

COMPARATIVE ANALYSIS OF SOIL FERTILITY, MAIZE YIELD AND SOIL–YIELD RELATIONSHIPS UNDER FARMER-MANAGED *GLIRICIDIA SEPIUM* AGROFORESTRY AND CONVENTIONAL FARMING IN KATETE DISTRICT, ZAMBIA

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Abstract

Declining soil fertility remains a major constraint to sustainable maize production among smallholder farmers in Zambia, highlighting the need for sustainable land management practices such as agroforestry. This study comparatively assessed soil fertility, maize grain yield and soil–yield relationships under farmer-managed *Gliricidia sepium* agroforestry and conventional farming systems in Katete District, Zambia. A comparative cross-sectional study was conducted on 20 purposively selected smallholder farms comprising 10 agroforestry and 10 conventional maize farms. Composite soil samples (0–30 cm) were analysed for soil pH, organic carbon, total nitrogen, available phosphorus, and exchangeable potassium, calcium, magnesium and sodium. Maize grain yield was determined using the crop-cut method. Data were analysed using descriptive statistics, Welch's independent-samples t-test, Pearson's correlation and multiple linear regression. Agroforestry farms had significantly higher soil pH, organic carbon, total nitrogen, available phosphorus and exchangeable potassium than conventional farms ($p < 0.05$), while sodium, calcium and magnesium did not differ significantly ($p > 0.05$). Mean maize grain yield was significantly higher under agroforestry ($3,750.00 \pm 716.86 \text{ kg ha}^{-1}$) than conventional farming ($1,980.00 \pm 229.98 \text{ kg ha}^{-1}$), representing an 89.4% higher yield ($p < 0.001$). Maize grain yield was positively associated with several soil fertility parameters. Soil organic carbon and total nitrogen were independently associated with maize grain yield ($R^2 = 0.811$; adjusted $R^2 = 0.789$; $p < 0.001$). The findings indicate that farmer-managed *Gliricidia sepium* agroforestry is associated with improved soil fertility and higher maize grain yield.

Keywords: *Gliricidia sepium*, agroforestry, soil fertility, maize grain yield, smallholder farming, Zambia.

1. Introduction

Maize (*Zea mays L.*) is Zambia's principal staple crop and contributes significantly to national food security, household livelihoods, and the agricultural economy. It occupies the largest proportion of cultivated land and is grown by the majority of smallholder farmers across the country. According to

the Zambia Statistics Agency (ZamStats, 2024), maize accounts for the largest share of national cereal production and remains the country's most important food crop. Despite its importance, maize productivity has remained below its potential because of declining soil fertility, land degradation, erratic rainfall, and increasing climate variability. These constraints continue to threaten sustainable maize production and highlight the need for climate-smart land management practices capable of improving soil fertility and crop productivity.

Continuous maize cultivation, inadequate nutrient replenishment, declining soil organic matter, and limited access to inorganic fertilizers have accelerated soil nutrient depletion across many smallholder farming systems in sub-Saharan Africa. As a result, reductions in soil organic carbon, total nitrogen, and available phosphorus have impaired soil productivity, reduced nutrient-use efficiency, and increased the vulnerability of farming systems to climate variability (Pan et al., 2025). Restoring soil fertility through sustainable land management practices has therefore become a priority for improving agricultural productivity while maintaining environmental sustainability.

Agroforestry has emerged as one of the most promising climate-smart agricultural practices for restoring degraded soils and improving crop productivity. The integration of trees with annual crops enhances nutrient cycling, increases soil organic matter, improves soil structure, reduces soil erosion, and promotes water infiltration, thereby contributing to sustainable agricultural intensification (Kuyah et al., 2019; van Noordwijk, 2021). Fertilizer-tree systems further improve soil fertility through biological nitrogen fixation, deep nutrient capture, and continuous biomass inputs, which collectively enhance nutrient availability for associated crops (Nair et al., 2022; Lehmann et al., 2020).

Among the fertilizer-tree species promoted in southern Africa, *Gliricidia sepium* is widely recognised for its contribution to improving soil fertility and sustaining maize production. Long-term studies have shown that *Gliricidia sepium* increases soil organic matter, enhances biological nitrogen fixation, and improves nutrient cycling through the continuous addition of nutrient-rich leaf litter and root biomass (Pan et al., 2025; Nair et al., 2022). These processes improve soil organic carbon accumulation, increase nutrient availability, and enhance long-term soil productivity. Consequently, *Gliricidia sepium* has been widely promoted in Zambia as a climate-smart agricultural practice for restoring degraded soils, improving fertilizer-use efficiency, and enhancing the productivity and resilience of smallholder farming systems.

Previous studies have consistently reported positive effects of agroforestry on soil fertility and crop performance. Meta-analyses have shown that agroforestry systems generally improve soil organic carbon, nutrient availability and crop productivity compared with conventional monocropping systems (Kuyah et al., 2019; Pan et al., 2025). Similarly, comparative studies conducted under smallholder farming conditions have demonstrated that agroforestry contributes to higher maize yields through improvements in soil fertility, moisture conservation and resilience to climate variability (Thierfelder et al., 2018;). Nevertheless, the magnitude of these benefits varies considerably among agroecological regions because of differences in soil characteristics, climatic conditions, tree management practices and farming systems.

Despite growing evidence supporting agroforestry adoption, important knowledge gaps remain. Most previous studies have either evaluated soil fertility or crop productivity independently, while relatively few have simultaneously assessed soil fertility parameters, maize grain yield and the relationships

between these variables under farmer-managed agroforestry systems. Furthermore, much of the available evidence has been generated from experimental research stations or multi-country assessments, with limited empirical evaluation under actual smallholder farming conditions in Zambia. Site-specific evidence remains particularly limited for farmer-managed *Gliricidia sepium* agroforestry systems in Katete District, where agroforestry has been promoted as a sustainable strategy for restoring soil fertility and improving maize productivity. The original study underlying this article was designed to address this evidence gap by comparing soil fertility parameters, maize grain yield and soil–yield relationships between agroforestry and conventional farming systems in Katete District. This study therefore comparatively assessed soil fertility, maize yield and soil–yield relationships under farmer-managed *Gliricidia sepium* agroforestry and conventional farming systems in Katete District, Zambia. Specifically, the study sought to

- (i) Compare selected soil fertility parameters between agroforestry and conventional farming systems,
- (ii) Compare maize grain yield between the two farming systems, and
- (iii) Determine the relationships between soil fertility parameters and maize grain yield.

It was hypothesised that significant differences exist in soil fertility and maize yield between agroforestry and conventional farming systems and that soil fertility parameters are significantly associated with maize grain yield. The findings contribute empirical evidence to support sustainable land management policies and agroforestry promotion among smallholder farmers in Zambia. The remainder of the article reviews relevant literature on agroforestry, soil fertility and maize productivity, describes the materials and methods used in the study, presents and discusses the findings, and provides the conclusions and recommendations.

2. Literature Review and Theoretical Framework

2.1 Agroforestry and Soil Fertility in Smallholder Farming Systems

The sustainability of smallholder farming systems depends largely on maintaining soil fertility. Agroforestry is widely recognised as a sustainable land management practice that improves soil chemical, physical, and biological properties. Its effects on soil fertility, however, vary with agroecological conditions, tree species, management practices, and study design. Kuyah et al. (2019), through a systematic review and meta-analysis of 126 studies across Sub-Saharan Africa, found that agroforestry improved soil pH by enhancing nutrient cycling and organic matter inputs. Although comprehensive, the study combined different agroforestry systems and geographical regions, making it difficult to isolate the effects of *Gliricidia sepium*. Alamu et al. (2023) similarly reported higher soil pH under long-term *Gliricidia*-maize intercropping than under maize monocropping in Southern Malawi, attributing the improvement to enhanced organic matter and nutrient recycling. However, the experiment was conducted under controlled research conditions, limiting its applicability to farmer-managed systems. Chavula et al. (2023) observed modest improvements in soil pH among Zambian farmers practising agroforestry. Nevertheless, soil pH was not the primary variable, and detailed laboratory comparisons between agroforestry and non-agroforestry fields were lacking. Soil organic carbon is a key indicator of soil quality because it influences nutrient availability, soil structure, moisture retention, and biological activity. Agroforestry enhances soil organic carbon through litter deposition, root turnover, and reduced soil disturbance. Pan et al. (2025), using a meta-analysis of more than 100

tropical studies, found significantly higher soil organic carbon under agroforestry than under conventional agriculture, particularly in long-established systems. However, the findings represent diverse environments and do not specifically evaluate *Gliricidia sepium* or its influence on maize productivity. Pan et al. (2025) demonstrated that fertilizer-tree systems in Zambia and Malawi significantly increased soil organic carbon and nutrient retention, although the work was conducted under research-managed conditions. Likewise, Nair et al. (2022) concluded that agroforestry enhances soil carbon sequestration but focused primarily on environmental benefits rather than crop productivity. Nitrogen deficiency remains a major constraint to crop production in Sub-Saharan Africa. Leguminous trees such as *Gliricidia sepium* improve soil nitrogen through biological nitrogen fixation and biomass decomposition. Alamu et al. (2023) reported consistently higher nitrogen concentrations under fertilizer-tree systems across Zambia, Malawi, and Mozambique. Chavula et al. (2023), however, found that nitrogen accumulation varied considerably among farms due to differences in tree density and management, indicating that agroforestry benefits depend on implementation. Similarly, Chavula et al. (2023) observed higher soil nitrogen among agroforestry adopters in Zambia but focused mainly on adoption and economic outcomes. Kuyah et al. (2019) further argued that increased nitrogen alone does not guarantee higher yields unless accompanied by improvements in other soil fertility parameters.

Available phosphorus is essential for root development, energy transfer, and grain formation, yet deficiencies are common in tropical soils. Agroforestry improves phosphorus availability through enhanced nutrient cycling and organic matter decomposition. Kuyah et al. (2019) demonstrated that increased organic matter promotes microbial processes that release phosphorus into plant-available forms, although the review lacked field-specific evidence. Tchima et al. (2025) found significantly higher phosphorus levels under agroforestry in Cameroon, while Kuyah et al. (2019) showed that phosphorus responses varied according to local soil conditions. In Zambia, Chavula et al. (2023) observed improved soil nutrient status following the establishment of fertilizer trees but did not specifically evaluate the contribution of *Gliricidia sepium*.

Exchangeable bases, including potassium, calcium, magnesium, and sodium, are essential for maintaining soil fertility and crop productivity. Agroforestry enhances these nutrients through nutrient recycling, biomass decomposition, and deep-root nutrient uptake. Alamu et al. (2023) demonstrated that deep-rooted trees improve exchangeable base concentrations through nutrient uplift, while Lehmann et al. (2020) reported higher potassium and calcium under agroforestry across several African countries. Islam & Das (2021) similarly found greater potassium and magnesium concentrations in fertilizer-tree systems, although the study focused mainly on nutrient restoration. Islam & Das (2021) also reported significantly higher calcium and magnesium under agroforestry in West Africa. Despite these findings, research from Zambia has given limited attention to exchangeable bases under farmer-managed *Gliricidia sepium* systems and their relationship with maize grain yield.

2.2 Agroforestry and Maize Grain Yield

The effectiveness of any soil fertility management practice is ultimately measured by its ability to improve crop productivity. Although agroforestry is widely recognised for restoring soil fertility, its effects on maize grain yield vary across environments, management practices, and agroforestry systems. Alamu et al. (2023) evaluated long-term fertilizer-tree systems in Zambia, Malawi, and Tanzania using field experiments conducted over several cropping seasons. Their findings showed that

maize grown under *Gliricidia*-based systems consistently outperformed conventional unfertilised systems, with yields increasing from below 2 t ha⁻¹ to over 5 t ha⁻¹. However, the experiments were conducted under controlled conditions with technical support, limiting their applicability to typical smallholder farming conditions. Using a cross-sectional survey in Nyimba District, Zambia, Chavula et al. (2023) found that households practising agroforestry achieved significantly higher maize yields than non-adopters. Nevertheless, the study focused on adoption and household welfare without incorporating detailed soil laboratory analyses to explain yield differences. Not all studies have reported consistent yield improvements. Baier et al. (2023) demonstrated that excessive competition for light, moisture, and nutrients can reduce maize yields where tree density and pruning are poorly managed. Similarly, Baier et al. (2023) observed that agroforestry benefits were greatest on degraded soils and less pronounced in relatively fertile areas. Kuyah et al. (2019), through a meta-analysis of over 100 studies, concluded that agroforestry generally enhances crop productivity but that responses vary considerably with environmental conditions and management practices. Alamu et al. (2023) compared *Gliricidia*-based agroforestry with conventional maize production in Southern Malawi over several seasons. Agroforestry plots consistently produced higher maize yields, particularly during low-rainfall years, owing to improved soil fertility and moisture conservation. However, the controlled experimental setting may not reflect the variability found under farmer-managed conditions. Thierfelder et al. (2018) evaluated agroforestry through on-farm trials across Southern Africa and found that agroforestry generally outperformed conventional systems in degraded and moisture-stressed environments. Nevertheless, agroforestry was assessed alongside other sustainable intensification practices, making it difficult to isolate its independent contribution.

In contrast, Giller et al. (2021) argued that agroforestry does not consistently outperform conventional agriculture because benefits may be constrained by labour shortages, delayed tree establishment, and competition between trees and crops. Likewise, Chavula et al. (2023) found a positive association between agroforestry and crop productivity in Zambia but relied mainly on self-reported production data without direct soil fertility measurements. Overall, the literature suggests that agroforestry frequently outperforms conventional farming systems, particularly where soils are degraded and rainfall is variable. However, the magnitude of these benefits depends on management practices and local environmental conditions.

2.3 Relationship Between Soil Fertility and Maize Grain Yield

Soil pH is widely regarded as a master variable because it influences nutrient availability, microbial activity, and root development. Ichami et al. (2019) found that maize yields declined significantly when soil pH fell below 5.5 due to reduced nutrient availability and increased aluminium toxicity. However, the findings were largely based on experimental conditions rather than farmer-managed production systems. Similarly, Laub et al. (2025) reported a significant positive relationship between soil pH and maize grain yield, although soil pH explained only part of the variation in maize yield. In contrast, Vanlauwe et al. (2015) found that improvements in soil pH did not always translate into higher maize yields where nitrogen deficiency, moisture stress, or poor agronomic practices remained limiting factors.

Soil organic carbon influences nutrient retention, water-holding capacity, soil structure, and microbial activity. Laub et al. (2025) revealed a strong positive association between soil organic carbon and maize yield, although the relationship varied depending on nutrient availability, rainfall, and management

practices. Asamoah et al. (2024) identified soil organic carbon as one of the strongest predictors of maize grain yield using regression analysis. Likewise, Bationo and Fening (2018) found that soil organic carbon influenced maize productivity both directly and indirectly through improved nutrient availability and soil moisture retention, with the benefits being more pronounced in degraded soils than in relatively fertile environments.

Nitrogen is widely recognised as the nutrient that most frequently limits maize production in Sub-Saharan Africa. Vanlauwe et al. (2015) identified nitrogen deficiency as one of the major constraints to maize productivity but emphasised that yield responses varied with rainfall, soil conditions, and the availability of other nutrients. Similarly, Laub et al. (2025) found that total nitrogen was one of the strongest predictors of maize grain yield. Laub et al. (2025), also demonstrated that nitrogen use efficiency depended on complementary factors, particularly phosphorus availability and soil organic matter, highlighting the interactive nature of soil fertility parameters.

Phosphorus is an essential macronutrient required for energy transfer, root development, flowering, and grain formation. Alamu et al. (2023) identified phosphorus deficiency as a major cause of low maize yields. Similarly, Laub et al. (2025) reported a strong positive relationship between phosphorus availability and maize grain yield but noted that responses varied with soil organic matter content and rainfall. Bationo et al. (2018) found that phosphorus was one of the strongest predictors of maize yield after nitrogen. Nevertheless, these studies largely focused on fertilizer management and conventional cropping systems rather than farmer-managed agroforestry.

Exchangeable bases also contribute to maize productivity. Laub et al. (2025) found that potassium deficiencies significantly reduced maize yields, particularly in soils that had been continuously cultivated for many years. Laub et al. (2025) identified exchangeable potassium as a significant predictor of grain yield, while calcium and magnesium exerted indirect effects through their influence on soil chemical balance and nutrient uptake efficiency. Chivenge et al. (2017) similarly showed that maize yields declined substantially where potassium availability was inadequate, even when nitrogen and phosphorus were supplied in sufficient quantities. However, most available research has focused on fertiliser trials, nutrient omission experiments or conventional farming systems.

2.4 Theoretical Framework

This study is informed by the Sustainable Livelihoods Framework, Human Capital Theory and Diffusion of Innovation Theory. These theories provide complementary perspectives on how smallholder farmers adopt agroforestry practices and how such practices contribute to improved agricultural productivity and livelihood outcomes. The Sustainable Livelihoods Framework was developed by the Department for International Development and was largely influenced by the work of Chambers and Conway (1992). The framework explains how households utilise available livelihood assets to pursue strategies that improve their welfare and resilience. Livelihood outcomes are influenced by access to natural, human, social, physical and financial capital. Natural capital is particularly important in agricultural systems because it includes land, water and soil resources upon which farming depends. Agroforestry contributes directly to natural capital by improving soil fertility, increasing biodiversity and enhancing environmental sustainability. Human Capital Theory was developed by Becker (1964) and argues that investments in knowledge, skills and education increase the productivity and efficiency of individuals. The theory is relevant to agroforestry because successful establishment and management of

agroforestry systems require technical knowledge regarding tree management, pruning, soil fertility improvement and crop-tree interactions. However, Human Capital Theory focuses primarily on individual capabilities and pays limited attention to environmental and institutional factors that influence agricultural outcomes.

Diffusion of Innovation Theory was developed by Rogers (2003) and explains how new technologies and innovations spread within a social system over time. Agroforestry is often introduced as an agricultural innovation requiring behavioural change among farmers. The adoption of *Gliricidia sepium* agroforestry depends on farmers' perceptions regarding its benefits, costs and compatibility with existing farming systems. Despite its usefulness in explaining technology adoption, the theory focuses mainly on the adoption process and provides limited insight into how agroforestry affects soil fertility, crop productivity and livelihood outcomes after adoption. Although all three theories contribute to understanding different dimensions of agroforestry, the Sustainable Livelihoods Framework serves as the guiding theory for this study. Unlike Human Capital Theory and Diffusion of Innovation Theory, which focus primarily on knowledge acquisition and technology adoption respectively, the Sustainable Livelihoods Framework provides a broader perspective linking natural resource management to livelihood outcomes. Agroforestry improves natural capital through enhanced soil fertility, which in turn increases agricultural productivity and contributes to improved livelihoods.

2.5 Conceptual Framework

The conceptual framework posits that the adoption of *Gliricidia sepium*-based agroforestry systems enhances soil fertility through improvements in soil pH, soil organic carbon, total nitrogen, available phosphorus and exchangeable bases, thereby increasing maize grain yield and ultimately contributing to improved household livelihoods, food security and economic well-being among smallholder farmers, while these relationships are influenced by prevailing biophysical and socio-economic conditions (Figure 1).

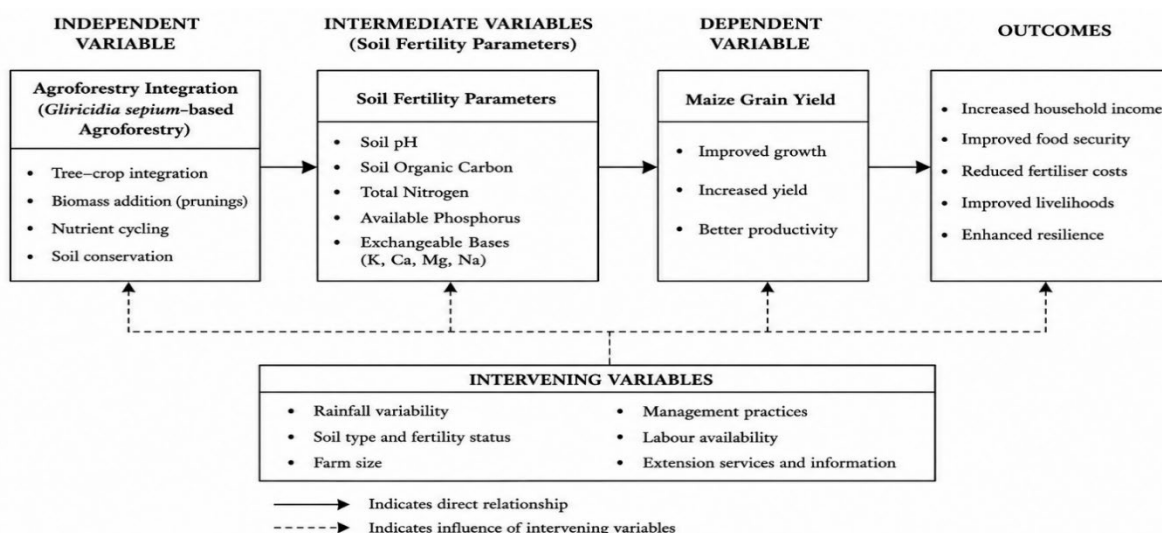


Figure 1: Conceptual Framework Showing the Relationship Between Agroforestry Integration, Soil Fertility Parameters and Maize Grain Yield

Source: Authors

2.6 Knowledge Gap and Contribution of the Study

Although numerous studies have demonstrated the potential of agroforestry to improve soil fertility and enhance crop productivity, important knowledge gaps remain. Existing research has largely been conducted under controlled experimental conditions, long-term research station trials or broad regional assessments, limiting the generalizability of findings to farmer-managed production systems. While studies by Alamu et al. (2023) reported positive effects of fertilizer trees on soil fertility and maize productivity, most focused on experimental plots where management practices were carefully controlled. Consequently, there is limited empirical evidence on the performance of agroforestry systems under the diverse management conditions encountered by smallholder farmers. Furthermore, many studies have examined either soil fertility improvement or crop productivity independently, with relatively few simultaneously assessing the relationship between specific soil fertility parameters and maize grain yield. Where such relationships have been investigated, emphasis has often been placed on individual nutrients, particularly nitrogen and phosphorus, with limited attention given to the combined influence of soil pH, soil organic carbon, total nitrogen, available phosphorus and exchangeable bases on maize productivity. At the national level, research on agroforestry in Zambia has primarily concentrated on technology adoption, soil fertility restoration and household welfare outcomes. Comparatively little attention has been devoted to generating site-specific evidence from Eastern Province, particularly Katete District, where *Gliricidia sepium* based agroforestry has been promoted among smallholder farmers. In addition, limited studies have directly compared soil fertility parameters and maize grain yield between agroforestry and non-agroforestry fields under farmer-managed conditions. Therefore, the existing literature provides insufficient evidence regarding the extent to which *Gliricidia sepium* based agroforestry influences soil fertility parameters and how these changes translate into maize productivity and economic benefits for smallholder farmers in Katete District. The present study addresses this gap by undertaking a comparative assessment of soil fertility status and maize grain yield in agroforestry and non-agroforestry farming systems and by determining the relationship between selected soil fertility parameters and maize productivity under smallholder farming conditions.

3. Materials and Methods

3.1. Study design and context

The study employed a comparative cross-sectional field design to evaluate differences in soil fertility parameters and maize grain yield between farmer-managed *Gliricidia sepium* agroforestry and conventional farming systems. The design enabled the simultaneous assessment of soil fertility status, maize productivity and the relationships between selected soil fertility parameters and grain yield under naturally occurring farmer-managed field conditions. The study was conducted in Chilembwe and Mzime Agricultural Camps of Katete District, Eastern Province, Zambia. Katete District is located within Zambia's Agro-Ecological Region II, characterized by an average annual rainfall of approximately 800–1,000 mm, with the rainy season extending from November to April, and mean annual temperatures ranging from 18°C to 30°C, conditions favourable for rain-fed maize production (Alvarez et al., 2018; Zambia Meteorological Department, 2023). The district was purposively selected because farmer-managed *Gliricidia sepium* agroforestry systems coexist with conventional maize production systems, providing an appropriate setting for evaluating the effects of contrasting land management practices on soil fertility, maize grain yield and soil–yield relationships.

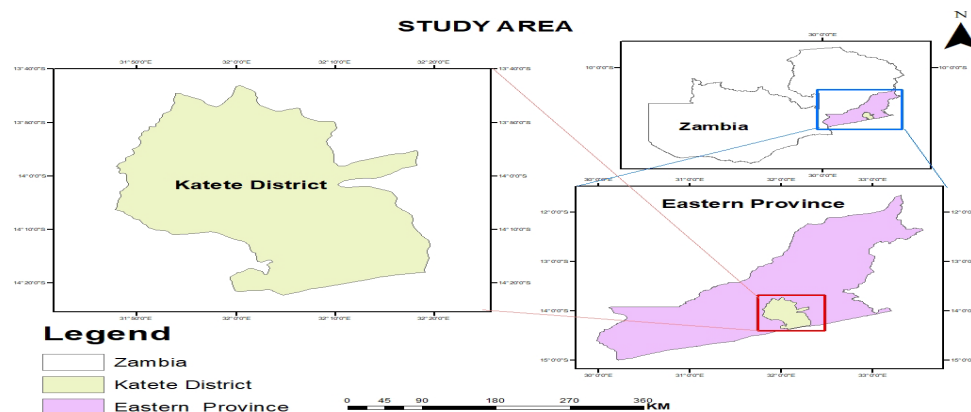


Figure 2: Location of Chilembwe and Mzime Agricultural Camps in Katete District, Eastern Province, Zambia.

Source: Authors' construction based on administrative boundary data, 2026

3.2. Data, variables, and sampling

A purposive matched sampling technique was employed to select 20 smallholder farms from Chilembwe and Mzime Agricultural Camps in Katete District. The sample comprised 10 farmer-managed *Gliricidia sepium* agroforestry farms and 10 conventional maize farms. Farmers practising *Gliricidia sepium* agroforestry were identified with the assistance of Agricultural Extension Officers based on the established presence of *Gliricidia sepium* trees integrated within their maize fields and their willingness to participate in the study. The study sample was distributed equally between the two agricultural camps. Ten farms were selected from Chilembwe Agricultural Camp and ten farms from Mzime Agricultural Camp. Within each agricultural camp, five farmer-managed *Gliricidia sepium* agroforestry farms and five conventional maize farms were selected, ensuring equal representation of both farming systems across the two study locations. To improve comparability between the farming systems, each agroforestry farm was matched with a nearby conventional maize farm having similar soil type, topography, field size and general management history. This matched sampling approach was intended to minimise environmental variation unrelated to the farming system and improve the validity of comparisons between agroforestry and conventional farming. Eligible agroforestry farms had established *Gliricidia sepium* trees integrated within maize fields and were actively managed under the agroforestry system during the study period. Conventional farms consisted of maize monocropping fields without *Gliricidia sepium* or other agroforestry tree species and were cultivated under comparable environmental conditions. All selected farms were under active maize production during the study season and were accessible for soil sampling and maize grain yield assessment. Purposive sampling was considered appropriate because farmer-managed *Gliricidia sepium* agroforestry systems are relatively uncommon within the study area and the study specifically required farms with established agroforestry systems for comparison with conventional maize farms. Although this sampling approach limits statistical generalisation to the wider farming population, the matched design strengthened internal validity by reducing environmental differences between the two farming systems. The study included 20 farms, comprising 10 farmer-managed *Gliricidia sepium* agroforestry farms and 10 conventional maize farms. The sample was constrained by the number of eligible and accessible farmer-managed agroforestry systems within the selected agricultural camps and should

therefore be regarded as a focused comparative field sample rather than a population-representative survey. A sensitivity power analysis was conducted to determine the magnitude of group difference that could be detected using 10 farms per group, a two-sided significance level of 5% and statistical power of 80%. The analysis indicated that the study could reliably detect a standardised mean difference of approximately 1.32 or greater. The observed standardised difference in maize grain yield was substantially larger, with Cohen's $d = 3.32$ and Hedges' $g = 3.18$, corresponding to statistical power exceeding 99%. The sample was therefore adequate for detecting the large observed yield difference between the two farming systems. Nevertheless, the sample may have been insufficient to detect small or moderate differences in some soil properties, and non-significant results should not automatically be interpreted as evidence that the farming systems were equivalent. The farmer-managed *Gliricidia sepium* agroforestry systems included in the study had been established for at least three years before data collection. This minimum establishment period was considered sufficient to permit measurable changes in soil fertility and maize production arising from the integration of *Gliricidia sepium* into the farming system. The *Gliricidia sepium* trees were planted in rows within maize fields, following the agroforestry practices commonly promoted by agricultural extension services in the study area. Tree management involved at least one pruning during the cropping season to reduce shading and minimise competition with maize. The pruned biomass, comprising leaves and small branches, was left on the soil surface to decompose naturally, thereby contributing organic matter and recycling nutrients within the field. The agroforestry fields did not receive inorganic fertilisers during the study period. Soil fertility management was based primarily on the biological nitrogen fixation capacity of *Gliricidia sepium* and the decomposition of pruned biomass. This management approach enabled the study to evaluate the associations between farmer-managed *Gliricidia sepium* agroforestry, soil fertility and maize grain yield under low-external-input smallholder farming conditions.

Soil samples were collected from the 0–30 cm depth because this layer represents the active root zone for maize and is the portion of the soil most influenced by cultivation, fertiliser application, organic matter decomposition, and other soil management practices. Consequently, it provides the most representative assessment of changes in soil fertility resulting from agroforestry and conventional farming systems (Hazelton & Murphy, 2016). Samples were air-dried, gently crushed and passed through a 2-mm sieve before laboratory analysis.

Laboratory analyses were conducted at the Zambia Agricultural Research Institute (ZARI), Msekera Research Station, following standard analytical procedures. Soil pH was determined in a 1:2.5 soil-to-calcium chloride (CaCl_2) suspension. Soil organic carbon was determined using the Walkley–Black wet oxidation method (Walkley & Black, 1934), total nitrogen using the Kjeldahl digestion method (Bremner, 1996), available phosphorus using the Bray I extraction method (Bray & Kurtz, 1945), while exchangeable potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na) were extracted using 1 M ammonium acetate and quantified by atomic absorption spectrophotometry (Thomas, 1982).

Maize grain yield was determined at physiological maturity using the standardized crop-cut method. A $10\text{ m} \times 10\text{ m}$ (100 m^2) quadrat was randomly established within each field while excluding border rows to minimise edge effects. All maize plants within the quadrat were harvested, shelled and weighed. Grain weights were adjusted to the standard 15.5% moisture content, after which grain yield was converted to kilograms per hectare (kg ha^{-1}) for statistical analysis. Participation in the study was entirely voluntary. Before data collection, the purpose and objectives of the study were clearly

explained to all participating farmers. Farmers who agreed to participate provided informed verbal consent prior to soil sampling, field measurements and the collection of maize yield data. Participants were informed that their involvement was voluntary and that they were free to withdraw from the study at any stage without any adverse consequences.

The study involved non-invasive field observations, soil sampling and crop yield measurements conducted on farmers' fields and did not involve human clinical interventions, collection of sensitive personal information or activities that posed physical, psychological or social risks to participants. Consequently, formal institutional ethical approval was not required. Nevertheless, the study was conducted in accordance with the ethical principles of voluntary participation, informed consent, confidentiality and respect for participants. Personal identifiers were not recorded, and all data were analysed and reported in aggregate form to protect participants' privacy. Permission to conduct the study was obtained from the relevant agricultural authorities in Katete District, and data collection was undertaken with the cooperation of Agricultural Extension Officers and the participating farmers.

3.3. Analytical methods

Data were analysed using Python version 3.12. Statistical analysis was conducted at a 5% level of significance. The dataset consisted of 20 farms, comprising 10 farmer-managed *Gliricidia sepium* agroforestry farms and 10 conventional maize farms. Descriptive statistics, including means, standard deviations, minimum values and maximum values, were initially calculated for maize grain yield and the selected soil fertility parameters. The distribution of each continuous variable was assessed using the Shapiro–Wilk test, histograms and normal quantile plots. Equality of variances between the two farming systems was assessed using Levene's test. Differences in soil fertility parameters and maize grain yield between agroforestry and conventional farming systems were evaluated using Welch's independent-samples t-test. Welch's test was applied consistently because it does not require equal group variances and is more robust than the conventional Student's t-test when group sample sizes are small. Results were reported using group means and standard deviations, mean differences, t-statistics, Welch-adjusted degrees of freedom, exact p-values and 95% confidence intervals. Hedges' g was calculated as the standardised effect size because it provides a small-sample correction to Cohen's d. Absolute Hedges' g values of approximately 0.20, 0.50 and 0.80 were interpreted as small, moderate and large effects, respectively. The adequacy of the sample for the comparison of the two farming systems was evaluated using a two-sided sensitivity power analysis at $\alpha = 0.05$ and 80% statistical power. With 10 farms in each group, the study was capable of reliably detecting a standardised difference of approximately 1.32 or greater. Consequently, the group comparisons were considered sufficiently powered for large differences but not for small or moderate effects. Pearson's correlation analysis was used to assess the bivariate relationships between maize grain yield and individual soil fertility parameters. Correlation coefficients were interpreted according to their direction, magnitude and statistical significance. Since the study was cross-sectional and observational, the correlation results were interpreted as associations rather than causal relationships.

The original regression model containing eight soil predictors was considered overly complex relative to the sample of 20 farms. A parsimonious multiple linear regression model was therefore specified using soil organic carbon and total nitrogen as predictors of maize grain yield. These variables were retained because they represent key mechanisms through which leguminous agroforestry systems may influence soil fertility and maize productivity, while also showing low multicollinearity in the revised

model. The reduced model provided approximately 6.7 observations per estimated regression parameter (20 observations divided by three estimated parameters, including the intercept) and was treated as exploratory because of the limited sample size.

The regression model was evaluated using the coefficient of determination, adjusted coefficient of determination, overall F-test, unstandardised coefficients, standardised coefficients, standard errors, t-statistics, exact p-values and 95% confidence intervals. Multicollinearity was assessed using variance inflation factors. Residual normality was assessed using the Shapiro–Wilk test and a normal Q–Q plot, while homoscedasticity was assessed using the Breusch–Pagan test and a plot of standardised residuals against fitted values. Influential observations were examined using Cook’s distance, leverage values and externally studentised residuals. No observation was deleted solely based on statistical influence unless it was confirmed to represent a measurement or data-entry error.

4. Results

4.1 Soil Fertility under Farmer-Managed *Gliricidia sepium* Agroforestry and Conventional Farming Systems

Table 1 shows that soil fertility differed between farmer-managed *Gliricidia sepium* agroforestry and conventional farming systems for five of the eight parameters assessed. Soil pH was significantly higher under agroforestry than conventional farming, with a mean difference of 1.28 pH units (95% CI: 1.15 to 1.42; $p = 1.83 \times 10^{-13}$) and an extremely large effect size (Hedges’ $g = 8.50$). Soil organic carbon was also significantly higher under agroforestry, with a mean difference of 0.50 percentage points (95% CI: 0.36 to 0.64; $p = 5.96 \times 10^{-7}$) and a very large effect size (Hedges’ $g = 3.25$).

Table 1. Comparison of soil fertility parameters between farming systems

Soil parameter	Agroforestry, mean $\pm$ SD	Conventional, mean $\pm$ SD	Mean difference	95% CI	Welch’s t	Df	Exact p	Hedges’ g
pH, CaCl ₂	6.38 $\pm$ 0.13	5.09 $\pm$ 0.16	1.28	1.15 to 1.42	19.86	17.54	1.83×10^{-13}	8.50
Organic carbon, %	1.62 $\pm$ 0.16	1.12 $\pm$ 0.14	0.50	0.36 to 0.64	7.59	17.59	5.96×10^{-7}	3.25
Total nitrogen, %	0.031 $\pm$ 0.010	0.018 $\pm$ 0.008	0.013	0.005 to 0.021	3.24	17.11	0.0048	1.39
Available phosphorus, mg kg ⁻¹	19.92 $\pm$ 1.79	13.60 $\pm$ 4.97	6.32	2.65 to 9.99	3.78	11.31	0.0029	1.62
Potassium, ppm	176.23 $\pm$ 3.49	131.65 $\pm$ 24.72	44.58	26.82 to 62.33	5.65	9.36	0.00027	2.42
Sodium, ppm	92.53 $\pm$ 17.47	82.79 $\pm$ 9.37	9.74	–3.72 to 23.21	1.55	13.78	0.1429	0.67
Calcium, ppm	1,555.50 $\pm$ 238.88	1,517.66 $\pm$ 352.28	37.85	–247.73 to 323.42	0.28	15.83	0.7822	0.12
Magnesium, ppm	215.58 $\pm$ 60.90	250.21 $\pm$ 10.00	–34.63	–78.44 to 9.18	–1.77	9.49	0.1081	–0.76

Source: Field and laboratory data, 2026.

Note: Positive differences indicate higher means under agroforestry. Confidence intervals are for the difference between agroforestry and conventional farming. Hedges' g is corrected for small-sample bias. Welch's independent-samples t -test was used for all comparisons.

Total nitrogen was significantly higher under agroforestry, with a mean difference of 0.013 percentage points (95% CI: 0.005 to 0.021; $p = 0.0048$; Hedges' $g = 1.39$). Available phosphorus was similarly higher under agroforestry, with a mean difference of 6.32 mg kg⁻¹ (95% CI: 2.65 to 9.99; $p = 0.0029$; Hedges' $g = 1.62$). Exchangeable potassium was also significantly higher under agroforestry, with a mean difference of 44.58 ppm (95% CI: 26.82 to 62.33; $p = 0.00027$) and a very large effect size (Hedges' $g = 2.42$). In contrast, the differences in exchangeable sodium ($p = 0.1429$), calcium ($p = 0.7822$) and magnesium ($p = 0.1081$) were not statistically significant. Thus, the results show significant differences between the two farming systems for soil pH, organic carbon, total nitrogen, available phosphorus and exchangeable potassium, while no significant differences were observed for sodium, calcium and magnesium.

4.2 Maize Grain Yield under Farmer-Managed *Gliricidia sepium* Agroforestry and Conventional Farming Systems

Table 2 presents the comparison of maize grain yield between farmer-managed *Gliricidia sepium* agroforestry and conventional farming systems.

Table 2. Comparison of maize grain yield between farming systems

Variable	Agroforestry, mean $\pm$ SD	Conventional, mean $\pm$ SD	Mean difference	95% CI	Welch's t	df	p-value	Hedges' g
Maize grain yield, kg ha ⁻¹	3,750.00 $\pm$ 716.86	1,980.00 $\pm$ 229.98	1,770.00	1,245.02 to 2,294.98	7.43	10.83	0.0000142	3.18

Note: The mean difference was calculated as agroforestry minus conventional farming. Welch's t -test was used because the variance in maize grain yield differed between the two groups.

Source: Field data, 2026.

Maize grain yield was significantly higher on farmer-managed *Gliricidia sepium* agroforestry farms than on conventional farms. Agroforestry farms produced a mean grain yield of 3,750.00 $\pm$ 716.86 kg ha⁻¹, whereas conventional farms produced a mean of 1,980.00 $\pm$ 229.98 kg ha⁻¹. The estimated mean difference was 1,770.00 kg ha⁻¹, representing an approximately 89.4% higher mean yield under agroforestry. Welch's independent samples test showed that this difference was statistically significant, $t(10.83) = 7.43$, $p = 0.0000142$. The 95% confidence interval indicated that the mean yield difference was likely to range from 1,245.02 to 2,294.98 kg ha⁻¹. The magnitude of the difference was very large, Hedges' $g = 3.18$. The observed effect exceeded the minimum detectable standardized difference of approximately 1.32 obtained from the sensitivity power analysis. The results therefore provide strong evidence that the sampled agroforestry farms had higher maize grain yields than the sampled conventional farms. However, because farming systems were not randomly assigned, the result should be interpreted as an association rather than proof of a causal effect of agroforestry.

4.3 Relationship between Soil Fertility Parameters and Maize Grain Yield

4.3.1 Correlations between Soil Fertility Parameters and Maize Grain Yield

Table 3 presents the Pearson correlations between soil fertility parameters and maize grain yield.

Table 3. Pearson correlations between soil fertility parameters and maize grain yield

Soil parameter	Pearson's r	p-value	Interpretation
pH, CaCl ₂	0.860	0.00000113	Strong positive association
Organic carbon, %	0.855	0.00000157	Strong positive association
Total nitrogen, %	0.555	0.01109	Moderate positive association
Available phosphorus	0.609	0.00434	Moderate positive association
Potassium, ppm	0.668	0.00130	Moderate positive association
Sodium, ppm	0.471	0.03619	Moderate positive association
Calcium, ppm	0.073	0.75877	Negligible, non-significant association
Magnesium, ppm	-0.320	0.16851	Weak negative, non-significant association

Source: Field and laboratory data, 2026.

Note: $n = 20$ farms. Pearson's correlation coefficients describe associations and do not establish causality.

Pearson's correlation analysis indicated that maize grain yield was positively and significantly associated with soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable potassium and exchangeable sodium. Soil pH had the strongest positive relationship with grain yield, $r = 0.860$, $p = 0.00000113$, followed closely by soil organic carbon, $r = 0.855$, $p = 0.00000157$. These coefficients indicate that higher values of soil pH and organic carbon were strongly associated with higher maize grain yield within the sampled farms.

Moderate positive relationships were observed between grain yield and exchangeable potassium, $r = 0.668$, $p = 0.00130$; available phosphorus, $r = 0.609$, $p = 0.00434$; and total nitrogen, $r = 0.555$, $p = 0.01109$. Exchangeable sodium had a weaker but statistically significant positive relationship with grain yield, $r = 0.471$, $p = 0.03619$.

Exchangeable calcium was not significantly associated with grain yield, $r = 0.073$, $p = 0.75877$. Exchangeable magnesium showed a negative but statistically non-significant relationship with grain yield, $r = -0.320$, $p = 0.16851$.

These findings demonstrate bivariate associations between soil fertility conditions and maize grain yield. They should not be interpreted as causal effects because the analysis did not control for all differences in farm management, cropping history and environmental conditions.

4.3.2 Parsimonious Regression Model of Soil Fertility and Maize Grain Yield

Table 4 presents the reduced multiple linear regression model used to examine the independent associations of soil organic carbon and total nitrogen with maize grain yield.

Table 4. Parsimonious multiple linear regression model of soil fertility and maize grain yield

Predictor	<i>B</i>	SE	Standardised β	<i>t</i>	p-value	95% CI for <i>B</i>	VIF
Constant	-1,506.67	530.00	—	-2.84	0.01125	-2,624.88 to -388.46	—
Organic carbon, %	2,674.36	397.24	0.754	6.73	0.000004	1,836.26 to 3,512.46	1.13
Total nitrogen, %	28,627.34	10,646.35	0.301	2.69	0.01553	6,165.50 to 51,089.18	1.13

Model summary: $R^2 = 0.811$; adjusted $R^2 = 0.789$; $F(2, 17) = 36.53$; $p = 0.00000070$; residual standard error = 480.17 kg ha⁻¹; $n = 20$.

Source: Field and laboratory data, 2026.

Note: *B* represents the unstandardised regression coefficient. The regression was treated as exploratory because of the limited sample size.

The reduced model was statistically significant, $F(2, 17) = 36.53$, $p = 0.00000070$. Soil organic carbon and total nitrogen jointly explained 81.1% of the observed variation in maize grain yield, $R^2 = 0.811$. After adjustment for the number of predictors, the model explained 78.9% of the variation, adjusted $R^2 = 0.789$. The residual standard error was 480.17 kg ha⁻¹.

Soil organic carbon was positively and significantly associated with maize grain yield after adjustment for total nitrogen. A one-percentage-point increase in soil organic carbon was associated with an estimated increase of 2,674.36 kg ha⁻¹ in grain yield, $B = 2,674.36$, $SE = 397.24$, standardised $\beta = 0.754$, $t = 6.73$, $p = 0.000004$. The 95% confidence interval ranged from 1,836.26 to 3,512.46 kg ha⁻¹.

Total nitrogen was also independently and positively associated with maize grain yield. A one-percentage-point increase in total nitrogen was associated with an estimated increase of 28,627.34 kg ha⁻¹ in grain yield, $B = 28,627.34$, $SE = 10,646.35$, standardised $\beta = 0.301$, $t = 2.69$, $p = 0.01553$. The large unstandardised coefficient reflects the small numerical scale on which total nitrogen was measured. Its standardised coefficient indicates that the association was weaker than that of soil organic carbon.

The fitted exploratory model was:

Maize grain yield = $-1,506.67 + 2,674.36$ (organic carbon) + $28,627.34$ (total nitrogen)

The coefficients represent adjusted associations within the observed data and should not be interpreted as causal effects or used for prediction beyond farming conditions comparable to those included in the study.

4.3.3 Regression Diagnostic Assessment

Table 5 presents the diagnostic assessment of the reduced regression model.

Table 5. Diagnostic assessment of the reduced regression model

Diagnostic	Result	Interpretation
VIF, organic carbon	1.13	No problematic multicollinearity
VIF, total nitrogen	1.13	No problematic multicollinearity
Shapiro–Wilk test	$W = 0.983, p = 0.970$	No evidence of non-normal residuals
Breusch–Pagan test	$\chi^2(2) = 3.76, p = 0.153$	No evidence of heteroscedasticity
Breusch–Pagan F-test	$F(2, 17) = 1.97, p = 0.170$	Homoscedasticity supported
Maximum Cook’s distance	0.345	No severely influential observation
Maximum leverage	0.360	No observation warranted removal
Maximum absolute studentised residual	2.32	No extreme residual exceeding ± 3

Source: Field and laboratory data, 2026.

Diagnostic tests indicated that the reduced regression model adequately satisfied the main assumptions of multiple linear regression.

The variance inflation factor was 1.13 for both soil organic carbon and total nitrogen. These values were substantially below commonly applied thresholds of 5.0 or 10.0, indicating that multicollinearity was not a concern in the reduced model.

The Shapiro–Wilk test showed no statistically significant departure of the regression residuals from normality, $W = 0.983, p = 0.970$.

The Breusch–Pagan test was not statistically significant, $\chi^2(2) = 3.76, p = 0.153$. The corresponding F-test was also non-significant, $F(2, 17) = 1.97, p = 0.170$. These results indicated no evidence that the variance of the residuals systematically changed across the fitted values.

Influential-observation diagnostics did not identify any farm with Cook’s distance greater than 1.00. The largest Cook’s distance was 0.345, while the maximum leverage value was 0.360. The largest absolute externally studentised residual was 2.32. Although several observations exerted moderate influence because of the small sample, none provided sufficient statistical or substantive grounds for exclusion. All 20 farms were therefore retained in the final analysis.

5. Discussion

5.1 Soil Fertility under Farmer-Managed *Gliricidia sepium* Agroforestry and Conventional Farming Systems

The present study demonstrated that farmer-managed *Gliricidia sepium* agroforestry significantly improved soil pH, organic carbon, total nitrogen, available phosphorus and exchangeable potassium compared with conventional maize farming. These findings indicate that integrating *Gliricidia sepium* into maize-based farming systems enhances soil chemical fertility under smallholder production conditions. The significantly higher soil organic carbon and total nitrogen observed under agroforestry are consistent with the role of leguminous trees in improving soil quality through biological nitrogen fixation and the continuous addition of organic residues from leaf litter and root turnover. These processes increase soil organic matter, stimulate microbial activity and promote nutrient cycling, thereby enhancing soil fertility. Similar conclusions were reported by Muyabe et al. (2025), who identified agroforestry as an effective strategy for improving soil health, nutrient cycling and climate-

resilient crop production in Zambia. Likewise, Phiri et al. (2025) observed that land-use systems with greater vegetation cover maintained superior soil fertility indicators, including soil pH and nutrient status, compared with continuously cultivated cropland. These findings are also reported by Alamu et al. (2023), who reported that leguminous agroforestry species increase soil nitrogen availability and organic matter through biomass decomposition, thereby improving soil fertility.

The significant increases in available phosphorus and exchangeable potassium observed in the present study further suggest that *Gliricidia sepium* agroforestry promotes nutrient retention and recycling within the soil profile. In contrast, exchangeable sodium, calcium and magnesium did not differ significantly between the two farming systems, suggesting that these nutrients may be influenced more by inherent soil characteristics than by the management practices evaluated in this study. Overall, the findings reinforce the potential of farmer-managed *Gliricidia sepium* agroforestry as a sustainable land management practice for improving soil fertility and supporting resilient maize production systems.

5.2 Maize Grain Yield under Farmer-Managed *Gliricidia sepium* Agroforestry and Conventional Farming Systems

The present study demonstrated that maize grain yield was significantly higher under farmer-managed *Gliricidia sepium* agroforestry than under conventional maize farming. The yield advantage observed under agroforestry is consistent with the improvements in soil pH, organic carbon, total nitrogen, available phosphorus and exchangeable potassium recorded in the present study, suggesting that enhanced soil fertility contributed to improved maize productivity.

These findings agree with Alamu et al. (2023), who reported that fertilizer tree systems incorporating *Gliricidia sepium* significantly increase maize yields by improving nutrient availability and soil fertility. Similarly, Muyabe et al. (2025) observed that agroforestry enhances crop productivity by improving ecosystem functions, nutrient cycling and resilience to climatic variability. These studies support the view that integrating leguminous trees into cropping systems provides long-term benefits for crop production beyond the immediate effects of fertilizer application.

However, the present findings differ from those reported by Muyabe et al. (2025), who observed that the productivity benefits of agroforestry may vary according to tree density, species composition, management practices and environmental conditions. In some situations, competition between trees and crops for light, water and nutrients may reduce crop performance, particularly during the early stages of system establishment or where tree management is inadequate. In the present study, the *Gliricidia sepium* systems had been established for at least three years, the trees were planted in rows, pruned at least once during the cropping season, and the pruned biomass was retained in the fields to decompose naturally. Furthermore, no inorganic fertilisers were applied to the agroforestry fields.

These management practices may have promoted nutrient recycling and soil organic matter accumulation while reducing excessive tree–crop competition, thereby contributing to the higher soil fertility indicators and maize grain yields observed under the agroforestry system.

Nevertheless, because the study was observational, these management characteristics should be interpreted as conditions associated with the observed outcomes rather than direct evidence of causation. This finding highlights the importance of appropriate agroforestry management in maximizing crop productivity while maintaining soil health under smallholder farming conditions.

5.3 Soil Fertility Maize Yield Relationships

The present study demonstrated significant positive associations between maize grain yield and soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable potassium and exchangeable sodium. However, the parsimonious multiple regression model showed that only soil organic carbon and total nitrogen remained independently associated with maize grain yield after adjustment for one another. These findings suggest that although several soil fertility indicators were positively associated with maize productivity at the bivariate level, soil organic carbon and total nitrogen explained most of the variation in maize grain yield within the reduced multivariable model. The strong association between soil organic carbon and maize grain yield agrees with the findings of Oldfield et al. (2019), who reported that increases in soil organic carbon improve soil structure, nutrient retention and water-holding capacity, thereby creating favourable conditions for enhanced crop productivity. Similarly, Lal (2020) emphasised that soil organic carbon is a fundamental indicator of soil health because it regulates nutrient cycling, microbial activity and soil physical properties that collectively support crop growth. The independent association observed between total nitrogen and maize grain yield is also consistent with Giller et al. (2021), who reported that nitrogen availability remains one of the principal determinants of maize productivity in smallholder farming systems because it supports vegetative growth, chlorophyll formation and grain development.

Although soil pH, available phosphorus and exchangeable potassium exhibited significant positive correlations with maize grain yield, they did not remain significant independent predictors after adjustment in the reduced regression model. This finding suggests that the observed bivariate relationships may partly reflect shared variation among soil fertility indicators rather than independent effects on maize grain yield. Similar observations were reported by Oldfield et al. (2019), who noted that soil fertility parameters are often closely interrelated, causing individual variables to lose statistical significance when analysed simultaneously in multivariable regression models. Likewise, Lal (2020) observed that improvements in crop productivity generally result from the combined influence of several interacting soil properties rather than the effect of a single nutrient.

The absence of significant relationships between exchangeable calcium and magnesium and maize grain yield contrasts with studies that have identified these nutrients as important determinants of crop productivity under nutrient-deficient conditions (Hawkesford et al., 2014). The discrepancy may reflect the relatively adequate levels of calcium and magnesium observed in the study area, reducing their influence on maize productivity compared with nutrients that were more limiting to crop growth. This finding highlights the importance of evaluating soil fertility as an integrated system rather than considering individual nutrients in isolation.

The correlation and regression analyses indicate that soil fertility was closely associated with maize grain yield among the sampled farms. Soil organic carbon and total nitrogen emerged as the strongest independent soil fertility indicators associated with maize grain yield after statistical adjustment. These findings highlight the importance of management practices that promote soil organic matter accumulation and maintain adequate nitrogen availability in supporting sustainable maize production.

6. Conclusions

This study compared soil fertility and maize grain yield under farmer-managed *Gliricidia sepium* agroforestry and conventional farming systems in Katete District, Zambia. Agroforestry farms had significantly higher soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable potassium and maize grain yield than conventional farms.

Pearson's correlation analysis showed positive associations between several soil fertility parameters and maize grain yield, while the reduced multiple regression model identified soil organic carbon and total nitrogen as the principal soil fertility indicators independently associated with maize grain yield.

The findings suggest that farmer-managed *Gliricidia sepium* agroforestry is associated with improved soil fertility and higher maize grain yield under the conditions represented in this study. However, because of the observational design and limited sample size, these relationships should be interpreted as associations rather than evidence of causation.

6.1. Practical and policy implications

The findings suggest that farmer-managed *Gliricidia sepium* agroforestry can support sustainable soil fertility management and maize production under low-external-input smallholder farming systems.

Appropriate management practices, including row planting, periodic pruning and retention of pruned biomass, may enhance nutrient cycling and soil organic matter accumulation. The results provide useful evidence for agricultural extension services and policymakers promoting climate-smart agriculture and sustainable land management. However, because the study was observational and based on a relatively small sample, the findings should be interpreted alongside evidence from larger and longer-term studies.

6.2. Limitations and future research

This study has several limitations that should be considered when interpreting the findings. First, the sample comprised only 20 farms (10 agroforestry and 10 conventional farms). Although the sensitivity analysis indicated that this sample was adequate to detect the large observed differences in soil fertility and maize grain yield, it had limited power to detect smaller effects.

Second, the cross-sectional observational design limits causal interpretation. The higher soil fertility and maize grain yields observed on agroforestry farms may also have been influenced by unmeasured factors such as previous land management, maize variety, planting date, weed and pest control, and farmer experience.

Third, the purposive selection of farms limits the generalisability of the findings beyond farming systems with conditions like those in Chilembwe and Mzime Agricultural Camps.

Finally, although all agroforestry farms had established *Gliricidia sepium* systems managed under similar practices, variations in tree density, pruning intensity and other management characteristics may have influenced the results. The reduced regression model was also exploratory and should not be interpreted as establishing causal relationships.

Future studies should include larger sample sizes, repeated measurements across multiple growing seasons and longitudinal or experimental designs, while collecting more detailed information on agroforestry management and environmental conditions.

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