Heliyon 10 (2024) e33037

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Integrating *Metarhizium anisopliae* entomopathogenic fungi with border cropping reduces black bean aphids (*Aphis fabae*) damage and enhances yield and quality of French bean

Anthony Emaru *, Jane G. Nyaanga, Mwanarusi Saidi

Department of Crop, Horticulture and Soil (CHS), Faculty of Agriculture, Egerton University, P.O Box, 536-20115, Njoro, Nakuru, Kenya

ARTICLE INFO

Keywords:
Border cropping
Metarhizium
Metarril
Wheat
Sunflower

ABSTRACT

French bean growers, rely mainly on pesticides for pest management. The acceptable tolerance for pesticides residue in French beans is a major concern and has led to several tonnes of the crop continuously rejected and listed as unsafe for human consumption. There is growing demand for alternative approaches and products that are effective at managing pests without the side-effects associated with reliance on pesticides. A field study to determine the combined effects of Metarhizium anisopliae, (Metarril WP E9 and Biomagic) biopesticides and border crops (Sunflower and wheat) on aphid population, damage severity, growth, yield and quality of French bean. A two-factor experiment was conducted at the Egerton University, Kenya. First factor included two border crops (sunflower and wheat) and no border crop (control). Second factor included spraying Metarril WPE9 (2×10^8 cfu/g), Biomagic (2×10^8 cfu/ml) biopesticides, alpha-cypermethrin (synthetic insecticide) and water. Data on growth, yield and quality parameters were collected and analyzed using the SAS version 9.4M8. Results showed that M. anisopliae and border crop significantly ($p < 0.0005$) enhanced growth, yield and quality of French bean in both seasons. French bean grown with wheat or sunflower borders showed a significant reduction in aphid population ($p < 0.0001$) and damage severity ($p < 0.0001$) when sprayed with various treatments compared to the control. Plots with wheat border caused an increase in collar diameter of French bean. The plots (Metarril and wheat border) caused a 4 % and 5 % increase in marketable yield, a 2 % and 12 % reduction in non-marketable yield. To exploit the benefits of biopesticides, the study recommends their integration with and border crops. Thus, French bean growers could benefit more from fungal-based biopesticides in aphid-IPM approach, as it reduces pre-harvest intervals and residues compared to synthetic insecticides.

1. Introduction

French bean (*Phaseolus vulgaris* L.) also known as green beans, snap beans, kidney beans, haricot beans, or string beans [1] is an exotic vegetable that continues to gain commercial value due to its huge demand in the export market. The immature pods are eaten fresh as salads and desserts, cooked as soups or frozen and canned. French beans play an important dietary role across continents, serving as a rich source of essential minerals, vitamins, proteins, fats and carbohydrates [2]. It is also a potential income earner for stallholder farmers in Kenya and several other countries across the world [3,4]. Despite the French bean economic and nutritional

* Corresponding author.
E-mail address: emaruanthony@gmail.com (A. Emaru).

https://doi.org/10.1016/j.heliyon.2024.e33037
Received 7 February 2024; Received in revised form 12 June 2024; Accepted 13 June 2024
Available online 14 June 2024

importance, its productivity and profitability is still constrained by many biotic and abiotic factors including insect pests, diseases, drought and soil fertility [5,6]. More than 37 insect pest species have been associated with the crop throughout its growth cycle in several countries [7]. The most common pests of French bean are the sap-sucking insect, among them are aphids, thrips, leafhoppers and spider mites [8].

Black bean aphid (*Aphis fabae* Scopoli) is ranked high among the major insect pests limiting the realisation of maximum yields and quality of French beans worldwide. There has been a recorded decline in productivity of french bean [9], raising concerns about sustaining production while maintaining growth, yield, and quality. The black bean aphids is capable of causing yield losses of up to 30–70 % [10,11]. The losses are due to direct damages caused by sucking plant sap and wounding plant tissues or indirect damage through the transmission of various viruses [12–14]. The sugary and sticky honeydew secreted by aphids attracts sooty mould and other fungi on leaves and immature pods which reduces photosynthetic capacity and final quality [15]. Efforts to control the black bean aphids has forced farmers to over-rely synthetic pesticides which are readily available and often effective. Synthetic pesticides are associated environmental effects and human health. The acceptable tolerance for pesticides residue in French beans is a major concern to the consumers. Strict guidelines on quality and maximum residue levels (MRL) in the export market have seen several huge consignments of French beans continuously rejected and listed as unsafe for human consumption. The concerns over the adverse effects of synthetic pesticides create an impetus for French bean growers to seek for alternative approaches and products that are not only effective in managing insect pests but are also safe and acceptable to consumers.

Natural pest regulation using biological agents such as predators, parasitoids, or entomopathogenic fungi and companion planting as an intercrop or border crop present safe alternatives to synthetic pesticides [16]. Several species of entomopathogenic fungi (EPF) have been studied for use as an eco-friendly strategy for management of a wide range of agricultural pests [17–20] presenting an opportunity to be used to manage insect pests such as aphids. Entomopathogenic fungi are a beneficial group living in the soil that infects insects by penetrating insect cuticles and their bodies to eventually kill the pest [21]. According to Bamisile et al. [22], EPFs are pathogenic to insect pests with broad host plants and are potential pest management approaches. Farmers in other parts of the world, including some parts of Asia, North America, Europe and South Africa, have successfully used EPF products to control a wide range of pests alone or in combination with other pest management methods.

Biopesticides containing entomopathogenic fungi (EPF) strains like *Beauveria*, *Metarhizium*, *Isaria*, *Hirsutella* and *Lecanicillium* have also been reported as safer for the environment and humans and can be a better addition to other methods used to manage insect pests such as aphids [23]. However, the effectiveness of some EPFs, particularly *Metarhizium anisopliae,* has been reported as more influenced by several factors such as weather, the presence of ultra-violet light, temperatures, crops and its associated cropping system. Zhang et al. [24] highlighted the importance of integrating cropping systems and microbial biopesticides for additional benefits beyond the main crop's yield. Integrating border crops with biopesticides could enhance insect pest management and offer a safer option to synthetic chemicals in managing crop pests. Border crops has been reported to enhance the efficient use of available plant growth resources as well as reduce the population of insects such as aphids, white flies and many other pests [25–28]. A field experiment by Waweru et al. [29] reported that the use of maize (Zea Mays L.), sorghum (*Sorghum bicolor* L.) and sunflower (*Helianthus annuus*) as either a border or companion crop managed to reduce viral disease incidences spread by aphids in hot pepper. Border crops act as either repellent or attractant of pests and can reduce pest effects on the primary crop. Its effectiveness in controlling aphids in collards [30], hot pepper [29] and sweet pepper [31], significantly reducing on the use of pesticides [32]. The current study sought to investigate the effects of integrating border cropping systems with *Metarhizium anisopliae*, an entomopathogenic fungus biopesticide in controlling black bean aphids and increase growth, yield and quality of French bean. The study hypothesised that use of *Metarhizium anisopliae*, an and border cropping reduced the black bean aphid population and subsequent damage, as well increase yield and quality of French bean.

2. Materials and methods

2.1. Experimental site description and planting materials

The study was conducted at the Horticulture Research and Demonstration Field at Egerton University, Njoro- Kenya. The field lies at latitude 3.0° S and longitude 36–39.0° E in the Lower Highland III Agro-ecological Zone (LH3) at about 2238 m above sea level. The site receives an annual average rainfall of 1180–1400 mm and an annual daily temperature range of 16–22 °C. The soil types are predominately Mollic Andosols, well-drained, moderate in fertility, containing medium levels of organic carbon, low levels of phosphorus and recorded a pH range of 6.0–6.5 [33].

2.2. Planting materials

French bean variety "Enclave", was used in this study. It is a determinate variety commonly grown in Keny and highly susceptible to black bean aphids. The variety Enclave produces more extra fine-grade quality pods, is high yielding and is adaptable to wide agroecological zones compared to other varieties cultivars. The French bean seeds were procured from Hygrotech (EA) Ltd- Naivasha. Sunflower (*Helianthus annuus* L.) variety "Kenya Fedha" and wheat (*Triticum aestivum* L.) variety "Njoro bread wheat two" used as border crop were procured from Kenya Agricultural and Livestock Research Organization (KALRO) Njoro, Kenya. These two border crops were chosen because of their relevance in the agro-ecological zone. The wheat variety is highly preferred by insect pests, with a dwarf growth habit that could reduce and less shade effects. The sunflower used in this study is an open-pollinated variety with uniform maturity, well suited to medium and high altitudes and the most preferred in the agricultural region where this study was conducted area showed is Table 1 and the experimental site location as shown in Fig. 1.

2.3. Experimental design and treatments

A 4 × 3 factorial experiment conducted in Randomized Completely Block Design (RCBD) and replicated three times in the open field. Metarril Wettable powder (2 × 10^8 cfu/ml), was chosen based on its superior performance during the laboratory bioassay experiment, (ii) Bio-magic 15 LF as commercialised biopesticide product and (iii) alpha-cypermethrin (8 ml/20 L) as a commercialised synthetic insecticide as positive control while (iv) water as the negative control. Border cropping at three levels: (i) sunflower as a border crop, (ii) wheat as border crops and (iii) no border crop as a control. Treatment combinations is as shown in Table 1.

2.4. Field preparation, layout and crop management

Experimental plots measuring 4.2 m by 3 m each were laid out at the site location wihin the Horticulture Research and Demonstration Field at Egerton University (Fig. 1). The experimental plots were then were ploughed and harrowed to obtain a moderate tilth suitable for planting French beans and the border crops. Sunflower border crop was planted at a spacing of 30 cm × 75 cm with two (2) seeds later thinned to one plant per hill, two weeks after germination. Wheat seeds were thinly drilled at a spacing of 30 cm. The distance between border crops and the first row of French bean crop was 60 cm (Fig. 2). French bean was planted three weeks (3 weeks) after wheat at spacing (Fig. 2A) and with a sunflower border crop at spacing of 75 cm (Fig. 2B). This allowed the border crops time to establish to at least 2–3 leaves. French bean was planted at a spacing of 30 × by 15 cm, with two (2) seeds later thinned to one plant per hill (Fulano, 2016). The experimental field was ploughed and harrowed using a tractor before planting to obtain a moderate tilth suitable for planting French beans and the border crops. Diammonium phosphate (DAE) fertilizer was applied to French bean plots during planting at the rate of 200 kg/ha [34]. Calcium Ammonium Nitrate (CAN) at a 150 kg/ha rate was applied as a top dress in two equal split applications at three (3) true leaves at the onset of flowering as the growth stages recommended for application in French bean plants to enhance essential nutrient availability [35]. Weeding was done manually three weeks after germination. The experiment was rain-fed with supplemental irrigation provided using a drip irrigation system only during prolonged dry spells. Unlike crop management, Fig. 2, shows a detailed description of the experimental unit measurement, border crop (sunflower and wheat) and primary crop (French bean), spacing and plant population. The visual and illustration showing the spatial arrangement of French bean with Fig. 3A (French beans as sole crop) and Fig. 3 B (wheat or sunflower and French beans as sole crop) is as shown in Fig. 3.

2.5. Treatment application

Black bean aphids were collected from the greenhouse cultures. The aphids were introduced into the field by placing six infested French bean leaves with ten (10) aphids per leaf at the center of each experimental unit. This allowed the aphids equal chance to spread to other parts of the plots.

The foliar applied treatment application Spraying of the foliar treatments began or started at 21 days after the French bean emerged from the soil. The spraying was repeated four times at every 14 days interval for a total of four time targeting mainly the susceptible vegetative growth stage of French bean plants. A growth stage or timing period was chosen because it targets a stage of plant growth when insect pests cause severe damage by attacking auxiliary buds and tender growing points, as described Sayed et al. [36]. The decision to spray every 14 days spray interval was guided and adopted based on a previous study by Boni et al. [12] as the most effective range for insect pest mortality in open field experiments using entomopathogenic fungi, as this period duration provides enough time for the pathogenic fungi such as M. anisopliae to cause insect death as a result of both primary and secondary infection and in open field experiment. Before application, Metarril wettable powder E9 (2 × 10 8 cfu/g), Biomagic 1.5 LF (2 × 10 8 cfu/ml), and alpha-Cypermethrin. The treatments were separately and thoroughly mixed in water containing 0.05 % integra (3 ml per 20L) for 5 min to ensure a homogenous solution. Integra is a surfactant that helps the spray solution spread evenly on the plants surface. To minimize the likelihood of contamination, or prevent contamination, four different knapsack sprayers (Kenplastic Knapsack sprayer, 20 L) but with similar calibration to discharge 350L/acre and nozzle pressure of 2.88 kgf m −2 were used. Each sprayer was used exclusively for one treatment; Metarril (2 × 10 8 cfu/g) E9, Biomagic (2 × 10 8 cfu/ml), alpha-cypermethrin (8 ml/20 L) or water. Spraying was done early in the morning, between 06:00 and 08:00 h East Africa Time (EAT), to minimize treatment drift caused by wind.

Table 1
Description of treatment combinations.

Treatment combinations	Sunflower	Wheat	No border crop
Metarril	MS	MW	MN
Biomagic	BS	BW	BN
Alpha-cypermethrin	AS	AW	AN
Water	WS	WW	WN

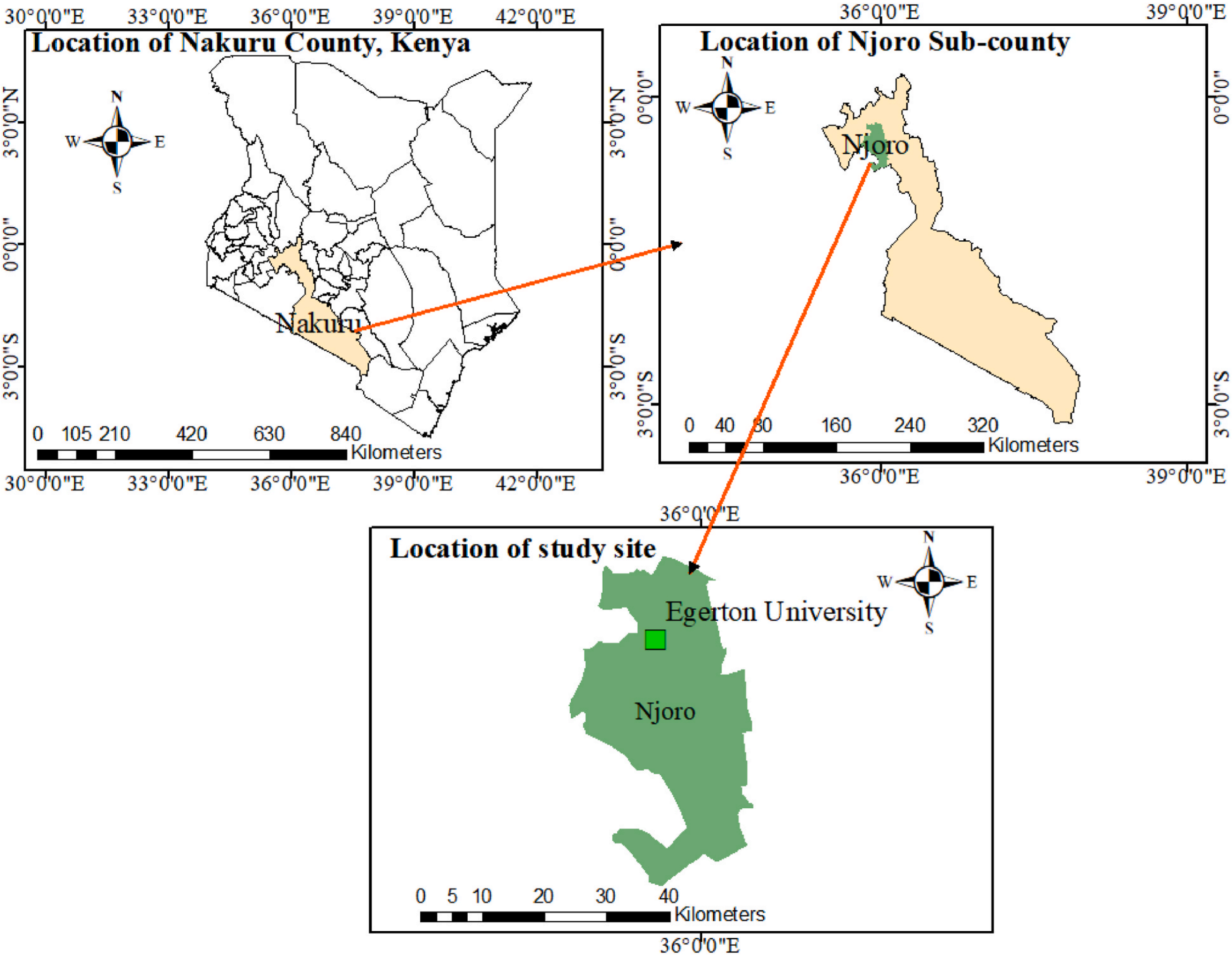

Fig. 1. Map showing the experiment site for field study research at Egerton University.

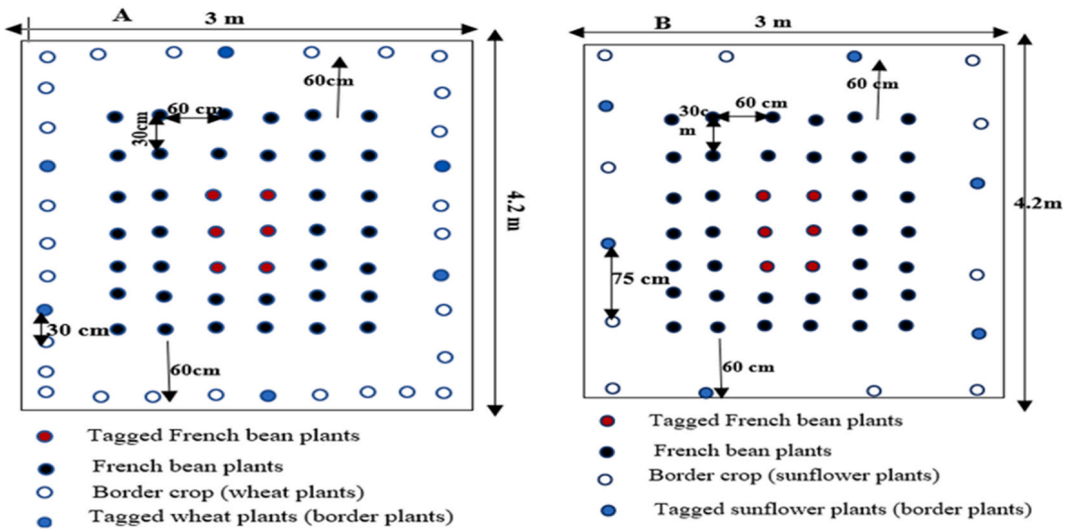

Fig. 2. The spatial arrangement of French bean with A (Wheat as border crop) and B (Sunflower as border crop).

Fig. 3. Plot with no border crop (a) and Plots with border crop of either wheat or sunflower (b).

2.6. Data collection

Data on aphid population were collected from six tagged plants in the inner row of each experimental unit just before the treatment spray (pre-spray). A 14,28,42 and 45 days after spraying (DAS). Visual observation and scoring of the aphid population using 6-point scale described by Mkenda et al. [37] was adopted. Where 1 = no aphids; 2 = a few scattered aphids (1–100); 3 = a few small colonies (101–300); 4 = several small colonies (301–600); 5 = large isolated colonies (601–1000); and 6 = large continuous colonies (>1000) and data obtained were used to compute the average number of aphids per plant (no. of aphids/plant). Data was collected in the early morning hours between 07:00 and 08:00 h when most aphids were inactive on the leaves. The aphid damage score was collected using 5-point scale universally accepted scoring literature adopted from Mkenda et al. [37], where 1 = no infestation or damage, 2 = light damage and infestation, <25 % plant parts damaged or infested, 3 = average damage and infestation, 26%–50 % plant parts damaged, 4 = high infestation and damage, 51%–75 % plants parts damaged showing yellowing of lower leaves and 5 = severe infestation, >75 % damage resulting to plants with high infestation levels with yellow and severely curled leaves or dead plant. The data obtained were later used to compute the average damage caused on each French bean plant.

Data collection on growth variables or parameters (plant height, collar diameter and the number of branches) started two weeks (14) days after the emergency (DAE) of the French bean when the crop had two 2–6 true leaves. The parameters used in this was sought and believed could provide valuable insights into plant growth and development, enabling comparison between different treatment combinations. Data collection on leaf, index, shoot dry weight and root dry weight were not collected. Plant height was measured in centimeters (cm) at two weeks intervals using a meter ruler from the ground level to the highest tip of the plant began two weeks (14 days) after the emergency of French bean. The number of branches was also counted and recorded on each tagged plant (no. of branches/plant). Stem collar diameter was measured at ≈ 4 cm from the ground level using a digital vernier caliper (Model 599-577-1/ USA). Data obtained were used to compute the average stem collar diameter (mm) for the different treatments.

Data on yield and quality parameters variables data **(**pod numbers, average pod weight, and total fresh pod weight). Pods were harvested from the six tagged plants twice per week for four weeks by removing pods that had attained the horticultural maturity stage (about 56 DAE) of French bean. According to Abebe et al. [38], firm and fleshy pods with small green immature seeds are considered physiologically matured and ideal for harvest, thus meeting the export grade requirement. The number was recorded and later used to compute the average number of pods per plant (no./plant) and total pod weight in kilo gram per treatment combination. The pods were then weighed in grams (g) using a weighing balance (Advanced Technocracy Inc. Ambala); weights obtained were recorded in grams per experimental unit and later converted to tonnes per hectare (t/ha) of the total weight. At each harvest, French bean pods harvested from each experimental unit were sorted into three grades. These grades include (i) extra-fine grade (4–6 mm in width as the diameter of the pod cross section and 8–10 cm in length), (ii) fine grade (6–9 mm width and 10–17 cm length) and (iii) bobby pods (more than 9 mm width and with small seeds that were not too large) and considered as marketable yield [39,40]. The three grades in the export market can also be classified as extra class, class I and class II. Therefore, pods that do not meet the latter grading are considered unmarketable yield. A vernier caliper was used to measure the pod diameter and a ruler was used to measure the pod length. The weight of each grade was recorded weekly, summed up as total weight per grade (g/grade) and converted to yield in to tonnes per hectare. Unlike marketable yield, harvested pods that did not meet the grading scale (overgrown pods, off-type, blemished pods due to insect pests, sooty mould or injured and those with physical or physiological defects) were classified as non-marketable. The total grade weight (sum of extra-fine, fine and bobby) percentage per treatment combination was computed by dividing the weight per grade by the total sum of grade weight result multiplied by 100 to convert to percentages shown in equation below.

$$\text{Total weight } (\%) = \left(\frac{\text{Total sum of grade weight}}{\text{Total yield}}\right) \times 100 \quad (1)$$

2.7. Data analysis

Data were subjected to Shapiro-Wilk and Levene's tests for homogeneity of variances at a probability level of 0.05 for normality tests using the Proc univariate procedure of SAS 9.4M8 version (January 2023, SAS Institute, Cary, NC) before analysis. Data were then subjected to ANOVA using the GLM procedure of SAS at $P \leq 0.05$. Means for significant treatments at the F test were separated using Tukey's honestly significant difference (THSD) test at $P \leq 0.05$. The RCBD model fitted for the experiment was. $Y_{ijk} = \mu + \alpha_{(i)} + \beta_j +$

$(\alpha\beta)_{ij} + block_k + \varepsilon_{ijk}$. Where; Y_{ijlk} the response from ***k***th experimental unit receiving the ***i***th types of treatment and control sprayed and ***j***th type of border crop and control used, μ is the overall mean, $\alpha_{(i)}$ effect due to the ***i***th type treatments and control sprayed, β_j effect due to the ***j***th type of the border crops and control used, $(\alpha\beta)_{ij}$ an interaction effect of the ***i***th type of treatment and control sprayed with the ***j***th type of border crop and control used, $block_k$ is effects due to $_k$th block, ε_{ijk} is the random error associated with the response from the ***k***th experimental unit receiving the ***i***th type treatment and control sprayed combined with the ***j***th level of border crop.

3. Results

3.1. Aphid population and damage severity

The results from this study showed found that treatment and combinations significantly ($p < 0.0005$) influenced the aphid population on French bean plants in both seasons. Results showed That plots treated with *M. anisopliae* biopesticide (Metarril WP E9) had significantly lower aphid population (2.96, 2.44) for season 1 and 2, respectively (Table 2). The highest aphid population (3.96, 2.93) in season 1 and (3.65,2.63) in season 2 was recorded no border and treated with water during season 1. The interaction between Metarril biopesticide and border crops significantly ($p < 0.0005$) influenced aphid population. This was however not significantly different in plots treated with Biomagic (3.18) in season 1. The lowest aphid mortality of 1.56 was recorded in plots treated with alpha-cypermethrin A similar trend was observed for damage severity with the negative control (water) showing the highest damage severity of 2.64 and 2.40 in season one and two, respectively. There were no significant differences in the damage severity between Metarril WP E9 and Biomagic in both seasons. Generally, season one had a higher aphid population and damage severity compared to season two. Although, among biopesticides, Metarril sprayed plants with wheat combination had the lowest aphid population. The study found significant differences in damage severity on French bean plants across different treatments in both seasons. The lowest damage severity was observed on plants sprayed with alpha-cypermethrin, followed by plants in plots sprayed with Metarril E9 and Biomagic. Water-sprayed plots had the highest damage severity. Biopesticide (Metarril) sprayed plots also reduced damage severity by 3.1 % and 3.4 %, respectively. However, alpha-cypermethrin reduced aphid populations by 12.8 % and 9.6 %. Plants with a sunflower or wheat border crop had lower aphid population and damage severity scores (Table 3) and 4 show the mean aphid abundance and damage severity with border crops in season 1 and 2 based on single factor of border or biopesticide treatments.

The results showed that *Metarhizium anisopliae* biopesticide application on the aphid population and damage severity were significant ($p < 0.05$) in season two (Table 3). Results showed a significant reduction in aphid population (2.96) and (2.44) in season I and 2 in plot treated with Metarril WP E9 compared to the control with 3.28 and 3.04. There was however no significant reduction in aphid population between Metarril and Biomagic in season one. The lowest aphid population (<1.56) was recorded in all treatment combinations with alpha-cypermethrin is a synthetic insecticide. The lowest damage severity (<1.42) was recorded in plots sprayed alpha cypermethrin at all treatment combinations in both seasons. Metarril WP E9 showed a significant reduction of about 2.00 damage severity score in season 2.

The use of border crops had significant ($p < 0.0005$) effects on the population of aphids and damage severity in both seasons (Table 4). Plots with no border crop recorded the highest aphid population (3.18, 2.95) for season 1 and 2, respectively. A low aphid population (2.76, 2.32) was recorded in plots with sunflower as border crop in both season one and two, respectively. This was however not significantly different with plots with wheat as border crops. A similar trend was observed for damage severity with plots with no border crop the highest damage severity of 2.40 and 2.32 in season one and two, respectively. Results further showed that plots without border crops had higher damage severity across the treatment combinations and dates compared to plots planted with border crops.

Growth variables; different treatments combinations significantly ($p < 0.0001$) influenced growth variables measured in both

Table 2
Effect of *Metarhizium anisopliae* and border crop on aphid population and damage severity in both season one (April to July 2022) and season two (September to December 2022).

Aphid population (no./plant)					Damage severity (no./plant)			
Border crop					Border crop			
Treatment	No border	Wheat	Sunflower	**Spray Means**	No border	Wheat	Sunflower	**Spray Means**
Season one								
Water	3.96a*	3.39ab*	3.27ab*	**3.54ab***	2.93a*	2.73a*	2.2.6abc*	**2.64a***
Biomagic	3.55ab	3.00b	2.99b	**3.18ab**	2.80a	2.33abc	2.26abc	**2.46a**
Metarril	3.18ab	2.81bcd	2.89bc	**2.96b**	2.47a	2.20abc	2.47a	**2.36ab**
Alpha-cypermethrin	2.04cde	2.06de	1.90e	**1.98e**	1.53bc	1.46c	1.47c	**1.49c**
Border crop	**3.18ab**	**2.80bcd**	**2.76bcd**		**2.40a**	**2.18abc**	**2.13abc**	
Season two								
Water	3.65ab*	3.16abc*	2.79abcd*	**3.20abc***	2.63a*	2.37ab*	2.37ab*	**2.40ab***
Biomagic	3.70a	2.76bcd	2.66dc	**3.04abc**	2.60ab	2.01abc	2.19abc	**2.22abc**
Metarril	2.83abcd	2.14de	2.34de	**2.44de**	2.51ab	1.94bc	2.01abc	**2.19abc**
Alpha-cypermethrin	1.65e	1.52e	1.51e	**1.56e**	1.68c	1.54c	1.54c	**1.59c**
Border crop	**2.96abcd**	**2.39de**	**2.33de**		**2.32ab**	**1.97bc**	**2.01abc**	

*Means followed by the same letter within a column and within a season are not significantly different according to Tukey's HSD test ($p \leq 0.05$).

Table 3
Effects of *Metarhizium anisopliae* on mean aphid abundance and damage severity in season 1 and 2.

Biopesticide	Season one		Season two	
	Aphid population	Damage severity	Aphid population	Damage severity
Water	**3.54a***	**2.64a***	**3.20a***	**2.40a***
Biomagic	**3.18b**	**2.46ab**	**3.04a**	**2.22a**
Metarril	**2.96b**	**2.36b**	**2.44b**	**2.19a**
Alpha cypermethrin	**1.56c**	**1.49c**	**1.56c**	**1.59b**

*Means in a column followed by the same letters are not significantly different using Tukey's.

Table 4
Effects of border cropping on the mean aphid abundance and damage severity in season 1 and 2.

Border crop	Season one		Season two	
	Aphid population	Damage severity	Aphid population	Damage severity
No border crop	3.18a*	2.40a*	2.95a*	2.32a*
Wheat	2.80b	2.18b	2.39b	2.08b
Sunflower	2.76b	2.13b	2.32b	1.97b

*Means in a column followed by the same letter are not significantly different using Tukey's test at $p < 0.05$.

seasons. Spray type significantly influenced plant height ($p < 0.002$), collar diameter ($p < 0.0001$) and number of branches ($p < 0.0001$) in season two while only variable plant height ($p < 0.0001$) was observed in season one. Border crops also significantly impacted plant height ($p < 0.0005$), collar diameter ($p < 0.0001$) and number of branches ($p < 0.0001$) in season two. Interaction effect between the type of spray applied and border crop used was significant for plant height ($p < 0.0001$), collar diameter ($p < 0.0001$) and number of branches ($p < 0.0001$) in season two while plant height ($p < 0.0001$) in season one.

Significant differences in plant height among different treatments in both seasons (Table 3). During both seasons, French bean plants grown in plots with border crops (wheat or sunflower) had significant differences in plant height compared to plants grown in plots which had no border crop (Table 5). Although, the highest plant heights were observed for plants grown in plots with a sunflower border crop compared to a wheat border crop or with no border crop. Plots with sunflower or wheat as a border crop and sprayed with different treatments were generally taller than those without a border crop. The study found that collar diameters were larger in plots with wheat border crops during both growing seasons (Table 5). Significant differences were observed in collar diameters for plants sprayed with different treatments and border crop types. Plants in plots sprayed with alpha-cypermethrin recorded the largest collar diameter, followed by plants sprayed with Metarril E9, Biomagic compared to plants sprayed with water in both seasons. The largest diameter was recorded in plots with alpha-cypermethrin and wheat border crops, while the thinnest was in water and no border crop. Amongst *M. anisopliae* treatments, plants sprayed with Metarril E9 and Biomagic with either border type crops differed significantly in the collar diameter size in season one compared control.

Table 5
Effect of *Metarhizium anisopliae* and border crop on aphid population and damage severity in both season one (April to July 2022) and season two (September to December 2022).

Plant height (cm)					**Collar diameter (mm)**			
Border crop								
Treatment	No border	Wheat	Sunflower	**Spray Means**	No border	Wheat	Sunflower	**Spray Means**
Season one								
Water	14.54e**	18.52bcde**	17.55cde**	**16.88c****	0.39e**	050b**	0.44c**	**0.46c****
Biomagic	15.26de	21.18bc	22.33bc	**19.80b**	0.44c	0.51ab	0.49b	**0.47c**
Metarril	17.23cde	20.48bcd	22.40bc	**20.04b**	0.48b	0.54ab	0.54ab	**0.51ab**
Alpha-cypermethrin	21.16bc	23.72a	28.62a	**24.51a**	0.53ab	0.57a	0.55a	**0.55a**
Border crop	**18.68b**	**19.51b**	**22.73a**		**0.47b**	**0.53ab**	**0.51ab**	
Season two								
Water	38.24d**	40.28bcd**	43.93ab**	**41.95***	0.66*	0.72*	0.67*	**0.67***
Biomagic	38.43dec	40.98bcd	39.55bcd	**41.50**	0.68	0.73	0.68	**0.70**
Metarril	42.55abc	41.01bcd	42.17abc	**41.03**	0.69	0.75	0.70	**0.71**
Alpha-cypermethrin	39.83bcd	43.51ab	46.24a	**40.40**	0.71	0.76	0.71	**0.72**
Border crop	**40.16b**	**40.54b**	**42.97a**		**0.70**	**0.71**	**0.69**	

Plots sprayed with alpha-cypermethrin and Biomagic (positive control), plots sprayed with water (negative control) and plots with no border crop (control).
*Means not followed by a letter within a column and within a season are not significantly different according to Tukey's HSD test ($p \leq 0.05$).
**Means followed by the same letter within a column and within a season are not significantly different according to Tukey's HSD test ($p \leq 0.05$).
Both data plant height and collar diameter were square root transformation before analysis, but the values presented are original means.

Plants in plots sprayed with water recorded the highest number of branches, followed by plants sprayed with Biomagic and Metarril E9 compared to plots sprayed with alpha cypermethrin in season two. Although plants from plots with border crops (wheat or sunflower) recorded significant differences in the number of branches compared to plants in plots with no border crop for season two only (Table 6). The highest number of branches per plant were in plots sprayed with water in both seasons. Plants from plots with no border crop had the highest number of branches per plant and the lowest number of branches per plant was recorded in plots with a sunflower border crop. Amongst *M. anisopliae* treatments, plant plots sprayed with Biomagic and had no border crop recorded the highest number of branches per plant compared to plots that received the Metarril and had wheat or sunflower border crops in both seasons.

Yield and yield variables results showed that different treatments influenced the number of pods ($p < 0.031$), ($p < 0.0001$), average pod weight ($p < 0.005$), ($p > 0.040$) and total pod yield ($p < 0.008$), ($p < 0.0012$) of French bean in season one and two, respectively. Spray treatment applied influenced the number of pods ($p < 0.0001$) ($p < 0.0021$), average pod weight ($p < 0.0004$) ($p > 0.271$), total pod yield ($p < 0.0003$) ($p < 0.0004$) in season one and two respectively. Similarly, use of border crops influenced the number of pods ($p < 0.039$) and total pod yield ($p > 0.329$) in season two only. The interaction effect was significant for the total yield of French bean plants in both seasons.

The study found that number of pods per plant were significantly different amongst treatment combinations in seasons two only (Table 7). Plants sprayed with alpha-cypermethrin had the highest number of pods per plant (437.78), followed by plants sprayed with Metarril E9 and Biomagic. French bean plants grown with border crops (wheat or sunflower) had significant differences in pod number compared to plots no border crop. The highest number of pods were recorded for plants with a wheat border while the lowest were recorded for plants with no border crop. Amongst biopesticide treatments, plants in plots sprayed with Metarril E9 and had a wheat border crop recorded the highest number of pods per plant (557.33) while the lowest number of pods (158.66) was recorded for plants in plots sprayed with Biomagic and had a no border crop. Different treatments sprayed on French bean plants impacted the average pod weight significantly (Table 7). The average pod weights of plants were lowest for plants in plots sprayed with water as a control and the highest average pod weight was recorded for plants in plots sprayed with alpha-cypermethrin in both seasons. Plants in plots with a wheat border crop had the highest average pod weight, followed by no border crop compared to sunflower border plots with the lowest average pod weight.

The study found that different treatment combination significantly impacted the total pod yield of French bean in both growing seasons (Table 8). Alpha-cypermethrin sprayed plants yielding the highest (11.82) t/ha, followed by Metarril E9, Biomagic and water treated plots recorded the lowest in both seasons. Plants from plots sprayed with Metarril E9 and Biomagic were not statistically different in the total pod yield both seasons. Border cropping (wheat or sunflower) treatments had significant differences in total pod yield compared to control (Table 8). Plots with a wheat border crop had the highest total pod yield while plots without a border crop had the lowest. Although the highest total pod yield (18.43 t/ha) was recorded in plots sprayed with alpha-cypermethrin and wheat border crop while the lowest yield (2.93 t/ha) in water-sprayed plots and no border. Among the biopesticide treatment combinations, French bean plants sprayed with Metarril and wheat border crop had the highest total yield (17.48 t/ha) while Biomagic and no border crop had the lowest yield (12.69 t/ha) in season two. The study found that French bean grown under *M. anisopliae* significantly impacted export yield in both seasons. Alpha-cypermethrin and wheat border crops were the most effective for enhancing export yield, followed by Metarril E9 and Biomagic. Wheat bordered plots had the highest export yield followed by sunflower and no border the least. However, water and no border crop had no significant impact on export yield.

Use of *M. anisopliae* significantly influenced the different quality of pods based on pod maturation rate of the different pod grades in both seasons as shown in Fig. 4; with 4a representing season one and 4b for season two. Border crops did significantly affect non-marketable French bean), however, more extra fine than fine grade pods were obtained in plots sprayed with the different treatments and had a wheat or sunflower border crop compared to the control plots. The study also found that different spray treatments and border crop types affected pod maturation rate. Plants with wheat or sunflower border crops had more extra fine and fine pods

Table 6
Effects of *Metarhizium anisopliae* and border crop on number of branches of French bean in both season one (April to July 2022) and season two (September to December 2022).

Spray type	No border	Wheat	Sunflower	Spray Means
Border crop				
Season one				
Water	4.73*	4.80*	4.53*	4.91*
Biomagic	5.00	4.80	4.60	4.91
Metarril	5.00	4.80	4.66	4.73
Alpha-cypermethrin	5.13	4.86	4.63	4.71
Border crop means	4.88	4.88	4.68	
Season two				
Water	6.80a**	4.60dc**	4.47dc**	5.28a**
Biomagic	5.80b	4.73dc	4.40dc	4.97 ab
Metarril	4.93c	4.80dc	4.20dc	4.64bc
Alpha-cypermethrin	4.47dc	4.33dc	4.13d	4.31c
Border crop means	5.50a	4.62b	4.30c	

*Means not followed by a letter within a column and within a season are not significantly different according to Tukey's HSD test (p ≤ 0.05).
**Means followed by the same letter within a column and within a season are not significantly different according to Tukey's HSD test ($p \leq 0.05$). Data were subjected to square root transformation before analysis, but the values presented are original means.

Table 7
Effects of *Metarhizium anisopliae* and border crop on number of branches of French bean in both season one (April to July 2022) and season two (September to December 2022).

Number of pods (no. of pod/plant)					**Average pod weight yield (g)**			
Border crop					Border crop			
Treatment	No border	Wheat	Sunflower	**Spray Means**	No border	Wheat	Sunflower	**Spray Means**
Season one								
Water	117.00*	288.33*	172.33*	**192.55b****	1.40*	2.00*	2.06*	**1.82b****
Biomagic	158.66	345.67	225.67	**239.78b**	2.06	2.63	2.06	**2.30b**
Metarril	197.33	345.00	298.33	**280.44 ab**	2.10	2.13	2.10	**2.08b**
Alpha-cypermethrin	475.33	447.00	361.00	**437.78a**	2.86	3.13	2.73	**2.87a**
Border crop	**289.67**	**293.33**	**279.91**		**2.25**	**2.34**	**2.25**	
Season two								
Water	313.00c**	349.00c**	338.67c**	**333.56c****	1.74*	2.40*	1.89*	**2.15***
Biomagic	406.33bc	433.33bc	351.33c	**451.00b**	2.64	3.92	3.68	**3.10**
Metarril	444.33bc	557.33b	448.00bc	**429.33bc**	1.81	2.97	2.31	**2.56**
Alpha-cypermethrin	602.33a	648.33a	515.67b	**558.78b**	3.35	3.99	2.99	**3.42**
Border crop	**447.91bc**	**497.08b**	**407.00bc**		**2.60**	**3.30**	**2.53**	

*Means not followed by a letter within a column and a season are not significantly different according to Tukey's HSD test ($P \leq 0.05$).
**Means followed by the same letter within a column and a season are not significantly different according to Tukey's HSD test ($P \leq 0.05$). Both data of number of pods and average pod weight were subjected to square root transformation before analysis, but the values presented are original means.

Table 8
Effects of *Metarhizium anisopliae* and border crop on total pod yield (tonnes/ha) and extra fine yield (t/ha) in both season one (April to July 2022) and season two (September to December 2022).

Total pod yield (t/ha)					**Export yield (t/ha)**			
Border crop					Border crop			
Treatment	No border	Wheat	Sunflower	**Spray Means**	No border	Wheat	Sunflower	**Spray Means**
Season one								
Water	2.93c*	7.86abc*	3.10c*	4.63b*	0.63d*	2.18bcd*	1.58dc*	**1.47b**
Biomagic	3.33bc	7.43abc	5.00abc	5.26b	1.27dc	3.71abcd	2.35bcd	**2.52b**
Metarril	3.87bc	7.03abc	7.70abc	6.20b	2.12bcd	3.94abcd	4.68abcd	**3.51b**
Alpha-cypermethrin	12.70 ab	13.63a	9.13abc	11.82a	8.80 ab	9.95a	7.36abc	**8.71a**
Border crop means	**6.94a**	**7.35a**	**6.63a**		**3.59a**	**4.64a**	**3.91a**	
Season two								
Water	8.17b	10.26 ab	11.32 ab	9.92b	2.19c	2.62c	2.20c	**2.33c**
Biomagic	12.69 ab	13.60 ab	10.92 ab	12.07b	3.28c	6.02abc	3.37c	**4.55bc**
Metarril	10.72 ab	17.48 ab	11.89 ab	13.70 ab	4.27bc	6.56abc	4.62bc	**4.82b**
Alpha-cypermethrin	18.43a	18.96a	14.97 ab	17.45a	8.98 ab	9.65a	7.34abc	**8.66a**
Border crop means	**13.43 ab**	**14.95a**	**11.49b**		**4.85a**	**6.05a**	**4.38a**	

*Means not followed by the same letter within a column are not significantly different according to Tukey's Honestly Significant Difference at ($p \leq 0.05$). *Means followed by the same letter within a column within a season are not significantly different according to Tukey's Honestly Significant Difference at ($p \leq 0.05$). Data on total yield were subjected to square root transformation before analysis values presented are original means.

than those without borders. The highest amount of extra-fine pods was obtained under alpha-cypermethrin and wheat border crop. Among the biopesticides, Metarril and had a wheat or sunflower border crop had more extra fine than fine grade pods, followed by Biomagic and wheat or sunflower border crop.

French bean plants grown with alpha-cypermethrin, Metarril, and Biomagic showed higher marketable pod yields in both seasons, respectively. Wheat and sunflower bordered plots produced the highest marketable yield. A substantial increase in marketable yield in plots with (7.9 % increase) or a sunflower border (7.1 % increase) compared to the control plots. Plants sprayed with Metarril E9 and had a wheat border crop had more marketable yields, but water-sprayed plants recorded the highest non-marketable yield as shown in Table 9. Moreover, the study recorded a strong correlation between aphid population and yield variables as shown in Table 10.

4. Discussion

Based on the current study, aphid population and damage severity were significantly reduced in plots where wheat or sunflower border crop was used compared to plots with no border crop in both seasons. Unlike the high aphid population and damage severity on French beans that were recorded in plots with no border crop. Wheat and sunflower used as border crops reduced aphid population and damage severity to French bean plants significantly. The results demonstrate that increasing crop biodiversity at the border offers an alternate habitat (s), food resource or intermediate hosts for predators and parasitoids population build-up, thus increasing natural enemies in the border cropping system [41,42]. Finding similar to this current study have showed that border crop integrated with

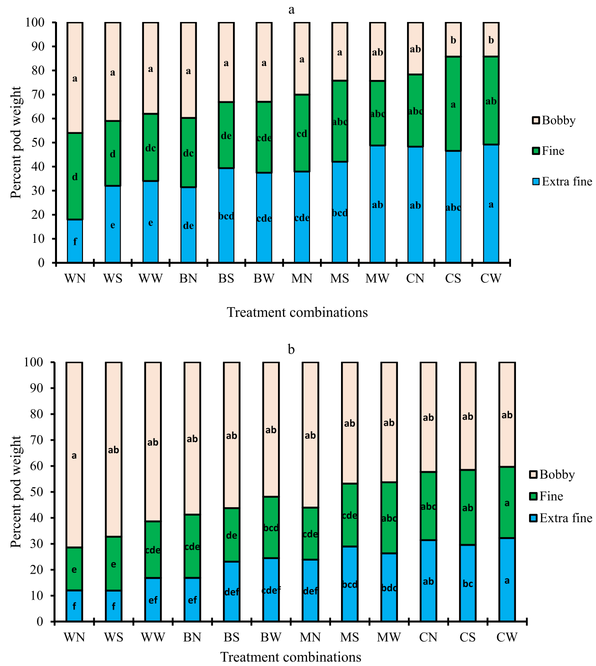

Fig. 4. Effects of *Metarhizium anisopliae* and border crop on average percent pod weight per plant of the extra fine, fine and bobby French bean pods during French bean production in both season one (Fig. 4a) and two (Fig. 4b). WN (water and no border), BN (Biomagic and no border), MN (Metarril E9 and no border), AN (alpha-cypermethrin and no border), WW (water and wheat), BW (Biomagic and wheat), MW (Metarril and wheat), AW (alpha-cypermethrin and wheat), WS (water and sunflower), BS (Biomagic and sunflower), MS (Metarril and Sunflower), AS (alpha-cypermethrin and sunflower). Means followed by the same letter within a column within bar and within a season are not significantly different according to Tukey's Honestly Significant.

Table 9
Effects of *Metarhizium anisopliae* and border crop on percent marketable and non-marketable yield in both season one (April to July 2022) and season two (September to December 2022).

Border crop								
Non-marketable yield					Marketable yield			
Treatment	No border	Wheat	Sunflower	Spray Means	No border	Wheat	Sunflower	Spray Means
Season one								
Water	59.31a**	41.97 ab**	37.47abcd**	**46.25a****	67.41*	71.42*	68.19*	**69.01c****
Biomagic	40.31abc	27.88abcd	26.20abcd	**31.46 ab**	79.97	71.21	69.83	**73.67bc**
Metarril	30.65abcd	26.92abcd	25.12bcd	**27.56b**	76.99	77.62	81.32	**78.64 ab**
Alpha- cypermethrin	16.55bcd	12.74d	14.49dc	**14.59c**	85.55	86.42	82.41	**84.79a**
Border crop	**35.77a**	**25.81a**	**28.31a**		**75.44**	**77.48**	**76.67**	
Season two								
Water	32.58a*	28.58 ab*	31.80a*	30.99a	40.68d**	58.02c**	62.53bc**	**53.74c****
Biomagic	20.02bc	28.79 ab	30.17a	26.33 ab	59.69bc	69.35bc	73.79b	**68.53bc**
Metarril	23.01 ab	22.38bc	18.67bc	21.35bc	73.08b	72.12b	74.88abc	**72.43b**
Alpha-cypermethrin	18.67bc	14.59c	17.59bc	15.21c	83.45a	87.25a	85.51a	**85.40a**
Border crop	**24.55a**	**22.52a**	**23.33a**		**70.32b**	**78.19a**	**77.43a**	

*Percent means not followed by a letter within a column within a season are not significantly different according to Tukey's HSD test at ($p \leq 0.05$). **Percent means followed by the same letter within a column within a season are not significantly different according to Tukey's HSD test at ($p \leq 0.05$). Data were subjected to square root transformation before analysis, but values presented are original means.

other management system can effectively suppressed insect pest population and the subsequent damage effect on plants [27,29]. Border cropping approach is thought to effectively reduce aphid population by distracting pests to other crops not primary and attracting their natural enemies, reducing the target pest population and economic loss impact on the crop while enhancing biological control [43]. Unlike, the extra shelter and floral resources for insect pests and/or predators boosting ecosystem services functionality at the border crop system. Border crop integration has been documented to enhance the efficacy of entomopathogenic fungi in managing aphid population under open field conditions [41,44]. Mwani et al. [41] study on maize-dolichos intercrop system reported a 24.6 % reduction in bean aphid population compared to mono-crop which recorded a significantly higher infestation of 51.6 %. Similar finding was reported by Chopkar et al. [45], where aphid population was significantly reduced in Lablab bean plots with border crops

Table 10
Pearson correlation table between yield variable, aphid population and damage severity.

Pearson Correlation Coefficients, N = 180: Prob > |r| under H0: Rho = 0					
	Number of pods	Total yield	Total average weight	Aphid population	Damage severity
Number of pods	1.00000	0.97604 <0.**0001**	0.33293 <0.**0001**	−0.22279 **0.0026**	−0.22373 **0.0025**
Total yield	–	1.00000	0.38574 <0.**0001**	−0.30324 <0.**0001**	−0.29412 <0.**0001**
Total average weight	–	–	1.00000	−0.15447 <0.**0001**	−0.16696 **0.0251**
Aphid population	–	–	–	1.00000	0.56655 <0.**0001**
Damage severity	–	–	–	–	1.00000

with sweet corn as a border crop recorded the least aphid population mean, followed by marigold, safflower, cowpea, mustard, coriander, sunflower, and sesame, respectively. The current study based on Pearson correlation analysis showed a strong negative correlation between aphid population and yield variables. Mansion-Vaquié et al. [46] observed a similar observation, showing that yield decreased when bug populations increased and vice versa. In regard to the current study, border crop plant structure for crops could have provided a barrier by interfering with the movement and access of the inset pest to the intended host plant, thereby enhancing main crop performance and reducing pest effects. Mansion-Vaquié et al. [46] study on intercrop of wheat (*Triticum aestivum* L.) with common peas (*Pisum sativum* L.) or White Clover (*Trifolium repens* L.) concluded that intercropping wheat with clover significantly reduced cereal aphid densities and thus less damage caused and more yield. The study attributed this response to chemical and physical responses that interfered with host location, slower female development, decreased fecundity and increased mortality. Most plants elicit compounds that may exhibit chemical repellency, attractancy, oviposition deterrence, insecticidal effects, or luring pests away from the main crop, leading to decreased pest pressure [27,47] The study explores the potential of integrating biopesticides and border crop systems in open fields to enhance agro-ecological sustainable management of black bean aphids. Therefore, such approach is potential alternative as aphids are less likely to develop resistance. In addition to the less harm impact on most natural enemies; thus, they offer a better comparative advantage to alpha-cypermethrin in comparison for their impact to the ecosystem.

The study also found that growing French beans with border crops significantly influenced growth and yield variables. Plant height, collar diameter, and number of branches were positively influenced in plots bordered with border crops compared to control (no border crop). Previous study as report by Nelson et al. [48], where border cropping use enhanced plant growth (plant height, collar diameter and branching) for Faba bean intercropped with wheat compared to sole cropping align with the current study results. Other authors [49–51] also recorded enhanced growth and productivity through intercropping. However, use of sunflower border crops had negative effect has caused etiolation with thinner collar diameter and few branches compared to wheat or no border. Wei et al. [50] also reported that use of taller border crop caused shading effects to the primary crop thus led to rapid stem elongation thus etiolated plants thus affects growth through promoting lodging of plants. Excessive shade effects caused an increases plant height and lodging rate affecting leaf orientation, hindering the transportation of nutrients, water, and photosynthetic products and ultimately causing considerable losses in growth through interspecific competition [52]. Shade avoidance syndrome affects plants by increase the competition for resources required by the plant, promote apical growth leading to etiolation process which result from variations in hormonal activities [53]. The current study observed higher branching ability on French bean plants in plots bordered with wheat as a border crop or no border crop compared to plots with sunflower border. This could be attributed to the optimal light intensity absorbed by French bean compared to those bordered by sunflower which had a higher shade effect [54]. Increased shade is associated with decreased light incidents that promote low-red or far-red light that affects branching ability and similar research was reported on Arabidopsis plant on effects of shade [55].

Research by Kabir et al. [56] also proved that shows that taller border crops can cause shading effects leading to taller plants with thinner leaves and decreased photosynthetically active radiation (μmol m 2 s 1) affecting the growth a primary crop. The research suggests that the shade effect in border crops is due to the morphology of the plant, which can either promote or reduce chlorophyll content similar to the research findings by Dhale et al. [57]. A study by Raai et al. [58] on wing beans for the effects of different shading regimes, heavy (60 %), moderate (30 %) and control (0 % shade), reported that shade effect negatively interferes with plant morphological features, photosynthetic, gas exchange and growth characteristics.

The current study where plots bordered with wheat or sunflower significantly increased number of pods, export grade pod yield, quality and marketable pod yield of French bean compared to the control plots. These results agreed with findings reported by Nelson et al. [48], where border cropping use increased yield by 11.4 % and 34.2 % for Faba bean intercropped with wheat compared to sole cropping. However, when integrating with microbial, their performance is often affected by relative humidity and Ultra-violet light content. Therefore, improving relative humidity and reducing fungal spore degradation due to light interception by use of border crop plot could have enhanced the efficacy of biopesticides [59]. Combined use of a wheat border and sprayed with *M. anisopliae* effects on growth and yield of French bean plants could be partly attributed to diverse effects that lead to either additive, synergistic, or antagonistic [27]. Such as increased relative humidity and minimize ultra-violet light penetration into the lower canopy crop that can outcompete or enhanced the pathogenic fungi [60]. A study by Wang et al. [49] reported that when wheat or maize was used as a border crop thus, they positively influence the plant plasticity and structure of the main crop. Sunflower as a border crop however, caused a reduction in yield compared to plots with wheat as a border. The latter research also reported a 50 % yield reduction in soybean with sorghum border, affecting light inception, photosynthetic rate, and prioritizing vegetative growth over reproductive activities. Different treatment combination with wheat as a border crop based on the current reported an increase in marketable yield by 2–8%, export grade yield by 2–5% and lowered non-marketable yield by 2–10 % in both seasons compared to control. These findings were consistent with results reported by Kefelegn et al. [61] that increased yield and marketable yield per hectare from intercropping. Kabaale et al. [62] also recorded higher marketable yield gain exceeding 22 % and a cost-benefit ratio greater than 2.8 (BCR∼3) when plots were sprayed with biopesticide products and were intercropped.

Based on this current study, a wheat border crop recorded the highest significant total pod yield (14.95 tonnes/ha) and marketable yield (78.19 tonnes/ha) while the lowest was in a sunflower border. Highest total pod yield per hectare (18.96 tonnes/ha) and export yield (9.95 tonnes/ha) were obtained from alpha-cypermethrin and wheat, followed by Metarril and a wheat border. Mollaei et al.'s [63] study on intercropping canola and Faba beans, field peas, or garlic showed improved canola crop yield due to reduced insect pest density, improved resource use efficiency, and increased biodiversity. The results were attributed to better resource use efficiency, physical barrier, increased biodiversity, repelling pests and attracting natural enemies and impeding weed growth. Nawar et al. [64] attributed the increase in yield quality of soybean and sunflower intercrop with less shade effect to reduced canopy layers, increased light interception efficiency and reduced interplant competition between sunflower and soybean. Increase in yield trend though cautions on continuous heavy use of alpha-cypermethrin as non-selective with negative impact on non-target organisms and with a great possibility of resistance development [65]. Unlike synthetic insecticides, studies [66–68] have also shown that biopesticides derived from entomopathogenic fungus (EPF) are compatible with integrated pest management (IPM) strategies and has wide host range. Although their low efficacy under field conditions slows down their widespread use (Mweka et al., 2020). EPF-based biopesticides containing *Metarhizium anisopliae* (Hypocreales: Clavicipitaceae) have widely been integrated into managing most agricultural pests since they are recommended as safe for crop production. *Metarhizium anisopliae* biopesticides are considered cheaper, environment-friendly, specific in their mode of action, sustainable, do not leave residues and are not associated with the release of greenhouse gases [13,69,70]. Combined with other practices, such as cropping systems using border crops, can enhance performance *Metarhizium anisopliae* derived biopesticide. Also, the use of biopesticide products compared to synthetic insecticides offers a comparative added advantage such as less residues on produce since synthetic products have been documented as very toxic to insect pests, humans and the environment [13,71]. Putnoky-Csicsó et al. [72] compared the effect of *M. anisopliae* with soil insecticide alpha-cypermethrin and reported significantly lower number of survived *Melolontha melolontha* larvae with α-cypermethrin treatment than *M. anisopliae* treatment and control. Research by Zekeya et al. [71] to evaluate the use of biopesticide use of *M. anisopliae*, pheromone traps and chemical pesticides to manage *Phthorimaea absoluta* in field conditions reported significant increase in marketable yield. The finding attributed that *M. anisopliae* could have benefited from favorable moisture conditions facilitating its growth in the rhizosphere and uptake by plant roots, thus increasing the plant performance, growth and productivity. Although based on this current study alpha-cypermethrin significantly recorded an increase in growth, yield and quality of French bean compared to all other treatments. Its use needs to be considered with caution due to its broad effects on non-target organisms and the environment [65]. A research study by Bao-jie et al. [73] on intercropping reported a boost in growth parameters, increased plant diversity, compatibility with other measure thus offer more economic benefits, reduced pests and disease infestation. Border cropping creates a micro-climate and ecological structure conditions in favor of natural enemies in the open field environment [73]. Research by Varenhorst et al. [74] described sunflower as a crop that is also suitable host for various aphid species, inclusive of bean aphids for bean plants, however, the preference of aphids for sunflower compared to bean species has not been fully studied. Therefore, the sunflower crop could provide an alternative host for bean aphids, thus a potential option that could be used as a border crop. Wheat crop attract generalist natural enemies of aphids such as lacewings, ladybird beetle, hoverflies and other parasitoids that can prey on back bean aphids. Border crops could be a sustainable and integrated strategy for horticultural crop production, meeting international export market requirements for safe production. This study did not do cost benefits analysis, field evaluations in different ecological niches and may not captured the long-term effects of the integrated strategy used and external factor impacting the biopesticide that could be the major limitation to this study.

5. Conclusion

Based on the findings of this study, it can be concluded that; (i) Use of border crops and *Metarhizium anisopliae* influences aphid population, damage severity, growth of French bean with spraying of Metarril and a wheat border crop contributing significantly to reduced aphid population and damage. (ii) Use of border crops and *Metarhizium anisopliae* also influences growth and yield of French bean with spraying of Metarril and a wheat border crop resulting in the highest total pod weight per hectare. (iii) Use of border crops and *Metarhizium anisopliae* did also influence quality of French bean pod with spraying of Metarril and a wheat border crop resulting in the highest weight per hectare of extra-fine and fine grade yield. The study recommended the incorporation of wheat as a border crop and biopesticides, particularly Metarril (2×10^8 cfu/g) in the French production system. More field evaluation needs to evaluated at different ecological niches to validate and optimize the proposed strategies for wider applicability.

Funding statement

This work was supported by the MasterCard Foundation through Regional Universities Forum for Capacity Building in Agriculture (RUFORUM).

Data availability statement

The data support the findings of this study are available from the corresponding author AE, upon reasonable request.

CRediT authorship contribution statement

Anthony Emaru: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jane G. Nyaanga:** Visualization, Validation, Supervision, Conceptualization. **Mwanarusi Saidi:** Writing – original draft, Visualization, Validation, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Anthony Emaru reports statistical analysis and writing assistance were provided by Ruforum. Anthony Emaru reports a relationship with Ruforum that includes financial support-scholarship. Anthony Emaru has patent NA issued to NA. C0-Author A E is a previous beneficiary of the Ruforum scholarship If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The study was made possible by the generous financial support through a scholarship of the MasterCard Foundation in partnership with the Regional Universities Forum for Capacity Building in Agriculture (MCF@RURORUM) through the program “Transforming African Agricultural Universities to Meaningfully Contribute to Africa’s Growth and Development (TAGDEV)". The authors also acknowledged the family of Dr. James Kisaakye, Dr. Dennis Beesigamukama, Mrs. Kwagala Solome Mungoma, Mr. Enock Kwizera, Mr. Rwotonen. I. Bob and Dr. Sam Elolu for their kind guidance through the research process and ensuring that the research process was in line with the ethic and integrity of research is completed. The authors are indebted to the three anonymous reviewers whose invaluable input gave this work its current shape.

References

[1] N.A. Khondoker, F.M.J. Uddin, MdA.R. Sarker, Influence of nitrogen and phosphorus level for the performance of French bean (Phaseolus vulgaris L.), Acta Sci. Malays. 4 (2020) 34–38, https://doi.org/10.26480/asm.01.2020.34.38.
[2] S. Chaurasia, Green beans, in: Nutritional Composition and Antioxidant Properties of Fruits and Vegetables, second ed., Elsevier, United States, 2020, pp. 289–300, https://doi.org/10.1016/B978-0-12-812780-3.00017-9.
[3] C. Didinger, H.J. Thompson, Defining nutritional and functional niches of legumes: a call for clarity to distinguish a future role for pulses in the dietary guidelines for Americans, Nutrients 13 (2021) 1–10, https://doi.org/10.3390/nu13041100.
[4] J.R. Myers, L.T. Wallace, S. Mafi Moghaddam, A.E. Kleintop, D. Echeverria, H.J. Thompson, M.A. Brick, R. Lee, P.E. McClean, Improving the health benefits of snap bean: genome-wide association studies of total phenolic content, Nutrients 11 (2019) 2509, https://doi.org/10.3390/nu11102509.
[5] N. Shaban, Correlation and path analysis of interaction between snap beans yield and its components with crop management, TJS 19 (2021) 86–96, https://doi.org/10.15547/tjs.2021.01.014.
[6] Z.-K. Yang, C. Qu, S.-X. Pan, Y. Liu, Z. Shi, C. Luo, Y.-G. Qin, X.-L. Yang, Aphid-repellent, ladybug-attraction activities, and binding mechanism of methyl salicylate derivatives containing geraniol moiety, Pest Manag. Sci. 79 (2023) 760–770, https://doi.org/10.1002/ps.7245.
[7] A. Mondal, U. Shankar, D.P. Abrol, A. Kumar, A.K. Singh, Incidence of major insect pests on French bean and relation to environmental variables, Indian J. Entomol. 80 (2018) 51–55.
[8] S. Sahoo, R.S. Giraddi, Insect pest spectrum of French bean Phaseolus vulgaris (pole type) grown under nethouse, Indian J. Entomol. (2022) 1–3, https://doi.org/10.55446/IJE.2021.389.
[9] W.P. Mwangi, A. Otieno, A. Anapapa, Assessment of French beans production at Kariua in Kandara, Murang’a county- Kenya, AJPAS 5 (2019) 1–16, https://doi.org/10.9734/ajpas/2019/v5i430141.
[10] T. Nordey, C. Basset-Mens, H. De Bon, T. Martin, E. Déletré, S. Simon, L. Parrot, H. Despretz, J. Huat, Y. Biard, T. Dubois, E. Malézieux, Protected cultivation of vegetable crops in sub-Saharan Africa: limits and prospects for smallholders, A review, Agron. Sustain. Dev. 37 (2017) 53, https://doi.org/10.1007/s13593-017-0460-8.
[11] T. Nordey, S.B. Boni, M.K. Agbodzavu, R. Mwashimaha, N. Mlowe, S. Ramasamy, E. Deletre, Comparison of biological methods to control Aphis fabae Scopoli (Hemiptera: Aphididae) on kalanchoe crops in East Africa, Crop Protect. 142 (2021) 105520, https://doi.org/10.1016/j.cropro.2020.105520.
[12] S.B. Boni, R.A. Mwashimaha, N. Mlowe, P. Sotelo-Cardona, T. Nordey, Efficacy of indigenous entomopathogenic fungi against the black aphid, Aphis fabae Scopoli under controlled conditions in Tanzania, Int. J. Trop. Insect Sci. 14 (2020) 1643–1651, https://doi.org/10.1007/s42690-020-00365-8.
[13] R. Srinivasan, S. Sevgan, S. Ekesi, M. Tamò, Biopesticide based sustainable pest management for safer production of vegetable legumes and brassicas in Asia and Africa, Pest Manag. Sci. 75 (2019) 2446–2454, https://doi.org/10.1002/ps.5480.
[14] R.M.K. Ullah, F. Gao, A. Sikandar, H. Wu, Insights into the effects of insecticides on aphids (Hemiptera: Aphididae): resistance mechanisms and molecular basis, Int. J. Mol. Sci. 24 (2023) 6750, https://doi.org/10.3390/ijms24076750.
[15] F.O. Wamonje, T.D. Tungadi, A.M. Murphy, A.E. Pate, C. Woodcock, J.C. Caulfield, J.M. Mutuku, N.J. Cunniffe, T.J.A. Bruce, C.A. Gilligan, J.A. Pickett, J. P. Carr, Three aphid-transmitted viruses encourage vector migration from infected common bean (Phaseolus vulgaris) plants through a combination of volatile and surface cues, Front. Plant Sci. 11 (2020) 613772, https://doi.org/10.3389/fpls.2020.613772.
[16] C.Y. Colmenarez, N. Corniani, S. Mundstock Jahnke, M.V. Sampaio, C. Vásquez, Use of parasitoids as a biocontrol agent in the neotropical region: challenges and potential, in: H. Kossi Baimey, N. Hamamouch, Y. Adjiguita Kolombia (Eds.), Horticultural Crops, second ed., Intech Open, Brazil, 2020, pp. 1–23, https://doi.org/10.5772/intechopen.80720.
[17] J. Kisaakye, H. Fourie, D. Coyne, L. Cortada, S. Masinde, S. Subramanian, S. Haukeland, Evaluation of the entomopathogenic potential of Beauveria bassiana, Metarhizium anisopliae and Isaria fumosorosea for management of cosmopolites sordidus Germar (Coleoptera: Curculionidae), Agriculture 11 (2021) 1290, https://doi.org/10.3390/agriculture11121290.

[18] A. Nawaz, F. Razzaq, A. Razzaq, M.D. Gogi, G.M. Fernández-Grandon, M. Tayib, M.A. Ayub, M. Sufyan, M.R. Shahid, M.A. Qayyum, M. Naveed, A. Ijaz, M. J. Arif, Compatibility and synergistic interactions of fungi, Metarhizium anisopliae, and insecticide combinations against the cotton aphid, Aphis gossypii Glover (Hemiptera: Aphididae), Sci. Rep. 12 (2022) 4843, https://doi.org/10.1038/s41598-022-08841-6.
[19] V.M. Paradza, F.M. Khamis, A.A. Yusuf, S. Subramanian, K.S. Akutse, Efficacy of Metarhizium anisopliae and (E)–2–hexenal combination using autodissemination technology for the management of the adult greenhouse whitefly, Trialeurodes vaporariorum Westwood (Hemiptera: Aleyrodidae), Front. Insect, Sci 2 (2022) 1–15, https://doi.org/10.3389/finsc.2022.991336.
[20] R. Shanker, M.R. Prajapati, R.P. Singh, R. Singh, J. Singh, P. Kumar, Isolation, molecular characterization of indigenous Metarhizium anisopliae (Metchnikoff) isolate, using ITS-5.8s rDNA region, and its efficacy against the Helicoverpa armigera (Hubner) (Lepidoptera: Noctuidae), Egyptian Journal of Biological Pest Control 33 (2023) 23, https://doi.org/10.1186/s41938-023-00670-7.
[21] J. Rajula, S. Karthi, S. Mumba, S. Pittarate, M. Thungrabeab, P. Krutmuang, Chapter 4 - current status and future prospects of entomopathogenic fungi: a potential source of biopesticides, in: S. De Mandal, A.K. Passari (Eds.), Recent Advancement in Microbial Biotechnology, Academic Press, 2021, pp. 71–98, https://doi.org/10.1016/B978-0-12-822098-6.00013-6.
[22] B.S. Bamisile, K.S. Akutse, J.A. Siddiqui, Y. Xu, Model application of entomopathogenic fungi as alternatives to chemical pesticides: prospects, challenges, and insights for next-generation sustainable agriculture, Front. Plant Sci. 12 (2021) 1–28.
[23] S.K. Sain, D. Monga, R. Kumar, D.T. Nagrale, S. Kranthi, K.R. Kranthi, Comparative effectiveness of bioassay methods in identifying the most virulent entomopathogenic fungal strains to control Bemisia tabaci (Gennadius) (Hemiptera: Aleyrodidae), Egypt J Biol Pest Control 29 (2019) 1–11, https://doi.org/10.1186/s41938-019-0130-z.
[24] Y. Zhang, M. Han, M. Song, J. Tian, B. Song, Y. Hu, J. Zhang, Y. Yao, Intercropping with aromatic plants increased the soil organic matter content and changed the microbial community in a pear orchard, Front. Microbiol. 12 (2021) 616932, https://doi.org/10.3389/fmicb.2021.616932.
[25] S. Afrin, A. Latif, N.M.A. Banu, M.M.M. Kabir, S.S. Haque, M.M.E. Ahmed, N.N. Tonu, M.P. Ali, Intercropping empower reduces insect pests and increases biodiversity in agro-ecosystem, Agric. Sci. 8 (2017) 1120–1134, https://doi.org/10.4236/as.2017.810082.
[26] A.R.A. de A. Hendges, J.W. da S. Melo, M. de A. Guimaraes, J. da S. Rabelo, Intercropping kale with culinary herbs alters arthropod diversity and hinders population growth in aphids, Hortscience 53 (2018) 44–48, https://doi.org/10.21273/HORTSCI12010-17.
[27] C.P. Huss, K.D. Holmes, C.K. Blubaugh, Benefits and risks of intercropping for crop resilience and pest management, J. Econ. Entomol. 115 (2022) 1350–1362, https://doi.org/10.1093/jee/toac045.
[28] A.S. Lithourgidis, C.A. Dordas, C.A. Damalas, D.N. Vlachostergios, Annual intercrops: an alternative pathway for sustainable agriculture, AJCS 5 (2011) 396–410.
[29] B.W. Waweru, P. Rukundo, D.C. Kilalo, D.W. Miano, J.W. Kimenju, Effect of border crops and intercropping on aphid infestation and the associated viral diseases in hot pepper (Capsicum sp.), Crop Protect. 145 (2021) 105–623, https://doi.org/10.1016/j.cropro.2021.105623.
[30] L.M. Gontijo, A.V. Saldanha, D.R. Souza, R.S. Viana, B.C. Bordin, A.C. Antonio, Intercropping hampers the nocturnal biological control of aphids: companion plants hinder predators at night, Ann. Appl. Biol. 172 (2018) 148–159, https://doi.org/10.1111/aab.12407.
[31] R. Ben-Issa, L. Gomez, H. Gautier, Companion plants for aphid pest management, Insect Sci. 8 (2017) 1–12, https://doi.org/10.3390/insects8040112.
[32] E. Joyce, W.E.G.C. Parker, C. RodriguezSao, Companion planting and insect pest control, in: S. Soloneski (Ed.), Weed and Pest Control - Conventional and New Challenges, InTech, USA, 2013, pp. 1–30, https://doi.org/10.5772/55044.
[33] R. Jaetzold, H. Schmidt, B. Hornetz, C. Shisanya, Farm Management Handbook of Kenya, Ministry of Agriculture, Kenya, 2012. https://d-nb.info/109742894X/34. (Accessed 9 October 2021).
[34] Greenlife Crop Protection Africa, French Beans, Nairobi, Kenya, Greenlife, 2021. https://www.greenlife.co.ke/french-beans/. (Accessed 2 November 2021).
[35] E. Oseko, T. Dienya, Fertilizer consumption and fertilizer use by crop (FUBC) in Kenya. https://africafertilizer.org/wp-content, 2015. (Accessed 3 November 2021).
[36] S.M. Sayed, E.F. Ali, S.S. Al-Otaibi, Efficacy of Indigenous Entomopathogenic Fungus, Beauveria bassiana (Balsamo) Vuillemin, Isolates against the Rose Aphid, Macrosiphum rosae L. (Hemiptera: Aphididae) in Rose Production, vols. 1–29, Egyptian Journal of Biological Pest Control, 2019, p. 19, https://doi.org/10.1186/s41938-019-0123-y.
[37] P. Mkenda, R. Mwanauta, P.C. Stevenson, P. Ndakidemi, K. Mtei, S.R. Belmain, Extracts from field margin weeds provide economically viable and environmentally benign pest control compared to synthetic pesticides, PLoS One 10 (2015) 1–14, https://doi.org/10.1371/journal.pone.0143530.
[38] M. Abebe, H.M. Beshir, A. Gobena, Improving yield and pod quality of green bean (Phaseolus vulgaris L.) through application of nitrogen and boron fertilizers in the central rift valley of Ethiopia, J. Appl. Sci. 19 (2019) 662–674, https://doi.org/10.3923/jas.2019.662.674.
[39] A.M. Fulano, G.M.W. Lengai, J.W. Muthomi, Phytosanitary and technical quality challenges in export fresh vegetables and strategies to compliance with market requirements: case of smallholder snap beans in Kenya, Sustainability 13 (2021) 1–21, https://doi.org/10.3390/su13031546.
[40] (UNECE) United Nations Economic Commission for Europe, Standard FFV-06 concerning the marketing and commercial quality control of beans. https://unece.org/standard/Beans, 2017. (Accessed 24 November 2021).
[41] N.C. Mwani, K.E. Cheruiyot, J. Nyaanga, JoshuaO. Ogendo, K.P. Bett, R. Mulwa, C.P. Stevenson, E.J.S. Arnold, R.S. Belmain, Intercropping and diverse field margin vegetation suppress bean aphid infestation in dolichos, Jppr 61 (2021) 290–301, https://doi.org/10.24425/jppr.2021137953.
[42] L.O. Ochieng, J.O. Ogendo, P.K. Bett, J.G. Nyaanga, E.K. Cheruiyot, R.M.S. Mulwa, S.E.J. Arnold, S.R. Belmain, P.C. Stevenson, Field margins and botanical insecticides enhance Lablab purpureus yield by reducing aphid pests and supporting natural enemies, J. Appl. Entomol. 146 (2022) 838–849, https://doi.org/10.1111/jen.13023.
[43] B.J. Ndakidemi, E.R. Mbega, P.A. Ndakidemi, S.R. Belmain, S.E.J. Arnold, V.C. Woolley, P.C. Stevenson, Plant-rich field margins influence natural predators of aphids more than intercropping in common bean, Insects 13 (2022) 569, https://doi.org/10.3390/insects13070569.
[44] U. Amala, T.M. Shivalingaswamy, Effect of intercrops and border crops on the diversity of parasitoids and predators in agroecosystem, Egypt J Biol Pest Control 28 (2018) 11, https://doi.org/10.1186/s41938-017-0015-y.
[45] P. Chopkar, V. Desai, R. Samrit, A. Uparkar, R. Choudhari, S. Shelke, Effect of border crops on pest population in Lablab bean (Lablab purpureus L.), Journal of Entomology and Zoology Studies 8 (2020) 1407–1412.
[46] A. Mansion-Vaquié, A. Ferrer, F. Ramon-Portugal, A. Wezel, A. Magro, Intercropping impacts the host location behaviour and population growth of aphids, Entomol. Exp. Appl. 168 (2020) 41–52, https://doi.org/10.1111/eea.12848.
[47] V. Alarcón-Segura, I. Grass, G. Breustedt, M. Rohlfs, T. Tscharntke, Strip intercropping of wheat and oilseed rape enhances biodiversity and biological pest control in a conventionally managed farm scenario, J. Appl. Ecol. 59 (2022) 1513–1523, https://doi.org/10.1111/1365-2664.14161.
[48] W.C.D. Nelson, D.J. Siebrecht-Schöll, M.P. Hoffmann, R.P. Rötter, A.M. Whitbread, W. Link, What determines a productive winter bean-wheat genotype combination for intercropping in central Germany? Eur. J. Agron. 128 (2021) 126–294, https://doi.org/10.1016/j.eja.2021.126294.
[49] Z. Wang, X. Zhao, P. Wu, Y. Gao, Q. Yang, Y. Shen, Border row effects on light interception in wheat/maize strip intercropping systems, Field Crops Res. 214 (2017) 1–13, https://doi.org/10.1016/j.fcr.2017.08.017.
[50] W. Wei, T. Liu, L. Shen, X. Wang, S. Zhang, W. Zhang, Effect of maize (zeal mays) and soybean (Glycine max) intercropping on yield and root development in Xinjiang, China, Agriculture 12 (2022) 1–996, https://doi.org/10.3390/agriculture12070996.
[51] Y. Xu, W. Qiu, J. Sun, C. Müller, B. Lei, Effects of wheat/faba bean intercropping on soil nitrogen transformation processes, J. Soils Sediments 19 (2019) 1724–1734, https://doi.org/10.1007/s11368-018-2164-3.
[52] L. Feng, M.A. Raza, Z. Li, Y. Chen, M.H.B. Khalid, J. Du, W. Liu, X. Wu, C. Song, L. Yu, Z. Zhang, S. Yuan, W. Yang, F. Yang, The influence of light intensity and leaf movement on photosynthesis characteristics and carbon balance of soybean, Front. Plant Sci. 9 (2019). https://www.frontiersin.org/articles/10.3389/fpls.2018.01952. (Accessed 1 April 2023).
[53] S. Maitra, A. Hossain, M. Brestic, M. Skalicky, P. Ondrisik, H. Gitari, K. Brahmachari, T. Shankar, P. Bhadra, J.B. Palai, J. Jena, U. Bhattacharya, S.K. Duvvada, S. Lalichetti, M. Sairam, Intercropping—a low input agricultural strategy for food and environmental security, Agronomy 11 (2021) 343, https://doi.org/10.3390/agronomy11020343.

[54] B. Babec, S. Šeremešić, N. Hladni, S. Terzić, B. Vojnov, N. Ćuk, S. Gvozdenac, Effect of intercropping sunflower with legumes on some sunflower morphological traits, Ratarstvo i Povrtarstvo 57 (2020) 1–61.

[55] W.B. Youn, J.O. Hernandez, B.B. Park, Effects of shade and planting methods on the growth of Heracleum moellendorffii and Adenophora divaricata in different soil moisture and nutrient conditions, Plants 10 (2021) 2–203, https://doi.org/10.3390/plants10102203.

[56] M. Kabir, J. Díaz-Pérez, S.U. Nambeesan, Effect of shade levels on plant growth, physiology, and fruit yield in bell pepper (Capsicum annuum L.), Acta Hortic. 2 (2020) 311–318, https://doi.org/10.17660/ActaHortic.2020.1268.42.

[57] S. Dhale, I. Bv, A. Head, S. Wasim, Parbhani, I. Maharashtra, B. Asewar, S. Chand, I. Mirza, W. Narkhede, Effect of Soybean: Pigeonpea Strip Cropping on Growth Parameters, Yield Attributes and Yield under Mechanization, vol 11, 2022, pp. 684–687.

[58] M.N. Raai, N.A.M. Zain, N. Osman, N.A. Rejab, N.A. Sahruzaini, A. Cheng, Effects of shading on the growth, development and yield of winged bean (Psophocarpus tetragonolobus), Cienc, Rural Times 50 (2020) e20190570, https://doi.org/10.1590/0103-8478cr20190570.

[59] A.V. McGuire, T.D. Northfield, Tropical occurrence and agricultural importance of Beauveria bassiana and Metarhizium anisopliae, Front. Sustain. Food Syst. 4 (2020) 1–23, https://doi.org/10.3389/fsufs.2020.00006.

[60] A. Mweke, K.S. Akutse, C. Ulrichs, K.K.M. Fiaboe, N.K. Maniania, S. Ekesi, Integrated management of Aphis craccivora in cowpea using intercropping and entomopathogenic fungi under field conditions, J Fungi (Basel) 6 (2020) 1–16, https://doi.org/10.3390/jof6020060.

[61] G.A. Kefelegn, Influence of intercropping combinations on growth, components, yield, and quality of faba bean and potato, BJSTR 49 (2023) 1.28, https://doi.org/10.26717/BJSTR.2023.49.007821.

[62] F.P. Kabaale, V. Tumuhaise, W. Tinzaara, G. Turyasingura, S. Subramanian, F.M. Khamis, K.S. Akutse, First report of field efficacy and economic viability of Metarhizium anisopliae-ICIPE 20 for Tuta absoluta (Lepidoptera: Gelechiidae) management on tomato, Sustainability 14 (2022) 146–148, https://doi.org/10.3390/su142214846.

[63] M. Mollaei, S.A.A. Fathi, G. Nouri-Ganbalani, M. Hassanpour, A. Golizadeh, Effects of strip intercropping of canola with faba bean, field pea, garlic, or wheat on control of cabbage aphid and crop yield, Plant Protect. Sci. 57 (2021) 59–65, https://doi.org/10.17221/132/2019-PPS.

[64] A.I. Nawar, H.S.A. Salama, H.E. Khalil, A.I. Nawar, H.S.A. Salama, H.E. Khalil, Additive intercropping of sunflower and soybean to improve yield and land use efficiency: effect of thinning interval and nitrogen fertilization, Chil. J. Agric. Res. 80 (2020) 142–152, https://doi.org/10.4067/S0718-58392020000200142.

[65] MdA. Khan, W. Ahmad, Synthetic chemical insecticides: environmental and agro contaminants, in: MdA. Khan, W. Ahmad (Eds.), Microbes for Sustainable Insect Pest Management : an Eco-Friendly Approach, Springer International Publishing, Cham, 2019, pp. 1–22, https://doi.org/10.1007/978-3-030-23045-6_1.

[66] D. Abdollahdokht, Y. Gao, S. Faramarz, A. Poustforoosh, M. Abbasi, G. Asadikaram, M.H. Nematollahi, Conventional agrochemicals towards nano-biopesticides: an overview on recent advances, Chemical and Biological Technologies in Agriculture 9 (2022) 13, https://doi.org/10.1186/s40538-021-00281-0.

[67] E.O. Fenibo, G.N. Ijoma, T. Matambo, Biopesticides in sustainable agriculture: a critical sustainable development driver governed by green chemistry principles, Front. Sustain. Food Syst. 5 (2021) 1–12, https://doi.org/10.3389/fsufs.2021.619058.

[68] G.M.W. Lengai, J.W. Muthomi, Biopesticides and their role in sustainable agricultural production, J Bio &Med Sci 6 (2018) 7–41, https://doi.org/10.4236/jbm.2018.66002.

[69] M.S. Ayilara, B.S. Adeleke, S.A. Akinola, C.A. Fayose, U.T. Adeyemi, L.A. Gbadegesin, R.K. Omole, R.M. Johnson, Q.O. Uthman, O.O. Babalola, Biopesticides as a promising alternative to synthetic pesticides: a case for microbial pesticides, phytopesticides, and nanobiopesticides, Front. Microbiol. 14 (2023), https://doi.org/10.3389/fmicb.2023.1040901, 1040–0901.

[70] J. Kumar, A. Ramlal, D. Mallick, V. Mishra, An overview of some biopesticides and their importance in plant protection for commercial acceptance, Plant Sci. (Limerick, Irel.) 10 (2021) 1–28, https://doi.org/10.3390/plants10061185.

[71] N. Zekeya, T. Dubois, J. Smith, S. Ramasamy, Field effectiveness of Metarhizium anisopliae and pheromone traps against Phthorimaea absoluta on tomato in Tanzania, Crop Protect. 156 (2022) 105940–105942, https://doi.org/10.1016/j.cropro.2022.105942.

[72] B. Putnoky-Csicsó, S. Tonk, A. Szabó, Z. Márton, F. Tóthné Bogdányi, F. Tóth, É. Abod, J. Bálint, A. Balog, Effectiveness of the entomopathogenic fungal species Metarhizium anisopliae strain NCAIM 362 treatments against soil inhabiting melolontha melolontha larvae in sweet potato (Ipomoea batatas L.), J Fungi (Basel) 6 (2020) 116, https://doi.org/10.3390/jof6030116.

[73] B. Chi, D. Zhang, H. Dong, Control of cotton pests and diseases by intercropping: a review, J. Integr. Agric. 20 (2021) 3089–3100, https://doi.org/10.1016/S2095-3119(20)63318-4.

[74] A. Varenhorst, P. Rozeboom, P. Wagner, Sunflower insect pests, in: Insect Pests of Crops in South Dakota, first ed., South Dakota State University, USA, 2021, pp. 11–26. https://extension.sdstate.edu/sites/default/files/2022-03/P-00205-11-v2.