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Prevalence of banana diseases and post-harvest losses in Kenya, and biocontrol potential of arbuscular mycorrhizal fungi against *Fusarium* wilt

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Summary: The demand for bananas (*Musa* spp.), which is ranked as the most important fruit crop in Kenya has been on the rise owing to both their dietary contribution and income generation. Meeting this demand has however been hampered by losses during production or post-harvest. This study assessed banana disease and post-harvest losses in leading producing counties in Kenya namely; Kisii, Nyamira and Embu. The study also assessed the efficacy of *Rhizophagus irregularis* in controlling *Fusarium oxysporum* f.sp. *cubense*. Structured questionnaires were used to collect data on post-harvest losses. Disease scoring tables, charts and photos were used to confirm observed symptoms and hence, disease occurrence and severity. AMF biocontrol efficacy experiment was conducted using tissue culture bananas grown in the greenhouse. The study revealed that most smallholder farmers were unaware of the causes or the prevalence of post-harvest losses. The findings also revealed a significant difference ($p<0.05$) in the severity of banana diseases across various cultivars from the three counties. The AMF treated bananas showed a significant difference ($p<0.05$) in plant height, total leaf area and chlorosis in comparison to other treatments. The study also revealed a reduction of *Fusarium's* pathogenic effects including chlorosis, reduced leaf surface area and eventual necrosis.

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Key words: arbuscular mycorrhizal fungi, *Musa* spp., *Rhizophagus irregularis*, post-harvest losses, *Fusarium* wilt, sigatoka

Introduction

Banana (*Musa* spp.) is an important global food source and the most important fruit crop in production and trade (Wahome et al., 2021). It is estimated by FAO (2023) that there are at least 1,000 banana types, with the Cavendish being the most marketed and frequently farmed type. The leading producers of bananas globally include Brazil, Ecuador, Philippines, China, and India (Campos et al., 2022). According to FAO (2023), a hectare yields between 40 and 60 tons of bananas. However, pests and diseases significantly reduce yields in most banana farming regions (FAO, 2017). In Kenya, banana production is predominantly by smallholder farmers in areas like Kisii, Nyamira, and Embu counties (FAO, 2017). Farmers in these areas lose up to 50% of their produce due to improper handling, transportation and storage (Muthee et al., 2019; Wahome et al., 2021), as well as biotic constraints that include panama wilt caused by *Fusarium oxysporum* f. sp *cubense* (Malaka et al., 2023).

Banana production in Kenya has decreased in regions that were formerly thought to be the center of production (Wachira et al., 2013). The decrease is associated with bacterial and fungal infections which supposedly affect various cultivars differently. The sigatoka disease caused by *Mycosphaerella* spp. (*M. fijiensis* and *M. musicola*), cigar end rot caused by *Musicillium theobromae* and *Fusarium* wilt caused by *Fusarium oxysporum* f.sp. *cubense* are among the most common banana diseases reported in Kenya (Wachira et al., 2013; Malaka et al., 2023). Other diseases significant to banana farmers include the *Xanthomonas* wilt and corm rot. Some of the diseases such as *Fusarium* wilt and black sigatoka can result in losses of up to 80% (Ploetz, 2015; Blomme et al., 2017).

In recent years, the use of biocontrol agents (BCAs) has gained much attention since it is an ecologically friendly, more sustainable and affordable disease management strategy as compared to synthetic pesticides (Siamak & Zheng, 2018; Bubici et al., 2019; Widijanto et al., 2021; Malaka et al., 2023). Banana diseases caused by bacteria and fungus can be controlled by use of biocontrol agents (Guo et al., 2013; Deltour et al., 2017). According to Raza et al. (2016), arbuscular mycorrhizal fungi (AMF) is a soil fungus that forms symbiotic relationships with various plant roots, acting as biofertilizers and biocontrol agents. Asparagus infection brought on by *Fusarium oxysporum* is one of several crop diseases that AMF can suppress (Waweru et al., 2013). The effectiveness of AMF as a biocontrol agent against *Fusarium oxysporum* f.sp. *cubense* banana diseases have not been well investigated in Kisii, Nyamira, and Embu counties. Investigating AMF's potential as a biocontrol agent against banana diseases is thus important.

The main objective of the current study was to examine the prevalence and severity of banana diseases and post-harvest losses in Kisii, Nyamira, and Embu Counties which are among the major banana-producing regions in Kenya. The study also examined the use of *Rhizophagus irregularis*, formerly known as *Glomus intraradices* as a biocontrol agent against *Fusarium oxysporum* f.sp. *cubense*. The findings of the study provide useful insights that can be used to enhance the management of banana diseases.

Materials and methods

Study site description

The study was conducted in Kisii, Nyamira, and Embu counties, Kenya (***Figure 1***). These are among the major banana producing counties in Kenya. Embu County is situated on the windward side of Mt. Kenya, at an elevation of 2500 m above sea level. The study site falls under the Upper midland zone (UM 1), located at an altitude of 1600-1850 m and receiving an average annual rainfall of 1395 mm. The average temperatures range from 17.5-18.9 ºC. The primary cash crops in the area are tea and coffee, while bananas are grown both for subsistence and commercial purposes. The region has deep, well-drained dusky red to reddish brown soils (Jaetzold et al., 2010). According to Jaetzold et al. (2010), the study sites in Nyamira County fall within the UM 1 agro ecological zone, featuring deep well-drained soils. The area experiences a bimodal rainfall pattern with no dry seasons between the wet seasons. The region also experiences a warm and temperate climate with an annual temperature average of 20.5 °C. The study sites in Kisii County have an average elevation of 1400-1500 m above sea level. These regions are classified as Lower midland zones (LM 2), specializing in sugarcane and banana cultivation (Jaetzold et al., 2010). The areas receive an annual rainfall ranging from 1400-1600 mm, with average temperatures between 20.5-21 °C.

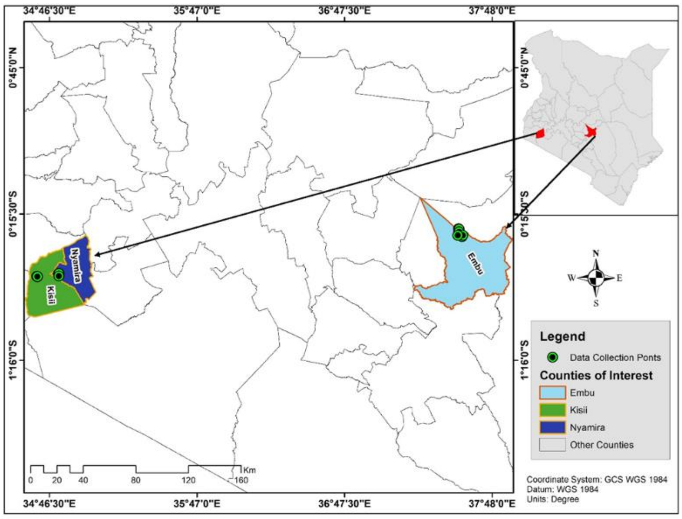

Figure 1. A map of Kenya showing the study sites in Embu, Kisii, and Nyamira counties generated from GPS coordinates.

Research design and sampling procedures

The survey design approach was used to investigate smallholder farmers' preferred banana cultivars and the occurrence of post-harvest losses and their causes in Kisii, Nyamira, and Embu counties. These regions are among the principal banana-producing areas in Kenya. The target population was all the banana farmers who had more than 30 banana stools. An objective sampling method was used to select the banana farmers for this study. Farms with more than 30 banana stools were identified in Kisii, Nyamira, and Embu counties. A total of 90 banana farmers were selected, which comprised of 30 farmers from each County. The sample size for each County was averaged to 30 after calculation using the formula recommended by Snedecor & Cochran (1989), considering the population size, proportion and accepted error.

$$n = \frac{4pq}{l^2}$$

Where n = sample size, *l*= Accepted error, *p* = proportion presenting population, and *q* = 1-*p*.

The targeted household population in Kisii County was 13,300. A proportion of 250 households was used to calculate to get a sample size of 29.51. In Nyamira County, a proportion of 295 farmers representing a population of 15,000 gave a sample size of 30 farmers. The total household population in Embu County, was 14,250. A proportion of 300 households was used to calculate the sample size, giving an approximate sample of 30 farmers.

Research instrument

Disease incidences and prevalence in Kisii, Nyamira and Embu Counties were assessed through questionnaires and the use of disease scoring tables and photos to confirm the presence or absence of banana diseases in a given farm. Banana farmers filled out a questionnaire detailing their farm's banana cultivars, disease incidence, and the occurrence of post-harvest losses. A pilot study was conducted in three villages in Kisii County to identify potential issues and flaws in the research methodology. Content and face validity were used to ensure that the research tools consistently measured what they were designed to measure (Kothari et al., 2012). Reliability was achieved through a consistent environment for respondents, an adequate number of questions and self-administration of the questionnaire. The study instrument was tested on ten individuals using the split-half method and the Pearson Product Moment Correlation Analysis to correlate the obtained coefficients.

Assessing major banana cultivars and associated post-harvest losses

Data on banana cultivars and post-harvest losses was collected using questionnaires that were administered to 30 farmers in every study site. To substantiate the respondents' statements and to have more reliable estimates, the farms were visited, and data regarding losses of bananas at the farm level were recorded separately. A total of 90 questionnaires were completed for the entire study. The farmers reported on the post-harvest losses they experienced and the causes of these losses.

Determination of disease severity and incidence

The severity of the diseases was determined by evaluating the symptoms displayed on the infected plant parts and then comparing them with scoring tables to establish the extent of the infection and hence, the disease severity. Plants that displayed symptoms such as leaf chlorosis, dried leaves and skirt formation were assessed examined for *Fusarium* wilt (Momanyi et al., 2021). The plants' pseudostem tissues were also checked for the reddish-brown coloring of the tissues, an unmistakable characteristic symptom of the *Fusarium* wilt. A scoring table advanced by Mohammed et al. (2001) based on the Leaf symptom index (LSI) was used for scoring for the disease severity. For every farm, a random selection of the plants was made to help in the individual scoring of the plants. The other diseases were similarly scored by using specific protocols and scoring tables as follows; black sigatoka (Carlier et al., 2002), yellow sigatoka (Romero et al., 2005), *Xanthomonas* wilt (Biruma et al., 2007), and cigar end rot (Gul et al., 2018). Disease severity mean was analyzed for all infected plants for every County. The number of plants that displayed *Fusarium* wilt symptoms was recorded. This was used to calculate the disease incidences for every farm and eventually for every region using the formula given by Viljoen (2002).

$$Disease\ incidence = \frac{No.of\ infected\ plants}{No\ of\ plants\ sampled} \times 100$$

The disease scoring by Carlier et al. (2002) was used to score for the black sigatoka disease. Symptoms such as dark brown specks on the lower leaf surfaces, oval-round yellow lesions, elongated necrotic lesions, incomplete fruit filling, and drying of the entire leaves indicated a *Pseudocercospora* infection.

The severity of yellow sigatoka was determined using the scale proposed by Gomes et al. (2018), where the disease severity was scored as 0 for no infection, 1 for 1-25% infected leaves, 2 for 26-50% infected leaves, 3 for 51-75% infected leaves, and 4 for 76-100% infected leaves. For *Xanthomonas* wilt, disease incidence and severity were determined by checking for the characteristic symptoms of water-soaked lesions and the yellowing of leaves according to the protocol by Biruma et al. (2007). The presence of the bacterial ooze was also checked by cutting across the pseudostem. The incidence and severity of cigar end rot and corm rot were evaluated by checking for the characteristic symptoms such as stem and corm rot, respectively, following the scoring tables provided by Youssef et al. (2020) and Thangavelu & Mustaffa (2010).

Assessing the biocontrol efficacy of AMF against Fusarium oxysporum

The efficacy of *Rhizophagus irregularis* (BEG 44) in controlling *Fusarium oxysporum* f.sp. c*ubense* infection in tissue culture bananas was assessed in greenhouse trials. The experiment was conducted using a Completely Randomized Design (CRD) and replicated five times. Three treatments and a control were set up as shown in ***Table 1***.

Table 1. Applied treatments.

Treatment	Composition
Treatment I (A)	100 spores of *Rhizophagus irregularis*
Treatment II (FW)	106/ml suspension of *Fusarium oxysporum* f.sp. *cubense*
Treatment III (AF)	106/ml suspension of *Fusarium oxysporum* f.sp. *cubense* followed with 100 spores of *Rhizophagus irregularis*.
Control (C)	Banana plantlets with no treatment

The AMF inoculum was prepared by germinating AMF spores with Bermuda grass, drying and crushing the soil to obtain inocula. Sterile soil was mixed with 5 g of the inoculum (containing approximately 100 AMF spores) the mixture potted, and banana plantlets planted. In the greenhouse, plant growth parameters were studied over 35 days with a 7-day interval after weaning in soil. Inoculation with *F. oxysporum* spores was carried out at the end of the third week. The inocula suspension was constituted to a concentration of 10^6/ml of sterile distilled water following the method by Purwati & Hidayah (2008) and drenched directly to the plant roots that had been slightly injured. Plant growth parameters, including plant height, leaf width, length and the number of leaves were recorded weekly. The number of chlorotic and dead leaves was also recorded for six weeks. The total green leaf area of the plant was estimated using the formula by (Kumar et al., 2012).

$$Total\ leaves\ area = 0.8 * L * W * N$$

Where: Total green leaves area (cm^2)
L = Length of the third fully developed middle leaf (cm);
W = Width of the same leaf (cm);
N = Total number of green leaves in a plant.

Data analysis

Data on disease incidences and prevalence in the three counties was analyzed using the Statistical Package for Social Sciences (SPSS) version 22.0 computer software. One-way ANOVA was used to analyze the transformed disease severity data from the three counties. To determine the relationship between banana variety and disease incidence, survey data were analyzed using the Chi-square test of independence at a 5% significant level. In addition, data on plant growth characteristics were gathered and statistical analysis using one-way ANOVA with repeated measures was performed to identify any notable variations between the treatments. The Tukey's HSD test was used for the separation of means.

Results

Prevalence and causes of post-harvest losses

There were noteworthy post-harvest losses in Embu (23.33%), Nyamira (13.33%), and Kisii (10%) (***Table 2***). The majority of participants lacked knowledge regarding the underlying causes of post-harvest losses, whereas a subset of respondents attributed such losses to potential factors such as theft, pests, diseases, and other related variables (***Table 2***). Banana diseases were ranked as the single major cause of losses in Embu at 10% followed by theft at 6.67%. In Kisii, theft accounted for 3.33% while pests and diseases both accounted for 0%. In Nyamira, diseases and theft accounted for 0% while pests ranked as the major cause of the losses at 3.33%.

Disease incidences on the common banana cultivars in Nyamira, Embu, and Kisii Counties

The sampled bananas exhibited symptoms such as wilting, chlorosis, leaf defoliation, necrotic lesions, skirt formation and dieback. The symptoms observed also included premature ripening and drying of banana fingers, which remained attached to the plant. Upon splitting of plants that were symptomatic of *Fusarium* wilt, the corm or pseudo-stem showed brown lesions. Grey ashy symptoms were observed in cigar end rot infected bananas (***Figure 2***).

Table 2. *Prevalence and causes of post-harvest losses in selected farms in Kisii, Nyamira, and Embu counties.*

County	% of farmers reporting losses	% of farmers reporting no losses	% of farmers reporting each cause of post-harvest-loss			
			Pests	**Diseases**	**Theft**	**Combination**
Embu	23.33	76.67	3.33	10	6.67	3.33
Kisii	10	90	0	0	3.33	10
Nyamira	13.33	86.67	3.33	0	0	13.33

Table 3. Disease incidences on the common cultivars in Nyamira, Embu, and Kisii counties.

Cultivar	*Fusarium* wilt	Black sigatoka	Yellow sigatoka	*Xanthomonas* wilt	Cigar end rot	Corm rot
Nyamira County						
'Ng'ombe'	0.22±0.88b	2.33±0.29a	0.89±0.20a	0.11±0.06a	0.00	0.00
'Kienyeji'	0.00±0.00c	1.33±0.20b	0.78±0.10b	0.00	0.00	0.00
'Sukari'	0.67±0.23a	0.33±0.11c	0.00±0.00c	0.00	0.55±0.13a	0.00
Embu County						
'Israel'	0.33±0.14a	2.11±0.25a	1.00±0.21a	0.00	1.67±0.25a	0.22±0.09a
'Sukari'	0.33±0.14a	0.22±0.13d	0.00	0.00	0.22±0.09c	0.22±0.09a
'Kiganda'	0.00	0.77±0.18c	0.00	0.00	0.33±0.11b	0.00
'Kampala'	0.00	0.99±0.19b	0.00	0.00	0.00±0.00d	0.00
Kisii County						
'Eng'oche'	0.11±0.06b	1.33±0.33c	0.00	0.00	0.00±0.00c	0.00
'Kienyeji'	0.00±0.00c	2.78±0.26a	0.44±0.12a	0.00	0.11±0.06b	0.00
'Sukari'	0.78±0.18a	1.33±0.25b	0.00	0.00	0.56±0.16a	0.00
P values	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

Values followed by the same letter within a column of each county are not significantly different at p<0.05, (Tukey HSD test)

Table 4. Disease severity and incidence in Nyamira, Embu, and Kisii Counties.

Disease	No. of affected farms	% of affected farms	Mean severity (± SD)
Embu County			
Fusarium wilt	4	13.33	0.17±0.05b
Black sigatoka	23	76.67	1.02±0.10a
Yellow sigatoka	8	26.67	0.06±0.06e
Xanthomonas wilt	0	0	0.00±0.00f
Cigar end rot	16	53.33	0.08±0.02d
Corm rot	4	13.33	0.11±0.03c
Nyamira County			
Fusarium wilt	5	16.67	0.30±0.08c
Black sigatoka	25	83.33	1.33±0.13a
Yellow sigatoka	13	43.33	0.56±0.09b
Xanthomonas wilt	1	3.33	0.04±0.02e
Cigar end rot	5	16.67	0.19±0.75d
Corm rot	0	0	0.00±0.00f
Kisii County			
Fusarium wilt	7	23.33	0.30±0.07b
Black sigatoka	28	93.33	1.81±0.17a
Yellow sigatoka	3	10	0.15±0.04d
Xanthomonas wilt	0	0	0.00±0.00e
Cigar end rot	5	16.67	0.22±0.06c
Corm rot	0	0	0.00±0.00e
P value			< 0.05

Table 5: Plant height recorded at 7-day interval for 35 days after planting in pots in the greenhouse.

	Measurements (cm)					
Treatment	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**
A	13.70±0.10a	17.20±0.10a	20.50±0.10a	21.40±0.20a	22.60±0.10a	23.10±0.10a
FW	13.27±0.06b	14.80±0.10c	17.13±0.06c	18.10±0.10c	18.50±0.06d	18.73±0.06d
AF	12.43±0.06c	13.83±0.06d	15.80±0.10d	17.83±0.06c	19.23±0.06c	20.47±0.06c
C	12.40±0.10c	14.40±0.10c	17.60±0.10b	18.90±0.10c	19.80±0.10b	20.60±0.10b

Figure 2. Symptoms on infected parts of the banana plants.
A- Necrotic lesions indicating black sigatoka on leaves; B- yellow sigatoka on leaves; C- Severe cigar end rot on banana fingers

In Nyamira County, three major banana cultivars, 'Ng'ombe', 'Kienyeji', and 'Sukari' were identified. The susceptibility of the cultivars to the various diseases differed significantly at $p < 0.05$ except for corm rot where zero incidences were recorded (***Table 3***). Field investigations in Embu County identified 'Israel', 'Sukari', 'Kiganda', and 'Kampala' as the commonly cultivated banana cultivars. The susceptibility of these cultivars to the studied diseases showed significant differences, except for *Xanthomonas* wilt ($p < 0.05$). Three cultivars were identified in Kisii namely 'Sukari', 'Kienyeji' and 'Eng'oche'. The different cultivars differed significantly in their susceptibility to *Fusarium*, sigatoka and cigar end rot ($p < 0.05$).

The highest incidence of *Fusarium* wilt was recorded in the 'Sukari' cultivars having a mean of 0.78 and 0.67 in Kisii and Nyamira counties respectively. In contrast, there was no disease incidence reported in the 'Kienyeji' and 'Kiganda' cultivars in Nyamira and Embu counties. For black sigatoka, the cultivar 'Kienyeji' had the highest average incidence of 2.78, followed by 'Israel' having an incidence of 2.33. The lowest incidence of black sigatoka was recorded in 'Sukari' cultivar in Embu with a mean of 0.22 as indicated in ***Table 3***.

Yellow sigatoka disease incidence was highest in *Israel* (1.00), followed by the ''Ng'ombe'' (0.89) cultivars in Embu and Nyamira respectively. 'Sukari', 'Kampala' and 'Kiganda' did not record any case of yellow sigatoka diseases in the three regions. *Xanthomonas* wilt was only recorded in Nyamira County, infecting 'Ng'ombe' cultivars having a mean incidence of 0.11. All the other cultivars in the three study sites did not record any incidence of the bacterial wilt disease.

'Israel' cultivar in Embu had the highest incidence of cigar end rot, (1.67), followed by *'*Sukari' in Nyamira (0.55). The lowest incidence was reported in ''Ng'ombe'', 'Kienyeji' and 'Eng'oche' cultivars. For corm rot, Embu County had the only recorded incidences with both 'Israel' and 'Sukari' cultivars with a mean of 0.22. All the other cultivars in the three counties had zero incidences (***Table 3***).

Disease severity and incidences in selected farms in Nyamira, Embu, and Kisii Counties

All counties recorded *Fusarium* wilt, with Kisii and Nyamira having the highest mean severity (0.30) (***Table 4***). Kisii had the greatest mean black sigatoka severity (1.81), followed by Nyamira (1.33) and Embu (1.02). The severity of yellow sigatoka was highest in Nyamira County (0.56) and least in Embu County at 0.06. Although most farms in Kisii and Embu were free from X*anthomonas* wilt, the disease was recorded in Nyamira County with a mean severity of 0.04. Corm rot was only recorded in Embu County with a mean severity of 0.11. There were significant differences ($p < 0.05$) in the disease severity and incidence rates in farms across the three counties. ***Table 4*** summarizes the severity of the diseases in the three counties.

The efficacy of AMF as a bio-control agent against banana diseases pathogens

In the greenhouse experiment, treatments I with *Rhizophagus. irregularis* and treatment II with *Rhizophagus irregularis* + *Fusarium oxysporum* displayed the highest leaf count beyond the 5th measurement (Day 29), whereas treatment III (*F. oxysporum* infected plants) showed no increase in leaves beyond day 15 (3rd measurement) (***Figure 3***).

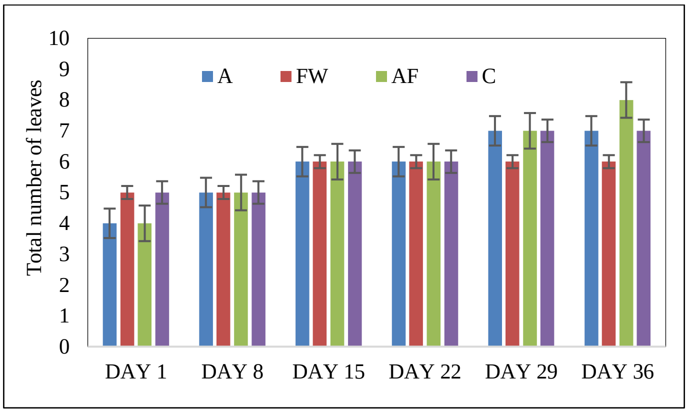

Figure 3. Plants' total number of leaves recorded at 7-day intervals for 35 days after planting in pots in the greenhouse. All values are mean and standard error of three replicates of each banana plant.
A-Amf, Fw- Fusarium wilt, Af- Amf+ Fw, and C-Control.

Initially, all plants grew normally without phenotypical differences compared to the control plants. No chlorotic leaves were recorded for the first seven days, but FW treatment displayed chlorotic leaves on day 8 (2nd measurement) (***Figure 4***). In subsequent measurements, the number of chlorotic leaves was similar across all treatments, except for FW treatment, which showed increased chlorotic leaves in the 5th and 6th measurements. The presence of AMF significantly affected the development of chlorotic leaves (***Figure 5***).

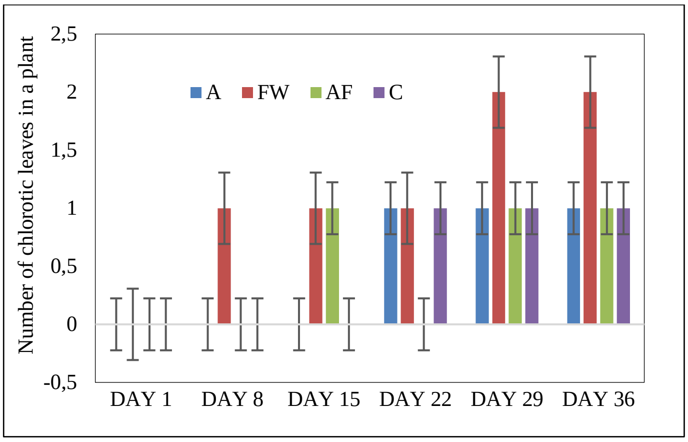

Figure 4. Number of chlorotic leaves recorded at 7-day intervals for 35 days after planting in pots in the greenhouse.
A-AMF, Fw- Fusarium wilt, Af- Amf + Fw, and C-Control.

Figure 5. Leaves chlorosis.
A, Chlorosis development in plants treated *Fusarium* spores,
B, Absence of chlorosis in plants inoculated with AMF and *Fusarium* spores on the 5th measurement.

The total leaf surface area (LSA) varied significantly across the various treatments ($p < 0.05$). The A, AF treatments and the control had a gradual increase in LSA from the 1st to the 6th measurement. Most of the FW treatments had an increase in LSA during the first three measurements which were followed by either a decrease or no change in the leaf surface area (***Figure 6***).

Discussion

The study aimed to assess the occurrence of post-harvest losses and their causes in Kisii, Nyamira, and Embu counties, determine the incidences and severity of the common bacterial and fungal diseases associated with different banana cultivars, and evaluate the efficacy of *Rhizophagus irregularis* as a biocontrol agent against *Fusarium oxysporum* f.sp. *cubense* banana pathogens. A decline in banana production in the three counties is attributable to diseases and pests worsened by poor control measures as revealed in this study and also supported by similar findings by Muthee et al. (2019). Knowledge of disease prevalence and incidences concerning the cultivars can help farmers cultivate less susceptible cultivars. The study is, therefore, significant, as it provides insights into managing banana diseases in the region and identifies sustainable disease management strategies that can reduce post-harvest losses and increase productivity.

According to this study, farmers from Kisii, Embu and Nyamira reported different factors that caused banana post-harvest losses. The most commonly cited causes were pests, diseases and theft. However, it was noted that most farmers did not report cases of post-harvest losses, which was attributed to the small production scale. Other studies have noted that farmers with low production volumes tend to have better management during harvesting and sales, reducing yield losses (Momanyi et al., 2021; Onyambu et al., 2021). As observed in this study in corroboration to earlier findings from Hassan et al. (2010) & Molla et al. (2012), significant losses occur after harvest, which necessitates the need for farmers to have better post-harvest practices. Improper handling of bananas during post-harvest processes including processing, storage, and transportation leads to significant losses. This is corroborated by studies reported by Molla et al. (2012) and Hassan (2010). Thus, farmers must improve post-harvest operations to reduce losses and boost profits.

This study found that bananas from the three counties recorded different disease cases and severity. Of the diseases, black sigatoka emerged as the most prevalent and severe disease across all three counties, with Kisii County having the highest mean severity of 1.70. *Fusarium* wilt and cigar end rot were also prevalent in all counties, with Nyamira County having the highest number of affected farms (8) and a mean severity of 0.68 ± 0.50. On the other hand, yellow sigatoka and *Xanthomonas* wilt were relatively rare, with Nyamira County having the highest number of affected farms (3) and a mean severity of 0.19. Cigar end rot and corm rot were less pronounced in the study area compared with the other diseases like sigatoka and *Fusarium* wilt. Notably, corm rot was not significantly reported in the farms in the three counties. The differences in these diseases' frequency and severity point to the necessity for region-specific management methods that take into account the particular elements that affect disease prevalence and severity in each County.

The results of the present study show that black and yellow sigatoka infections are both present in Kenyan banana-growing regions, with black sigatoka being more common. The results of this study are consistent with previous studies that have reported black sigatoka as one of the most important and destructive diseases of bananas worldwide (Henderson et al., 2006; Ugarte et al., 2020; George et al., 2022). The higher incidence and severity of black sigatoka in Kisii and Nyamira counties could be attributed to the high rainfall and humidity in these regions, which are known to favor the development and spread of the disease (Onyambu et al., 2021). The black sigatoka disease causes more significant damage and is more challenging to control than the yellow sigatoka disease, as Ugarte et al. (2020) reported. The control measures for sigatoka diseases are costly and challenging for resource-poor farmers, as highlighted by Ebimieowei & Wabiye (2011). The study asserts that controlling sigatoka diseases requires a multi-faceted approach that incorporates cultural methods, the use of resistant cultivars, and the proper nourishment of plants.

Xanthomonas wilt was prevalent in the 'Ng'ombe' cultivar from Nyamira County, while corm rot was observed in 'Israel' and 'Sukari' cultivars from Embu County. The results of this study corroborate those from earlier studies by Tripathi et al. (2009) and Ocimati et al. (2018), which also noted the vulnerability of banana cultivars to bacterial infections. Corm rot disease and *Xanthomonas* wilt are two serious hazards to banana crops posed by bacteria (Ploetz et al., 2015a; Ploetz & Evans, 2015; Blomme et al., 2017; Dita et al., 2018; Tinzaara et al., 2021). Most of the farmers in the study were found to grow hybrid banana cultivars, which attract various categories of insect pollinators and hasten disease spread, as suggested by Tooker & Frank (2012). The high incidence of *Xanthomonas* wilt observed in Nyamira County may be attributed to the close proximity of banana farms to each other, which could facilitate the spread of the disease (Uwamahoro et al., 2019). Additionally, the observed high prevalence values during the wet season may be attributed to high precipitation, which encourages the survival, multiplication and dispersion of the *Xanthomonas* pathogen (Aung et al., 2018; Onyambu et al., 2021; Kang et al., 2021). In contrast, only a few cases were reported in Embu County, and no incidences of *Xanthomonas* were recorded in Kisii County, which could be due to the source of sample material used in the analysis or the absence of *Xanthomonas* wilt symptoms in parent sucker plants (Ocimati et al., 2018).

In conformity with previous studies, the current study also reported *Fusarium* wilt as a destructive disease across the three counties. The wilt is caused by a fungus, *Fusarium oxysporum* f.sp. *cubense* which prevents the movement of sap in the xylem (Ploetz, 2015). The disease is not easy to control because the fungus survives in the plant debris and attacks the new roots of the banana plants (Malaka et al., 2023). A study by Momanyi et al. (2021), conducted in Kisii County, reported that *Fusarium* wilt is common in the region because of poor management practices that do not meet the required strategies for avoiding or controlling the disease. Significant differences ($p < 0.05$) were reported for the severity of *Fusarium* wilt disease across the three regions. Nonetheless, common symptoms were reported across the regions. Similar environmental conditions across the regions make the *Fusarium* pathogen thrive (Ploetz, 2015; Momanyi et al., 2021). The soil characteristics, cropping practices, and environmental factors may also impact the severity of *Fusarium* wilt. According to Li et al. (2011), small-scale farmers may be contributing to the rapid spread of the disease by using uncertified banana suckers for replanting and having insufficient awareness of banana *Fusarium* wilt. The soil-borne pathogen can survive in the fields for extended periods once the disease has been introduced into the farm, ultimately infecting the subsequent banana crops (Li et al., 2017).

The study identified significant differences in the susceptibility of different banana cultivars to the studied diseases across the three counties. Variations in the rate of defense response and response magnitude that depends on the expression of resistant genes could be attributed to these differences (Mwangi & Nakato, 2009; Tripathi et al., 2009). The initiation of proteolysis process, for instance, highly influences the defense response in plants. Also, a delay in the production of proteins such as Osmotin-like protein, a PR5, and a Germin-like protein could aggravate plant susceptibility to pathogens (Breen & Bellgard, 2010; Chowdhury et al., 2017). This study's findings align with those of previous studies, such as those of Tripathi et al. (2010), and Nakato et al. (2017) which observed the susceptibility of different banana varieties to *Xanthomonas campestris* pv. *musacearum* pathogen.

Moreover, the results reveal variations in the incidence of *Fusarium* wilt, black sigatoka, yellow sigatoka, *Xanthomonas* wilt, cigar end rot and corm rot across the three counties. Kisii County had the highest incidence of *Fusarium* wilt, black sigatoka and yellow sigatoka, while Nyamira County had the lowest incidence of these diseases. The highest incidence of *Xanthomonas* wilt was observed in Nyamira County, while Kisii and Embu counties had the lowest incidence. Embu County had the highest incidence of cigar end rot, and corm rot compared with the other study areas. The findings suggest a need for targeted interventions to manage these diseases and reduce their impact on regional banana production. Farmers in Kisii County, in particular, may need to implement more aggressive control measures to prevent the spread of these diseases.

In determining the effectiveness of *Rhizophagus irregularis* as a biocontrol agent against *Fusarium* wilt, the results revealed that its application significantly influenced plant height, which increased across the treatment with an increased number of days (***Table 5***). AMF-treated plants also produced a more significant total leaf area than other treatments. Inoculation with *R. irregularis* also significantly reduced the development of chlorotic leaves caused by *F. oxysporum* f.sp. *cubense* treatment. The increase in plant growth parameters could be due to mycorrhizal-induced compensation processes in plants treated with AMF, as they may compensate for the loss of root mass or function caused by pathogens through their dense mycelial network (Mohandas et al., 2010). Other studies have also reported the effectiveness of AMF as a biocontrol agent against plant pathogens. For instance, Graham & Menge (1981) and Durán et al. (2018) reported that AM fungi reduced wheat take-all disease caused by *Gaeumannomyces graminis*. Similarly, Declerck et al. (1995) reported that AM fungi reduced root rot of bananas caused by *Cylindrocladium spathiphylii*.

Previous studies have shown that AMF establishment can change both total microbial populations and specific functional groups of microorganisms in the rhizosphere soil, which may lead to stimulation of the microbiota antagonistic to root pathogens (Mohandas et al., 2010; Olowe et al., 2018; Bubici et al., 2019; Boutaj et al., 2022; Weng et al., 2022;). In the rhizospheric soil, the presence of AM fungi can alter both the total microbial population and particular functional groups of microorganisms (Meyer & Linderman, 1986; Linderman, 2000). This could stimulate the microbiota and reduce root pathogens (Harrier & Watson, 2004; Gryndler et al., 2018).

The loss of root mass or function caused by pathogens can be compensated for by plants treated with AMF when AM fungi are present (Schouteden et al., 2015; Weng et al., 2022). Additionally, there is improvement in the host plant's mineral nutritional status resulting from the colonization of AM fungus which can promote plant development (Declerck et al., 1995). However, the increased mineral nutrition of AMF-treated plants cannot fully explain the host plant protection offered by AM fungus (Caron et al., 1986). Several studies have also demonstrated the positive impact of AM fungi on nutrient uptake and growth of banana plants (Declerck et al., 1995; Jaizme-Vega et al., 1997; Declerck et al., 2002; Elsen et al., 2009).

Furthermore, the root colonization by AM fungi can result in structural and biochemical changes in the cell walls of plants, such as increased concentrations of phytoalexins (Morandi et al., 1984; Aloui et al., 2012), which may enhance the resistance of plants to fungal pathogens. The positive effect of AM fungi on banana growth was more pronounced under stressed conditions caused by *Fusarium oxysporum* than in the absence of stress (Rufyikiri et al., 2000). Moreover, AM-inoculated plants possess a robust vascular system, which imparts greater mechanical strength to diminish the effects of pathogens (Sharma et al., 1992; Xue et al., 2015). Improved resistance to biotic stresses, such as *Fusarium oxysporum* f.sp. *cubense*, has been reported in banana plants (Jaizme-Vega et al., 1997). The AMF can produce some active substances that can act as an initial defense against soil-borne pathogens (Xue et al., 2015; Chu et al., 2016).

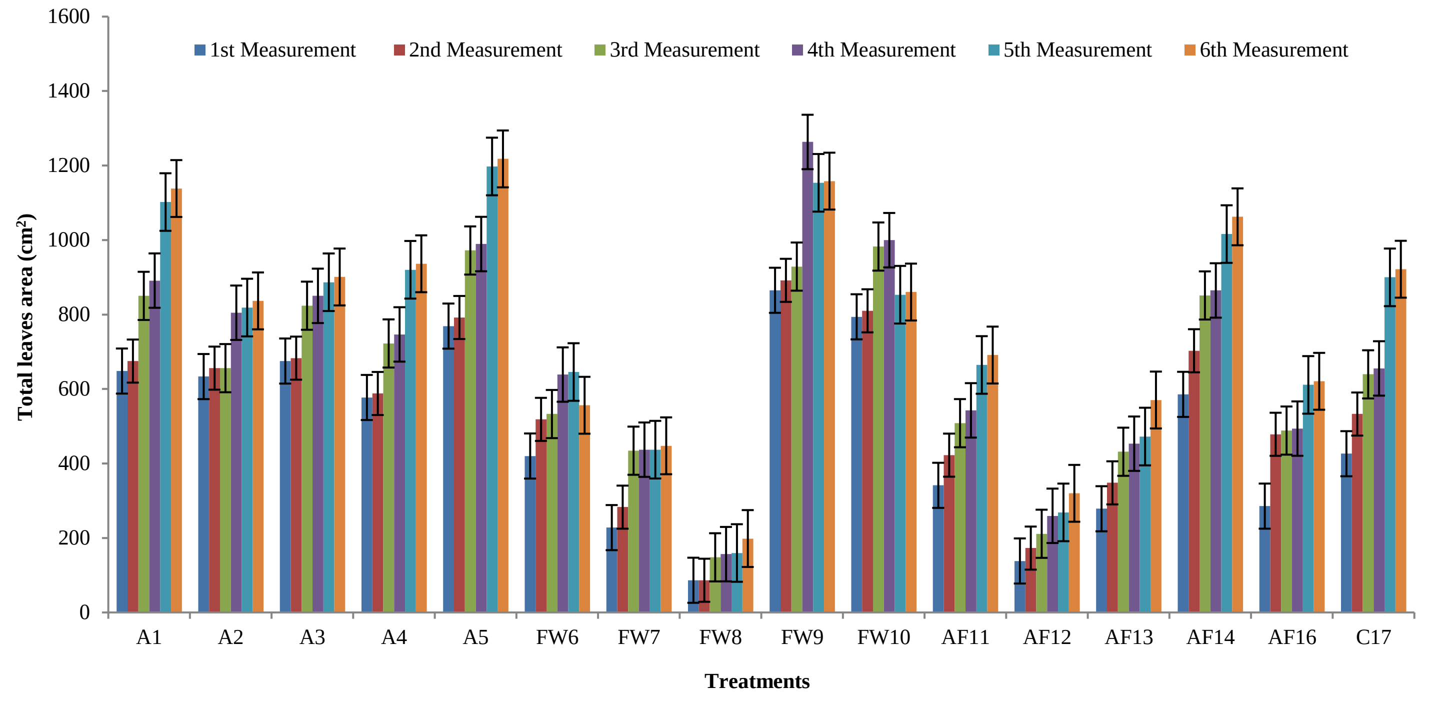

Figure 6. Plant total leaves area (cm^2) recorded at 7- day interval for 35 days after planting in pots in the greenhouse.
(A1- A5- AMF-*Rhizophagus irregularis* treatments; Fw6-Fw10 - *Fusarium* wilt treatments; Af11- Af16- AMF + *Fusarium* wilt treatment, and C17-Control.)

The demonstrated bio-control ability of AMF provides a glimpse of hope for using AMF in curbing banana diseases (Jaizme-vega et al., 2003; Muthee et al., 2019). This would also aid in ensuring that correct control measures are taken to prevent frequent incidences and potential outbreaks, as evidenced by previous studies (Ilyas et al., 2007; Nayak et al., 2018; Saha et al., 2021; Rajapaksha et al., 2021; Sugianti et al., 2022).

The results of this investigation shed light on *R. irregularis* potential as a biocontrol agent for the *Fusarium* wilt of bananas. The combination of different mechanisms of action using AMF can create new inoculants, which can be more effective in employing bio-control techniques in the future to control diseases (Beneduzi et al., 2012). However, there are a lot of issues that need to be resolved, like the limitations of their cultivation techniques, the effects of biocontrol microorganisms on the health of the soil, and the ideal inoculation interval, dose, and ecological circumstances for optimizing plant benefits. Even though many studies have demonstrated that AMF improves plant resilience to biotic and abiotic stressors, there are still discrepancies in the results because test materials and settings vary. Additional research is required to evaluate the biocontrol effects of AMF in a scientifically sound manner and to investigate the relationship between the many signaling molecules that AMF induces and the expression mechanism that results from those signals.

Conclusions

This study provides valuable insights into managing banana diseases in the study areas, highlighting sustainable disease management strategies that can reduce post-harvest losses and increase productivity. Post-harvest losses were identified as a significant challenge for farmers, with up to 23.33% losses reported in Embu County. The study also found significant variations in the incidence and severity of banana diseases across the three counties, with black sigatoka and *Fusarium* wilt being the most prevalent diseases. The variations in cultivar susceptibility to diseases, can be exploited by farmers whereby they can cultivate less susceptible but productive cultivars. Inoculating banana plantlets with *Rhizophagus irregularis* improved their growth and reduced their susceptibility to *Fusarium oxysporum* f.sp. *cubense*. However, further study is needed to discover the best treatment dose and administration strategy for large-scale agricultural systems and field conditions. The study emphasizes the importance of integrated disease management strategies that combine various approaches to effectively control banana diseases and increase productivity in smallholder farming systems.

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