

Article

Potential of Moisture Conservation Practices to Improve Soil Properties and Nutrient Status of Robusta Coffee Plant

Judith Kobusinge ^{1,2,*}, Geoffrey Gabiri ³, Godfrey H. Kagezi ², Godfrey Sseremba ² , Alice Nakitende ², Geoffrey Arinaitwe ² and Charles K. Twesigye ¹

¹ Department of Biological Sciences, Kyambogo University, Kyambogo P.O. Box 1, Uganda

² National Coffee Research Institute, National Agricultural Research Organization, Mukono P.O. Box 185, Uganda

³ Department of Geography, Kyambogo University, Kyambogo P.O. Box 1, Uganda

* Correspondence: judithkobusinge25@gmail.com

Abstract: Soil moisture conservation practices (SMCPs) have been adopted in Uganda to adapt to the effects of climate variability. However, limited information exists on how conservation measures influence the physico-chemical properties of soil and coffee leaf nutrient concentrations. Thus, we determined the effects of selected SMCPs on the soil physio-chemical properties and leaf nutrient concentrations in Robusta coffee in a randomized incomplete block design, replicated three times, in Kituza, Uganda. Soil samples were collected from 0 to 20 cm and 20 to 40 cm depths, and analyzed in the laboratory following standard procedures for selected physio-chemical properties. Coffee leaf samples were picked from each treatment (open sun coffee (COSS), coffee cover crop, *Desmodium intortum* (CCS), coffee mulch, *Miscanthidium violaceum* (CMS), and coffee *A. coriaria* (ACS)). Bulk density was significantly ($p < 0.001$) the highest under ACS (1.61 g cm^{-3}) and lowest under CCS (1.29 g cm^{-3}), and it significantly ($p < 0.001$) increased with depth. The soil organic matter was higher than the optimum range of 1–3% at the 0–20 cm depth across different SMCPs, but within the optimum range at the 20–40 cm depth. Leaf nitrogen was significantly the highest under ACS (3.19%) and lowest under COSS (2.30%). Overall, the findings suggest that SMCPs improve the soil physio-chemical attributes and leaf nutrients for sustainable coffee productivity. However, ACS improved the leaf plant nutrition better compared to other SMCPs.

Keywords: soil moisture conservation practices; soil physio-chemical properties; Robusta coffee leaf nutrient



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1. Introduction

One of the principal factors limiting crop output in sub-Saharan Africa is nutrient loss that results in decreased soil fertility [1]. For instance, losses of 130 kg N, 5 kg P, and 25 kg K $\text{ha}^{-1} \text{ year}^{-1}$ have been noted in the East African highlands. Almost 60% of the population in Uganda relies on agriculture as a significant source of income, yet farmers rarely ever use fertilizers, as well as soil and water conservation methods [2,3]. Low soil organic matter (SOM) concentration as a result of continuous cultivation highlights the need for careful management to sustain adequate crop yields [4]. The nutrient depletion is mainly attributable to produce harvesting (nutrient mining) and soil erosion without replenishment [5]. However, smallholder farmers in Uganda have limited financial resources to purchase mineral fertilizers to correct this inherent declining soil fertility [4]. Hence, coffee growers attempt to boost production by expanding the area under the crop, but this is becoming challenging due to the rising pressure of the population on the limited land [6]. The only realistic course of action is to increase coffee productivity. Smallholder coffee producers, who make up the majority of the industry, have continued to produce without proper SMCPs [7]. Only a small percentage of growers (20%) use certain fertilizers when growing coffee [3,8]. This is partly due to limited access to extension services and

programs among farmers in Uganda [9]. When coffee is exported, the soils used to grow it continually lose nutrients without being replenished [3]. As a result, the coffee yields have continued to either paltry stagnate or decline. Though a strategic Robusta coffee producer, Uganda experiences low average yield at 0.6 t ha^{-1} of clean coffee, which is only about 27% of the potential yield of 2.2 t ha^{-1} [10,11]. Thus, in order to boost and sustain coffee production and productivity, the issue of declining soil fertility needs to be addressed. One method of controlling soil fertility is by the application of inorganic fertilizers, but farmers hardly ever do so because there is not any actual data showing that fertilizer application results in profitable coffee yields [3]. The majority of smallholder coffee producers also have restricted access to fertilizers, and others are unwilling to spend further money [3].

Farmers also employ soil conservation practices to improve soil fertility [12,13]. The soil conservation techniques allow for the preservation of the soil potential for productivity [14]. Ridge planting, zero tillage, crop rotation, strip cropping, grass strips, mulching, agroforestry, terracing, contour planting, cover crops, water harvesting, tree planting, and trenching are among the trustworthy and scientifically validated SMCPs used today [12]. The techniques are intended to protect and improve the soil's physical, chemical, and biological characteristics [13]. Moreover, they increase the soil's ability to hold onto moisture and promote aquifer power to support agricultural activity. When population pressure is significant and upland soil degradation is having devastating effects downstream in places that are much more densely populated, it maintains the fertility quality of the soil [15,16]. Recent research by Dagnachew et al. [17] has shown the value of these conservation methods in boosting soil nutrition. By evaluating soil's physical and chemical characteristics, such as texture, water-holding capacity, bulk density, porosity, soil organic carbon, total nitrogen, available phosphorus, exchangeable potassium, soil pH, and electrical conductivity, management-induced changes in soil can be evaluated [17,18]. Information on plant analyses is also crucial for managing soil fertility and producing crops in a sustainable way. According to Sousa et al. [19], the investigation of the link between the nutrients in the soil and the plants can be utilized to calculate the recommended fertilizer rate. It is therefore essential to precisely integrate these two methods to determine the status and presence of nutrients. Therefore, this study was envisaged to evaluate the effect of selected SMCPs on the improvement of soil fertility and plant nutrition. Our hypothesis is that soil moisture conservation practices improve the soil properties and coffee leaf nutrients as compared to open sun coffee. Such studies would produce agroecology-specific knowledge that could aid in informing soil management and increase coffee yield.

2. Materials and Methods

2.1. The Study Area

The research was undertaken at the National Coffee Research Institute (NaCORI), located in the Mukono district, Lake Victoria crescent agroecological zone, approximately 35 km from the Eastern part of Kampala capital city in central Uganda. Mukono is located within low–medium altitude areas of Uganda at about 1200 m.a.s.l. The study site is at a latitude of $N 0^{\circ}15'26.9874''$ and longitude $E 32^{\circ}47'27.69648''$, with a slope of 4% (Figure 1). The rainfall pattern is bimodal, ranging from 1400 to 1600 mm annually. The study area experiences two rainy seasons, the March–May being the first long rains, while September–November are the second short rains. The minimum annual temperatures range between 15°C and 18°C , and maximum temperatures from 25°C to 28°C [20,21]. The major soils of the study area are ferrallisols constituting sandy clay-loams [20]. The NaCORI was purposively selected so as to conduct the experiment under a controlled environment compared to farmers' fields with much variability. Additionally the institute site already has the selected SMCPs existing.

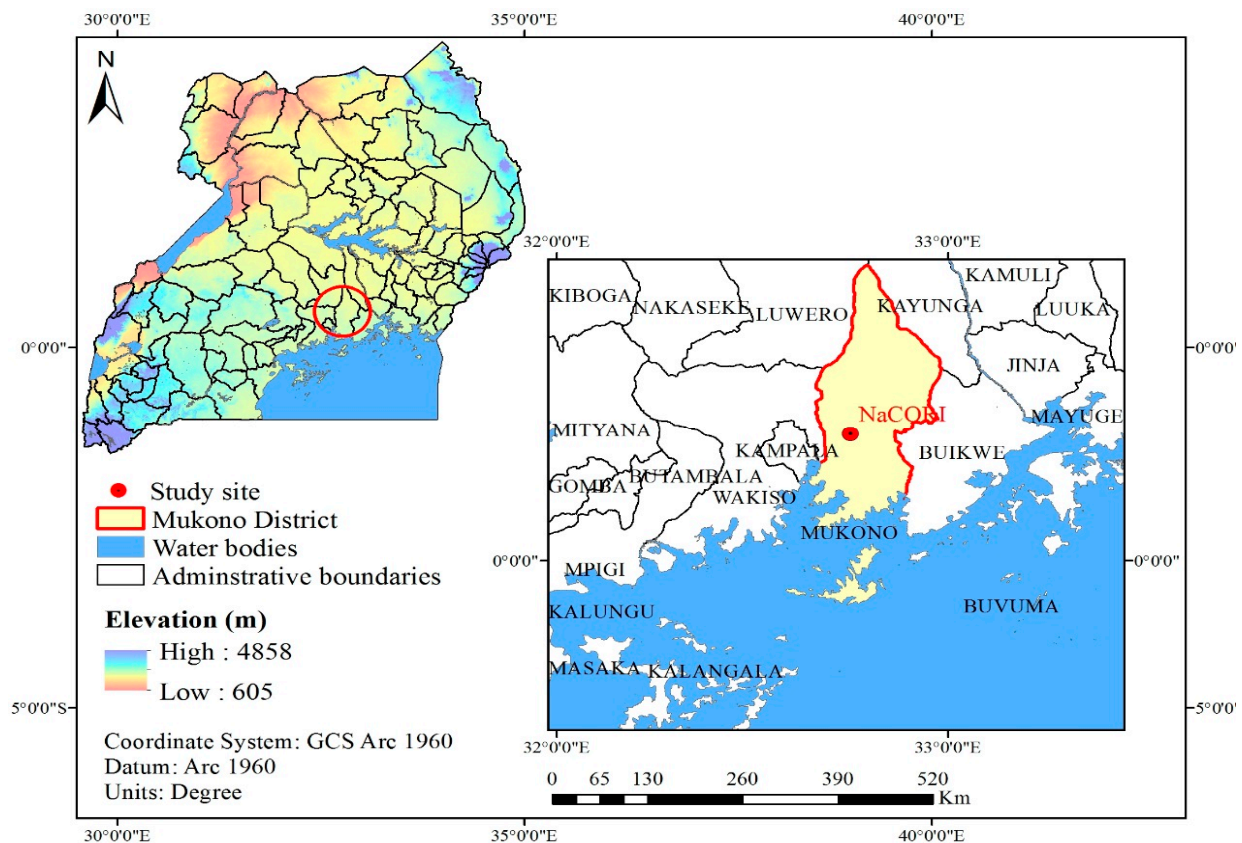


Figure 1. Study site in the Mukono district, Central Uganda. The map was drawn using QGIS 3.6.

2.2. Study Design

The experiment was set up in an incomplete randomized block design, because only two of the replicates had *Albizia coriaria*. The experiments consisted of four (4) treatments (coffee systems) replicated three times, which were superimposed on an already existing 2.2 acre coffee field that was established in 2009. The experiment was superimposed on the coffee plants of a breeding population that was developed and gave rise to the current NARO Kituza Robusta (KR) line varieties that are wilt-resistant [22,23]. The stumping of the field is done at a 6-year interval and has been stumped twice, with the last one being in 2019. Treatments were: open sun coffee (COSS), coffee cover crop, *Desmodium intortum* (CCS), coffee mulch, *Miscanthidium violaceum* (CMS), and coffee *A. coriaria* (ACS), with a plot size of 9 × 9 m (Scheme 1). The replicates were placed along the slope of 4%. The shade tree species, mulch and cover crops assessed were selected because they are commonly used by the farmers and were also being promoted by extension in Uganda [23]. Coffee was spaced at 3 m by 3 m, while shade trees were spaced at 15 m by 15 m, and the mulch was maintained at a thickness of 10 cm, as recommended by the UCDA [21] and Kakaire et al. [24]. The cover crop was planted in November 2020, while the shade trees during the establishment of the coffee garden. On the other hand, mulch was first applied in August 2021. All the replicates were set on the same day separated by 15 m. Soil and plant samples were collected on 21 July 2022, when the coffee was having its fruit phenological stages. All the samples were collected on the same day. The maximum temperature was 28 °C, and minimum temperature 17.6 °C, while there was no rainfall on the day of sampling.



Scheme 1. Treatments used in the study: (1) coffee mulch, *Miscanthidium violaceum* (CMS); (2) coffee *A. coriaria* (ACS); (3) coffee cover crop, *Desmodium intortum* (CCS); (4) open sun coffee (COSS).

To supply the coffee nutrient requirements, 0.28 t ha^{-1} of NPK 25:5:5 fertilizers were applied as a blanket treatment twice a year during the rainy season across all treatments, with the last application carried out in March 2022.

2.3. Sample Collection and Analysis

2.3.1. Soil Data Collection and Analysis

In each plot, one soil pit, measuring 1 m by 1 m by 1.2 m, was dug, giving a total of 11 soil pits. Both disturbed and undisturbed soil samples were picked from the pits. Using a sharp edged, closed, circular auger manually inserted in the walls of the profile at each depth, the disturbed soil samples were taken for chemical analysis from the upper 0–20 cm and 20–40 cm depths. One composite sample was picked per depth. This composite sample at a particular depth was picked from the four walls of the pit. For undisturbed soil samples, three soil cores were pushed into the soil pit walls at depths 0–20 cm and 20–40 cm. Each core's ends were trimmed with a sharp knife, and then they were wrapped in polythene bags and brought to the laboratory for analysis. Before being crushed and examined, the materials were dried and screened on 2 mm mesh. The disturbed soils were used for soil chemical analysis (soil pH, available phosphorous (SP), potassium (SK), total nitrogen (TN), magnesium (SMg), calcium (SCa), and soil organic matter (SOM)). The physical characteristics of the undisturbed soils, including saturated hydraulic conductivity (Ksat), bulk density (BD), and particle size distribution (PSD), were analyzed. Soil parameters that were important for the growth and production of coffee were specifically chosen for analysis.

For undisturbed soil samples, Ksat was measured using the positive head method cores when a constant rate has been reached [25]. Using undisturbed core samples, as reported by Hishe [26], the bulk density of the soil was calculated. The hydrometer approach was used to investigate the distribution of particle size, as described earlier by Usowicz and Lipiec [25].

For disturbed soils, samples were crushed and put through a 2 mm sieve after being dried for 2 days at 45°C . Organic matter was determined colorimetrically at 660 nm, using a modified Walkey and Black method. The Kjeldahl digestion technique was used to calculate total N [27]. By utilizing a flame photometer, K was measured. Using the Bray 1 approach, available P was calculated [28]. In a 1:5 soil–water extract, the pH of the soil was determined [28]. At pH 7, NH_4OAC was used to extract the exchangeable bases, and an atomic absorption spectrophotometer was used to measure the concentrations of K, Ca,

and Mg [28]. After extracting the soil samples with 1N NH_4OAc at pH 7.0 and distilling the ammonium released by leaching with NaCl solution, the cation exchange capacity (CEC) was calculated [29].

2.3.2. Plant Sample Collection and Analysis

Newly grown leaves with petioles were picked from the third or fourth pairs of leaves from the apex of the branch, in the center of the plants, from all cardinal directions. Coffee leaf samples were gathered from a net area of 81 m^2 in each SMCP [17]. The leaves were picked on the same day the soil sampling was done. To remove any dirt or other source-related dust contamination, the samples were washed with distilled water. The gathered plant samples were sealed in paper bags, allowed to air dry in a room free of dust, then transferred into plastic bags and labeled for examination in the lab at Agrotech Analytical Laboratory Services LTD (Wakiso district, Uganda).

Using methods devised by Liberato et al. [30], all plant chemical analysis (N, P, K, Ca, and Mg) measurements were performed using the Agilent 4200 Microwave Plasma Atomic Emission Spectrometer (MP-AES), coupled with the Agilent 4107 Nitrogen Generator.

2.4. Coffee Growth Parameters

Yield-related coffee growth parameters measured included: coffee diameter, coffee canopy height, and the number of primaries within the active bearing head. These were measured during both dry and wet seasons. All coffee plants within the study plots were collected. The measurements were made in reference to Sseremba et al. [31].

2.5. Statistical Analyses

The Genstat 12th edition statistics software (VSNi International, England, UK) was used to analyze the impact of the SMCPs on soil physiochemical, coffee leaf attributes and coffee growth parameters.

The impact of the SMCPs and soil depth on specific soil and leaf attributes was studied using analysis of variance (ANOVA) with an unbalanced treatment structure. The effects of SMCPs and seasons on coffee growth parameters were determined using an ANOVA with an unbalanced treatment structure. After the main effects were determined to be significant at $p = 0.05$, the least significance difference (LSD) was employed to distinguish significantly different treatment means. To determine the magnitudes and directions of correlations between particular soil physico-chemical factors and the coffee leaf variables, Pearson's correlation analysis was carried out.

The simple linear regression analyses were conducted in IBM SPSS version 21 (IBM SPSS, Armonk, NY, USA). The soil physical variables were the independent variables, while the soil chemical properties were the dependent variable for the relationship between the soil physical and chemical properties. The soil chemical properties were independent variables, and the leaf chemical nutrients were the dependent variables for the relationship between soil chemical properties and leaf chemical properties.

3. Results

3.1. Effect of SMCPs on Selected Soil Properties

Table 1, below, summarizes the results of analysis of selected soil physio-chemical properties in the four SMCPs at 0–20 cm depth. There was a significant ($p < 0.01$) difference in soil organic matter across the different SMCPs. Bulk density (BD), Ksat, clay content, and SOS variations were significantly ($p > 0.05$) across the different SMCPs. BD was the highest under ACS (1.61 g cm^{-3}) and the lowest under CCS (1.29 g cm^{-3}); whereas, Ksat was the highest under CMS (21.34 mm h^{-1}) and the lowest under COSS (5.72 mm h^{-1}). Furthermore, the clay content was the highest under COSS (33.55%) and the lowest under CSS (26.11%); whereas, SOS was the highest under ACS (5.26%) and the lowest under COSS (3.84%).

Table 1. Mean $\pm$ SD of selected soil (0–20 cm) physical and chemical properties across the four SMCPs.

Soil Properties	Soil Moisture Conservation Practices				$p < 0.05$	CV	LSD
	COSS	ACS	CCS	CMS			
pH	6.55 $\pm$ 0.31	6.34 $\pm$ 0.14	6.45 $\pm$ 0.21	6.21 $\pm$ 0.27	ns	3.46	
SOM (%)	3.84 $\pm$ 0.12 c	5.26 $\pm$ 0.57 a	4.61 $\pm$ 0.27 b	4.64 $\pm$ 0.25 b	0.022	6.97	0.71
TN (%)	0.19 $\pm$ 0.01	0.24 $\pm$ 0.01	0.22 $\pm$ 0.02	0.22 $\pm$ 0.01	ns	6.81	
SP (ppm)	70.75 $\pm$ 7.10	102.14 $\pm$ 2.40	75.08 $\pm$ 15.86	72.63 $\pm$ 12.57	ns	17.37	
SK (cmol(+)/kg ^{−1})	1.06 $\pm$ 0.13	1.46 $\pm$ 0.34	1.24 $\pm$ 0.29	1.39 $\pm$ 0.10	ns	19.98	
SCa (cmol(+)/kg ^{−1})	11.04 $\pm$ 2.82	17.76 $\pm$ 1.09	12.98 $\pm$ 2.37	14.58 $\pm$ 3.99	ns	23.47	
SMg (cmol(+)/kg ^{−1})	5.03 $\pm$ 1.56	8.12 $\pm$ 0.703	5.03 $\pm$ 0.85	7.18 $\pm$ 2.46	ns	29.09	
CEC (cmol(+)/kg ^{−1})	24.1 $\pm$ 1.06	23.91 $\pm$ 2.9	24.46 $\pm$ 2.48	23.03 $\pm$ 0.78	ns	7.71	
BD	1.48 $\pm$ 0.03 b	1.61 $\pm$ 0.03 a	1.29 $\pm$ 0.05 c	1.31 $\pm$ 0.02 c	0.001	2.95	0.09
Ksat (mmh ^{−1})	5.72 $\pm$ 1.58 c	7.36 $\pm$ 2.65 bc	17.4 $\pm$ 10.39 ab	21.34 $\pm$ 3.29 ab	0.026	33.88	10.31
Clay (%)	33.55 $\pm$ 3.63 a	31.59 $\pm$ 2.95 a	26.11 $\pm$ 5.49 b	28.94 $\pm$ 1.49 b	0.04	7.47	5.05
Silt (%)	12.82 $\pm$ 5.64	12.8 $\pm$ 4.24	10.93 $\pm$ 1.95	7.88 $\pm$ 0.76	ns	35.86	
Textural class	sandy clay loam	sandy clay loam	sandy clay loam	sandy clay loam			

SP, soil phosphorous; SK, soil potassium; TN, total nitrogen; SCa, soil calcium; SMg, soil magnesium; CEC, cation exchange capacity; ppm, parts per million; kg, kilogram; cmol(+)/kg^{−1}, centimoles of positive charge per kilogram of soil; mmh^{−1}, millimeters per hour; SOM, soil organic matter; Ksat, saturated hydraulic conductivity; BD, bulk density; COSS, open sun coffee system; CCS, coffee cover crop system; CMS, coffee mulch system; ACS, coffee *A. coriaria* system. Within the mean row, data followed with the same letter were not significantly different from each other.

Table 2 summarizes the findings of the analysis of specific soil physico-chemical parameters in the four SMCPs between 20 and 40 cm of depth. Results showed that only phosphorus (P), potassium (K), and BD varied significantly ($p < 0.05$) across the treatment among the assessed parameters. The highest amounts of P were recorded under ACS (44.25 cmol(+)/kg^{−1} soil), while the lowest were under COSS (26.83 cmol(+)/kg^{−1} soil). On the other hand, K was highest under ACS (0.50 cmol(+)/kg^{−1} soil) and the lowest under CCS (0.30 cmol(+)/kg^{−1} soil); whereas, the highest BD was observed under ACS (1.92 gcm^{−3}) and the lowest under CCS (1.52 gcm^{−3}).

Table 2. Mean $\pm$ SD of selected soil (20–40 cm) physical and chemical properties across the four SMCPs.

Soil Properties	Soil Moisture Conservation Practices				p -Value	c.v.	LSD
	COSS	ACS	CCS	CMS			
pH	6.74 $\pm$ 0.12	6.57 $\pm$ 0.14	6.64 $\pm$ 0.12	6.54 $\pm$ 0.23	ns	2.52	
SOM (%)	2.47 $\pm$ 0.25	2.59 $\pm$ 0.42	2.53 $\pm$ 0.21	2.83 $\pm$ 0.12	ns	6.37	
TN (%)	0.14 $\pm$ 0.01	0.15 $\pm$ 0.01	0.17 $\pm$ 0.01	0.17 $\pm$ 0.02	ns	9.73	
SP (ppm)	26.83 $\pm$ 3.01 c	44.25 $\pm$ 4.41 ab	37.85 $\pm$ 0.95 b	42.5 $\pm$ 2.94 a	0.006	8.77	7.40
SK (cmol(+)/kg ^{−1})	0.31 $\pm$ 0.06 b	0.50 $\pm$ 0.05 a	0.30 $\pm$ 0.09 b	0.43 $\pm$ 0.03 a	0.013	12.77	0.11
SCa (cmol(+)/kg ^{−1})	6.29 $\pm$ 1.80	6.65 $\pm$ 0.40	8.15 $\pm$ 2.06	6.70 $\pm$ 0.77	ns	25.3	
SMg (cmol(+)/kg ^{−1})	1.61 $\pm$ 0.17	3.43 $\pm$ 0.73	3.03 $\pm$ 0.66	3.19 $\pm$ 0.58	ns	22.72	
CEC (cmol(+)/kg ^{−1})	8.66 $\pm$ 3.11	10.4 $\pm$ 0.38	11.47 $\pm$ 2.68	10.34 $\pm$ 1.29	ns	25.58	
BD	1.68 $\pm$ 0.11 b	1.92 $\pm$ 0.04 a	1.57 $\pm$ 0.13 c	1.62 $\pm$ 0.14 c	0.006	3.4	0.13
Ksat (mmh ^{−1})	1.40 $\pm$ 0.67	1.11 $\pm$ 0.18	2.33 $\pm$ 1.13	2.54 $\pm$ 0.90	ns	37.76	
Clay (%)	47.06 $\pm$ 4.17	46.79 $\pm$ 2.00	46.39 $\pm$ 6.39	43.47 $\pm$ 1.95	ns	9.23	
Silt (%)	14.36 $\pm$ 3.07	14.97 $\pm$ 0.77	14.86 $\pm$ 3.38	11.22 $\pm$ 0.52	ns	15.23	
Textural class	sandy clay loam	sandy clay loam	sandy clay loam	sandy clay loam			

SP, soil phosphorous; SK, soil potassium; TN, total nitrogen; SCa, soil calcium; SMg, soil magnesium; CEC, cation exchange capacity; ppm, parts per million; kg, kilogram; cmol(+)/kg^{−1}, centimoles of positive charge per kilogram of soil; SOM, soil organic matter; mmh^{−1}, millimeters per hour; Ksat, saturated hydraulic conductivity; BD, bulk density; COSS, open sun coffee system; CCS, coffee cover crop system; CMS, coffee mulch system; ACS, coffee *A. coriaria* system; ns, non-significant. Within the mean row, data followed with the same letter were not significantly different from each other.

3.2. Effects of SMCPs on Coffee Plant Tissue Nutrients

Table 3 summarizes the effect of SMCPs on coffee plant nutrients. All the nutrients, except Ca, varied significantly ($p > 0.05$) across the coffee systems. N concentration was the highest in coffee leaves under ACS (3.19%) and the lowest in leaves under COSS (2.3%). Similarly, the highest concentrations of P were recorded in coffee leaves under ACS (0.31%) and the lowest in coffee leaves under COSS (0.16%). Furthermore, K concentrations were the highest under ACS (2.29%) and the lowest under CCS (1.6%), while Mg was the most concentrated in coffee leaves under ACS (0.33%) and the least in coffee leaves under COSS (0.24%).

Table 3. Mean $\pm$ SD of effects of SMCPs on coffee plant tissue nutrients.

Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
COSS	2.30 $\pm$ 0.18 c	0.16 $\pm$ 0.01 d	1.72 $\pm$ 0.16 c	1.06 $\pm$ 0.34	0.24 $\pm$ 0.02 d
ACS	3.19 $\pm$ 0.11 a	0.31 $\pm$ 0.04 a	2.29 $\pm$ 0.09 a	1.29 $\pm$ 0.05	0.33 $\pm$ 0.02 a
CCS	3.06 $\pm$ 0.12 a	0.19 $\pm$ 0.01 c	1.60 $\pm$ 0.08 d	1.01 $\pm$ 0.15	0.29 $\pm$ 0.01 b
CMS	2.71 $\pm$ 0.06 b	0.22 $\pm$ 0.02 b	1.89 $\pm$ 0.13 b	1.11 $\pm$ 0.11	0.25 $\pm$ 0.02 c
<i>p</i> -value	<0.001	<0.001	<0.001	ns	0.009
LSD	0.16	0.03	0.16	0.48	0.04
CV	2.61	6.1	3.91	19.4	6.27

P, phosphorous; K, potassium; N, nitrogen; Ca, calcium; Mg, magnesium; COSS, open sun coffee system; CCS, coffee cover crop system; CMS, coffee mulch system; ACS, coffee *A. coriaria* system; ns, non-significant. Within the mean row, data followed with the same letter were not significantly different from each other.

3.3. Correlations and Regressions between Measured Variables

3.3.1. Soil Physico-Chemical and Leaf Nutrient Parameters

Tables 4 and 5 show the correlation and regression results between soil chemical and physical variables, respectively. BD significantly ($p \leq 0.05$) reduced with the increase in soil chemical attributes, SOM ($r = -0.16$, $R^2 = 0.34$), SK ($r = -0.59$, $R^2 = 0.32$), and CEC ($r = -0.69$, $R^2 = 0.44$). Ksat significantly ($p \leq 0.05$) reduced as the pH increased ($r = -0.42$, $R^2 = 0.14$) and significantly ($p \leq 0.05$) increased as the SOM ($r = 0.67$, $R^2 = 0.42$), TN ($r = 0.61$, $R^2 = 0.34$), SP ($r = 0.58$, $R^2 = 0.30$), and SCa ($r = 0.56$, $R^2 = 0.28$) increased. Furthermore, the percentage clay significantly ($p \leq 0.05$) increased as the pH increased ($r = 0.47$, $R^2 = 0.18$) and reduced as the SOM ($r = -0.86$, $R^2 = 0.73$), TN ($r = -0.78$, $R^2 = 0.59$), SP ($r = -0.80$, $R^2 = 0.62$), SCa ($r = -0.71$, $R^2 = 0.48$), SMg ($r = -0.67$, $R^2 = 0.43$), SK ($r = -0.85$, $R^2 = 0.71$), and CEC ($r = -0.86$, $R^2 = 0.73$) increased. In addition, the percentage silt was significantly ($p \leq 0.05$) increased with the increase in pH ($r = 0.49$, $R^2 = 0.20$) and significantly ($p \leq 0.05$) reduced as the SOM ($r = -0.44$, $R^2 = 0.16$), SMg ($r = -0.45$, $R^2 = 0.17$), and SK ($r = -0.55$, $R^2 = 0.27$) increased.

3.3.2. Soil and Coffee Leaf Chemical Variables

The coffee leaf N content significantly ($p \leq 0.05$) increased as the SOM ($r = 0.76$, $R^2 = 0.54$), TN ($r = 0.75$, $R^2 = 0.52$) and SP ($r = 0.87$, $R^2 = 0.39$) increased (Tables 6 and 7). Leaf P levels increased significantly ($p \leq 0.05$) with increasing SP ($r = 0.85$, $R^2 = 0.70$), SCa ($r = 0.66$, $R^2 = 0.38$), SMg ($r = 0.71$, $R^2 = 0.45$), and SK ($r = 0.71$, $R^2 = 0.45$). Leaf K content significantly ($p \leq 0.05$) increased as the SP ($r = 0.70$, $R^2 = 0.43$), SMg ($r = 0.67$, $R^2 = 0.39$), and SK ($r = 0.60$, $R^2 = 0.29$) increased. Leaf Ca levels increased significantly ($p \leq 0.05$) as the SCa ($r = 0.76$, $R^2 = 0.53$) and SMg ($r = 0.60$, $R^2 = 0.41$) increased. Mg in the leaves increased with the increase in SP ($r = 0.77$, $R^2 = 0.55$).

Table 4. Correlation between soil chemical and physical variables.

Soil Physical Variables	Chemical Variables							
	pH	SOM (%)	TN (%)	SP (ppm)	SCa (cmol(+)kg ^{−1})	SMg (cmol(+)kg ^{−1})	SK (cmol(+)kg ^{−1})	CEC (cmol(+)kg ^{−1})
BD (gcm ^{−3})	0.40 ^{ns}	−0.61 ^{**}	−0.57 ^{**}	−0.51 [*]	−0.54 ^{**}	−0.46 [*]	−0.59 ^{**}	−0.69 ^{***}
Ksat (mmh ^{−1})	−0.42 [*]	0.67 ^{***}	0.61 ^{**}	0.58 ^{**}	0.56 ^{**}	0.57 ^{**}	0.68 ^{***}	0.63 ^{**}
Clay (%)	0.47 [*]	−0.86 ^{***}	−0.78 ^{***}	−0.80 ^{***}	−0.71 ^{***}	−0.67 ^{***}	−0.85 ^{***}	−0.86 ^{***}
Silt (%)	0.49 [*]	−0.44 [*]	−0.39 ^{ns}	−0.28 ^{ns}	−0.33 ^{ns}	−0.45 [*]	−0.55 ^{**}	−0.34 ^{ns}

SP, soil phosphorous; SK, soil potassium; TN, total nitrogen; SCa, soil calcium; SMg, soil magnesium; CEC, cation exchange capacity; ppm, parts per million; kg, kilogram; cmol(+)kg^{−1} soil, centimoles of positive charge per kilogram of soil; mmh^{−1}, millimeters per hour; SOM, soil organic matter; Ksat, saturated hydraulic conductivity; BD, bulk density; ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$; ns, non-significant.

Table 5. Coefficients of determination (R^2) and regression models for relating soil chemical and physical variables.

Soil Physical Variables	Chemical Variables							
	pH	SOM	TN	SP	SCa	SMg	SK	CEC
BD	• $y = 5.78 + 0.47x$ • $R^2 = 0.11$ • $p = 0.069$	• $y = 8.71 - 3.34x$ • $R^2 = 0.34$ • $p = 0.003$	• $y = 0.34 - 0.10x$ • $R^2 = 0.29$ • $p = 0.006$	• $y = 154.76 - 62.96x$ • $R^2 = 0.23$ • $p = 0.014$	• $y = 29.05 - 12.13x$ • $R^2 = 0.26$ • $p = 0.009$	• $y = 12.85 - 5.44x$ • $R^2 = 0.17$ • $p = 0.031$	• $y = 3.14 - 1.50x$ • $R^2 = 0.32$ • $p = 0.004$	• $y = 56.09 - 25.34x$ • $R^2 = 0.44$ • $p < 0.001$
Ksat	• $y = 6.60 - 0.01x$ • $R^2 = 0.14$ • $p = 0.05$	• $y = 2.92 + 0.08x$ • $R^2 = 0.42$ • $p = 0.001$	• $y = 0.17 - 0.002x$ • $R^2 = 0.34$ • $p = 0.003$	• $y = 45.17 + 1.63x$ • $R^2 = 0.30$ • $p = 0.005$	• $y = 8.13 + 0.29x$ • $R^2 = 0.28$ • $p = 0.006$	• $y = 3.28 + 0.16x$ • $R^2 = 0.29$ • $p = 0.006$	• $y = 0.52 + 0.04x$ • $R^2 = 0.44$ • $p < 0.001$	• $y = 12.91 + 0.54x$ • $R^2 = 0.37$ • $p = 0.002$
Clay	• $y = 6.05 + 0.01x$ • $R^2 = 0.18$ • $p = 0.027$	• $y = 7.41 - 0.10x$ • $R^2 = 0.73$ • $p < 0.001$	• $y = 0.30 - 0.003x$ • $R^2 = 0.59$ • $p < 0.001$	• $y = 137.04 - 2.09x$ • $R^2 = 0.62$ • $p < 0.001$	• $y = -2.90 + 0.25x$ • $R^2 = 0.48$ • $p < 0.001$	• $y = 10.94 - 0.17x$ • $R^2 = 0.43$ • $p = 0.001$	• $y = 2.58 - 0.05x$ • $R^2 = 0.71$ • $p < 0.001$	• $y = 43.03 - 0.69x$ • $R^2 = 0.73$ • $p < 0.001$
Silt	• $y = 6.10 + 0.03x$ • $R^2 = 0.2$ • $p = 0.02$	• $y = 5.27 - 0.14x$ • $R^2 = 0.16$ • $p = 0.038$	• $y = 0.24 - 0.004x$ • $R^2 = 0.21$ • $p = 0.033$	• $y = 81.72 - 1.94x$ • $R^2 = 0.11$ • $p = 0.073$	• $y = 15.56 - 0.42x$ • $R^2 = 0.07$ • $p = 0.131$	• $y = 8.2 - 0.30x$ • $R^2 = 0.17$ • $p = 0.034$	• $y = 1.80 - 0.08x$ • $R^2 = 0.27$ • $p = 0.008$	• $y = 25.81 - 0.71x$ • $R^2 = 0.12$ • $p = 0.071$

SP, soil phosphorous; SK, soil potassium; TN, total nitrogen; SCa, soil calcium; SMg, soil magnesium; CEC, cation exchange capacity; SOM, soil organic matter; Ksat, saturated hydraulic conductivity; BD, bulk density.

Table 6. Correlation between soil and coffee leaf chemical variables.

Soil Parameters	Coffee Leaf Chemical Variables				
	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
pH	−0.123 ^{ns}	−0.31 ^{ns}	−0.04 ^{ns}	0.42 ^{ns}	0.15 ^{ns}
SOM (%)	0.76 ^{**}	0.60 ^{ns}	0.50 ^{ns}	0.49 ^{ns}	0.48 ^{ns}
TN (%)	0.75 ^{**}	0.51 ^{ns}	0.31 ^{ns}	0.24 ^{ns}	0.47 ^{ns}
SP (ppm)	0.67 [*]	0.85 ^{***}	0.70 [*]	0.41 ^{ns}	0.77 ^{**}
SCa (cmol(+)/kg ^{−1})	0.57 ^{ns}	0.66 [*]	0.51 ^{ns}	0.76 ^{**}	0.53 ^{ns}
SMg (cmol(+)/kg ^{−1})	0.57 ^{ns}	0.71 [*]	0.67 [*]	0.68 [*]	0.48 ^{ns}
SK (cmol+)/kg ^{−1})	0.55 ^{ns}	0.71 [*]	0.60 [*]	0.30 ^{ns}	0.46 ^{ns}
CEC (cmol+)/kg ^{−1})	0.53 ^{ns}	0.15 ^{ns}	0.07 ^{ns}	0.46 ^{ns}	0.30 ^{ns}

SP, soil phosphorous; SK, soil potassium; TN, total nitrogen; SCa, soil calcium; SMg, soil magnesium; CEC, cation exchange capacity; SOM, soil organic matter; P, phosphorous; K, potassium; N, nitrogen; Ca, calcium; Mg, magnesium; ***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$; ns, non-significant.

Table 7. Coefficients of determination (R^2) and regression models for relating soil and coffee leaf chemical variables.

Soil Parameters	Coffee Leaf Chemical Variables				
	N	P	K	Ca	Mg
pH	$y = 4.42 - 0.25x$ $R^2 = 0.09$ $p = 0.72$	$y = 0.82 - 0.09x$ $R^2 = 0.01$ $p = 0.356$	$y = 2.29 - 0.07x$ $R^2 = 0.11$ $p = 0.897$	$y = -1.95 + 0.47x$ $R^2 = 0.198$ $p = 0.086$	$y = 0.07 + 0.03x$ $R^2 = 0.086$ $p = 0.662$
SOM	$y = -0.10 + 0.81x$ $R^2 = 0.54$ $p = 0.006$	$y = -0.13 + 0.94x$ $R^2 = 0.29$ $p = 0.051$	$y = 0.37 + 0.41x$ $R^2 = 0.17$ $p = 0.113$	$y = 0.09 + 0.28x$ $R^2 = 0.16$ $p = 0.125$	$y = 0.09 + 0.05x$ $R^2 = 0.143$ $p = 0.137$
TN	$y = -0.82 + 19.15x$ $R^2 = 0.52$ $p = 0.007$	$y = -0.15 + 1.92x$ $R^2 = 0.18$ $p = 0.108$	$y = 0.69 + 6.12x$ $R^2 = 0.003$ $p = 0.35$	$y = 0.49 + 3.28x$ $R^2 = 0.05$ $p = 0.482$	$y = 0.04 + 1.22x$ $R^2 = 0.14$ $p = 0.143$
SP	$y = 1.29 + 0.03x$ $R^2 = 0.39$ $p = 0.024$	$y = -0.1 + 0.81x$ $R^2 = 0.70$ $p = 0.001$	$y = 0.64 + 0.02x$ $R^2 = 0.43$ $p = 0.017$	$y = 0.60 + 0.01x$ $R^2 = 0.06$ $p = 0.21$	$y = 0.10 + 0.003x$ $R^2 = 0.55$ $p = 0.005$

Table 7. Cont.

Soil Parameters	Coffee Leaf Chemical Variables				
	N	P	K	Ca	Mg
SCa	$y = 1.78 + 0.10x$ $R^2 = 0.25$ $p = 0.061$	$y = 0.04 + 0.02x$ $R^2 = 0.38$ $p = 0.026$	$y = 1.15 + 0.07x$ $R^2 = 0.18$ $p = 0.11$	$y = 0.37 + 0.07x$ $R^2 = 0.53$ $p = 0.007$	$y = 0.18 + 0.009x$ $R^2 = 0.20$ $p = 0.095$
SMg	$y = 2.02 + 0.17x$ $R^2 = 0.26$ $p = 0.064$	$y = 1.04 + 16.25x$ $R^2 = 0.45$ $p = 0.014$	$y = 1.16 + 0.15x$ $R^2 = 0.39$ $p = 0.024$	$y = -0.61 + 0.11x$ $R^2 = 0.41$ $p = 0.020$	$y = 0.21 + 0.01x$ $R^2 = 0.14$ $p = 0.138$
SK	$y = 1.75 + 1.26x$ $R^2 = 0.23$ $p = 0.077$	$y = 0.07 + 0.03x$ $R^2 = 0.45$ $p = 0.014$	$y = 0.97 + 1.06x$ $R^2 = 0.29$ $p = 0.049$	$y = 0.80 + 0.37x$ $R^2 = 0.009$ $p = 0.365$	$y = 0.18 + 0.11x$ $R^2 = 0.13$ $p = 0.153$
CEC	$y = 0.4 + 0.14x$ $R^2 = 0.20$ $p = 0.097$	$y = 0.01 + 0.24x$ $R^2 = 0.085$ $p = 0.653$	$y = 1.60 + 0.01x$ $R^2 = 0.11$ $p = 0.842$	$y = -0.04 + 0.07x$ $R^2 = 0.13$ $p = 0.150$	$y = 0.13 + 0.01x$ $R^2 = 0.009$ $p = 0.365$

SP, soil phosphorous; SK, soil potassium; TN, total nitrogen; SCa, soil calcium; SMg, soil magnesium; CEC, cation exchange capacity; SOM, soil organic matter; P, phosphorous; K, potassium; N, nitrogen; Ca, calcium; Mg, magnesium.

3.4. Effects of Selected SMCPs on Coffee Growth Parameters

Table 8, below, summarizes the effects of selected SMCPs on the coffee growth parameters that determine the yield of coffee. All the growth parameters varied across the SMCPs, but not significantly ($p > 0.05$). However, in the dry season, the higher values were recorded under the SMCPs compared to the coffee under open sun. ACS registered the highest number of active primaries (31.4) and number of berries per cluster (14.1) in the wet season and the highest number of clusters per primary (10.2) in the dry season. On the other hand, CCS had the highest number of active primaries in the dry season (33.3) and number of clusters per primary in the wet season (9.4). In addition, the highest number of berries per cluster in the dry season was observed under CMS (28.5).

Table 8. Effects of selected SMCPs on coffee growth parameters.

Treatment	Number of Active Primaries		Number of Clusters per Primary		Number of Berries per Cluster	
	Dry	Wet	Dry	Wet	Dry	Wet
Open suncoffee system (COSS)	23.3 ± 3.1	31.1 ± 3.3	8.7 ± 1.3	7.4 ± 0.9	18.6 ± 5.8	13.7 ± 2.0
Coffee <i>Albizia coriaria</i> system (ACS)	25.9 ± 3.7	31.4 ± 4.2	10.2 ± 1.6	8.1 ± 1.2	19.8 ± 7.3	14.1 ± 2.5
Coffee cover crop system (CCS)	33.3 ± 2.9	27.8 ± 3.3	8.8 ± 1.3	9.41 ± 0.9	21.6 ± 5.8	13.7 ± 2.0
Coffee mulch system (CMS)	30.5 ± 2.9	31.3 ± 3.3	9.7 ± 1.3	5.9 ± 0.9	28.5 ± 5.8	8.0 ± 2.0
<i>p</i> -value	0.109	0.854	0.851	0.085	0.642	0.112
LSD	9.12	10.27	3.949	2.833	17.83	6.019
CV	35.5	38.04	47.83	41.67	89.57	55.39

4. Discussion

4.1. Effects of Selected SMCPs on Selected Soil Properties

Bulk density was low under mulch and CCS, but high under COSS and ACS. Similar findings showing that BD in conserved areas was lower than that of controls were observed by Jiru and Wegari [32] and Challa et al. [33]. More pore space and enhanced aeration result from a lower bulk density of the soil, which favorably influences biological activity [34]. For agricultural soils, 1.3 to 1.4 gcm^{−3} is the recommended range for BD [35]. Based on this, bulk density was very high under COSS and ACS across the studied soil depths. The increased clay content under ACS and COSS may be the cause of the high bulk density in both systems. In addition, the ACS and COSS systems had more silts that are easily compressed, leading to high bulk densities. A high bulk density shows that the soils have low soil porosity and are compacted. A high bulk density affects the soil's ability to hold water, its root development, movement of microbiological life, and flow of air and water. Reduced soil water infiltration might result in more runoff and erosion from sloping land or flooded soils in flat places. Crop yields are decreased by shallow plant roots and poor plant growth, brought on by a high bulk density [36]. BD increased with depth, due to the influence of SOM that affects soil structure [37]. This can mean that crop residues have contributed more organic matter to the topsoil than the subsurface layer. In this investigation, there was a negative and statistically significant correlation between BD and SOM.

Saturated hydraulic conductivity (Ksat) is among the most crucial soil characteristics that affects how water flow systems behave [38]. Ksat was significantly higher under CMS and CCS, but low under COSS. This could be related to the bulk density, and thus macropores. This means that more water can easily pass through soils [39]. Soils under these SMCPs have better infiltration rates, reduced runoff/erosion/nutrient loss, and increased water content compared to COSS treatment [40]. Ksat decreased across all SMCPs as the soil depth increased, possibly due to a decrease in porosity with depth, as activity of

macrobes and microbes also reduces [39]. A decrease in Ksat with depth hinders vertical water movement.

The soils examined under each soil moisture conservation technique had similar soil texture characteristics (sandy clay loam). Because soil texture depends on the parent materials from which it is created, this pattern of textural similarity revealed that they were derived from the same source. In support of this, the study by Komicha et al. [41] established that the soil parent material, rather than the influence of trees, was responsible for the soil texture class similarity between shaded and unshaded fields.

Clay was significantly the highest under COSS and the lowest under CCS at the 0–20 cm depth. Our results are consistent with those of Jiru and Wegari [32], who demonstrated that clay content was lower in conserved land as compared to non-conserved land. At 0–20 cm depth, the clay content under COSS and ACS was significantly different from that under CMS and CCS. In contrast, the clay content was higher under conserved compared to non-conserved land according to Belayneh et al. [42] and Dagnachew et al. [17]. The aeration of soil, nutrient uptake, water infiltration, and microbial activity are all impacted by soil texture [43]. The additional nutrients from fertilizers can easily be absorbed by clay minerals, making them stable and non-exchangeable [44]. A high clay content increases the bulk density of the soil leading to low water infiltration.

There was no significant difference in the pH across SMCPs. Selman [45] also found non-significant differences of the pH across SMCPs. The pH was above the optimum levels of 5.5–6.0 [46] for Robusta coffee across all SMCPs and depths. Due to the increase in clay content with depth, the pH of the soil was lower in the 0–20 cm soil layer than the 20–40 cm soil layer, due to the clay particles holding onto basic cations to raise the soil pH. In line with research by [47], the Pearson correlation matrix also revealed that clay was strongly and positively correlated with soil pH ($r = 0.42$). pH was also significantly related to clay particles ($R^2 = 0.18$, $p < 0.05$). These findings, however, are in contradiction to those of other investigators who found that non-conserved farms had lower pH values than conserved farms [32,48]. Soil with an above-the-recommended pH may lack essential nutrients such as zinc, copper, boron, and manganese. Micronutrients will also adhere strongly to soil surfaces at high pH levels [49]. There is therefore a need to use ammonium-based nitrogen fertilizers to lower the pH across all the SMCPs.

Soil organic matter (SOM) content varied significantly across the SMCPs, with the highest levels being observed under ACS and the lowest under COSS. Similarly, several earlier research studies have also recorded significantly more SOM in the coffee growing underneath shade trees compared to open areas (e.g., [32,50]). The SOM was higher than the optimum range of 1–3% [51] at the 0–20 cm depth across the different systems, but within optimum range at the 20–40 cm depth. At both depths, SMCPs had a higher SOM compared to COSS. This high organic matter could be from leaf litter fall [32] from coffee, shade tree, cover crop, and decomposition from mulch. Shade trees and cover crops are N-fixing species, thus increasing soil SOM [52]. The needed SOM level in the soil controls all physical, as well as chemical soil quality indexes favorably [17], affecting nutrient availability and soil–water functions. It acts as an ion exchange material, encourages the production of soil aggregates, which affects the physical characteristics and wetness of the soil, and serves as an energy source for soil microbes and macrofauna. Soil organic matter (SOM) is also a supplier and a sink of plant nutrients [53]. The SOM was optimum for coffee growth within all the studied coffee systems.

Though soil phosphorus (SP) was not significantly different across the SMCPs, it attained the highest concentration under ACS. Higher SP levels under coffee shade systems compared to open sun coffee have also been reported by Etafa [50]. SP is crucial for plant metabolism and energy transformation [54], and is essential for the development of the bearing branches in coffee. Available SP was within an optimum range of 20–100 ppm [55], except for ACS at the 0–20 cm depth, where it was slightly above the optimum. When the soil pH ranges from 6.0 to 6.5, P is more prevalent in the soil, according to Prasad and Power [56]. SP was higher under SMCPs as compared to COSS. Increased SP has

been noted in SMCPs in comparison to non-conserved plots [32,45], mostly because of better SOM, which boosts SP and protects against its removal and fixation. The strong and positive association between SOM and SP ($r = 0.89$) provides additional support for this. Moreover, SOM rates that decreased with soil depth might be used to account for the variation in the SP level between surface and deeper layers [57]. In this study, the SP levels were optimum for coffee growth across all conservation practices. However, it should be noted that even when soil tests indicate that there are sufficient amounts of those nutrients in the soil, excessive SP in the Robusta coffee *A. coriaria* system is likely to hinder the plant's capacity for absorbing necessary micronutrients, particularly iron and zinc, which will stunt coffee growth [58].

The ability of the soil to receive and release nutrients to crops is known as the cation exchange capacity (CEC). It implies that the ability of the coffee plants to absorb nutrients decreases as the CEC lessens. CEC is dramatically affected by pH. SMCPs resulted in a greater CEC, but the difference was not statistically significant. CEC was within an optimum of 12–25 cmolc/kg [59] at the 0–20 cm depth only, across all treatments. At the 20–40 cm depth, CEC was only below the optimum under COSS. This study revealed that only depth had a significant effect on CEC. This high CEC at 0–20 cm could be due to the high SOM in this layer [60]. CEC stands in for the main soil repository of readily available SK, SCa, SMg, and a number of micronutrients. Moreover, it aids in halting the loss of nutrients.

Soil potassium (SK) varied significantly across the SMCPs for the 20–40 cm depth, but not for 0–20 cm depth. However, in both cases, SK levels were the highest under ACS, agreeing with studies by Etafa [50]. SK is essential for supporting physiological functions, protein synthesis, and plant water balance [14]. It was within the optimum ranges of 0.4–2 cmolc/kg [55] at the 0–20 cm depth across treatments, however it was lower under COSS. At 20–40 cm, it was below the optimum under COSS and CCS. These findings concur with Bekele et al. [16] that showed that the SK decreases as the depth increases. Cárcelos Rodríguez [61] noted the beneficial impact of SMCPs on soil exchangeable SK. The cause for high amounts of SK under SMCPs could be the presence of high SOM, and this was proven by results of this study that showed a significantly high and positive correlation ($r = 0.91$) between SK and SOM. A low SK in open sun and Robusta coffee cover crop could affect coffee fruit set, dry weight and volume, and therefore the need to supplement with potassium-based fertilizers, such as muriate of potash.

Though soil magnesium (SMg) was not significantly different across the SMCPs, the highest amounts were recorded under ACS, as reported by Kinyilia et al. [62]. In addition, there was a significant effect of SMCPs and depth on SMg concentration. SMg is essential for a variety of processes in plants, including the production of genetic makeup, photosynthesis, and enzyme catalysis [63]. Mg was more abundant at the 0–20 cm depth than at 20–40 cm. SMg was within an optimum range of 0.8–4 cmolc/kg [55] at 20–40 cm, but above the optimum at 0–20 cm. SMg was generally higher under ACS and the lowest under COSS and CCS at the two soil depths. The elevated SK and SCa in this layer may be the reason behind the increased Mg levels at 0–20 cm. Alemu et al. [64] reported that SCa and SK deficiencies induced Mg deficiency. The strong significant relationship between SMg and SCa ($r = 0.93$) and K ($r = 0.82$) provides additional support for this. Coffee is very vulnerable to excess or insufficient magnesium. Both the quality and yield potential will be decreased in either circumstance. An excess of magnesium in the soil can also lead to a deficiency in certain nutrients, including potassium, sodium, and calcium, as well as reduce the availability of trace elements [65].

Soil calcium (SCa) controls the plant's response to intrinsic stimuli and stress signals [66]. SCa was within the optimum range of 1.6–10 cmolc/kg [55] at 20–40 cm, but above the optimum at 0–20 cm. SCa was higher under SMCPs and significantly different with depth; at 0–20 cm, it was higher under ACS. At 20–40 cm, it was higher under CCS. SCa decreased with depth. High levels of organic matter and CEC at 0–20 cm may also be responsible. The high SCa in conserved plots and surface soils concurred with results

of Bekele et al. [16] and Gadana et al. [52]. Too much Ca can cause ion imbalances affecting other nutrients (such as SK and SMg) or changing the pH and decreasing some ions' solubility, such as iron [67].

Total nitrogen (TN) is the most important nutrient influencing crop growth and yield [68]. Mean differences in TN among SMCPs were not significant. TN was below the optimum ranges of 0.3–0.6% [55] at all depth and SMCPs. At 0–20 cm, the TN was the highest under ACS, as also observed by Etafa [50], whereas at 20–40 cm, the highest value was obtained under CCS and CMS. The significance of SMCPs in improving the fertility of the soil has been noted by some studies, e.g., [32,60,68]. Continuous cultivation can be criticized for the decline in percent TN levels under COSS [69]. The high amount of SOM with SMCPs increases nutrient availability in the soil. Additionally, SMCPs may be facilitating favorable conditions for a variety of advantageous microorganisms, such as nitrogen fixers, since nitrogen-fixing bacteria aid in fixing atmospheric nitrogen into the soil, replenishing the soil. Below-optimum levels of TN could be due to leaching because of heavy rainfall and nutrients removed by harvested products [70]. There is a need to supplement the nitrogen supply by use of manure and nitrogen-based fertilizers to all soil moisture conservation systems.

4.2. Effects of Selected SMCPs on Nutrient Status of Coffee Plant

Nitrogen in the leaves was significantly different across SMCPs, with the highest concentrations being recorded under ACS. Similarly, Bote and Struik [71] observed that coffee grown under shade had more N in the leaves. N was the lowest in coffee under COSS and it was below the optimum range of 2.5–3% [72]. The low N in coffee leaves from open sun could be related to the low nitrogen in the soil, as explained by significant correlation ($r = 0.75$) between soil nitrogen and leaf nitrogen. However, the soil TN was below critical levels across all SMCPs, and yet it is only the open sun that had low N in the leaves. This could imply that total nitrogen values did not agree with plant tissue analysis, and that fertilizer recommendations would therefore not be appropriate without taking plant tissue analysis into account. The low N under COSS could explain the importance of soil moisture conservation practices in proper utilization of the applied fertilizers. Therefore, it is essential to consider the importance of other soil nutrient supply methods when making decisions about fertilizer use. Nitrogen (N) is a major mineral component needed in the optimum levels and its supply is a major factor limiting the growth and development of plants [66]. Its shortage will result in decreased production of amino acids and, consequently, of proteins, thus reduced growth [73]. Application of nitrogen-based fertilizer can alleviate the problem.

Leaf P was significantly different across SMCPs ($p < 0.001$), with the highest concentrations being recorded under ACS and the lowest under COSS. Our finding is in line with the fact that the high light intensity as in the open coffee system, has been reported to decrease plant shoot P concentration [74]. The P level was observed to be within the range of 0.15–0.20% [75] across all treatments, except for ACS where it was slightly higher (0.31%) implying that it was in the required amounts for coffee growth. The high P under ACS could be due to the high level of SP in the soil at that location. In fact, soil P was significantly positively correlated with leaf P ($r = 0.85$), agreeing with studies by [72,73]. The positive correlation explains the high P in the soil and leaves under ACS. SP was also significantly related with the leaf P ($R^2 = 0.70$, $p < 0.001$).

Leaf K was significantly different across all the treatments, with the highest concentration being realized under ACS and the lowest under CCS. Similarly, Mithamo [76] reported significantly higher levels of K in coffee leaves when intercropped with fruit trees compared to sun-grown coffee. However, it was within the optimum ranges of 2.1–2.6% [75] under ACS only. Leaf K was also significantly positively correlated ($r = 0.60$) with soil K [75]. The optimum K in the leaves of ACS could be due to the high values of K in the soils under this system. The reason for the low leaf K contents could be that K is highly absorbed by coffee

during berry development, leading to large amounts being exported especially in the years of high yield [66]. Thus, low K can lead to a low production and poor quality.

Mg concentration in the leaves was significantly different across the treatments, with the highest amounts being recorded under ACS and the lowest under COSS [71]. The leaf Mg was within the optimum range of 0.25–0.40% [72] across all the SMCPs, implying that it was available in sufficient amounts for plant utilization. The contributions of SOM and the level of exchangeable SMg could be one explanation for the high leaf Mg contents of coffee. Sousa et al. [19] noted that SMg greatly affects the coffee leaf Mg content, corroborating the findings of this investigation. Due to the element's importance in photosynthetic plants, as a component of chlorophyll and a stimulator of numerous plant enzymes, the Mg content of coffee leaves under COSS may have a direct impact on coffee yield [63]. However, the amount of SMg and Mg in the leaves did not correlate significantly.

Ca concentrations in leaves were above the optimum ranges of 0.75–1.5% [72] across the treatments, though the relationship was insignificant. Leaf Ca increased significantly along with the SCa contents ($r = 0.76$). Sousa et al. [19] also reported high contents of leaf Ca due to sufficient amounts of exchangeable calcium in soils. SCa was significantly related to leaf Ca ($R^2 = 0.53$, $p < 0.01$).

4.3. Effects of Selected SMCPs on Coffee Growth Parameters

Robusta coffee growth parameters were not significantly ($p > 0.05$) different across the various SMCPs. Similarly, Chemura [77] and Atnafu [78] observed no significant differences in Arabica coffee grown under different soil fertility management options. In the dry season, all the growth parameters were higher for Robusta coffee growing under SMCPs compared with coffee growing under the open sun system. SMCPs have been reported to improve coffee growth parameters, such as, for example, [79–82]. This is could in part due to the fact that the SMCPs improved soil physico-chemical properties and coffee plant nutrition, as observed in this study.

5. Conclusions

The findings demonstrated that all SMCPs improve soil physio-chemical attributes and leaf nutrients for sustainable productivity and quality of Robusta coffee. However, ACS improved the leaf plant nutrition better compared to other SMCPs, while CMS and CCS improved the soil physio-chemical properties. Nevertheless, there is a need to supplement with nitrogen-based fertilizers for all the SMCPs. Therefore, the government should subsidize the inorganic fertilizers for the smallholder farmers. In addition, these conservation methods should be maintained and expanded to new degraded regions, to ensure land productivity and environmental quality. There is, however, a need to conduct similar research on the long-term effects of SMCPs on the physio-chemical properties. Coffee yield and socioeconomic factors associated with SMCPs should also be determined.

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