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Effects of climate-smart alley cropping and conservation agriculture on selected soil physicochemical properties in Nyimba, Zambia

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Abstract

Climate change significantly impacts the livelihoods and food security of millions of smallholder farmers in Sub-Saharan Africa. Its effects hinder agricultural production, decrease food availability, and threaten the economic stability of agriculture-dependent nations. In Zambia, where agriculture is the primary economic activity, especially in rural regions, climate change affects farm productivity by changing the frequency and intensity of extreme weather events, as well as the average and variability of weather conditions like temperature and rainfall patterns. In Zambia's Nyimba District, a study was conducted to evaluate the effects of climate-smart farming methods on soil quality in croplands owned by smallholder farmers. Conventional agriculture, ripping, conservation agriculture basins, and *G. sepium* alley cropping were among the practices evaluated. Thirty composite soil samples, to a depth of 0–30 cm, were collected using a systematic sampling approach from six different areas: basins, *G. sepium* alley cropping, conservation agriculture ripping, and two types of conventional agriculture ($n = 6$ each). Minitab Statistical Software version 17 was utilized to analyze the soil samples, calculating Tukey's LSD, standard deviations, and mean values. As per the study findings, there were notable ($p < 0.05$) effects caused by *G. sepium* alley cropping, basins, and conservation agriculture ripping on various soil properties such as pH, bulk density, porosity, available phosphorus, total nitrogen, and exchangeable bases (sodium, calcium, magnesium, and potassium). Integrating climate-smart farming methods into agricultural systems can enhance soil fertility and contribute to the overall health of the agricultural landscape. These findings have significant implications for the development and implementation of Zambia's climate-smart agriculture policies and for future research endeavours.

Keywords: *Agroforestry, Climate-smart agriculture, Conservation basins, Soil physicochemical properties,*

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Introduction

In developing countries, climate change poses significant threats to food security and agricultural productivity, necessitating environmentally sound solutions (Chung *et al.*, 2019) and. Climate change involves long-term shifts in Earth's climate and weather patterns (Abdurahman *et al.*, 2024). This global issue significantly impacts the environment, particularly the agricultural sector (CIAT and World Bank, 2017). The detrimental effects of climate change on agricultural productivity have been observed across several regions, including sub-Saharan Africa, Asia, Europe, South America, and Latin America (Muluneh, 2021). For instance, smallholder farmers in Zambia have faced substantial challenges largely attributed to climate change (Karmaoui *et al*., 2020). Zambia, a landlocked country in Southern Africa, depends heavily on agriculture, with more than half of its population making their living from farming. This sector significantly contributes to the national economy (Nkomoki *et al*., 2019). However, Zambia's agricultural industry faces several challenges, including the need for sustainable farming methods, the impacts of climate change, and soil degradation.

In Zambia, the majority of rural households depend on agriculture for their income (Central Statistical Office, 2011). However, climate change affects about 80% of smallholder farmers in these areas, worsening poverty levels (Nkhuwa *et al*., 2020; Mwila *et al*., 2021) . Despite agriculture's substantial contribution to Zambia's GDP, farmers who rely primarily on rain-fed systems (CIAT and World Bank, 2017; Chavula *et al*., 2022) face increased risks due to climate change. Climate change has significantly undermined agricultural production, hitting rural smallholder farmers in Zambia particularly hard (Ng'ombe *et al*., 2017; Ngoma *et al*., 2021) . The far-reaching impacts of climate change have exacerbated poverty, food insecurity, and malnutrition across developing countries, including Zambia (Ngoma *et al*., 2021). For an economy deeply entrenched in agriculture like Zambia's, climate change poses a severe threat to economic progress, as the agricultural sector remains highly susceptible to its adverse effects (Amadu *et al*., 2020a, 2020b).

To combat the climate change-induced obstacles confronting smallholder farmers (Serote et al., 2021), Zambia has advocated and adopted diverse climate-smart agricultural (CSA) techniques for more than thirty years (Kuntashula and Mungatana, 2015; Arslan *et al*., 2018; Branca *et al*., 2019). These approaches encompass mixed cultivation, agroforestry systems, conservation agriculture practices, and other sustainable methods. These climate-smart agriculture, focus on resilience, adaptation, and mitigation, have emerged to alleviate the effects of climate change and enhance household income, and productivity (Makate *et al*., 2019). Agroforestry is regarded as a concept that covers land-use systems and practices using forest trees and agricultural crop integration, which provide multiple benefits to farmers (Leakey, 2017). The technology deliberately combines forest trees on the farming system with crops or livestock either in some form of spatial arrangements, or temporal sequence. Conservation agriculture is also referred to as a resource-efficient agriculture system with a greater output (Ng'ombe *et al*., 2014).

In Zambia, community-based organizations, non-governmental entities, and government agencies have actively promoted climate-smart agriculture (CSA) among smallholder farming communities. Among the various services offered by CSA, enhance soil nutrients and health for improved crop productivity while providing fodder for livestock, combating food shortages during dry seasons (CIAT and World Bank, 2017). Despite the numerous benefits derived from CSA practices such as agroforestry alley cropping and conservation agriculture, their adoption rate among Zambian smallholder farmers remains low (Ng'ombe *et al*., 2017; Chavula *et al*., 2023). Consequently, several studies have been undertaken to understand the factors influencing crop productivity and the adoption of CSA practices like agroforestry and conservation agriculture (Kuntashula and Mungatana, 2015; Ng'ombe *et al*., 2017). Many of these empirical investigations have focused on the role of agroforestry alley cropping and conservation agriculture in enhancing crop productivity and household welfare among smallholder farmers (CIAT and World Bank, 2017; Nkhuwa *et al*., 2019; Ngoma *et al*., 2021).

An analysis comparing soil physicochemical properties across agroforestry *G. sepium* alley cropping, conservation agriculture, and conventional agricultural systems remains largely unexplored territory in Zambia, especially in the Nyimba district. Furthermore, there is a paucity of literature delving into contribution of climate-smart agriculture *G. sepium* alley cropping and conservation agriculture on soil physicochemical properties particularly in Nyimba District, Zambian. This study aims to address critical gaps by investigating how CSA practices can improve soil physicochemical properties in the study area. Through understanding these effects, the research pursues to provide valuable insights into CSA practices that can enhance agricultural productivity and resilience in the face of climate change.

Climate, soil, and topography

Zone I of Zambia's agroecological classification covers the Nyimba district and includes the southern and eastern Rift Valleys of the Luangwa and Zambezi River basins, as well as some parts of the southern and western provinces (Gumbo *et al.,* 2016). The district receives an average annual rainfall of 600 to 900 mm, with the wettest months being December through February and the driest months from May through November. The daily air temperature ranges between 10.3 °C and 36.5 °C, with an average annual temperature of 24.2 °C. The topography features hills and plateaus, and the soils are categorized as *Fluvisol-Vertisols* in lowlands and *Lithosol-Cambisols* in higher areas. The western region of the district has higher altitudes, with elevations ranging from 450 to 1000 m.

Land use and farming systems

The Nyimba district spans roughly 10,500 km^2, with 82% of its residents living in rural areas where agriculture serves as the primary source of income, as indicated by the 2010 housing and population census (Central Statistical Office, 2010). Rural households in the district engage in mixed agriculture, cultivating crops such as groundnuts, soybeans, cowpeas, bananas, haricot beans, and finger millet. The district's diverse geography impacts farming activities. In addition to crops, smallholder farmers in Nyimba raise animals including goats, chickens, ducks, and doves. They also supplement their income by gathering firewood, charcoal, lumber, and non-timber forest products (NTFPs) from the miombo woodlands.

Materials and Methods

Location of the study area

The Nyimba district was chosen as the study area. It is located in Zambia's Eastern Province, 334 km east of Lusaka, the capital. It shares boundaries with Lusaka Province to the west, Petauke District to the east, Muchinga Province to the north, and Mozambique to the south.

Farming system of the study area

In the Nyimba district, smallholder farming is very common. Most farmers use tiny landholdings and a mixed crop-livestock system. The main staple crop is maize, which is also farmed for both domestic and commercial usage along with beans, groundnuts, sweet potatoes, and vegetables. Using crop wastes as fodder, many farmers incorporate livestock such as cattle, goats, and chickens into their farming operations. Although small-scale irrigation is used by certain farmers near rivers during the dry season, rain-fed agriculture is the norm. Due to a lack of resources, farming practices are primarily conventional with a limited use of mechanisation, fertilisers, and better seeds. Manure treatment and crop rotation are common practices for managing soil fertility.

Site selection

In order to acquire baseline data and an overview of the study location, prior soil samples were gathered and a reconnaissance was conducted there. The number of CSA host farmers' homes, the duration of the CSA's implementation, the exact location of the cropland, and the slope grade were among the data gathered throughout the exploration. The Geographic Positioning System (GPS) was used to determine the exact location of each field, and coordinates were entered onto the tablet.

Collection and Preparation of Soil Samples

Subsurface soil samples were taken from each field at a depth of 0 to 30 cm below the surface. For each identified field, we collected eight to ten random surface soil subsamples within the 0–30 cm depth range, following a zigzag pattern. These various subsamples were thoroughly mixed to create one-kilogram composite soil samples, which were then securely sealed in polybags. A total of thirty composite soil samples were prepared for laboratory analysis, with six samples obtained from each agricultural practice using the described sampling method.

Laboratory analysis

The analysis of selected soil physicochemical properties was conducted using specific methods: organic carbon and organic matter contents were determined using the Walkley-Black method, and soil pH was measured with a pH meter (Motsara and Roy, 2008). Total nitrogen (TN) was quantified using the Kjeldahl technique (Belay, 2018), available phosphorus levels were determined using Bray 1's method for acidic soils with spectrophotometric analytical instruments (Hortaand Torrent, 2007), Exchangeable bases including calcium, magnesium, sodium, and potassium were identified using Leachate Flame Atomic Absorption (FAAS) and Flame Emission Spectrometry (FES) techniques (Horta and Torrent, 2007). The cation exchange capacity (CEC) of soil samples was assessed using the Gillman and Sumpter Compulsive Exchange Method (Fauziah *et al.*, 1997), a recommended method known for its high accuracy, directness, and repeatability in quantifying soil CEC based on pH and ionic strength as endorsed by the Soil Science Society of America. The bulk density of the soil was ascertained from the undisturbed soil samples using the conventional laboratory procedure (Prikner *et al.,* 2004). The average estimate of the soil's particle density was assumed to be 2.65 g cm^{-3}, as mineral particle densities in soils typically fall within the range of 2.60 g cm^{-3} to 2.75 g cm^{-3}. The total solid soil porosity (f%) was calculated using the bulk density (P_b) and particle density (Pd) values with the following formula:

$$f(\%) = \left(1 - \frac{P_b}{P_d}\right) x\ 100$$

In this context, where f% represents porosity, Pb denotes bulk density, and Pd signifies particle density (Usoltseva *et al.,* 2021).

Data analysis

The significance of soil conditions resulting from gliricidia alley cropping, conservation agriculture basin, and ripping compared to conventional agriculture was assessed at a significance level of $p < 0.05$ using an analysis of variance (ANOVA) with Tukey's least significant difference (LSD) test using Minitab version 17 (Chandrashekar *et al.,* 2017). Data that were descriptive and inferential were both examined. The means, standard deviations, and comparisons of mean square differences between treatments were displayed along with the results.

Results

Table 1 summarizes key soil properties, including bulk density (Pb), total porosity (f), soil pH, organic carbon (OC), organic matter (OM), total nitrogen (TN), and available phosphorus (Av. P) under different croplands, revealing notable differences among treatments. Table 2 presents the exchangeable bases and cation exchange capacity (CEC) measured under different croplands, providing insights into the variations in soil nutrient content across various agricultural practices. Where; CV1= Conventional agriculture (field with no CSA) adjacent to Basin and Ripping, CV2= Conventional agriculture (field with no CSA) adjacent to *G. sepium* alley cropping.

Effects of climate-smart agricultural practices on soil bulk density and total porosity

The soil bulk density (P_b), values varied significantly across treatments, with CV1 showing the highest mean bulk density (1.69 g cm^{-3}), followed by ripping (1.31 g cm^{-3}), CV2 (1.61 g cm^{-3}), alley cropping (1.15 g cm^{-3}), and basin (1.05 g cm^{-3}). These differences were statistically significant ($p < 0.01$), indicating the impact of different agricultural practices on soil compaction. Total porosity (f) exhibited significant variability among treatments, with basin cropping showing the highest mean porosity (60.25%) (Table 1), followed by alley cropping (56.73%) and ripping (50.69%). Conversely, CV2 exhibited the lowest porosity (39.43%). These differences were statistically significant ($p < 0.01$), suggesting the influence of cropping techniques on soil structure and water-holding capacity.

Impacts of climate-smart agricultural practices on soil pH, organic carbon content, organic matter levels, total nitrogen concentrations, and available phosphorus levels

Soil pH values also differed significantly among treatments, with ripping (pH 5.63) and alley cropping (pH 5.58) exhibiting higher pH levels compared to CV1 (pH 5.16) and CV2 (pH 4.82). These differences were statistically significant ($p < 0.01$), indicating varying degrees of soil acidity or alkalinity based on cropping methods. For differences in soil pH (0–14), a significant p-value of 0.0001 ($p < 0.05$) was found. The conservation agriculture basin (5.60), ripping (5.63), and gliricidia alley cropping (5.58) all exhibited higher mean soil pH values compared to CV1 (4.82) and CV2 (5.16) (Table 1).

Organic carbon (OC) and organic matter (OM) contents were highest in alley cropping (OC 2.45%, OM 4.91%), followed by basin (OC 2.15%, OM 4.31%) and ripping (OC 1.77%, OM 3.53%). CV1 and CV2 exhibited the lowest OC and OM contents. The observed disparities were statistically significant ($p < 0.01$), underscoring the influence of agroforestry and conservation agriculture practices on soil organic content.

Total nitrogen (TN) concentrations were significantly higher in alley cropping (0.49%) and ripping (0.34%) compared to CV1 (0.25%) and CV2 (0.29%). This indicates the influence of different cropping methods on soil nitrogen levels, with alley cropping and conservation agriculture showing higher TN contents. Alley cropping showed significantly higher levels of available phosphorus (Av. P) at 36.72 mg kg^{-1}, surpassing other treatments, with ripping at 10.34 mg $kg^{-1}$and basin at 9.55 mg kg^{-1}. CV1 and CV2 demonstrated lower Av. P values. These differences were statistically significant ($p < 0.01$), suggesting the effectiveness of certain agricultural practices in promoting phosphorus availability in the soil. These mean values suggest ample available phosphorus levels conducive to crop growth and development through conservation agriculture basin, ripping, and agroforestry gliricidia alley cropping.

Impacts of climate-smart Agricultural practices on soil Exchangeable bases and Cation Exchange Capacity

Initially, concerning calcium (Ca^{2+}) levels, CV1 showed the highest mean concentration at 1.08 mmol kg^{-1}, closely followed by alley cropping at 1.16 mmol kg^{-1} and ripping at 1.31 mmol kg^{-1}. These discrepancies in Ca^{2+} content was statistically significant ($p < 0.01$), highlighting the influence of cropping practices on soil calcium availability. Conversely, basin cropping displayed the lowest Ca^{2+} levels at 0.46 mmol kg^{-1}, significantly differing from other treatments (Table 2). In terms of magnesium (Mg^{2+}), ripping exhibited the highest mean concentration at 0.24 mmol kg^{-1}, markedly distinct from other treatments such as basin cropping (0.13 mmol kg^{1}) and alley cropping (0.23 mmol kg^{-1}) ($p < 0.01$). This implies that certain agricultural methods can influence soil magnesium levels. However, the study yielded statistically insignificant findings for exchangeable Mg^{2+} levels among gliricidia alley cropping, conservation agriculture ripping, and basins when compared to conventional agriculture croplands.

Concerning potassium (K^{+}), basin cropping exhibited the highest mean value at 0.05 mmol kg^{-1}, which was significantly divergent from other treatments ($p < 0.05$). This highlights the role of cropping techniques in influencing potassium availability in the soil. Exchangeable sodium (Na^{+}) levels were relatively consistent across treatments, with ripping and CV1 exhibiting slightly higher mean concentrations compared to basin and alley cropping. These differences were statistically significant ($p < 0.01$) (Table 2), indicating the influence of cropping practices on soil sodium content. Finally, cation exchange capacity (CEC) varied significantly among treatments, with basin cropping showing the highest CEC (22.33 mmol kg^{-1}) and alley cropping exhibiting the lowest (9.33 mmol kg^{-1}) ($p < 0.01$).

Table 1

Soil bulk density, total porosity, soil pH, organic carbon, organic matter, total nitrogen, and available phosphorus under different croplands

Treatment	P_b (g cm^{-3})	f (%)	pH	OC (%)	OM (%)	TN (%)	Av. P (mg kg^{-1})
Ripping	1.31^{b} ± 0.0677**	50.69^{b} ± 2.56**	5.63^{a} ± 0.0809**	1.77^{b} ± 0.1608**	3.53^{b} ± 0.322**	0.34^{a} ± 0.0646***	10.34^{b}± 3.924**
Basin	1.05^{c} ± 0.0787**	60.25^{a} ± 2.97**	5.6^{a} ± 0.1691**	2.15^{a} ± 0.1814**	4.31^{a} ± 0.363**	0.4^{a} ± 0.0898***	9.55^{b} ± 10.77**
CV1	1.69^{a} ± 0.0991**	36.34^{c} ± 3.72**	5.16^{b} ± 0.273**	1.05^{a} ± 0.0927**	2.09^{c} ± 0.1853**	0.25^{b} ± 0.1872***	9.87^{b}± 11.99**
Alley C.	1.15^{c} ± 0.0896**	56.73^{a} ± 3.38**	5.58^{a} ± 0.2135**	2.45^{c} ± 0.277**	4.91^{a} ± 0.553**	0.49^{b} ± 0.1781***	36.72^{a}±32.53**
CV2	1.61^{a}± 0.0677**	39.43^{c} ± 2.55**	4.82^{c} ± 0.2106**	1.01^{c} ± 0.257**	2.01^{c} ± 0.515**	0.29^{a} ± 0.2234***	10.78^{b} ± 8.29**

Where; CV1= Conventional agriculture (field with no CSA) adjacent to basin and ripping, CV2= Conventional agriculture (field with no CSA) adjacent to *G. sepium* alley cropping. Significance levels: ***1%, **5% and *10%.

Table 2

Exchangeable bases, and cation exchange capacity under different croplands

Treatment	Ca^{2+} mmol kg^{-1}	Mg^{2+} mmol kg^{-1}	K^{+} mmol kg^{-1}	Na^{+} mmol kg^{-1}	CEC mmol kg^{-1}
Ripping	1.31^{a} ± 0.45**	0.24^{a} ± 0.10	0.05^{b} ± 0.01*	0.04^{a} ± 0.01**	18.50^{a} ± 4.46**
Basin	0.46^{b} ± 0.33**	0.13^{a} ± 0.11	0.04^{b} ± 0.03*	0.02^{b} ± 0.01**	22.33^{b} ± 3.88**
CV1	1.08^{a} ± 0.28**	0.18^{a} ± 0.04	0.05^{b} ± 0.02*	0.04^{b} ± 0.01**	14.00^{c} ± 4.29**
Alley C.	1.16^{c} ± 0.22**	0.23^{a} ± 0.08	0.05^{a} ± 5.10*	0.04^{c} ± 0.01**	9.33^{c} ± 2.422**
CV2	0.51^{b}± 0.18**	0.19^{a} ± 0.09	0.03^{b} ± 0.02*	0.03^{a} ± 0.01**	10.00^{c} ± 2.83**

Where; CV1= Conventional agriculture (field with no CSA) adjacent to basin and ripping, CV2= Conventional agriculture (field with no CSA) adjacent to *G. sepium* alley cropping. Significance levels: ***1%, **5% and *10.

Correlation probability; correlations are estimated using the row-wise method

The correlation coefficients among various soil properties, providing insights into their relationships within the study area. Total Nitrogen (TN) content (%) shows a significant positive correlation with Sodium (Na+) levels (0.8909), indicating that higher TN content corresponds to elevated Na+ levels in the soil. This correlation is statistically significant ($p < 0.05$). Soil Organic Carbon (OC) (%) exhibits a weak positive correlation with TN (0.0298) and a moderate positive correlation with Soil Organic Matter (OM) ($p < 0.0001$). Similarly, OM (%) correlates positively with TN (0.0298), OC ($p < 0.0001$), and several other soil properties like bulk density (Pb), soil porosity (f %), pH, and exchangeable cations (Ca2+) (Table 3). Bulk density (Pb) shows weak positive correlations with several soil properties, including TN, OC, OM, and others ($p < 0.0001$), suggesting that changes in bulk density may influence these parameters. Soil porosity (f %) exhibits similar correlations with TN, OC, OM, and other properties ($p < 0.0001$), indicating interdependencies within the soil structure and composition. The availability of Phosphorus (Av. P) (mg kg-1) demonstrates a strong positive correlation with TN (0.8073) and moderate positive correlations with OC, OM, and other soil characteristics ($p < 0.05$), highlighting the influence of nutrient availability on organic matter content and other properties. Exchangeable cations such as Na+, K+, Mg2+, and Ca2+ also exhibit various levels of correlation with each other and with other soil properties. For instance, Na+ shows a strong positive correlation with K+ (0.8991), suggesting concurrent changes in their concentrations.

Table 3

Correlation probability; the correlations are estimated by the row-wise method

Soil Properties	TN (%)	OC (%)	OM (%)	P_b (g cm^{-3})	f (%)	pH	Av. P (mg kg^{-1})	Na^{+} (mmol kg^{-1})	K^{+} (mmol kg^{-1})	Mg^{2+} (mmol kg^{-1})	Ca^{2+} (mmol kg^{1})	CEC (mmol kg^{1})
TN (%)	1											
SOC (%)	0.0298	1										
SOM (%)	0.0298	<.0001	1									
P_b (g cm^{-3})	0.0098	<.0001	<.0001	1								
f (%)	0.0097	<.0001	<.0001	<.0001	1							
pH	0.0233	<.0001	<.0001	<.0001	<.0001	1						
Av. P (mg kg^{-1})	0.8073	0.0012	0.0012	0.0177	0.0178	0.0241	1					
Na^{+} (mmol kg^{-1})	0.8909	0.6884	0.6884	0.5467	0.5505	0.6744	0.0193	1				
K^{+} (mmol kg^{-1})	0.6923	0.8662	0.8662	0.8991	0.9045	0.0859	0.4444	0.0247	1			
Mg^{2+} (mmol kg^{-1})	0.4024	0.3554	0.3554	0.2608	0.2644	0.5528	0.6781	0.0042	0.0907	1		
Ca^{2+} (mmol kg^{-1})	0.9560	0.8119	0.8119	0.6765	0.6809	0.1706	0.4111	0.0013	0.0242	<.0001	1	
CEC (mmol kg^{-1})	0.0044	0.0003	0.0003	<.0001	<.0001	0.0035	0.7832	0.2116	0.6731	0.9614	0.8419	1

Discussion

Effects of Climate-Smart Alley Cropping and Conservation Agriculture on Selected Soil Physicochemical Properties in Nyimba, Zambia

This study specifically examined *G. sepium* agroforestry alley cropping, particularly focusing on plots that had been utilized for more than five years, given its widespread adoption in the study area. In this agroforestry technique, trees are planted in wide rows, allowing a companion crop to grow in the spaces created by the alleyways between the rows. Pruning the *G. sepium* trees in the alleys results in their leaves being used as mulch or green manure, which helps retain moisture in the soil. Careful management of tree components is essential to avoid shading main crops in alley cropping systems. The study also investigated conservation agricultural practices, particularly low-tillage approaches that reduce soil disturbance, such as ripping and basin formation. These methods are known to increase agricultural yields, reduce erosion, and promote soil infiltration. Agricultural rippers are used to creating rip lines, while regular and Chaka hoes are employed to form basins or planting holes. The study focused on croplands where conservation agriculture techniques, specifically basin and ripping methods, had been employed for over five years. Additionally, the study investigated nearby conventional agricultural croplands that were similar in slope and soil type to those practicing gliricidia alley cropping and conservation agriculture (using ripping and basin techniques). Conventional agriculture usually relies on chemical inputs like fertilizers to improve crop yields.

In preliminary research, an evaluation was conducted on six croplands that practice agroforestry, specifically gliricidia alley cropping, in combination with conservation agriculture using basin and ripping methods, alongside conventional agriculture. These croplands were selected based on their proximity to one another and shared a slope gradient ranging from 0% to 10%.

The study recorded bulk density to be significantly affected by cconservation agriculture techniques such as ripping and basin formation, along with agroforestry practices like gliricidia alley cropping, exhibited greater capacity for water retention and accelerated root development, rendering them advantageous for agricultural crop cultivation in the study area. *Gliricidia sepium* alley cropping, in particular, was noted to significantly enhance soil porosity and mitigate soil bulk density, thereby fostering optimal conditions for crop growth in the study region in conformity with the study findings by Alamu *et al*. (2023). Furthermore, Senarathne and Udumann (2023) observed significant alterations in soil bulk densities with the introduction of *G. sepium* in alley cropping systems. These findings illustrate the capacity of Climate-Smart Agriculture (CSA) to augment agricultural productivity through the provision of sufficient moisture and oxygen to sustain crop growth, while also preserving crop physical attributes over time. Additionally, climate-smart agricultural practices can exert a notable influence on soil porosity, which was the case in the study area.

Soil pH across the selected agricultural practices showed significant differences similar to Doumbia *et al.* (2020) findings, highlighting the advantages of *G. sepium* alley cropping in maize croplands, particularly regarding soil pH, organic matter, soil organic carbon percentage, soil porosity, and organic nitrogen. Similarly, Kumar *et al.* (2020) illustrates the substantial influence of alley-cropped *G. sepium* tree species on soil bulk density, organic matter, organic carbon, and porosity. The lower pH values observed in CV1 and CV2 may indicate increased use of blended chemical fertilizers, leading to soil acidity from organic matter decomposition (Kumari *et al.*, 2019). The topography of the area could also impact these findings, particularly concerning the accumulation of organic waste and sediment, particularly during the rainy season (Palm *et al*., 2014).

These findings also align with Murphy *et al.* (2014), emphasizing the role that gliricidia alley cropping, basin, and conservation agriculture practices play in increasing soil organic matter. These vvariations in OC and OM may be shaped by factors such as topography, soil moisture levels, and the decomposition of organic matter from agricultural residues (Neina and Agyarko-Mintah, 2022). Likewise, Eze *et al.* (2020) reported notable enhancements in OC and OM through the adoption of Conservation Agriculture (CA) methods, highlighting the significance of effective crop residue management in CA-adopting regions for promoting OC accumulation.

Conservation agriculture approaches often result in higher soil organic carbon accumulation compared to conventional agriculture and stubble retention alone, due to changes in soil characteristics and the combined impacts of conservation agriculture (Lejissa *et al.,* 2022). Conservation agriculture, by conserving agricultural residues and minimizing soil disturbance, has been shown to contribute to increased organic matter and organic carbon, consequently affecting soil bulk density (BD) (Okonkwo *et al*., 2009; Martinsen *et al*., 2014;). Over the medium and long term, gliricidia sepium alley cropping significantly increases soil organic matter, enhancing soil nutrients and maize yields (Beedy *et al*., 2010). Similarly, steady increases in OC and OM were reported by Ivezić *et al.* (2022) concerning the use of gliricidia alley cropping in agriculture, with alley cropping producing significantly larger OC inputs compared to solitary cropping controls according to Oelbermann *et al.* (2004).

The study area recorded total nitrogen significant across treatments consistent with Hazelton *et al*. (2019), who found that *G. sepium* alley cropping resulted in high soil TN content, while conservation agriculture ripping and basin resulted in intermediate levels. According to Hazelton *et al.* (2019), utilizing climate-smart farming techniques significantly enhances soil productivity. In accordance with Naab *et al.* (2017), who reported higher soil total nitrogen and organic carbon levels with Conservation Agriculture (CA) techniques compared to conventional methods, Bohoussou *et al.* (2022) noted a substantial rise in OC and total nitrogen content linked to certain elements of CA. The observed variations are probably influenced by site-specific factors in the study area, including significant temperature fluctuations, erosion (especially prevalent during the rainy season), and soil bulk density affected by livestock compaction resulting from uncontrolled grazing.

Available phosphorus recorded significant variations among agroforestry alley cropping, conservation agriculture basin, ripping and conventional agriculture backed by Makumba *et al*. (2006) who observed that tree species in alley-cropping systems absorb natural soil nutrients (such as Av. P, Ca^{2+}, Mg^{2+}, and K^{+}) and transport them to the soil surface. Gliricidia sepium alley cropping enhances soil nutrient availability by decomposing leaf biomass while simultaneously reducing net soil nutrient levels. In the study area, conservation agriculture basin, ripping, and agroforestry gliricidia alley cropping have been adopted to maintain soil available phosphorus levels for optimal crop production. Overall, the results underscore the importance of adopting specific cropping techniques, such as agroforestry and conservation agriculture, in influencing key soil properties essential for agricultural productivity. The observed differences in bulk density, porosity, pH, organic content, nitrogen, and phosphorus highlight the potential of climate-smart farming methods in improving soil health and fertility.

In addition, exchangeable base K^{+} and N^{+} produced insignificant results in the study area due to several factors arising from slope gradient, soil organic matter and use of blended fertilizers. Whilst, exchangeable Ca^{2+} comparable significant findings were reported by Okonkwo *et al*. (2009), who observed Ca^{2+} level variations in areas under gliricidia alley cropping. Additionally, Ferdush *et al.* (2019) documented statistically significant outcomes of exchangeable Ca^{2+} concerning gliricidia alley cropping in smallholder farmers' farming systems.

Cation exchange capacity (CEC) recorded positively significant suggesting that the choice of cropping method can impact the soil's ability to retain and exchange cations. Conservation agriculture techniques often enhance soil CEC, facilitating greater nutrient cation delivery to the soil solution for crop absorption, as indicated by Kumari *et al*. (2019) and Goswami *et al.* (2020). Furthermore, the study demonstrated the efficacy of CSA in altering soil chemical properties for enhanced crop growth and productivity per hectare. CSA significantly increased exchangeable sodium, magnesium, calcium, and potassium when coupled with optimal soil nutrient management, surpassing conventional tillage techniques (Lejissa *et al*., 2022). The study underscores the impact of agricultural practices on soil nutrient dynamics, revealing significant disparities in exchangeable bases and CEC across diverse croplands. These insights inform soil management strategies geared towards enhancing nutrient availability and fostering sustainable agricultural practices. In summary, the correlation coefficients highlight intricate relationships among soil properties, emphasizing the interconnected nature and interdependence of various factors within the soil ecosystem. These findings underscore the significance of concurrently assessing multiple soil parameters when evaluating soil health and fertility in agricultural contexts.

Conclusions

The study findings demonstrate the significant benefits of adopting climate-smart agricultural practices, such as agroforestry and conservation agriculture techniques, for smallholder farmers in Zambia. Compared to conventional agricultural practices, the implementation of gliricidia alley cropping combined with basins and ripping resulted in remarkable improvements in several soil characteristics, including pH levels, available phosphorus content, soil porosity, bulk density, cation exchange capacity, and exchangeable bases. These positive impacts on soil fertility were correlated with increased crop yields, underscoring the potential of climate-smart agriculture to enhance productivity and food security for smallholder farmers. Given the promising results, it is crucial for stakeholders, including the Zambian government, community-based organizations, and non-governmental organizations working towards agricultural development, poverty reduction, and climate change adaptation and resilience, to take note and actively promote the integration of climate-smart agriculture practices into smallholder farming systems. Comprehensive measures, such as policy reforms and support programs, are necessary to facilitate the widespread adoption of these sustainable and climate-resilient practices. While this study provides valuable insights into the effects of climate-smart agriculture on specific soil physicochemical properties, further research is warranted to address the challenges associated with implementation, evaluate the impact on soil micronutrient levels across different regions, and delve deeper into the experiences and perspectives of individual smallholder farmers. Additionally, future studies should consider other factors not covered in this analysis to provide a more comprehensive understanding of climate-smart agriculture's potential benefits and limitations in the Zambian context.

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Data availability

Data is available upon request from the journal editorial board.

Author’s declaration

All authors have read and agreed to the published version of the manuscript.

Extent of use of artificial intelligence tools

No artificial intelligence tools were used in designing this study.

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