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Effect of selected soil moisture conservation practices on the bean physical quality attributes and damage caused by the major pests and diseases on Robusta coffee, *Coffea canephora* (Pierre ex Fröhner)

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Abstract

Robusta coffee, *Coffea canephora* (Pierre ex A) contributes significantly to Uganda's foreign exchange and livelihood of its citizen. However, climate variability threatens coffee production and quality by increasing pests and diseases. This study aimed to determine how soil moisture conservation practices affect coffee defects, bean size, and relationship with pests and diseases. This study evaluated the effects of soil moisture conservation practices (SMCPs) on coffee bean defects, bean size, and their relationships with major pests and diseases. The study was conducted at the National Coffee Research Institute using an incomplete randomized block design with four SMCPs: coffee under open sun, coffee intercropped with *Desmodium intortum*, coffee mulched with *Miscanthidium violaceum*, and coffee under *Albizia coriaria*. Each treatment was replicated three times, and data were collected from four coffee plants per plot. Results showed no significant differences ($p \geq 0.05$) in coffee bean defects or screen size distribution across SMCPs. Overall, coffee grown under *Albizia coriaria* recorded the highest proportion of sound beans (82.31%), while coffee with mulch had the lowest (72.47%). Similarly, coffee bean size did not vary significantly ($p \geq 0.05$) among SMCPs. In contrast, pest and disease incidence differed significantly among systems ($P \leq 0.001$), except for berries with red blister disease, which showed no significant variation ($P = 0.709$). Coffee under open sun recorded the highest damage from leaf skeletonizers (10.43%), berry moth (20.11%), brown eye spot (3.48%), and clusters with red blisters (45.36%), whereas coffee with mulch consistently exhibited the lowest pest and disease pressure, except for berry moth (13.49%). Coffee under *Albizia coriaria* showed higher incidence of several pests and diseases, including black coffee twig borer (25.64%), leaf miners (11.82%), and berries with red blisters (32.29%), but had the lowest levels of berry moth (13.07%) and coffee berry borer (0.37%). In contrast, coffee with cover crop recorded the highest coffee berry borer infestation (3.05%). Overall, the findings indicate that although soil moisture conservation practices did not directly influence coffee bean physical attributes, they significantly affected pest and disease incidence, which in turn has implications for coffee quality. The results highlight the importance of integrating soil moisture conservation with pest and disease management strategies, with coffee mulching systems showing particular potential for reducing pest pressure and enhancing coffee quality.

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1 Introduction

Robusta coffee (*Coffea canephora*, Pierre ex A. Froehner) is an essential export for many developing nations and makes up to 44.1% of the world's coffee production in 2022/23 (ICO (International Coffee Organization), 2023). During the financial year 2022/23, Uganda exported 5.76 million bags of coffee, valued at $845.94 million (UCDA (Uganda Coffee Development Authority), 2023). More so, Robusta coffee is the primary source of income for millions of smallholder farmers in the world's tropical regions (Kath et al., 2021). With 9 million Ugandans, living in over 1.7 million households, depend on activities associated to coffee value chain for their income (Hill, 2005; Kagezi et al., 2021; Mugoya, 2018; NCP (National Coffee Policy), 2013). In 2011, Chotamonsak et al. (2011) and Dai (2013) predicted that the future of coffee production is threatened by the changes in temperatures and rainfall in many significant coffee-producing areas. The effects of climate change as predicted may be more detrimental to Robusta coffee sector since it is grown in rainfed systems (Dekens & Bagamba, 2014). Bracken et al. (2023) further alluded that the coffee plant development can be impacted by the amount and seasonal variance of precipitation. According to Läderach et al. (2017), coffee quality along with coffee yield, are susceptible to changes in climate as a results of increased temperatures. Crucially, the decline in quality takes place in an environment where customer knowledge has raised expectations for higher-quality products. This emphasizes how critical it is to increase climate resilience on farms.

The physical and chemical properties of coffee beans have a significant impact on the quality of the cup. The physical and chemical characteristics of coffee beans are greatly influenced by the species and genotype of coffee, microclimatic variables (temperature, water availability, irradiance), conditions during the fruit/bean maturation process, soil characteristics, agricultural crop management techniques (e.g., fertilization, irrigation), and post-harvest processing. The environmental conditions that prevail during fruit development are particularly important for the final bean quality (Carelli et al., 2006; Cheng et al., 2016; DaMatta & Ramalho, 2006; Ramalho et al., 2018). In addition coffee pests and disease have been reported to negatively affect coffee quality (Ribeyre & Avelino, 2012) and their incidence is predicted to increase with climate changes (Chengappa et al., 2017). On a brighter side, R. G. Muschler (2001) and Vaast et al. (2006) noted that soil moisture conservation practices can reduce the incidence of pests and disease. Soil moisture conservation practices such as mulching, covercrop and agroforestry improve soil moisture retention, improve soil physical and chemical properties which in turn improve coffee's tolerance to pests and disease. However, information on how these soil moisture conservation practices influence pests and diseases in coffee is still limited.

Defective beans can result in off-flavors and a reduction in the overall quality of the cup (e.g., discolored, immature, broken, insect-damaged, wrinkled, withered, shell/elephant, triage beans) (Casas et al., 2017; Hameed et al., 2020; Marie et al., 2020). Defective coffee beans also exhibit lower weight, density, brightness, and amounts of some biochemical quality precursors (such as total polyphenols, protein, fat, sucrose, and caffeine) as compared to normal (graded) beans (Ramalakshmi et al., 2007). This demonstrates that defective beans affect coffee's weight and out-turn in addition to lowering cup quality. However, a thorough investigation into the relationship between crop management and overall coffee quality has not been fully explored (Deribe, 2019). In order to secure the future financial security and sustainability of small-scale Robusta farmers across the global tropical regions, it is crucial to comprehend and mitigate the effects of unfavorable climatic circumstances on Robusta coffee beans (Kath et al., 2021). In turn, this will contribute to lowering the possibility of flaws, low out-turn and underweight coffee beans (Ayala et al., 2022; Oberthür et al., 2011). This will increase the price that farmers may obtain for their crop, particularly in unfavorable weather conditions (Kath et al., 2021). Additionally, focused research must be done to discover how soil moisture conservation practices that affect coffee quality amidst the changing climate. This will inform farmers on quality enhancing management practices (Läderach et al., 2011). This study therefore determined the influence of selected soil moisture conservation practices on coffee bean physical characteristics, pests and diseases. This will inform on climate adaptation in the coffee system for better bean quality.

2 Materials and Methods

2.1 Study site description and selection

The study was conducted at National Coffee Research Institute (NaCORI) which is located in Mukono district about 16km along Mukono-katosi road. NaCORI is situated at 0015'26.9874"N and 32047'27.69648"E (Kobusinge et al., 2023) (Fig 1). The annual minimum temperature ranges from 150C to 180C whereas the annual maximum temperature ranges from 250C to 280C. The annual rainfall is bimodal, varying between 1,400 and 1,600 mm (Kobusinge et al., 2023; Mukono District Local Government, 2015). The study site's soils are Ferrallisols (sandy clay-loams) (Kobusinge et al., 2023).

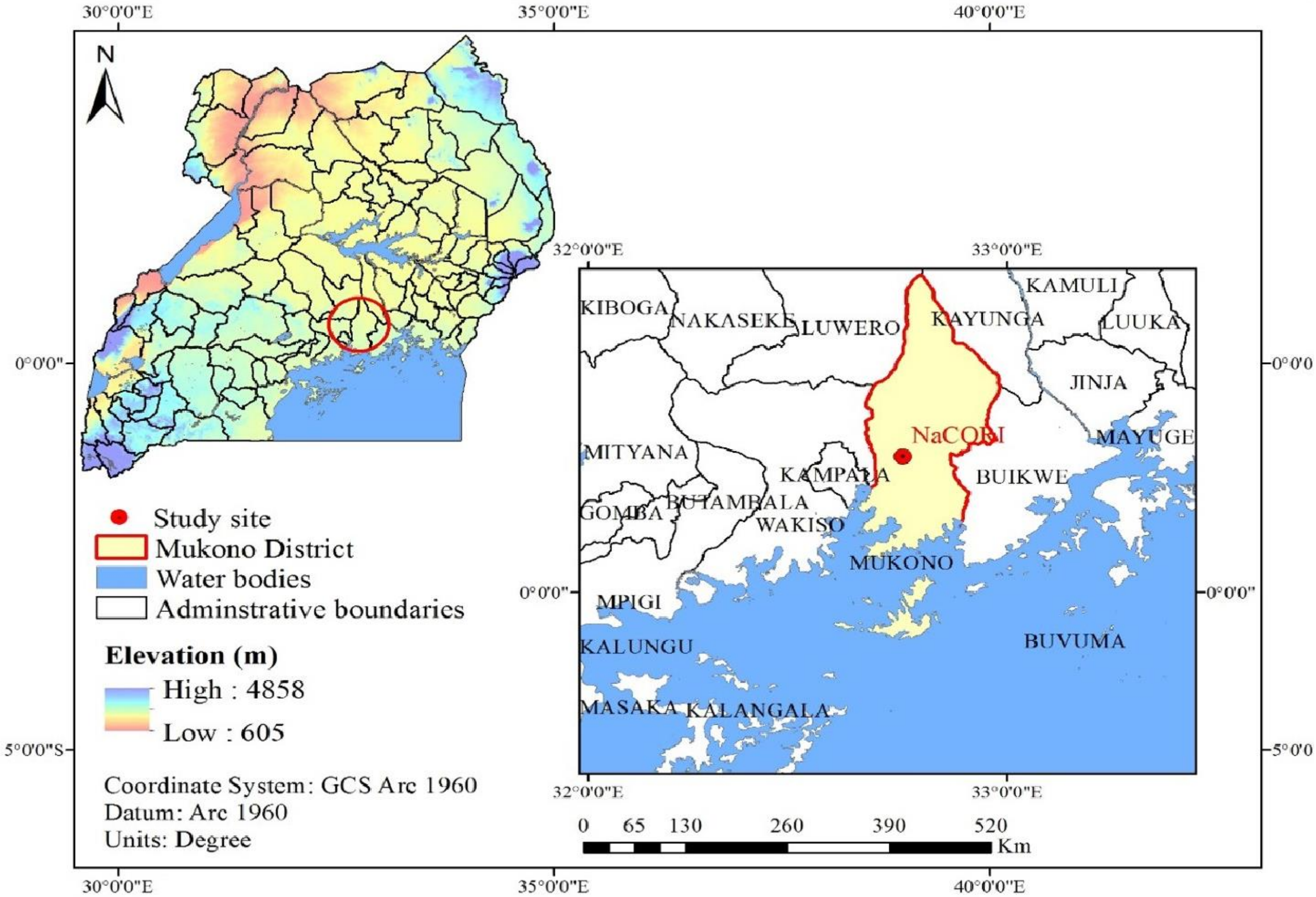

Figure 1: Location of study site, NaCORI, Mukono district (Adopted from Kobusinge et al., 2023)

2.2 Experimental design

The experiment was superimposed on Robusta coffee (*Coffea canephora* Pierre ex A. Froehner) of 2.2 acres that was planted in 2009. The coffee garden included a breeding population that gave raise to the Coffee Wilt Disease resistant (CWDr) varieties. This coffee was last stumped in 2019. All plots were uniformly managed with respect to weeding, pruning, and other cultural practices. An incomplete randomized block design was used with four soil moisture conservation practices (SMCPs) replicated three times. These consisted of; open sun coffee (COSS), coffee cover crop- *Desmodium intortum* (CCS), coffee mulch-*Miscanthidium violoceum* (CMS) and coffee *Albizia coriaria* (ACS). Replicate two didn't have ACS. Coffee was planted at a spacing of 3m by 3m while the shade tree was planted at a spacing of 15m by 15m. Mulch was maintained at a thickness of 10cm. Each treatment was of area 81m2 consisting of 16 Robusta coffee plants, with four plants used for data collection. This study ran from April 2022 to April 2023.

2.3 Methods of data collection

Harvesting and sample preparation of coffee cherries:

For physical analysis, 1 kg of well ripened coffee cherries from each tree under the four SMCPs was hand-picked, floated to remove any leaves, debris, and coffee cherries that looked diseased. The good beans were dried using a solar dryer on raised bed, made of stainless wire mesh and dried to attain a moisture content of 13-14% (UCDA (Uganda Coffee Development Authority), 2019). The moisture was evaluated using digital moisture meter (Draminski GMM mini, Poland).

Coffee physical quality analysis

The 44 samples (four trees per plot, 11 plots) were assigned a random identification code to avoid biased judgement during the analysis. The raw quality parameters of coffee were determined following the ISO 10,470 procedures (ISO (International Organization for Standardization), 2011). Three replicates of a 350g per sample were used for analysis as recommended by UCDA (Uganda Coffee Development Authority) (2019) for screen size.

a) Screen size (%):

Bean size percentage within the sample (350g) was analyzed using standard series of sieves with standard diameter holes. The sieves were arranged in descending screen sizes (19 being the largest and 12 being the smallest). The beans retained on each screen were weighted using an electric sensitive balance (0.01g) and recorded as percentages.

b) Weight of 100 sound beans (g):

100 green coffee beans were randomly picked from the each of the replicate 350g sample and weighed using an electric sensitive balance (0.01g). The means were computed for the three samples and used for analysis.

c) Raw quality (%):

The coffee quality attributes evaluated were bean colour, diseasing, pinhole, withered beans, chalky beans and other defects. From each of the 350g sample, weights of each category were taken and expressed in percentages and used for analysis. Colour of the green beans was defined as; bluish, brown, and greenish, blue greenish, or faded.

d) Raw beans odour:

The raw coffee bean odour (smell) was evaluated by experienced testers. The odour of coffee beans was evaluated subjectively as clean, fairly clean, off odour or strong off odour. Each category was weighed and expressed as percentages.

Collection of coffee pest and disease data

Throughout the course of a year (April 2022–April 2023), data on pests and diseases were collected on all the stems of the study four Robusta coffee plants per plot. The number of primary branches and BCTB-infested branches per stem were counted in order to determine the damage caused by the Black Coffee Twig Borer (BCTB). One primary branch (a twig) was chosen at random for data collection after the coffee plant was split into two sections, the upper and lower portions of the coffee plant. The overall number of leaves on selected primary and those affected by the (i) leaf miners (LM), (ii) leaf skeletonizers (LS), (iii) tailed caterpillars (TC) (iv) leaf eating beetles (LEB) and v) Brown Eye Spot (BES) were counted. The number of coffee clusters on the sampled primary twig were then counted, together with the number of clusters injured by (i) canopy mealy bugs (CM), (ii) canopy scales (CS), (iii) berry moth (BM), and (iv) red blister (CRB). The number of berries as well as those affected with the coffee berry borer (CBB) and red blisters (CRB) were counted in one (1) center cluster of the primary branch that was chosen.

2.4 Data Analysis

Prior to analysis, data on coffee bean physical attributes were tested for homogeneity of variances using Bartlett's test. The test indicated significant differences in variances among treatments ($P < 0.05$); therefore, the data were square root transformed and retested for homogeneity of variances, after which the assumption of homogeneity was met. The transformed data were analysed using ANOVA with an unbalanced treatment structure due to unequal treatment numbers. In Pest and disease data, outliers were removed and the homogeneity test done and then ANOVA was also conducted. Where treatment effects were significant, the Least Significant Difference (LSD) test was used for mean separation. Treatment means presented in brackets are the original values and were used for discussion. Pearson correlation analysis was conducted between coffee bean physical attributes and coffee pests and diseases to determine the magnitude and direction of relationships, using untransformed data. All statistical analyses were performed using GenStat (12th Edition).

3 Results

3.1 Effects of selected Soil Moisture Conservation Practices (SMCPs) on coffee bean defect

Results of our study showed that all the coffee bean quality defects did not significantly ($p \leq 0.05$) differ across the SMCP's (Table 1). The highest percentage (3.9%) were recorded under CMS while the lowest (1.2%) was under ACS. CCS and COSS registered the highest number of floats (1.0%) while ACS had the least (0.3%). The highest number of insect damaged beans (0.1%) was recorded in ACS whereas, the least was in CMS (0.0%). CMS had the highest number of nipped beans (13.3%) while CCS had the least (11.3%). Percentage number of partly black beans were highest under CMS (10.2%) and lowest under ACS (3.2%). ACS had the highest number of holes (0.03%) while CCS had the least (0.01%). The percentage of sound beans ranged from 72.5% under CMS to 82.3% under ACS, with ACS consistently exhibiting superior numerical performance in overall bean quality. Correspondingly, defective beans were highest under CMS (27.5%) and lowest under ACS (17.7%), although these differences were not statistically significant ($p = 0.261$). Furthermore, all the coffee beans sampled in ACS, CCS and COSS were clean while the small of 8.3% of the coffee samples from CMS was earthly (Table 2). In addition, >50% of the coffee beans in all the SMCPs were brownish green in colour, with CCS registering the highest percentage (85.7%) and ACS having the lowest (57.1%). Homogeneity of variance tests indicated no significant heterogeneity for any variable ($p \geq 0.05$), confirming that the assumptions for ANOVA were met.

Table 1: Percentage of coffee beans (Mean± sem) with defects under selected soil moisture conservation practices (SMCPs) on Robusta coffee

System	% Blacks	% Floats	% Insect	% Nipped	% Partly black	% Hole	% Sound beans	% Defects beans
ACS	1.0(1.2) ± 0.28(1.0)	0.29(0.6)± 0.23(0.5)	0.15(0.1)± 0.07(0.1)	3.55(12.8)± 0.26(2.0)	1.60(3.2)± 0.51(3.5)	0.00(0.0)± 0.05(0.02)	9.06(82.3)± 0.27(4.4)	4.10(17.7)± 0.41(4.3)
CCS	1.61(3.2)± 0.27(1.0)	0.75(1.0)± 0.22(0.5)	0.0(0.0)± 0.06(0.1)	3.28(11.3)± 0.25(1.9)	2.81(9.6)± 0.49(3.4)	0.01(0.01)± 0.05(0.02)	8.62(74.7)± 0.26(4.2)	4.91(25.3)± 0.39(4.2)
CMS	1.86(3.9)± 0.20(0.8)	0.68(0.6)± 0.17(0.4)	0.0(0.0)± 0.05(0.0)	3.55(13.3)± 0.19(1.5)	2.92(10.2)± 0.38(2.6)	0.01(0.02)± 0.04(0.01)	8.49(72.5)± 0.20(3.3)	5.16(27.5)± 0.31(3.3)
COSS	1.56(3.0)± 0.22(0.8)	0.78(1.0)± 0.18(0.4)	0.01(0.0)± 0.05(0.0)	3.47(12.5)± 0.21(1.6)	2.57(8.4)± 0.41(2.8)	0.01(0.02)± 0.0(0.01)	8.62(75.1)± 0.22(3.5)	4.83(24.9)± 0.33(3.5)
p value	0.141	0.373	0.339	0.864	0.141	0.871	0.443	0.261
Cv	40.12	88.49	98.22	18.85	51.24	98	7.89	21.54
Lsd	0.7099	0.5789	0.1734	5.048	1.317	0.1391	0.6901	1.047
Homogeneity test, p	0.846	0.186	1.00	0.494	0.181	0.449	0.114	0.478

ACS: coffee *Albizia coriaria*; CCS: coffee cover crop; CMS: coffee mulch system; COSS: Open sun coffee

Table 2: Percentage of coffee beans with different levels of smell and colour under selected soil moisture conservation practices (SMCPs) on Robusta coffee

Levels of variable	ACS (%)	CCS (%)	CMS (%)	COSS (%)
Smell of the coffee beans				
Clean	100.0	100.0	91.7	100.0
Earthly	0.0	0.0	8.3	0.0
Colour of the coffee beans				
Blue green	14.3	0.0	0.0	0.0
Greenish Brown	28.6	0.0	16.7	20.0
Brownish green	57.1	85.7	83.3	80.0
Pale	0.0	14.3	0.0	0.0

3.2 Effects of selected Soil Moisture Conservation Practices (SMCPs) on coffee bean size

Results further showed that there was no significant difference ($p \leq 0.05$) in coffee bean size among SMCPs (Table 3). Under ACS, the highest proportions were observed in screen 16 (27.9%) and screen 15 (21.6%), indicating a tendency toward medium-sized beans. CCS showed a more evenly distributed size profile, with comparable contributions from screens 14, 15, 16, and 17, each ranging between 14.8% and 19.3%. CMS exhibited a notable numerical shift toward larger beans, recording the highest proportions of screens 18 (17.0%) and 19 (9.4%) among all systems, suggesting improved bean filling under mulched conditions. Conversely, COSS was dominated by screen 17 (25.5%), followed by screen 16 (20.7%), indicating that open sun conditions favored the production of medium-to-large beans. Smaller beans (screens <12 and 13) constituted a relatively small proportion of the total across all systems, ranging from 4.8% to 8.4%, with CCS recording the highest proportion of the smallest beans (<12). The coefficients of variation were generally higher for the larger screen sizes (18 and 19), reflecting greater variability in the occurrence of larger beans across treatments. Homogeneity of variance tests confirmed that the assumptions for analysis of variance were met for all screen size classes ($p \geq 0.05$), supporting the reliability of the statistical.

Table 3: Effects of selected Soil Moisture Conservation Practices (SMCPs) on coffee bean size (Mean± sem)

System	Screen size							
	<12	13	14	15	16	17	18	19
ACS	2.56(7.0)± 0.29(1.6)	2.43(6.3)± 0.28(1.5)	3.39(12.1)± 0.31(2.1)	4.53(21.6)± 0.32(2.6)	5.22(27.9)± 0.26(2.5)	3.85(15.9)± 0.37(3.2)	2.17(6.9)± 0.53(3.6)	1.17(2.7)± 0.47(2.5)
CCS	2.77(8.4)± 0.28(1.6)	2.94(9.3)± 0.27(1.4)	3.75(14.8)± 0.30(2.0)	3.91(15.6)± 0.31(2.5)	4.37(19.3)± 0.25(2.4)	4.27(19.3)± 0.36(3.1)	2.85(9.2)± 0.51(3.5)	1.81(4.2)± 0.45(2.4)
CMS	2.18(4.8)± 0.21(1.2)	2.27(5.4)± 0.21(1.1)	3.13(10.3)± 0.23(1.6)	3.85(15.5)± 0.24(1.9)	4.48(20.5)± 0.19(1.9)	4.21(18.1)± 0.28(2.4)	3.82(17.0)± 0.40(2.7)	2.73(9.4)± 0.35(1.9)
COSS	2.50(7.1)± 0.23(1.3)	2.32(5.9)± 0.23(1.2)	2.92(9.0)± 0.25(1.7)	3.57(13.1)± 0.26(2.1)	4.52(20.7)± 0.21(2.0)	4.98(25.5)± 0.30(2.6)	3.69(14.1)± 0.43(2.9)	2.17(5.0)± 0.38(2.0)
p value	0.395	0.241	0.209	0.168	0.099	0.11	0.082	0.084
Cv	29.7	29.06	24.57	20.67	14.33	21.65	41.35	56.53
Lsd	0.7374	0.7175	0.8051	0.8175	0.6676	8.247	1.369	1.195
Homogeneity test, p	0.23	0.784	0.944	0.435	0.338	0.603	0.11	0.106

ACS: coffee *Albizia coriaria*; CCS: coffee cover crop; CMS: coffee mulch system; COSS: Open sun coffee

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3.3 Effects of selected Soil Moisture Conservation Practices (SMCPs) on major Robusta coffee pests and diseases

Table 4 below summarizes the effect of selected SMCPs on the major Robusta coffee pests and diseases. Significant differences among systems were observed for all pests and diseases ($P \leq 0.001$), except berries with red blister disease (BRB), which did not differ significantly among systems ($P = 0.709$). COSS recorded the highest LS (10.43%), BM (20.11%), BES (3.48%), and CRB (45.36%) damage. In contrast CMS consistently exhibited the lowest pest and disease damage except for BM (13.49%). ACS had higher BCTB (25.64%), LM (11.82%), CS (1.20%), CM (6.53%), LEB (14.94%), BRB (32.29%) and TC (25.26%) damage but least levels of BM (13.07%) and CBB (0.37%) damage. CCS had only the highest CBB (3.05%) damage. Homogeneity of variance tests indicated no significant heterogeneity for any variable ($p \geq 0.05$), confirming that the assumptions for ANOVA were met.

Table 4: Effects of selected Soil Moisture Conservation Practices (SMCPs) on the major Robusta coffee pests and diseases (Mean± sem)

System	LS	CBB	BCTB	LM	TC	CM	LEB	BM	CS	BES	CRB	BRB
ACS	9.26± 0.30b	0.37± 0.17c	25.64± 0.601a	11.82±0.24a	25.26± 0.34a	6.53± 0.49a	14.97± 0.18a	13.07± 0.49c	1.20± 0.08a	3.40± 0.12a	42.74± 1.07a	32.29± 1.03
CCS	8.06± 0.25c	3.05± 0.14a	21.25± 0.49b	10.79± 0.19b	22.76± 0.28c	3.81± 0.37b	13.38± 0.18b	15.24± 0.41b	0.84± 0.07b	2.99± 0.12c	37.12± 0.88b	32.50± 0.84
CMS	4.34± 0.27d	1.94± 0.15b	20.85± 0.55b	8.43± 0.21c	18.70± 0.31d	3.92± 0.42b	11.06± 0.20c	13.49± 045c	0.14± 0.07c	2.39± 0.13d	32.65± 0.97c	31.44± 0.93
COSS	10.43± 0.24a	2.15± 0.14b	25.26± 0.49a	10.45± 0.20b	23.81± 0.28b	4.34± 0.38b	13.66± 0.18b	20.11± 0.41a	0.03± 0.07c	3.48± 0.12a	45.36± 0.88a	31.31± 0.84
p-value	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	0.709
Cv	28.1	65.05	19.7	17.27	11.34	76.69	12.57	23.83	125.88	36.6	20.52	24.38
l.s.d	0.7462	0.4253	1.5	0.5876	0.8424	1.143	0.5467	1.232	0.2159	0.369	2.664	2.555
Homogeneity test, p	0.267	0.243	0.411	0.483	0.389	0.340	0.707	0.425	0.637	0.256	1.00	0.552

LS, leaf skeletonizers; CBB, coffee berry borer; BCTB, black coffee twig borer; LM, leaf miner; TC, tailed caterpillars; CM, canopy mealy bugs; LEB, leaf eating beetles; BM, berry moth; CS, canopy scales; BES, brown eye spot; CRB, clusters with red blister disease; and BRB, berries with red blister disease; ACS, coffee *Albizia coriaria*; CCS, coffee cover crop; CMS, coffee mulch system; and COSS, Open sun coffee.

3.4 Correlation between coffee pest and disease and coffee bean physical aflributes

Table 5 below summarizes the relationship coffee bean physical attributes and Robusta coffee pests and diseases. Among the coffee bean defects, positive and significantly ($p \leq 0.05$) correlations were observed in case of %blacks and BRB ($r=0.47$); %floats and CBB ($r=0.36$); %insect and CS ($r=0.77$); %insect and BM ($r=0.43$); %insect and CM ($r=0.34$) and %insect and CRB ($r=0.49$). Negative significant ($p \leq 0.05$) correlations were observed between colour and CS ($r=-0.63$); colour and BRB ($r=-0.37$); colour and CRB ($r=-0.44$) and %nipped and BRB ($r=-0.34$). For the screen sizes, positive and significant ($p \leq 0.05$) correlations were recorded in case of screen 15 and CS ($r=0.41$).

Table 5: Correlation between coffee pest and disease and coffee bean physical attributes

Coffee physical	Coffee pest and disease											
Attributes	CBB	BCTB	CS	BES	BM	LEB	BRB	CM	CRB	LS	TC	LM
Colour	0.1207	0.0816	-0.6338***	-0.1696	-0.234	0.4724*	-0.3417*	-0.367*	-0.4368**	0.1073	0.0735	-0.2374
% Blacks	0.3066	0.1418	0.2765	-0.2454	0.2361	0.2156	0.4745*	0.2233	0.2367	-0.2596	-0.0853	-0.2076
% floats	0.3618*	0.0012	0.0583	-0.132	-0.07	0.2417	-0.0283	-0.0418	-0.1391	-0.1893	0.0788	0.0609
% insects	0.0833	-0.0191	0.7723***	-0.0789	0.4303**	-0.1445	0.3881*	0.3364*	0.4926**	0.092	-0.1209	0.1703
% nipped	-0.3248	0.0398	-0.05	-0.0462	-0.1211	-0.0913	-0.3398*	0.07	-0.2216	-0.1134	-0.0218	0.0269
% partly	0.0647	0.1198	-0.1144	-0.3233	-0.2374	0.1076	-0.3161	-0.2146	-0.2622	-0.1415	-0.2987	0.0762
% hole	-0.1652	0.319	-0.0702	0.1312	-0.2058	-0.2043	-0.0898	0.0385	-0.1066	-0.076	-0.0502	-0.1387
Smell	0.0368	0.0249	-0.0601	-0.1548	0.1163	-0.0887	-0.3417	0.1336	0.0015	-0.0015	-0.0802	0.02
% sound	-0.0079	-0.1571	0.0302	0.3322	0.2033	-0.1155	0.2953	0.088	0.269	0.1778	0.2363	0.1277
% defect	0.0079	0.1571	-0.0302	-0.3322	-0.2033	0.1155	-0.2953	-0.088	-0.269	-0.1778	-0.2363	-0.1277
<12	-0.0006	0.117	0.2289	-0.1954	-0.1205	0.1843	-0.1008	0.1081	-0.0709	0.0078	0.0885	0.116
13	0.1474	0.0234	0.1093	-0.1104	-0.2447	0.1561	-0.1306	0.0351	-0.1767	-0.0788	0.1481	0.2276
14	0.1259	-0.0481	0.1935	-0.0234	-0.2266	0.07	0.0287	0.1643	-0.0526	-0.0855	0.0731	0.2858
15	-0.0004	-0.0479	0.4134*	0.0699	-0.0006	0.0081	0.2319	0.3092	0.2196	0.0714	-0.0443	0.1986
16	-0.0815	0.0794	0.2201	0.0666	0.1317	0.0959	0.1097	0.137	0.1265	0.2947	-0.1245	-0.0556
17	0.0302	0.0603	-0.3157	0.0773	0.2217	0.0973	-0.1458	-0.3005	-0.0133	0.1859	0.1066	-0.3286
18	-0.089	-0.0412	-0.2878	0.034	0.0124	-0.2009	0.0059	-0.1639	-0.0482	-0.2216	-0.0503	-0.117
19	-0.0242	0.082	-0.2063	-0.1708	0.0147	-0.1781	0.0422	-0.0454	-0.053	-0.174	-0.1432	-0.0712

LM, leaf miners; LS, leaf skeletonizers; TC, tailed caterpillars; LEB, Leaf eating beetles; BES, Brown Eye Spot; CM, canopy mealy bugs; CS, canopy scales; BM, berry moth; CRB, Clusters with Red blister; CBB, coffee berry borer, and BRB, Berries with Red blisters

4 Discussion

The demand for high-quality coffee is rising globally (Byers et al., 2008) and this quality is s mostly driven by the coffee's physical and chemical characteristics (Barbosa et al., 2012). These are in turn influenced by the interactions between the coffee species/genotype, environment as well as management of the coffee field and plant (Barbosa et al., 2012; Cheng et al., 2016; Decazy et al., 2003; Joët et al., 2010; Vaast et al., 2006). Results of our study showed that there was no significant (p≥0.05) difference across the SMCPs for all the coffee defects. These findings are in agreement with finding of Silva Neto et al. (2018) who observed that different management practices had no significant effect on the coffee bean defects. Nevertheless, though there was not significantly different in defects across the different treatments, the slight difference in percentage defective beans could negatively affect the final cup quality of coffee (Franca & Oliveira, 2008). ACS had generally the lowest number of blacks, floats, partly beans and highest percentage of sound beans. Our results agree with Odeney et al. (2015) who found that shade lowers the percentage of rejects which includes diseased, mummified or dried berries. Similarly, R. Muschler (1998) observed a decrease in coffee rejects from 10% to less than 1% for coffee grown under shade in Costa Rica. This could in part be due to the fact that shade reduces incidence of physical defects by delaying ripening and influencing uniformly ripening (R. G. Muschler, 2001; Vaast et al., 2006). According to DaMatta and Ramalho (2006), Obso (2006) and Vaast et al. (2006), shade creates a microclimate that decreases heat stressors in plants, boosts the leaf to fruit ratio and net photosynthetic rate, and extends berry maturity period. However, it has been noted that shade increases the yield of large coffee beans (Guyot et al., 1996; R. G. Muschler, 2001). Kathurima et al. (2012) noted that the shade in Kenya played a major role in the rise in premium grades, AA and AB, which are highly prized in the global coffee trade. Lower temperatures in shaded areas cause berries to grow and develop more slowly, giving them more time to fill and accumulate more sugar and phenolic compounds linked to aroma. This results in coffee that has a higher overall sensory quality (R. G. Muschler, 2001; Tolessa et al., 2017; Vaast et al., 2006).

However, Bosselmann et al. (2009) discovered that the presence of shade trees on plantations at high altitudes resulted in a drop in coffee quality. In addition, attacks of insect pests and diseases have a direct impact on the quality of the harvest because they impair the physical and sanitary quality, thereby altering the organoleptic characteristics of beans (Ribeyre & Avelino, 2012). Although all systems had percentages that were very near to zero, as also reported by Silva Neto et al. (2018), our data indicated that the greatest number of insect-damaged beans were recorded under ACS. Coffee berries may be attacked by a range of insect species but most of the damage observed on coffee beans is due to infestation by the coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari), coffee berry moth, *Prophantis Smaragdina* (Butler) and coffee bean weevil, *Araecerus fasciculatus* (De Geer) (Abedeta et al., 2011; Barrera, 2018; Gaitán et al., 2015). The coffee berry borer infestation is favored by shade, as evidenced by the greater infestation rates in shaded coffee plants as opposed to those planted in the sun (Bosselmann et al., 2009; Mariño et al., 2016; Soto-Pinto et al., 2002; Staver et al., 2001).

As Silva Neto et al. (2018) also revealed, our data further demonstrated that there was no significant difference in coffee bean size among SMCPs. However, CMS dominated in screen 18 and 19, COSS in screen 17, ACS in screen 15 and 16 while CCS in screen 14, 13 and <12. CMS dominated the upper screen sizes because bean size distribution has been reported to be affected by soil properties, particularly soil pH, organic matter, texture, and manganese (Mn) (Yadessa et al., 2020a, 2020b) and application of mulches in the coffee agro-systems increases soil organic carbon and plant nutrients (Nzeyimana et al., 2017, 2019). Mulching also enhances moisture retention in coffee agro-systems (Mohammedsani et al., 2018) and this could also have contributed to the bigger beans in CMS (Kobusinge, unpublished data) since mulching prevents shedding off coffee leaves as a result of insufficient water in the soil (Wangui, 2012). One of the main factors influencing bean size, according to Wrigley (1988), is soil moisture. This is because the size of the final bean is influenced by the elasticity of the parchment, which is the ovule's outer layer, and the volume of integument inside each ovule before the parchment lignifies and forms an embryonic sac that is eventually filled with endosperm. Soil moisture during the berry development's expansion phase determines the integument volume (Worku et al., 2022). Conversely, low soil moisture under ACS may have played a role in the small bean sizes (Kobusinge, unpublished data). However, coffee grown in shade produced larger beans than coffee grown in open sun because of fewer flowers and fewer fruits per plant.

Additionally, the findings demonstrated pests and disease damage were significant across the SMCPs demonstrating role of SMCPs in shaping pests and disease dynamics. The highest infestation of coffee leaf skeletonizers (LS), *Leucoplema dohertyi* (Warren) was recorded under COSS, implying that infestation by this insect pest significantly increased with reducing shade intensity. Similarly, studies conducted by Biru (2019) in Ethiopia showed that the incidence of L. dohertyi had a negative relationship with shade intensity in the dry season, though not significant. However, contrary to our finding, some authors have reported a positive association between shade and L. dohertyi (e.g. Samnegård et al., 2014; Nurihun et al., 2022; Shimales et al., 2023). On the other hand, the highest infestation of coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari) was recorded under CCS and this could be in part due to the fact that the cover crop used in this study, *Desmodium intortum* is a suspected potential host of H. hampei (Messing, 2012). However, Feliz Matos et al. (2004) and Bosselmann et al. (2009) observed more H. hampei infestation under shade than cover crop (Pohlan et al., 2008), while Jonsson et al. (2015) observed that H. hampei was more in open sun coffee. By promoting the formation of fungal toxins, H. hampei infection has a detrimental effect on coffee's organoleptic quality as well as its sanitary quality (**Taniwaki2007**). As a matter of fact, the International Organization for Standardization (ISO) assigns a medium influence (0.5) on the sensory quality of beans damaged by H. hampei, classifying them as "insect-infested beans" or "insect-damaged beans" (ISO (International Organization for Standardization), 2004). It has been observed that beans with H. hampei damage roast unevenly and turn darker. The bean may break if it is attacked more than once. Because broken beans are smaller, they roast more quickly and could burn. It also makes mold growth easier, which results in odd tastes and ochratoxin contamination (Ribeyre & Avelino, 2012). In addition, X. compactus infestation was highest under ACS and least under CMS. Our results are consistent with past research that have found higher infestation of X. compactus on Robusta coffee under shade systems compared to other coffee agro-systems (Anuar, 1986; Bukomeko et al., 2018; Hultman, 2016; Kagezi et al., 2013). One possible explanation for this could be that shade systems offer micro-environments that promote growth and the conclusion of the organism's life cycle (Bukomeko et al., 2018; Kagezi et al., 2013).

The development of the related ambrosia fungus may similarly be aided by these humid microclimates. Though damage caused by other pests and diseases did not vary significantly across the SMCP's, their attack on coffee beans can have a substantial effect on coffee quality (Etana & Merga, 2021). The highest damage caused by tailed caterpillar (TC), *Epicampoptera andersoni* (Tams), canopy mealybugs (CM), *Planococcus* spp., leaf eating beetles (LEB) and red blister disease on berries (BRB) caused by *Cercospora coffeicola* (B. & CKE.) was recorded under ACS. This implies that the damage caused by these insect species is increased by shade, agreeing with other research studies. Waller et al. (2007a) recorded severe damage caused by E. andersoni on coffee bordering forests where the canopy is generally higher whereas, a positive but not significant correlation was reported between *Planococcus* spp. and shade (Biru, 2019). Also, higher damage caused by LEB on coffee under closer spacing, which is more shaded due to self-shading (Long et al., 2015). However, contrary to our finding, Staver et al. (2001) and Karungi et al. (2015) reported lower incidence and damage of *Planococcus* spp. on coffee under shade since shade lowers the temperature (Lara-Estrada et al., 2023; Wagner, 2020) and this does not favor the presence of mealybugs (Jayakumar & Rajavel, 2019).

Likewise Staver et al. (2001) also reported low C. coffeicola on coffee grown under shade. Our findings demonstrated that the highest damage caused by the canopy scales (CS), *Coccus* spp. was recorded coffee grown highest under ACS. In contrast, Karungi et al. (2015) also reported low *Coccus* spp., on coffee growing under shade. BES caused by *Cercospora coffeicola* (B. & CKE.) however Staver et al. (2001) reported low C. coffeicola on coffee growing under shade. In addition, the incidence of leaf miner (LS), *Leucoptera coffeella* (Guérin-Mèneville & Perrottet) was highest on coffee under ACS and lowest under CMS. Similarly, Shimales et al. (2021b, 2021a) reported lower incidence of L. coffeella has been reported on coffee under mulch compared to other coffee agrosystems. However, in contrast to our finding, lower incidence of L. coffeella has been reported in coffee agroforestry systems compared to other coffee agrosystems (Androcioli et al., 2018; Nestel et al., 1994). On the other hand, the highest damage of the coffee berry moth (BM), *Prophantis smaragdina* (Butler) and coffee clusters with red blister disease caused by C. coffeicola was recorded on coffee growing under open sun and lowest under ACS. Our findings agree with earlier studies that show that shade decreases the damage caused by both BM and CRB (Biru, 2019; Staver et al., 2001). However. BM was highest under CMS, suggesting that ground cover creates favorable conditions (increased humidity) for the larvae to pupate (Kagezi et al., 2023). Insect damage has been reported to be the most commonly seen defect in coffee beans (Chen et al., 2020). The relatively high CV values observed for some variables reflect the inherent spatial heterogeneity associated with soil moisture conservation practices, where micro-environmental conditions vary considerably. Additionally, the experiment was conducted under field conditions representative of smallholder coffee systems, where higher variability is expected and enhances the applicability of the findings.

The positive and significant correlation between the percentage of black beans and berries with red blisters (BRB; r = 0.47) suggests that BRB infestation interferes with normal berry maturation, leading to incomplete filling and discoloration. Red blister associated disorders have been linked to disrupted nutrient translocation and localized tissue necrosis, which ultimately manifests as black or partially blackened beans at harvest (Waller et al., 2007a). Similarly, the positive correlation between floats and CBB (r = 0.36). CBB directly damages the endosperm by boring into developing beans, reducing bean density and increasing the proportion of lightweight beans that float during wet processing (Damon, 2000; Infante et al., 2014). The strongest relationship observed was between insect-damaged beans and CS (r = 0.77), followed by BM (r = 0.43), CM (r = 0.34), BRB (r=0.39) and CRB (r = 0.49). These results reflect the cumulative effects of sap-sucking and berry-feeding pests, which weaken berries, predispose them to secondary infections, and increase vulnerability to internal damage. Mealybugs and scales are known to reduce photosynthate availability through sap extraction and honeydew production, indirectly impairing bean filling and increasing insect-related defects (Perfecto et al., 2014). Berry moth larvae, on the other hand, cause direct penetration and feeding within the berry, producing visible insect damage similar to that of CBB (Le Pelley, 1968). The negative significant correlations between bean colour and CS (r = –0.63), BRB (r = –0.34), CM (r=-0.37) and CRB (r = –0.44) indicate that higher pest and disease incidence is associated with poorer bean appearance. Uniform bean colour is a key quality attribute, reflecting proper maturation and drying. Discoloration has been linked to stress-induced metabolic changes during berry development, including altered phenolic oxidation and uneven drying following pest damage (Chu, 2012; Clarke, 2012). Scale insects and mealybugs, by impairing canopy function, may reduce carbohydrate allocation to berries, resulting in uneven ripening and pale or blotchy beans (Wintgens, 2004). The negative association between nipped beans and BRB (r = –0.34). Red blister attacks cause a lot of light or empty berries (Waller, 1985), early coffee berry fall, and/or hollow, irregularly shaped grains, which lowers the bean's quality (Lima et al., 2012). Immature beans also cause loss of acidity, increased bitterness, distinctive aromas and green flavor (reminiscent of fresh green grass, green foliage, unripe fruit) (Wintgens, 2004). For screen sizes, the positive correlation between screen 15 and canopy scales (CS; r = 0.41) suggests a selective effect of pest pressure on bean size distribution. Under stress conditions, plants may produce a higher proportion of medium-sized beans due to constrained assimilate supply, rather than well-filled larger beans (Vaast et al., 2006). Sap-sucking pests such as scales can exacerbate this effect by continuously diverting plant resources, leading to altered size grading at harvest. The results reinforce previous evidence that effective pest management is not only critical for yield protection but also for maintaining bean quality and market value (Infante et al., 2014; Waller et al., 2007b). Integrated pest management strategies that reduce canopy pests (CS, CM), berry feeders (BM, CBB), and disease complexes such as BRB and CRB are therefore essential for improving both physical quality attributes and downstream cup quality.

5 Conclusion

The results show that SMCPs did not significantly alter coffee bean physical quality or size grades, but they significantly influenced pest and disease incidence. The results indicate that coffee bean defects are influenced by a combination of factors rather than solely by pest and disease incidence. Notably, the coffee mulch system (CMS) produced the highest proportion of large beans (screen sizes 18 and 19) while maintaining the lowest levels of most pest and disease damage. These findings suggest that CMS can enhance Robusta coffee resilience to pests and diseases and support the production of high-quality beans. Farmers are therefore encouraged to adopt mulching as a key soil moisture conservation strategy to improve both yield and bean quality in Robusta coffee systems.

Conflict of interest

The authors declare that they have no conflict of interest.

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Data availability Statement

Data can be made available on the behave of the request

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