 2012; Yadav and Singh, 2016). Contrary to the findings of these studies, Rudramuni *et al*. (2011) documented that lambda-cyhalothrin was amongst the treatments with the least benefit-cost ratio against sucking pests and bollworms of cotton.

Gadage *et al*. (2009) evaluated the efficacy of biopesticides against bollworms on cotton. They recorded a benefit-cost ratio of 1:9.46 in the treatment of *Beauveria bassiana* at 10^{10} conidia.ml^{-1}, 1:7.66 in *Nomuraea rileyi* at 10^9 conidia ml and 1:3.97 in HaNPV. However, in this study, the *Beauveria bassiana* treatments (Eco-Bb® and Bb endophyte) did not give the best benefit-cost ratios. This was due to very low yields obtained in the bollworm experiment during the 2016/17 season. Although Bandit® 350 SC and Chlorpyrifos® 480 EC were only used in the leafhopper experiment, the treatments had the highest mean benefit-cost ratios of 2.0 and 1.8, respectively. This is mainly attributed to the low cost of the products. Balakrishnan *et al*. (2004) evaluated the field efficacy of biopesticides against *H. armigera* on cotton. They have confirmed good benefit-cost ratios with chlorpyrifos 20 EC (1:3.66) followed by HaNPV (1:3.50). Despite the high cost of Bolldex®, in the bollworm experiment, the treatment was observed as the second-best pesticide with a benefit-cost ratio of 1.5.

Similarly, in a study to evaluate the efficacy of different HaNPV isolates, Jeyarani *et al*. (2010) recorded the highest benefit-cost ratio of 1:2.48. The income, benefit-cost ratio and the benefit of each treatment mainly rely on the price of the treatment, input costs and yield. The benefit-cost analysis in this study shows that whilst some of the treatments had higher yield, the net income and benefit-cost ratios were lower due to the high prices of the products. It was evident that the cost of biopesticides was higher than the synthetic pesticides. However, since all the biopesticides had overall benefit-cost ratios of more than one, cotton producers have the opportunity to select from the tested treatments to use in an integrated pest management programme.

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CHAPTER 6

GENERAL OVERVIEW

Cotton is the most produced natural fibre globally (Avadí *et al*., 2020), grown in more than 53 countries (Karli *et al*., 2017). In Sub-Saharan Africa, cotton remains one of the main sources of income (Maboudou Alidou and Niehof, 2020), and smallholder farmers mostly produce it as a cash crop (Matthews and Tunstall, 2006; IPBO, 2017; Partzsch *et al*., 2019; CMiA, 2020). However, the climate in Sub-Saharan Africa is favourable for the development of pests, which results in high levels of pest infestations on cotton and subsequent yield losses (Amanet *et al*., 2019). Furthermore, the constant rise of input costs and the instability of the output prices have a huge impact on the profitability and sustainability of cotton production (Belay *et al*., 2020).

In line with the challenges above, the studies that are presented in this thesis focused on:

- The survey on the farmers' knowledge of cotton pests, their current managing strategies and challenges
- The efficacy of different biopesticides in comparison with synthetic pesticides against cotton insect pests
- The benefit-cost analysis of biopesticides and synthetic pesticides on cotton to determine the cost of production inputs and the gross profit

From the results that were obtained from these studies, it was established that:

- Most farmers produce cotton on a small scale under dryland conditions with a mean yield of 700 kg.ha^{-1};
- Most farmers have knowledge of insect pests and rely mainly on synthetic pesticides to control the pests;
- The main constraints in cotton production include climatic conditions, labour costs, and insect infestations;

- The efficacy of different biopesticides against *H. armigera* larvae varied significantly; however, Karate® and Bolldex® resulted in better control of the pest;
- The treatments of Karate® ensured the maximum control of aphids and leafhoppers
- Eco-Bb® provided better control of whiteflies, thrips and cotton stainers;
- Delfin® exhibited the least significant number of spider mites while Bandit® had the least efficacy on the spider mite population;
- The highest mean seed cotton yield of up to 6 400 kg.ha^{-1} was recorded in the plots that were treated with Bolldex® and Bandit®;
- The cost of biopesticides was more expensive than the synthetic pesticides;
- The highest input cost was recorded from labour costs for weed control;
- Karate® EC and Bandit® 350 SC treated plots had the highest net profit and benefit-cost ratio.

As most farmers cultivate cotton in less than five hectares of land under dryland, this minimizes the potential profit received by the producers. With an average cottonseed yield of less than 1000 kg.ha^{-1}, dryland cotton farmers have the challenge to break even or increase their profit. The rain-fed cotton production depends on seasonal rainfall, and the yields may vary with planting date (Anwar *et al*., 2020). With an estimated break-even point of 3 780 kg.ha^{-1} (Coleman, 2019), irrigated cotton, which was found to yield more than 5 000 kg.ha^{-1}, is guaranteed to provide better profits for farmers. Application of Bolldex® and Bandit® has also proven to increase the seed cotton yield up to 6 400 kg.ha^{-1}.

Cotton production is regarded as labour intensive, and labour cost is the highest input cost (Belay *et al*., 2020). In Chapters 2 and 5, it is clear that labour costs remain a major constraint in cotton production. Similary, Odedokun *et al*. (2015) reported that labour input may account for more than half of the total cost of production. They further noted that family labour reduces the labour cost, which may be incurred from hired labour. The cost of manual weed control was observed to be the highest cost of labour.

The cost of manual weed control may always be high enough to make the use of herbicides more profitable.

However, the use of herbicides is subject to their accessibility and farmers' ability to afford the technology to apply them. On the other hand, manual harvesting can significantly increase the cost of cotton production. Cheng and Wang (2019) noted that costs of cotton picking by machine could be up to 35% lower than hand picking.

Over and above the high cost of labour, the cost of pesticides is also a concern for profitable cotton cultivation. In Chapter 2, it was evident that most farmers relied on synthetic pesticides to control cotton pests. As there is no single pest control strategy that is completely reliable, the use of synthetic pesticides may be necessary only when thresholds are reached, and they must be used cautiously. However, the overreliance on synthetic pesticides for cotton protection results in pest resistance, toxicity and environmental pollution (Ganda *et al*., 2018). Therefore, biopesticides are regarded as the best alternative to synthetic pesticides since they are target specific and reduce environmental risks. The variable performance of biopesticides may be observed between greenhouse and field conditions because of several environmental factors that affect field crops (Paulitz and Bélanger, 2001). Most biopesticides are unstable under environmental stresses such as ultraviolet radiation, rain and temperature (Basavaraj *et al*., 2018). Since the performance of biopesticides on the control of cotton pests has high efficacy under laboratory (Borkar *et al*., 2013; Mandage *et al*., 2015; Gayi *et al*., 2017) and greenhouse conditions (Lopez *et al*., 2014), the efficacy of different biopesticides was compared with synthetic pesticides under field conditions in Chapters 3 and 4.

The current studies have demonstrated that biopesticides can provide financial benefits that are comparable to synthetic insecticides. Biopesticides may be effective alternatives to conventional synthetic pesticides to control some of the insect pests on cotton. However, there is low adoption of biopesticides currently by smallholder farmers due to perceptions of their effectiveness, accessibility and affordability. Farmers’ perceptions can be addressed through constant interaction with the researchers and extension services.

Farmers are also an important source of agricultural innovations; however, little attention on these innovations has been documented by researchers (Tambo, 2018). The high price of biopesticides makes them a niche product in the insecticide market. However, in the near future, more biopesticide-based products are expected to decrease their costs and increase their role in the market (Conti, 2018). The additional labour expenses of applying biopesticides also limit and prevent their market growth (Olson, 2015). Similarly, the technology fees associated with genetically modified cotton have increased seed costs, resulting in some farmers reducing plant population density, where possible (Adams *et al*., 2019).

Yield remains a challenge in cotton production because most of the smallholder farmers plant cotton under dryland conditions. With the current mean seed cotton yield of 700 $kg.ha^{-1}$ in South Africa, dryland production is still not profitable for some smallholder cotton farmers. Dryland cotton is mainly affected by climatic conditions that influence crop growth, development and yield (Anwar *et al*., 2017). Some dryland cotton-producing regions receive adequate rainfall; however, the consistency and timeliness of these rainfalls are crucial for the crop's growth. In the past two decades, the South African government has introduced numerous agricultural policies and programmes and increased the budget to support smallholder farmers; however, little sustainable progress has been achieved (DAFF, 2011; Aliber and Hall, 2012; Frequin-Gresh *et al*., 2012; Khapayi and Celliers, 2016).

Although the cost analysis in this study shows some profit from the treatments, it is essential to consider gross margins in different regions that use similar resources as more comprehensive budgeting is required to indicate the actual profitability situation.

The use of biopesticides in this study showed that some of these products are financially viable and can be adopted by farmers because they had benefit-cost ratios greater than or on par with synthetic pesticides. Biopesticides have long-term effects, and the level of knowledge in their production is yet to increase over time (Warwick, 2010).

In summary, the efficacy of different biopesticides against cotton pests varied significantly and, in some instances, was on par with the synthetic pesticides. Therefore, keeping in view the effectiveness and eco-friendly nature of biopesticides, it is recommended for farmers to incorporate them in the integrated management of cotton pests.

Recommendations

Some limiting factors that affect the production of cotton in South Africa have been discussed in this thesis. Therefore, to enhance cotton production, the following strategies should be adopted:

- Integrated pest management strategies are required to reduce pest infestations and enhance the yield. The development of alternative control methods to minimise the use of agrochemicals is necessary.
- More affordable biopesticides need to be introduced into the market. However, before they are developed for commercialization, research must be done to assess their efficacy against cotton pests under different conditions. The research needs to focus on the formulation of the biopesticides, their persistence and benefit-cost analysis.
- There is a need for a cotton research programme that will address the genetic improvement and development of new varieties to combat diseases, weeds, and the detrimental effects of climate change.
- New mechanization technologies need to be explored to reduce the costs of labour that have a negative impact on the profitability of cotton production.
- As farmers are faced with high input costs and marketing problems, the government needs to speed up the implementation of adequate policies with farmers involved in the process. Furthermore, the government must subsidize the input costs to maximize the profit for farmers.

- Where farmers are unaware of the proper combination of inputs, they tend to either underutilize or overutilize the inputs. There is a need for appropriate guidance to farmers on best cultivation techniques. Therefore, researchers and extension must develop and provide a proper set of guidelines for farmers.
- Technology transfer is required to enhance farmers’ awareness of cotton pests, their control and implementation of conservation agriculture, as well as the value of soil analysis.

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