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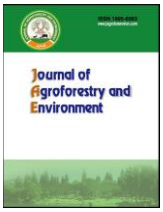

Assessing the Effect of Legume-based Fallows on Soil Acidity in Smallholder Agriculture in Sub-Saharan Africa: A Systematic Review

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Abstract: Legume-based fallows have been increasingly investigated for their potential to improve degraded soil health challenges in sub-Saharan Africa. This study evaluated legume fallows' potential to enhance soil pH, nitrogen, potassium, and phosphorus concentrations in smallholder farming systems. Nine hundred fourteen records were retrieved from three databases, covering academic journals, agricultural studies, and theses/dissertations, and were rigorously screened against the 7 eligibility criteria. The narrative analysis was performed on ten studies while the meta-analysis involved seven studies. Nigeria accounted for (50%) of the included studies, with *Cajanus cajan, Tephrosia vogelii*, and *Pueraria phaseoloides* dominant legume species. The results revealed that legume fallows had varied impacts on soil pH, with a small but non-significant impact, SMD = –0.38; p = 0.18). In contrast, nitrogen (SMD = 0.89), phosphorus (SMD = 1.06), and potassium (SMD = 0.56) significantly increased (p = 0.001) in fallows with legumes than non-legume fallow. Subgroup results also showed that soil type, fallow duration, and soil depth influenced outcomes. *Arenosols* under long-term fallow (>6 years) exhibited greater pH decline, while *Alfisols* and *Nitisols* contributed to enhanced nutrient retention in the top layer soil. Findings show that legume fallows enhance nutrient availability but are not consistent on soil acidity. Nonetheless, it is essential to combine other soil amendment strategies such as compost or manure application, or select legume species tailored to soil type and fallow duration to reduce soil acidity.

Keywords: Smallholder agriculture; Soil acidity; Legume-based fallows; Nutrient availability; Soil pH

INTRODUCTION

Smallholder farming remains an essential livelihood activity as it provides food and income to millions of rural residents (Kamara et al., 2019). However, soil acidity continuously impacts the success of this farming system because of practices associated with soil degradation (Agegnehu et al., 2021; Saturday, 2018). Over time, practices like those emphasizing market-oriented farming have led to widespread of acidic soils across sub-Saharan Africa, (Tully et al., 2015; Vanlauwe et al., 2017). Acidic conditions are associated with reduced nutrient availability and low yields of about 25 - 80% in smallholder farms (Tandzi et al., 2018).

To respond to these problems, several soil amendment strategies have been introduced. However, approaches such as smallholder farmers' access to external nutrient inputs and lime is limited (Golla, 2019). Although breeding of crop varieties which could tolerant acidic soils crop has been studied a potential solution, it's progress has been constrained by limited breeding programs and extension support (Fadda et al., 2020; Yadav et al., 2023; Zeigler et al., 1995). Given these limitations, agroecological practices like legume fallows are increasingly studied as accessible and sustainable solutions to improve soil fertility (Kaur et al., 2023; Mango & Hebinck, 2016; Tsufac et al., 2019).

Legume fallow is an agroforestry system that uses legume plants such as *Cajan cajan*, to restore the soil over a resting period. This system improves nutrient cycling, biomass and enhance biological processes (Hall et al., 2006; Olujobi, 2016). However, their effects on soil properties, particularly soil pH, are variable. While some studies report reduced aluminium toxicity and improved amounts of nutrients (Juo et al., 1995; Vieira et al., 2009), others recorded increase in soil acidic caused by hydrogen ions production during nitrogen fixation processes by legume species (Saplings et al., 2022).

Changes in nutrients under legume fallow are context-specific. While their potential to enhance nitrogen is posited in literature (Ashworth et al., 2016; Gou et al., 2023), their effects on phosphorus and potassium are not consistent (Aleixo et al., 2020; Maroko et al., 1999; van Heerwaarden et al., 2023). This disparity arises from difference in agroecological conditions, soil composition, and management strategies. Despite some studies reporting improved organic carbon and microbial activity (Jian et al., 2020), other studies recommend complementary nutrition of external inputs to optimize outcomes (Kihara et al., 2010).

Despite these evidence, there is a limited synthesis focused, particularly on exploring their potential to mitigate soil acidity in smallholder farming systems. Several previous systematic reviews have assessed broader soil fertility outcomes, yet few studies have evaluated the potential of legume fallows for reducing acidic soil under varying environmental conditions of sub-Saharan Africa.

This study evaluated legume fallows' potential to enhance soil pH nitrogen, potassium and phosphorus in smallholder farms across the region. The review aims to compare the effects of legume with non-legume fallows, and investigate influence of legume plants, soil depth, type of soil, and fallow period on soil acidity dynamics. By focusing on these elements, the study seeks to investigate the consistency and practical relevance of legume-based fallows as a sustainable soil amendment strategy for diverse smallholder contexts in sub-Saharan Africa.

MATERIALS AND METHODS

Three databases covering academic journals, agricultural studies, and theses/dissertations were thoroughly searched to find relevant papers between February 23, 2024, and March 20, 2024. The search terms were adjusted to the specific needs of each database to ensure that all relevant papers were found in the database. Five articles directly related to the topic were benchmarked to pretest and ensure that the search captured the compile papers. Key terms and Boolean operators used in this systematic review are as follows:

Web of Science search string: *TS = "Legume-based fallow" OR "Improved fallow" OR "planted fallow" OR "woody fallow" OR "fertilizer trees" OR "legum* fallows" OR "legum* trees" OR "legum* shrubs" OR "shrub legum* species" OR "shrubs" AND "soil acidity" OR "soil pH" AND ("Nutrient availability" OR "chemical properties") AND ("Smallholder agriculture" OR "Small-scale agriculture")*

AGRICOLA *search string: TS = ("Legume-based fallow" OR "Improved fallow" OR "planted fallow" OR "woody fallow" OR "fertilizer trees" OR "legum* fallows" OR "legum* trees" OR "legum* shrubs" OR "shrub legum* species" OR "shrubs") AND (("soil acidity" OR "soil pH")) AND ("Nutrient availability" OR "chemical properties)" AND ("Smallholder agriculture" OR "Small-scale agriculture") AND "sub-Saharan Africa"*

ProQuest Theses and Dissertations *search string: TS = ("Legume-based fallow" OR "Improved fallow" OR "planted fallow" OR "woody fallow" OR "fertilizer trees" OR "legum* fallows" OR "legum* trees" OR "legum* shrubs" OR "shrub legum* species" OR "shrubs") AND (("soil acidity" OR "soil pH")) AND ("Nutrient availability" OR "chemical properties") AND (Smallholder agriculture" OR "Small-scale agriculture") AND ("sub-Saharan Africa")*

To ensure relevant papers are retrieved, the search was refined using publication language, publication year, and region options.

Screening and study inclusion

The papers were downloaded and stored in the screening software (Cadima) (Kohl et al., 2018). During the screening process, any duplicated papers were first removed. The records which remained were screened against seven pre-designed eligibility criteria for inclusion, which were derived from the PICO framework (Table 1). Any peer-reviewed study conducted in sub-Saharan Africa, published in English between 1990 and 2024 or with available translation options, was included. Papers which were included assessed or measured legume fallows' impact on pH, nitrogen, potassium and phosphorus, comparing it with non-legume fallows, and used random complete block design, or controlled field trial or before-and-after studies.

A two-step selection method was used for the study. First, the title and abstract were checked to ensure the papers meet the requirements. Second, the same inclusion criteria (Table 1) were used to identify relevant papers in the full text.

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Table 1: Eligibility criteria for studies on legume fallows

Element	Criteria for inclusion	Criteria for exclusion
Population	On-farm experiment or research in smallholders farms in sub-Saharan Africa	Research conducted in a non-smallholder farming systems or outside of sub-Saharan Africa.
Intervention	Studies evaluating legume fallow's effect on soil pH, nitrogen, potassium and phosphorus.	Papers focusing on conventional farming.
Comparison	Studies that compare legume fallow to non-legume fallows	Studies comparing legume fallows with conventional farming system
Outcome	Research evaluating changes in soil chemical properties such as soil pH, base saturation, exchangeable acids, nitrogen, phosphorus and potassium.	Papers that report only on nitrogen or potassium or phosphorus.
Study Design	Research articles reporting primary data, such as field-based trials, randomized block experiments, and before-and-after evaluations	Reviews, commentaries, or theoretical papers.
Time	Papers written between 1990 and 2024.	Studies lacking accessible full-text
Language	Papers available in English, either originally written or officially translated	Non-English papers or without available translations.

Data extraction

Data on soil pH, nitrogen, potassium and phosphorus were extracted using a standardized form. Each species in the study was handled as a distinct observation. For example, a study in which *Tephrosia vogelii, Cajanus cajan*, and bush fallow are compared, were considered three separate observations within one day.

Five papers were randomly selected to test the standardized form, ensuring that the extracted data were accurate and repeatable. Missing information was estimated using available numerical values. The specific methods used to calculate the missing statistics are those suggested by (Hozo et al., 2005).

For the research papers that reported Standard Errors (SE), the standard deviation was calculated by employing the formula: Standard Deviation = Standard Error x √sample size. For those that only reported Coefficient of variation, $SD = Cv/\ mean\ x$ 100 was employed, where, SD stand for Standard Deviation, and CV stand for coefficient of variation

Quality assessment of studies

The table of risk of bias assessed potential bias and quality of studies. Eighty percent (80%) of the studies had moderate risk, while 20% low risk.

The ratings based on factors such as research design, number of participants, control arrangement, data analysis techniques, degree of replication, possible source of bias, declared conflict of interest, and procedures employed for measurement. The Studies classified as low risk met all or most criteria. If three elements (confounding, sample size, and replication) were absent, the study was classified as moderate risk. High-bias studies failed to meet most of the criteria. However, no studies were excluded due to a high-risk category.

Quantitative Analysis

Legume fallow's impact on pH, nitrogen, phosphorus, and potassium concentrations was quantified using Metafor, powered by R in RStudio. The effect sizes of all the variables were calculated as standardized mean differences (SMD). The subgroup analysis investigated the factors that influence the legume fallows effect on soil chemical properties.

The soil type, depth, duration of fallow and the type of plants were the major subgroup analysis. The linear mixed-effect model explored the interaction between legume plants, type of soil, fallow period, and soil depth in reducing soil acidity. The data processed from the three quantitative analyses are presented in tables and Figure.

RESULTS AND DISCUSSION

Study selection

PRISMA 2020 guidelines were used in the process of selecting studies to include (Page et al., 2021). Figure 1 presents the screening process along with number of records that were included and excluded. The systematic search in the three database retrieved 1,037 records. Search terms in the Web of Science retrieved 425 records after filtering the search by publication year and region. The search in the AGRICOLA database retrieved 545 records; 425 articles were retained after refining the search by publication year, while 67 records were retained in the ProQuest Thesis & Dissertation database. After removing 123 duplicates, 914 articles were retained and subjected to screening. The narrative synthesis involved 10 papers, while 7 papers in the meta-analysis.

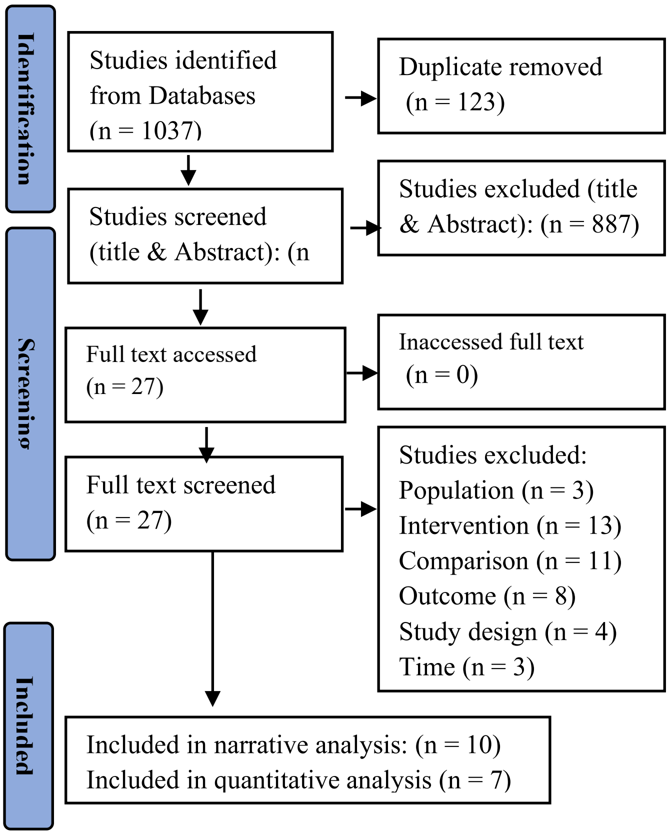

Figure 1: Flow diagram (PRISMA) of the selected studies

Study characteristics

The included studies came from 5 sub-Sahara African countries. The studies and their characteristics regarding specific location, fallow type, crop involved, legume fallows and soil type are presented in Table 2. Nigeria accounted for 5 studies (50%) (Table 2). Cameroon (2) (20%), Mali, Ethiopia and Democratic Republic of Congo (DRC) each accounted for 1 (10%) study each. These countries experience moderate to strong acidic conditions (Agegnehu et al., 2021; Uwiragiye et al., 2023).

The studies reported diverse legume species, with *Cajanus cajan, Tephrosia vogelii*, and *Pueraria* being the common species. The species were assessed in different cropping systems, including maize, Cassava, and sorghum (Table 2), which showed the predominant farming practices in sub-Sahara African countries.

Three studies experimented legume-based fallow under 3-year fallow duration. Others 1-year, 2-year and 7-years fallows were used. However, one study presented years in a range form such as as 1 - 3, 3 - 5, and 5 - 7 years, without assigning the specific year.

The experiments were conducted in 10 distinct soil types, such as *Alfisol, Nitisol, Ferruginous*, sandy clayey, sand, Clayey, *Rhodic Kandiudult, Typic Kandiudult and Typic Kandiudox* (Table 2). Nevertheless, *Alfisol* was the common soil type.

Table 2: Study characteristics on legume-based fallow

Study	Location	fallow type	Crop	Fallow duration	soil type
Koutika et al., 2002	Cameroon	*Pueraria phaseoloides*	Maize	3	Sandy Clayey, sand , clayey
Adediran et al., 2001	Nigeria	*Mucuna utilis, Centrosema brasiliensis, Cajanus cajan, Canavalia ensiformis*	Maize	3	*Alfisol (Rhodic plinthustalf)*
Mamuye et al., 2020	Ethiopia	*Tephrosia vogelii, Cajanus cajan*	Maize	2	*Nitisols*
Kachaka et al., 2023	DRC	*Acacia auriculiformis*	No crop mentioned	6	*Arenosol*
Kaya et al., 2007	Mali	*Crotalaria ochroleuca, Indigofera hirsuta* L., , *Crotalaria. goreensis,* Devil bean, *Crotalaria paulina, Tephrosia vogelii, Crotalaria agatiflora*	Sorghum	1	*Ferruginous*
Tian et al., 2001	Cameroon	*Pueraria phaseoloides*	Maize	3	Sandy Clayey, sand , clayey
Koutika et al., 2005	Cameroon	*Pueraria phaseoloides*	Maize	3	*Rhodic Kandudult, Typic Kandiudult, Typic Kandiudox*
Ikpe et al., 2003	*Nigeria*	*Tephrosia candida*	Maize and Cassava	3	*Ultisol*
Juo et al., 1996	*Nigeria*	*Leucaena leucocephala, Cajanus cajan*	Maize and Cassava	3	Egbeda sandy loam
Obi, 1999	*Nigeria*	*Stylosanthes gracilis, Pueraria*	No crop mentioned	5	*Ultisol*

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Legume fallow's impact compare to Non-legume fallow

The effects of the two fallow types (Legume vs non-legume) on soil pH, nitrogen, potassium, and phosphorus concentrations were compared by performing a comparative analysis. The Figures 2, 3, 4, and 5 depict the results of the comparisons.

Soil pH was lower (5.38 units) under legume fallow than in non-legume fallow (5.45) (Figure 2), though no statistical significant difference observed (t = –1.011, df = 46, p = 0.317). The overlap of interquartile range shows pH variability caused by factors beyond the fallow type, such as species characteristics and environmental conditions. This aligns with Franke et al. (2008) who highlighted that the effects rely on the species trait and local conditions.

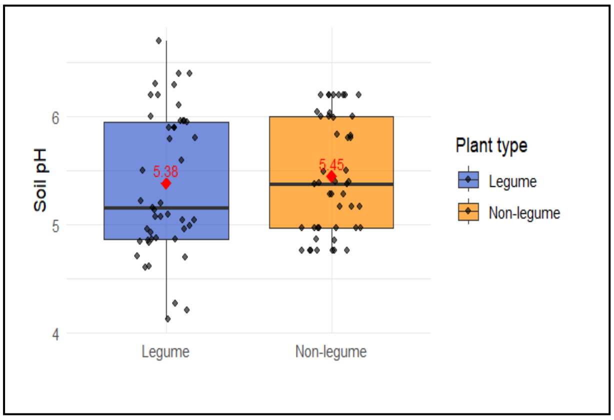

Figure 3: pH distribution in legume vs. non-legume fallows

Nitrogen concentration was significanly higher in legume fallow (0.69) than under non-legume fallow (0.63) (Figure 3). This aligns with legumes' known biological nitrogen-fixing ability (Dupont et al., 2011; Mahmud et al., 2020). Nonetheless, the overlapping data attributed to variability among studies, shows that legume fallow's impact arise due to differences in legume species and climatic conditions of study context.

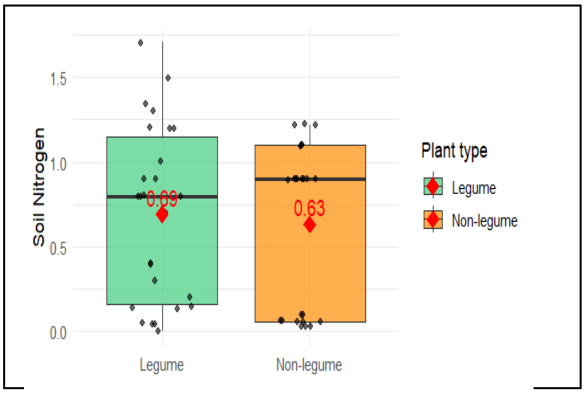

Figure 2: Nitrogen distribution in legume vs non-legume fallow

For potassium, higher content was observed under legume fallows (0.219) than non-legume fallows (0.184) (Figure 4), with the interquartile ranges showing significant overlap between the two fallows. This variation may be associated with difference in legume species, litter quality, decomposition rates, and soil texture. These findings are consistent with earlier reports that legumes improve soil fertility, though the magnitude of impact depends on the environmental condition (Kumar et al., 2022).

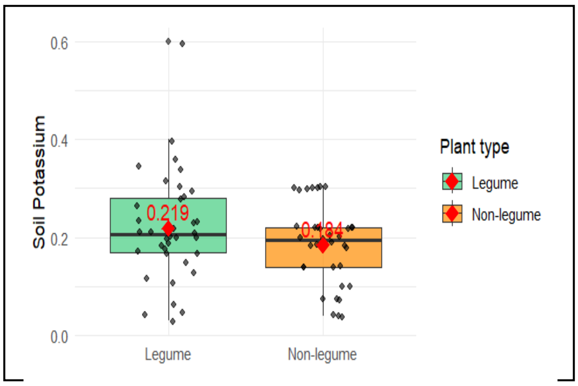

Figure 4: Potassium distribution in legume vs non-legume fallows

Higher phosphorus level (4.35) occurred in fallows with legume compared to non-legume fallow (2.64) (Figure 5). The outliers and overlapping data shown suggest variability caused by the differences in the root exudates decomposition, and phosphorus cycling through organic acid release (Sugiyama & Yazaki, 2011). Legume species were observed to improve phosphorus, though the effects differed across studies and seemed affected by the local environment.

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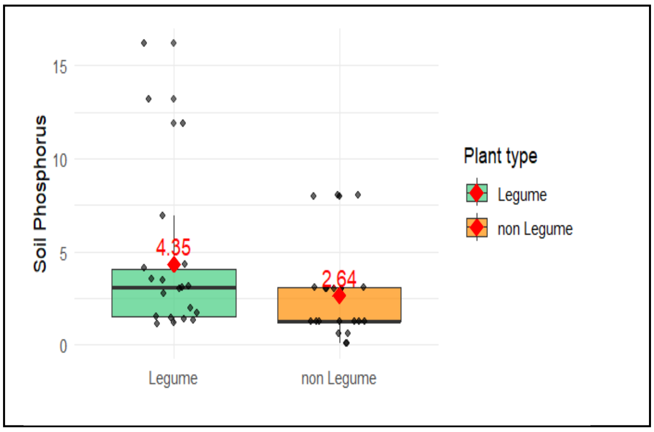

Figure 5: Nitrogen distribution in legume vs non-legume fallows

Effect of fallow system on soil acidity

Table 3 shows the summary of narrative synthesis of studies that measured soil acidity (pH) and the observed effects at various soil depth. The review showed that agroforestry fallows in sub-Saharan Africa incorporated 25 tree and shrub legume species. Among these, *Cajanus cajan*, *Tephrosia vogelii,* and *Pueraria* were the most commonly used each reported in 4 studies (Table 4), likely due to their adaptability characteristics to different environmental conditions.

Of the 10 included studies reviewed, five measured initial soil pH before the experiment. Reported pH changes ranged from 0.7 units to a maximum of 1.13 units. In two of the 5 studies, soil pH increased consistently during the fallow period. This likely to occur because of the high accumulation of biomass and soil – root crop interaction (Adediran et al., 2001; Mamuye et al., 2020). However, the other five studies did not provide any information (Table 3).

However, in 5 studies (50%), soil pH decreased between 0 and 1.6 units (Table 4). This decline was primarily linked to "organic acids production" during the decomposing of biomass and "root exudates" by legume species (Kachaka et al., 2023). Notably, the studies sampled diverse levels to measure soil pH, although the common level sampled for pH measurements. Although inconsistence sampling protocols occured due to varying reported depths, the linear mixed-effect model accounted for it in the subgroup analysis.

Table 3: Summary of narrative analysis on legume fallows and changes in soil pH

Study	Fallow system	Initial soil pH	Final soil pH	Soil level sampled	Reason for observed changes
Kachaka et al., 2023	*Acacia auriculiformis*	not measured	4.12-4.96	0-10 cm, 10-40 cm, 40-100 cm	pH decreased due to organic acid and root exudate during root growth
Mamuye et al., 2020	*Cajanus cajan, Tephrosia vogelii*	5.2	5.4-6.7	0-20 cm	pH increased due soil – root crop interaction
Kaya et al., 2007	*Crotalaria ochroleuca, Indigofera hirsuta* L., , *Crotalaria. goreensis,* Devil bean, *Crotalaria paulina, Tephrosia vogelii, Crotalaria agatiflora*	not measured	4.71-5.7	0-20 cm, 0-40 cm	Not mentioned
Koutika et al., 2005	*Pueraria phaseoloides*	not measured		0-10 cm	Not mentioned
Ikpe et al., 2003	*Tephrosia candida*	4.5	3.8-4.1	0-5 cm, 5-15 cm, 15-30 cm	Not mentioned
Koultika et al.,2002	*Pueraria phaseoloides*	not measured	5.96	0-10 cm	
Adediran et a., 2001	*Mucun, Centrosema, Cajanus Cajan, Canavalia*	5.7	5.9 - 6.4	0-10 cm	pH increased due high biomass production of legumes
Tian et al., 2001	*Senna, Acacia, Luecaena*	not measured	5.2 - 5.8	0-15 cm	Not mentioned
Obi, 1999	*Stylosanthes gracilis, Pueraria*	4.4	4.4	0-15 cm	Not mentioned

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Juo et al., 1996	*Leucaena leucocephala, Cajanus cajan*	6.5	5.37-6.10	0-10 cm	Not mentioned

Meta-analysis of soil pH

Figure 6 present the quantitative analysis plot of 7 studies involving 47 observations. The plot illustrates individual studies and pooled effect. The analysis revealed no consistent, significant increase in soil pH under legume fallows across studies. The overall SMD was -0.38, with a 95% confidence interval range of -0.12 to 0.29, and p-value of 0.18 (Figure 6). This suggests a small and non-significant decrease in pH. Although these results show that legume fallows can slightly acidify soil, the wide confidence interval and non-significant p-value provide a warning against a firm conclusion.

The heterogeneity was noticed to be high across studies (I^2 = 97.22%; p = <0.0001), suggesting varying effects across study contexts. For example, studies conducted in Nigeria reported minimal or no significant effects (Adediran et al., 2001), while those conducted in Ethiopia, had significant increase in soil pH (Mamuye et al., 2020) (Figure 6). These findings show that soil pH responses to legume fallow may depend on the agroecological zone, soil condition, legume species, and management strategies.

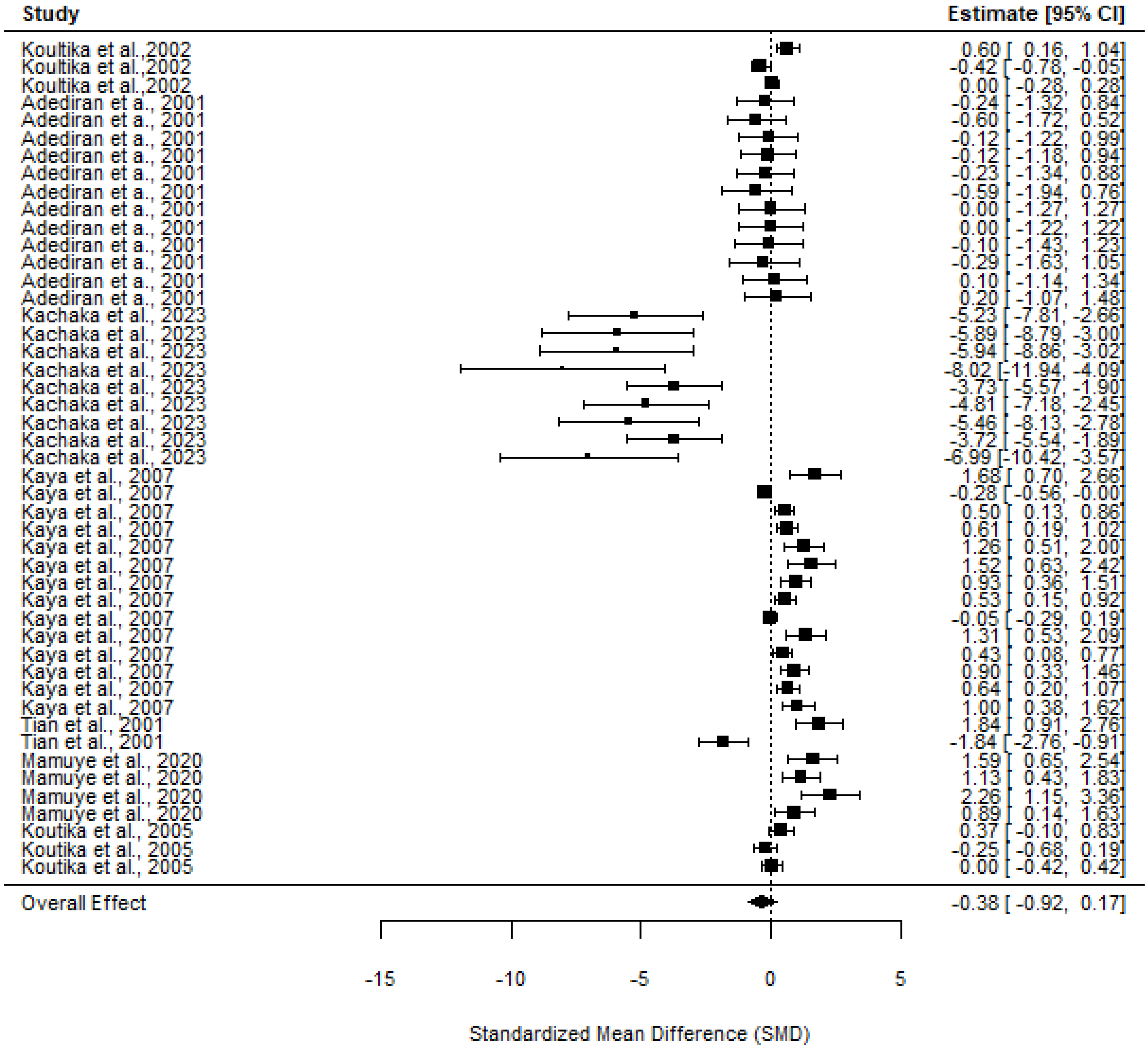

Figure 6: Forest plot of individual studies. Diamond at the bottom indication pooled effect size.

Effect on associated soil nutrient properties

Table 4 provide a summary of the narrative analysis of the effects of legume fallows on nutrients. The review showed that legume trees and shrubs enhance nutrients, possibly through litter accumulation and nitrogen fixation (Cardoso et al., 2025). Most of the studies reported increases in macro nutrients (nitrogen, potassium, phosphorus) under legume fallows (Table 4). On the other hand, nitrogen and potassium levels did not increase in several non-legume fallows.

Table 4: Narrative synthesis of effects between legumes vs. non-legume fallows on soil properties

Soil properties	**Legume fallow effect**	**Non Legume effect**	**Significance**
Nitrogen concentration	Increased in most of the studies	Not different in some from initial studies	Significant in reported cases
Potassium content	General increase	Did not increase in certain studies	Significant in reported case
Phosphorus level	General increase	General increase	Significant in reported case

Meta-analysis results of associated soil nutrient properties

Table 5 summarizes the pooled effect sizes of the three nutrient properties (nitrogen, potassium and phosphorus) included in the meta-analysis. Nitrogen was highly significant under legume fallows in the quantitative analysis of 4 studies involving 21 observations, SMD = 0.89, (95% CI: 0.366 to 1.420), p-value 0.0001 (Table 5). This suggested an increase in nitrogen content under legume fallow than non-legume.

These findings align to an existing body of knowledge that reported positive changes in nutrient recycling under legume fallows (Mamuye et al., 2020; Steinfeld et al., 2023, 2024). However, effects varied, with high heterogeneity (I^2 = 96.95%).

In a meta-analysis of 4 studies involving 25 observations, potassium (K) was moderate significant under legume fallow, SMD = 0.56(95% CI: 0.27 to 0.84), p-value 0.001 (Table 5) than non-legume fallow. This shows that legume fallows enhance potassium content in smallholder farming system. However, studies' results varied, heterogeneity (I^2 = 99.64%). This suggestis variability that may be attributed to factors other than the legume fallow itself.

Conversely, phosphorus had a strong, significant effect in the quantitative analysis of 4 studies involving 21 observations, SMD = 1.06 (95% CI: 0.642 to 1.477), p-value of 0.0001 (Table 5). The overall effect suggests an increase in phosphorus under legume fallows compared to fallows with no legumes. High heterogeneity was observed (I^2 = 75.16%), which suggested variability across studies. This highlights the influence of various local factors beyond legume fallow itself on phosphorus dynamics in agroforestry systems.

Table 5: The meta-analysis results of effects on nutrient properties

Soil Property	**Pooled SMD (95% CI)**	**p-value (0.05)**	**Heterogeneity (I^2)**	**Interpretation**
Nitrogen concentration	0.89 (0.366 to 1.420)	<0.001	96.95	Strong increase due to biological N fixation
Potassium concentration	0.56 (0.27 to 0.84)	<0.0001	99.64	Moderate increase
Phosphorus level	1.059 (0.642 to 1.477)	<0.0001	75.16	Strong significant increase, but high variability

Effect of subgroups and their interaction on soil properties

Soil pH

Table 6 and Figure 7 summarize subgroup analysis outcome. The subgroup analysis was performed using lin ear mixed-effect model to assess the influence of fallow type, soil type, soil depth, and their relationship with the change in pH.

Fallow duration significantly affected pH units (p = 0.001). This demonstrates that fallow length influences the change in soilpH units. Fallow type was not significant (p = 0.545) and its interaction with fallow duration (p = 0.280). This reveals that the change in soil pH are consistent over time across legume and non-legume fallow.Soil type and its interaction with fallow type significantly influenced soil pH, each indicated (p = 0.001) (Table 6), showing that a rise in soil pH may vary with soil type.

On the contrary, Fallow type (p = 0.535) and its interact ion with soil depth (p = 0.187) did not significantly influence soil pH (Table 6), indicating that using either legume-based or non-legume fallows would have the same effect on pH at any soil depth. It also suggests that the influence of fallow type does not primarily depend on soil depth to be effective. Moreover, soil depth significantly influenced soil pH (p = 0.001) (Table 6), suggesting that soil depth strongly impacts soil pH and varies with the change in soil layer.

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Figure 7 summarizes these influences and interactions. Soil pH had varying responses to legume fallows, which aligned with length of fallow, type of soil, and soil depth. It shows that extended fallow durations (4–6 years) tend to lower soil pH units, particularly in Ferruginous, and Arenosols soils, especially at deeper layers (0-10cm, 10-40 cm and 40-100 cm) (Figure 4). On the other hand, *Cajanus cajan* and *canavilia* showed strong influence and interation in shorter periods, particularly 1–3 years, lead to a slight increase in soil pH in *Alifsol*. *Tephrosia vogelii* caused the highest increase soil pH in *Nitisol* soil, especially (0-10 cm and 0-20 cm) (Figure 4). This suggests that the impact of legume fallow at a particular depth, may be limited by various factors such as soil buffering capacity, root distribution, nitrogen fixation processes, nutrient uptake forms, microbial activity, and leaching patterns (Chintu et al., 2004; Gathumbi et al., 2003; Tao et al., 2024; Wortmann & Kaizzi, 2000).

Table 6: Summary of subgroup Analyses on soil pH

	Fallow duration			**Soil type**			**Soil depth**		
Source	**Fallow Type**	**Duration**	**Fallow type × Duration**	**Fallow Type**	**Soil Type**	**Fallow type × Soil Type**	**Fallow Type**	**Depth**	**Fallow type × Depth**
df	1	5	5	1	9	9	1	5	5
Sum of Squares	0.102	8.556	1.761	0.102	25.489	3.449	0.102	9.376	2.012
Mean Square	0.102	1.711	0.352	0.102	2.832	0.383	0.102	1.875	0.402
p-value	0.545	0.00.	0.28	0.169	< 0.001	< 0.001	0.535	0.001	0.187
Significance	ns	***	ns	ns	***	***	ns	***	ns

Significance level: ns= not significant; *** = highly significant

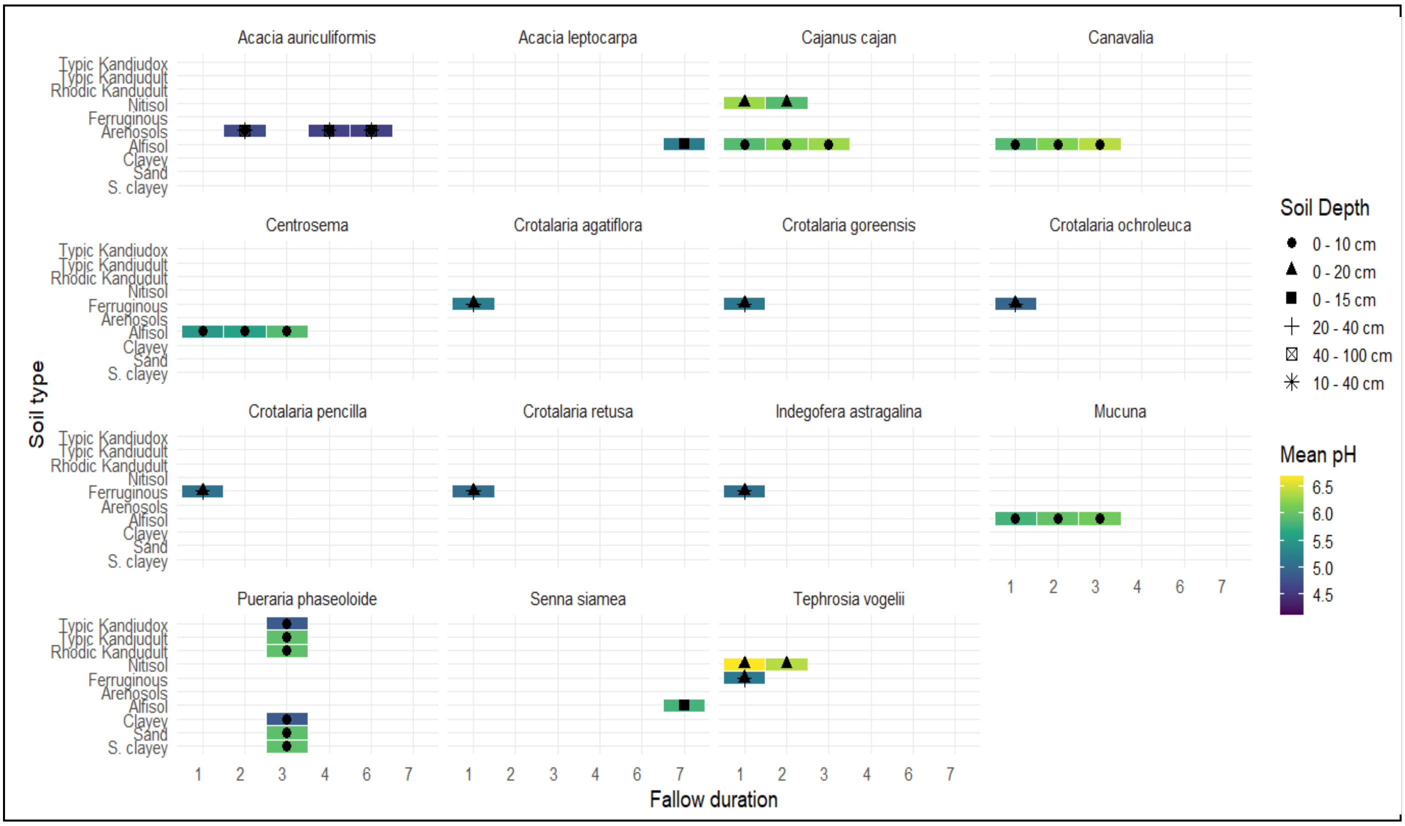

Figure 7: Interactive effect between fallow duration and soil type on soil pH across various leguminous species. Different shapes denote soil depth. The color gradient shows mean change in soil pH.

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Nitrogen concentration

The influence of subgroups on nitrogen concentration is summarized in Table 7. Soil type had a significant influence on nitrogen content (p = 0.000). However, there was no considerable effect observed in fallow type, and its interaction with soil type (p = 0.113 and p = 0.436) (Table 7), respectively. It suggests that the influence of fallow type on nitrogen is more soil-dependent than the interaction in both legume and non-legume fallows. This finding aligns with a previous study by Chen et al. (2019), who noted that soil characteristics often override the influence of species composition in nutrient restoration.

Fallow duration also significantly influenced nitrogen concentration (p = 0.000). However, no significant effect reviewed on fallow type (p = 0.363), nor their interaction with fallow duration (p = 0.110). This means that changes in nitrogen over time occur independent of the fallow type used, aligning to previous observations by (Schroth et al., 2001) on the temporal patterns of nitrogen mineralization in agroforestry systems..

Soil depth was also significant on nitrogen content (p = 0.000), while fallow type (p = 0.344) and their interaction (p = 0.667) were not significant (Table 7). These findings are supported by Warren et al., (1997) who reported similar results in legume fallow trials in East Africa.

Table 7: Summary of subgroup analysis on nitrogen content

	Fallow duration			**Soil type**			**Soil depth**		
Source	**Fallow Type**	**Duration**	**Fallow Type × Duration**	**Fallow Type**	**Soil Type**	**Fall Type × Soil Type**	**Fallow Type**	**Depth**	**Fallow Type × Depth**
Df	1	5	5	1	2	2	1	3	3
Sum of Squares	0.093	7.661	0.118	0.093	10.342	0.06	0.093	7.522	0.161
Mean Square	0.093	1.532	0.024	0.093	5.171	0.03	0.093	2.507	0.054
p-value	0.363	<0.001	<0.954	<0.113	<0.001	<0.436	<0.344	<0.001	<0.667
Significance	ns	***	ns	ns	***	ns	ns	***	ns

Significance level: **ns** = not significant; *** = highly significant

Potassium content

Table 8 summarizes the influence and interaction of subgroups on potassium content. Soil type and its interaction with fallow type were highly significant, with each indicated p = 0.001 (Table 8). Fallow type had moderate significant increase, (p = 0.021). These findings suggest that fallow type, soil type and it's interaction are essential to improve potassium concentration in the legume fallow systems. Similar findings by Neves et al. (2022) reinforce the study's findings that higher nutrient cycling in legume trees systems resulted from increased rate of decomposition of biomass input Zubillaga & Conti, (1994) also aligned the soil type influence with the structural function and mineralogy characteristics of soil which influenced the amount of potassium and its retention.

Fallow duration significantly influenced potassium content (p = 0.001). However, neither fallow type (p = 0.101) nor their interaction (p = 0.727) were not significant (Table 8). It suggest that time is essential for potassium to accumulate and the rate of change in potassium is relatively consistent, across legume and non-legume fallows. This is because the amount of nutrient released rely on factors such as decomposition rate, and nutrient concentration in the original crop residue (Lupwayi, 2005).

Soil depth was significant (p = 0.000), with fallow type indicating moderate significant on potassium (p= 0.044). Their interaction was not significant interaction (p= 0.456) (Table 8). It shows that the influence of fallow type rarely depends on soil depth, however, can improve potassium from deeper soil layers through deeper root system.

Table 8: Summary of subgroup analyses on potassium concentration

	Fallow duration			**Soil type**			**Soil depth**		
Source	**Fallow Type**	**Duration**	**Fallow Type × Duration**	**Fallow Type**	**Soil Type**	**Fallow Type × Soil Type**	**Fallow Type**	**Depth**	**Fallow Type × Depth**
df	**1**	**4**	**4**	**1**	**3**	**3**	**1**	**3**	**3**
Sum of Squares	**0.021**	**0.162**	**0.016**	**0.021**	**0.322**	**0.091**	**0.021**	**0.321**	**0.013**
Mean Square	**0.21**	**0.041**	**0.004**	**0.021**	**0.107**	**0.03**	**0.021**	**0.107**	**0.004**
p-value	**0.101**	**<0.001**	**<0.727**	**<0.021**	**< 0.001**	**< 0.001**	**<0.044**	**<0.001**	**<0.456**
Significance	ns	**	ns	*	***	***	*	***	ns

Significance level: ns = Not significant; *** = very highly significant; ** = highly significant; * = significant

Phosphorus levels

Fallow type, soil type and its interaction significantly influenced phosphorus levels, for each p = 0.001) (Table 9). This means that the change in phosphorus levels depends on fallow type and its interaction with soil type. This phosphorus - soil type connection is documented by Lemos et al. (2022), who highlight that soil mineralogy and phosphorus-fixation capacity can influence the effectiveness of fallow systems in the soils with abudant iron and aluminum oxides.

Similar significant influence was reviewed to occur in Fallow duraion, fallow type, and it's interaction, each had (p = 0.001) (Table 9). This shows the length of legume-based fallow may affect the accumulation of phosphorus levels. This finding align with Maroko et al. (1999), who indicated that the increase in phosphorus levels over time under legume fallow attributed to biomass inputs and biological activity.

Moreover, Soil depth, fallow type, and its interaction significantly influenced phosphorus concentration, for each (p = 0.001) (Table 9). This may have been influenced by the phosphorus immobilition and its tendency to accumulate in topsoil layers from residue decompostion (Soltangheisi et al., 2020). The positive soil depth – fallow type interaction suggests that legume-based fallows can enhance phosphorus levels at topsoil vs. subsoil due to the release of root exudates and biological cycling (Vanek & Drinkwater, 2019).

Table 9: Summary of subgroup analysis of Fallow duration, soil type, and soil depth on phosphorus levels

	Fallow duration			**Soil type**			**Soil depth**		
Source	**Fallow Type**	**Duration**	**Fallow Type × Duration**	**Fallow Type**	**Soil Type**	**Fallow Type × Soil Type**	**Fallow Type**	**Depth**	**Fallow Type × Depth**
df	1	2	2	1	2	2	1	2	2
Sum of Squares	30.8	383.6	51.6	30.8	382.3	45.5	30.8	401.7	33
Mean Square	30.75	191.79	25.8	30.75	191.17	22.73	30.75	200.86	16.5
p-value	<0.001	<0.001	<0.001	<0.001	< 0.001	< 0.001	<0.001	< 0.001	<0.001
Significance	***	***	***	***	***	***	***	***	***

Significance level: *** = very highly significant

Publication Bias Assessment

Table 10 illustrates the consolidated results of publication Bias analysis performed on included studies, using funnel plots, Egger's test and trim & fill test. Nitrogen had asymmetry funnel plot and a decrease in effect size. This suggests a selective publication bias that has been confirmed the missing two studies.

Conversely, soil pH, potassium, and phosphorus displayed asymmetry in the funnel plot, however, the analysis did not identify any missing studies (Table 10). This indicates that asymmetry does not necessarily confirm publication bias. Hence the results regarding the effect size of the measured soil parameters remain dependable. These findings are consistent with Sterne et al. (2011) and Furuya-Kanamori et al. (2018), who warned that funnel plot asymmetry alone does not confirm bias, highlighting the importance of using multiple diagnostic methods.

Table 10: Assessment of publication bias examining soil properties using *Egger's Test, Funnel Plot shape and adjusted Effect Sizes.*

Outcome	Egger's test				Funnel plot Test	Trim & Fill Test	Adjusted effect size
	Egger's Intercept	z-value	SE	p-value	Symmetry/Asymmetry	Missing studies	
Soil pH	1.9082	-8.376	0.295	< 0.0001	Asymmetry	0	-0.3755
Nitrogen	-0.6781	4.727	0.369	< 0.016	Asymmetry	2	0.708
Phosphorus	-0.6649	5.293	-0.339	< 0.0001	fairly symmetrical	0	0.9665
Potassium	-0.0948	6.677	0.106	< 0.0001	Moderate asymmetry	0	0.5575

CONCLUSION

This review reveals that legume-based fallow substantially improve nutrient levels, especially nitrogen (N) and phosphorus (P) across sub-Saharan Africa. However, their effect on soil acidity (pH) vary and depend on the environmental conditions. Subgroup analysis showed that fallow period, type of soil, and soil depth significantly impact outcomes. These results highlight the significance of tailored agroforestry practices to local soil conditions and agroecological contexts. To maximize benefits, legume species must be selected based on functional traits such as nitrogen-fixing capacity and potential to buffer soil pH. Incorporating legume-based fallows into national strategies for land restoration and climate adaptation can enhance soil fertility, productivity, and promote sustainable land use among smallholder farmers.

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Conflict of Interest

There was no conflict of interest associated with this work.

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