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Global systematic review of cassava production and meta-analysis of the effects of fertilization on yield

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Abstract. Cassava plays a significant role in global food security as a staple food crop for billions of people in developing countries. However, the systematic summary of recent studies on cassava production has not been thoroughly compiled. This study aimed to identify key aspects of cassava production, with a particular focus on the effects of fertilization, through a systematic review and meta-analysis. A search of the Scopus database from 1970 to 2022 identified 229 studies on cassava production, of which 83 met the inclusion criteria and were categorized into eight main topics: soil, pest and disease control, genetics and biotechnology, crop management, land, post-harvest and physiology, modeling, and environmental factors. The meta-analysis of studies regarding fertilizer application (n = 7) revealed a modest overall effect of fertilization on cassava yield (effect size = 0.75, 95% *CI*: 0.53–0.96), with micronutrients and macronutrients showing more significant effects compared to organic fertilizers. Additionally, the study found that regional differences influenced fertilization effectiveness, with South America and Southeast Asia showing higher positive responses to fertilization compared to Africa, likely due to varying soil fertility and nutrient limitations. Soil texture also significantly impacted fertilizer efficiency, with silt loam showing the highest fertilizer response. However, the results are based on a limited number of studies, highlighting a critical gap in agricultural research: the lack of comprehensive statistical reporting. This limitation hampers the ability to conduct more robust meta-analyses. Future research should focus on improving statistical reporting practices and exploring region-specific fertilizer strategies to enhance cassava yield sustainably.

Key words: Forest plot, Fresh root yield, On-field, Random effect model, Standard Mean Difference (SMD).

INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is a vital staple crop for millions in tropical and subtropical regions, valued for its resilience to drought and poor soils, and its critical role in food security and industrial applications (IAEA, 2018). Global cassava production has shown steady growth over the past decade, rising from approximately 275 million tonnes in 2012 to over 327 million tonnes in 2022 (FAOSTAT, 2023). Africa remains the leading cassava-producing region, accounting for about 60% of total global output, followed by Southeast Asia (26%) and South America (9%) (FAOSTAT, 2023). This upward trend underscores the crop's growing importance in enhancing food security and supporting livelihoods in developing regions.

Despite cassava's adaptability, yields remain suboptimal in many regions, primarily due to declining soil fertility and limited fertilizer use – challenges compounded by economic constraints faced by smallholder farmers (Howeler, 1991; Senkoro et al., 2018). The persistent yield gap, where actual yields fall far below potential, underscores the urgent need for research into agronomic practices, particularly fertilization strategies that can sustainably boost productivity (Howeler, 1991; Senkoro et al., 2018; Okoth Omondi & Yermiyahu, 2021). Although cassava can grow without fertilizer, reliance on natural soil fertility often leads to nutrient mining and long-term soil degradation, particularly in smallholder systems across Africa, Asia, and South America (Cadavid et al., 1998; Howeler, 2014).

Recent research on cassava production has increasingly focused on optimizing fertilizer management, understanding varietal responses, and improving soil health. Studies consistently demonstrate that cassava responds positively to nitrogen (N), phosphorus (P), and potassium (K) fertilization (Howeler, 1991; Wilson & Ovid, 1994; Senkoro et al., 2018; Chua et al., 2020; Okoth Omondi & Yermiyahu, 2021; Sinta & Dansa, 2023). Optimal rates and combinations of NPK fertilizers have been shown to increase root yield, starch content, and economic returns (Wilson & Ovid, 1994; Senkoro et al., 2018; Katuromunda et al., 2021; Sinta & Dansa, 2023;).

Furthermore, integrated fertilization strategies combining organic and inorganic fertilizers have shown significant promise. Both organic amendments (such as poultry manure, compost) and mineral fertilizers, as well as their combinations, can substantially enhance cassava growth, yield, and soil fertility (Nassy et al., 2020; Katuromunda et al., 2021; Ikeh et al., 2023). These integrated approaches not only boost yields but also improve soil organic matter, nutrient availability, and microbial diversity across diverse genotypes and environments, supporting sustainable production systems (Nassy et al., 2020; Ikeh et al., 2023). Additionally, the timing and method of fertilizer application, along with interactions with planting density and crop age, are recognized as important factors influencing cassava productivity (Yabuta et al., 2021; Enesi et al., 2022).

However, the literature on cassava fertilization presents conflicting results. Studies report both substantial yield increases and minimal or no benefits from fertilizer application, with outcomes often depending on the genotypes, types of fertilizer, and environmental conditions (Pimentel et al., 2021). Responses to fertilization can vary significantly by location, variety, and soil type, underscoring the need for site-specific recommendations (Wilson & Ovid, 1994; Katuromunda et al., 2021; Enesi et al., 2022). This variability makes it difficult for farmers, extension agents, and policymakers to make evidence-based decisions about fertilization strategies. Furthermore, the economic implications of fertilizer use are particularly important for smallholder farmers with limited resources, requiring careful evaluation of cost-effectiveness across different contexts.

Systematic reviews and meta-analyses provide robust tools for synthesizing empirical evidence across diverse studies, employing transparent and repeatable methodologies (Koricheva et al., 2013). In agriculture, they have been instrumental in evaluating practices such as conservation agriculture (Pittelkow et al., 2015), the impacts of organic farming (Tuck et al., 2014), the effects of climate change (Challinor et al., 2014), and yield stability (de Ponti et al., 2012). However, no comprehensive synthesis has been conducted specifically to evaluate the effects of fertilization on cassava productivity. This research gap is particularly concerning given that cassava production systems are highly diverse, spanning different continents, soil types, and management practices, making individual studies insufficient for generating broadly applicable recommendations.

To address this gap, this study conducted a systematic review and meta-analysis of cassava production research published between 1970 and 2022. The objectives were to: (1) identify key areas of research focus on cassava production, (2) assess the effects of different fertilizer types on cassava yield, and (3) highlight existing knowledge gaps that warrant further investigation. By statistically aggregating results from eligible studies, this analysis provides evidence-based insights into fertilizer effectiveness and supports the development of region-specific recommendations to enhance cassava yield sustainably.

MATERIALS AND METHODS

Search strategy

A systematic review on cassava production was conducted following the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses' (PRISMA) framework (Fig. 1; Tugwell & Tovey, 2021). The Scopus database was queried using the search string: (TITLE-ABS-KEY ('cassava production') AND TITLE-ABS-KEY (yield OR biomass OR tuber OR root OR 'storage root' OR 'root weight')) AND (LIMIT-TO (DOCTYPE, 'ar') OR LIMIT-TO (DOCTYPE, 'cp')). The search fields were restricted to abstract, keywords, and title, while the document type was limited to published articles or conference proceedings. The search was performed on March 16, 2022, encompassing publications from 1970 to 2022.

Study screening and selection

After searching studies according to the search strategy in Scopus, the abstracts of all retrieved studies were subsequently screened using AbstractR (Wallace et al., 2012). Initially, studies were included if productivity traits, such as fresh/dry root yield or biomass, related to cassava production were mentioned in the abstracts. Studies were excluded if (i) they were review articles or (ii) the abstracts indicated the topics of economics, food science, and energy. The studies that passed the abstract screening were further selected based on the following eligibility criteria: (i) full text availability in English; (ii) field-level experimental design; (iii) provision of information on control and treatments; and (iv) at least fresh root yield reported as the outcome data on cassava productivity. The studies meeting these criteria were then categorized into the following topics: soil, pest & disease control, genetic & biotechnology, crop management, land, post-harvest & physiology, modeling, and environmental factors to identify recent topics of research on cassava production.

Data extraction

After categorizing topics of studies and ranking them by the number of studies, the most frequently studied topic on cassava production was selected for meta-analysis. The productivity trait focused primarily on studies that presented data on fresh root yield. To be included in the analyses, studies had to report three main statistics for both control and treatment groups: mean ($\bar{X}$), standard deviation (*SD*) or standard error (*SE*), and sample sizes (replications). In some cases, studies reported only within-study SD instead of within-group *SD*; the within-study *SD* was used when all groups had equal sample sizes. Additionally, if studies did not report all *SD*s, the *SE* was recalculated to *SD* (Eq. 1). When data was represented in a bar graph, the image was digitized using the PlotDigitizer Free Online App (https://plotdigitizer.com) to extract values. The means, *SD*s, and sample sizes for both control and treatment groups of all studies were prepared in Microsoft Excel (version 16.89)

Data analysis and reporting

To perform a meta-analysis, all means, *SD*s, and sample sizes of each group in each study were calculated to a standardized mean difference (*SMD*) by Hedges'd method (Eq. 2; Hedges, 1981), being the mean difference between control and treatment weighted by pooled SD (Eq. 3). In this study, the *SMD* was used to quantify the magnitude of differences between the control group and each of the treatment groups, and it was used as an effect size to compare the results of different studies that focused on the same topic on a common scale. The *SMD* was calculated using the function 'metacont' in the R package 'meta' (version 4.3.2).

$$SE = \sqrt{n} \cdot SD \quad (1)$$

$$SMD = \left(\overline{X}_T - \overline{X}_C\right)/S_{pooled} \quad (2)$$

$$S_{pooled} = \sqrt{(n_T - 1)SD_T^2 + (n_T - 1)SD_C^2 \ / \ (n_T - 1) + (n_C - 1)} \quad (3)$$

where SE – the standard error; SD – the standard deviation; n – the sample size; SMD – the standardized mean difference; $\overline{X}_T$ – the mean of the treatment group; $\overline{X}_C$ – the mean of the control group; S_{pooled} – the pooled *SD*; n_T – the sample size of the treatment group; n_C – the sample size of the control group.

We generated an estimate of the overall mean effect size using both fixed-effect and random-effect models using the 'metacont' function in the R package 'meta' (version 4.3.2). Heterogeneity of effect sizes was assessed using the I^2 and τ^2 statistics (Copes & Ojiambo, 2021).

To visualize the results from the meta-analysis, a forest plot was used to represent the *SMD*s of each study with a 95% confidence interval (*CI*). The forest plot was generated using the function 'forestplot' in the R package 'meta' (version 4.3.2)

RESULTS

Distribution of topics in cassava yield research

Search results

The search in Scopus retrieved 229 studies on cassava production that were published between 1970 and 2022. From abstract screening, 83 studies met the inclusion criteria, including being research articles, having an English full-text access, related to cassava production, and reporting productivity traits (Fig. 1).

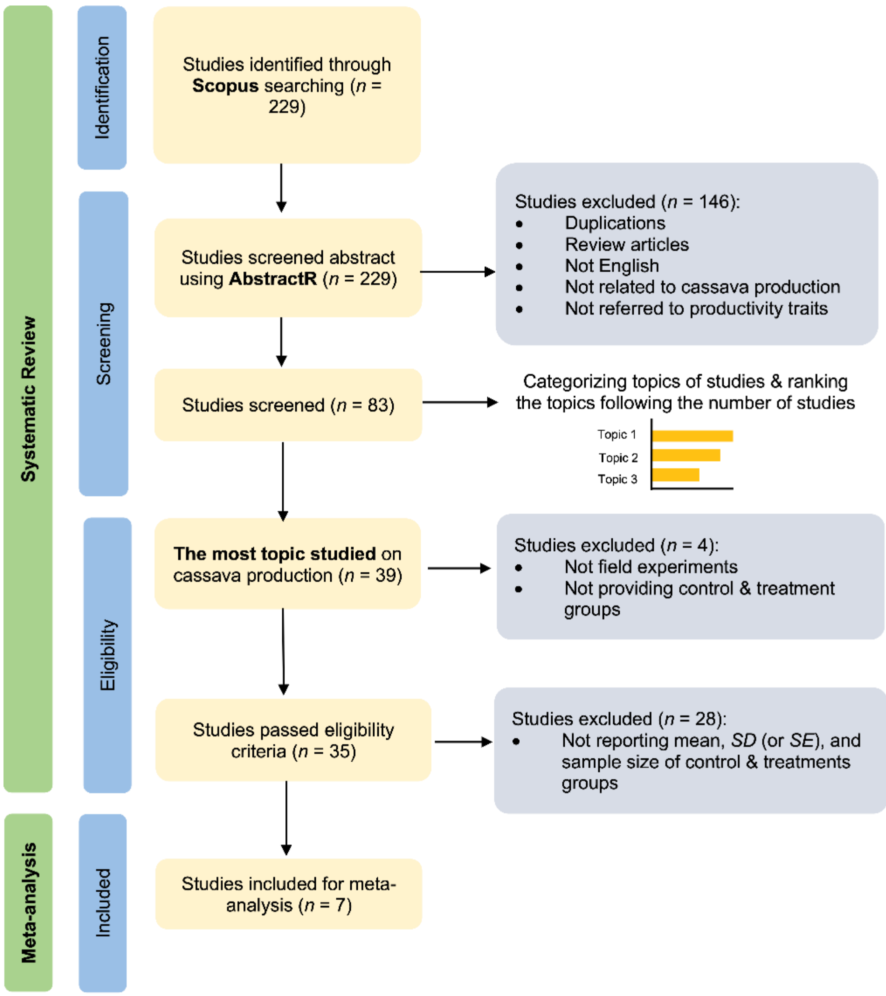

Figure 1. Identification, screening, and inclusion of the publications on cassava production using the Preferred Reporting Items for Systematic Reviews and Meta-analysis.

Geographical distribution of the included studies

The regions with the most studies (*n* = 42 out of 83 studies) were Africa, followed by Southeast Asia (*n* = 20), South America (*n* = 16), Asia (*n* = 4), and Australia (*n* = 2), respectively. Four countries with the highest number of studies were Nigeria (*n* = 19), Thailand (*n* = 11), Indonesia (*n* = 7), and Colombia (*n* = 7; Fig. 2).

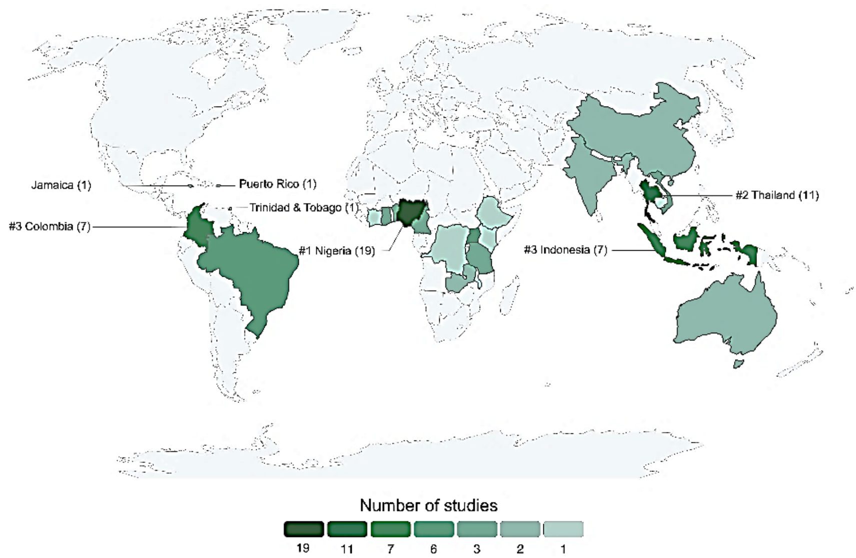

Figure 2. Countries with studies on cassava production meeting the inclusion criteria for systematic review. The #1, #2, and #3 symbols indicate the top three countries by the number of studies. Numbers in brackets refer to the number of studies.

Categorized topics of the included studies

The 83 abstract-screened studies could be identified based on different topics with individual studies potentially encompassing multiple topics, including soil (n = 39 out of 83 studies); pest & disease control (n = 24); genetics & biotechnology (n = 17); crop management (n = 13); land (n = 5); post-harvest & physiology (n = 4); modeling (n = 3); and environmental factors (n = 3), respectively. The soil topic had the most recent studies on cassava production, particularly fertilization (Fig. 3).

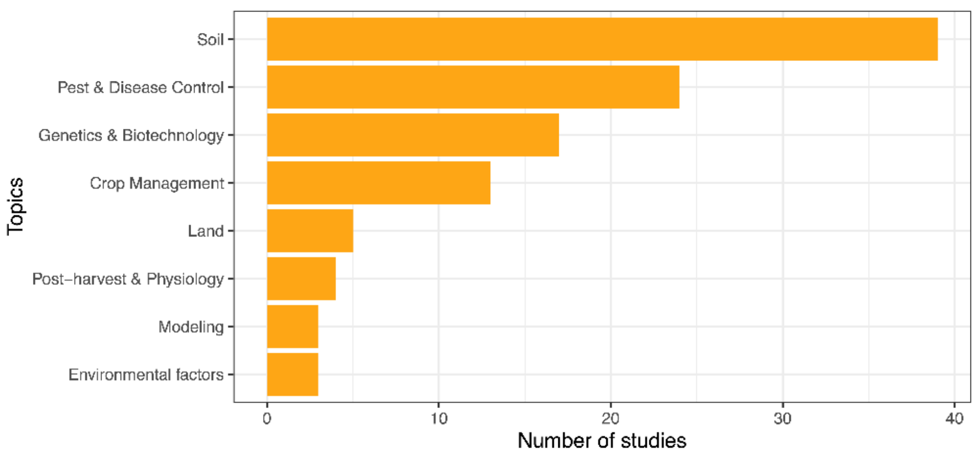

Figure 3. Main topics of 83 cassava production studies meeting the inclusion criteria for systematic review, with individual studies potentially encompassing multiple topics.

Within the fertilization topic, seven studies reported sample sizes and statistical data, including means, *SD*, and *SE*, which allowed us to perform a meta-analysis of fertilization on cassava production. Moreover, the studies were conducted a subgroup analysis based on fertilizer types, dividing the studies into three groups (macronutrients, organics, micronutrients); planting regions, dividing the studies into three groups (Africa, Southeast Asia, South America); and soil textures, dividing the studies into five groups (sandy loam, silt loam, clay, loamy sand, clay loam) (Table 1).

Table 1. Soil studies on cassava production for each categorical grouping in the meta-analysis

Categories		No. of studies	Authors
All studies (n = 7)			
Fertilizer types	Macronutrients	6	Cadavid et al. (1998); Aliyu et al. (2019) Odedina et al. (2012); Kaweewong et al. (2013) Carsky & Toukourou, (2005); Pypers et al. (2012)
	Organics	1	Odedina et al. (2012)
	Micronutrients	1	Marchi et al. (2020)
Planting regions	Africa	5	Cadavid et al. (1998); Aliyu et al. (2019) Carsky & Toukourou (2005) Odedina et al. (2012); Pypers et al. (2012)
	Southeast Asia	1	Kaweewong et al. (2013)
	South America	1	Marchi et al. (2020)
Soil textures	Sandy loam	5	Cadavid et al. (1998); Odedina et al. (2012) Carsky & Toukourou (2005) Pypers et al. (2012); Kaweewong et al. (2013)
	Silt loam	1	Aliyu et al. (2019)
	Clay	1	Kaweewong et al. (2013)
	Loamy sand	1	Kaweewong et al. (2013)
	Clay loam	1	Marchi et al. (2020)

Meta-analysis of fertilization on cassava yield

Overall effect

The meta-analysis of all studies (N = 7 studies, 67 treatments) provided an overall effect size of 0.75 (95% *CI*: 0.53, 0.96) based on the random-effects model. Effect sizes across all studies ranged widely, with 95% CIs spanning from – 1.70 to 20.68. Notably, the majority of treatments across all studies had 95% *CI*s that included zero. However, 6 out of 67 treatments, all involving phosphate addition, showed 95% *CI*s entirely above zero. Interestingly, the test for heterogeneity of effect sizes across all studies was not significant ($I^2 = 0\%$, $\tau^2 < 0.0001$, $p = 0.9603$) (Fig. 4). This lack of heterogeneity suggests that all studies share a common underlying effect size, despite the variability observed in individual treatment outcomes.

These findings highlight the generally positive impact of the treatments, particularly those involving phosphate addition. However, the wide range of confidence intervals and the prevalence of intervals including zero underscore the need for cautious interpretation of results across different contexts and treatment types.

Figure 4. Forest plot showing the magnitude of effect sizes derived from standardized mean differences across studies evaluating fertilization efficiency on cassava fresh root. The blue boxes represent the estimated true effect for each study, with horizontal lines indicating their 95% confidence intervals. The pink diamond at the bottom shows the overall pooled effect from all included studies.

Subgroup effects

These studies were further utilized for subgroup analyses, categorizing the data into three distinct groups: fertilizer types, planting regions, and soil textures (Table 1). The results of the subgroup analyses were as follows.

Fertilizer types. Analysis of the effect sizes revealed varying impacts across different fertilizer types. Micronutrients (N = 1 study, five treatments) showed an effect size of 1.26 (95% *CI*: 0.42, 2.10), with low heterogeneity ($I^2 = 3\%$, $\tau^2 = 0.1634$, $p = 0.39$). Macronutrients (N = 6 studies, 55 treatments) demonstrated a larger effect at 0.81 (95% *CI*: 0.57, 1.05), exhibiting no heterogeneity ($I^2 = 0\%$, $\tau^2 < 0.0001$, $p = 0.96$). However, organics (N = 1 study, seven treatments) exhibited a smaller effect of 0.05 (95% *CI*: –0.55, 0.66), with perfect homogeneity ($I^2 = 0\%$, $\tau^2 = 0$, $p = 1.00$). Notably, only the organic fertilizers' confidence interval spanned zero. The consistently low heterogeneity within subgroups corroborates the suggestion of a common effect size shared among fertilizer types (Table 2; Fig. 5).

Table 2. Effect sizes of fertilizations on cassava production (fresh root weight) by subgroups

Subgroups	N	n_t	SMD (95% CI)	Heterogeneity		
				I^2	τ^2	*P-value*
Fertilizer type						
Micronutrients	1	5	1.26 (0.42, 2.10)	3%	0.1634	0.39
Macronutrients	6	55	0.81 (0.57, 1.05)	0%	< 0.0001	0.96
Organic	1	7	0.05 (-0.55, 0.66)	0%	0.0000	1.00
Planting region						
South America	1	5	1.26 (0.42, 2.10)	3%	0.1634	0.39
Southeast Asia	1	18	1.08 (0.66, 1.49)	0%	0.0000	1.00
Africa	5	48	0.55 (0.28, 0.82)	0%	< 0.0001	0.85
Soil texture						
Silt loam	1	3	9.54 (5.68, 13.41)	0%	0.0000	0.54
Clay loam	1	5	1.26 (0.42, 2.10)	3%	0.1634	0.39
Loamy sand	1	4	1.19 (0.38, 1.99)	0%	0.0000	0.85
Clay	1	4	1.15 (0.34, 1.96)	0%	0.0000	0.62
Sandy loam	5	55	0.55 (0.32, 0.78)	0%	0.0000	1.00
OVERALL	7	67	0.75 (0.53, 0.96)	0%	< 0.0001	0.95

N – the number of studies; n_t – the number of treatments; *SMD* – standardized mean difference; 95% *CI* – 95% confidence interval.

Planting regions. Regional analysis unveiled varying degrees of impact. South America (N = 1 study, five treatments) showed the highest effect size at 1.26 (95% *CI*: 0.42, 2.10), with low heterogeneity ($I^2 = 3\%$, $\tau^2 = 0.1634$, $p = 0.39$). Southeast Asia (N = 1 study, 18 treatments) followed at 1.08 (95% *CI*: 0.66, 1.49), displaying no heterogeneity ($I^2 = 0\%$, $\tau^2 = 0$, $p = 0.93$). Africa ($n = 5$ studies, 48 treatments) displayed a more modest effect of 0.55 (95% *CI*: 0.28, 0.82), also with no heterogeneity ($I^2 = 0\%$, $\tau^2 < 0.0001$, $p = 0.85$). Importantly, all regions' confidence intervals excluded zero. The consistently low or absent within-group heterogeneity further supports the indication of a shared effect size across planting regions (Table 2; Fig. 6)

Soil textures. Soil texture analysis provided diverse results. Silt loam ($n = 1$ study, three treatments) exhibited an exceptionally high effect size of 9.54 (95% *CI*: 5.68, 13.41), with no heterogeneity ($I^2 = 0\%$, $\tau^2 = 0$, $p = 0.54$). Clay loam (N = 1 study, five treatments) and loamy sand (N = 1 study, four treatments) showed similar effects at 1.26 (95% *CI*: 0.42, 2.10) and 1.19 (95% *CI*: 0.38, 1.99), respectively. Clay loam displayed low heterogeneity ($I^2 = 3\%$, $\tau^2 = 0.1634$, $p = 0.39$), while loamy sand showed no heterogeneity ($I^2 = 0\%$, $\tau^2 = 0$, $p = 0.85$). Clay (N = 1 study, four treatments) demonstrated a lower effect of 1.15 (95% *CI*: 0.34, 1.96), with no heterogeneity ($I^2 = 0\%$, $\tau^2 = 0$, $p = 0.62$). All soil textures' confidence intervals were above zero. The consistently low or absent within-group heterogeneity across all soil textures reinforces the suggestion of a common effect size shared among soil types. (Table 2; Fig. 7)

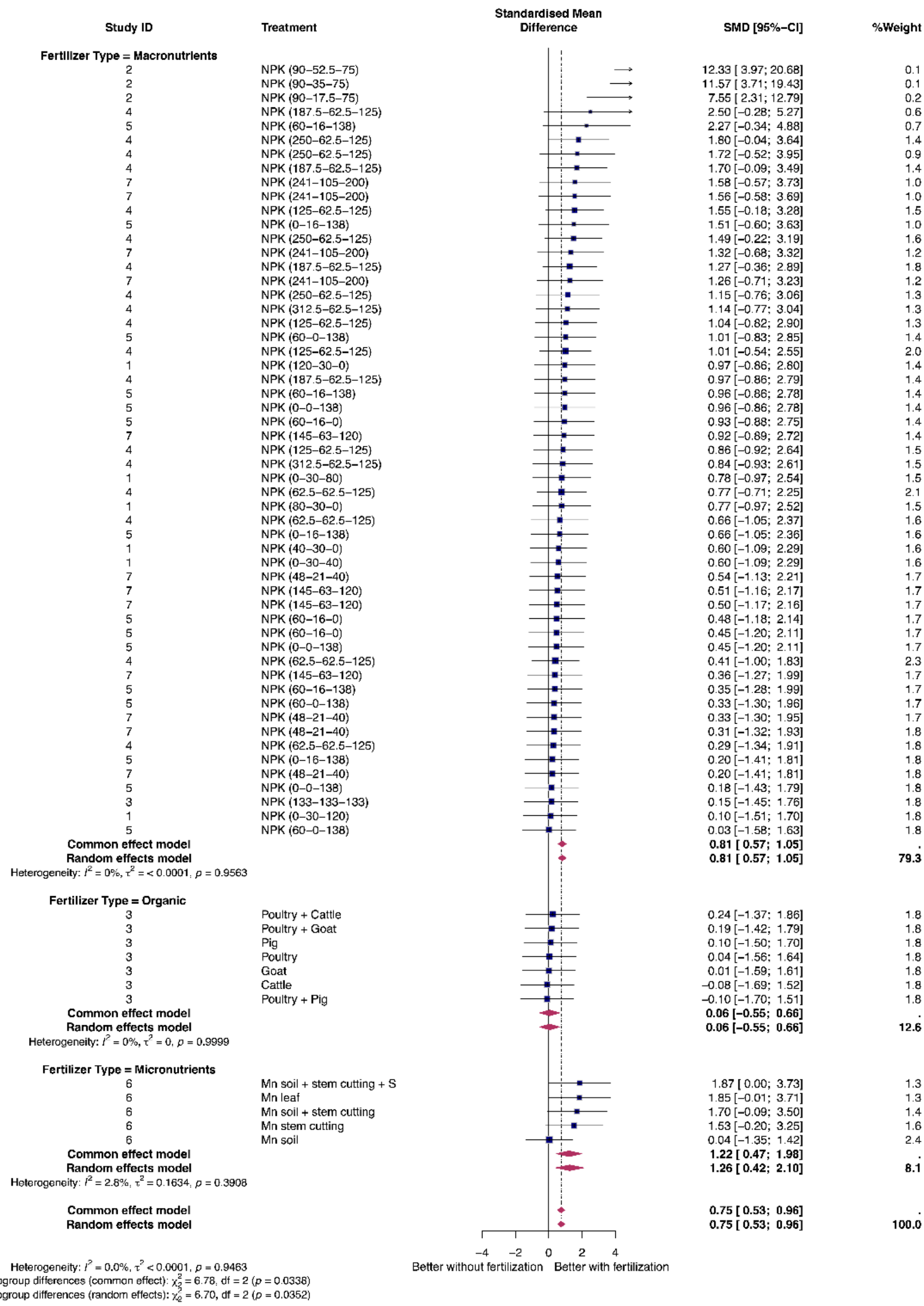

Figure 5. Forest plot of fertilization studies in cassava production, sup-grouped by fertilizer types.

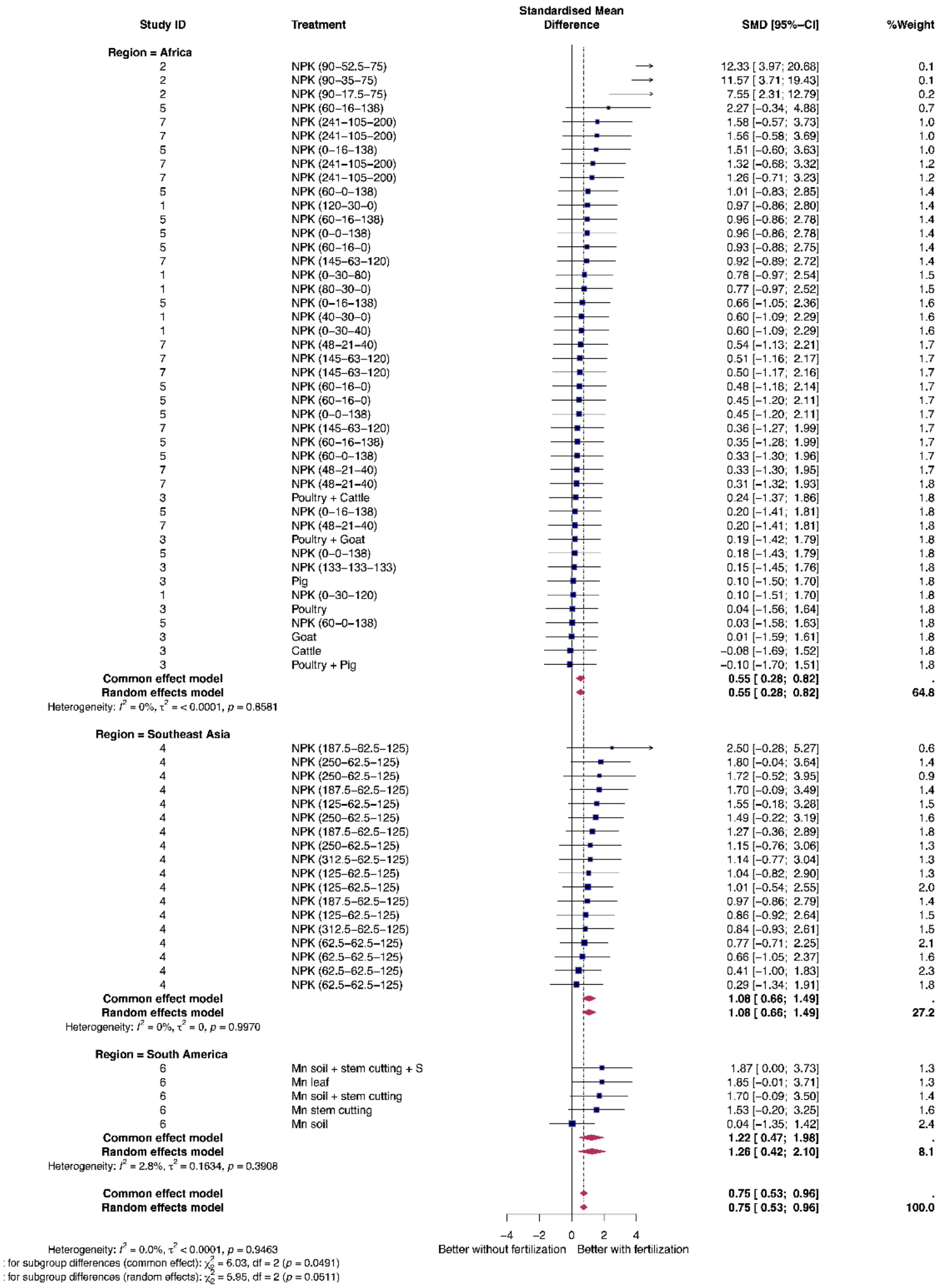

Figure 6. Forest plot of fertilization studies in cassava production, sup-grouped by continental regions.

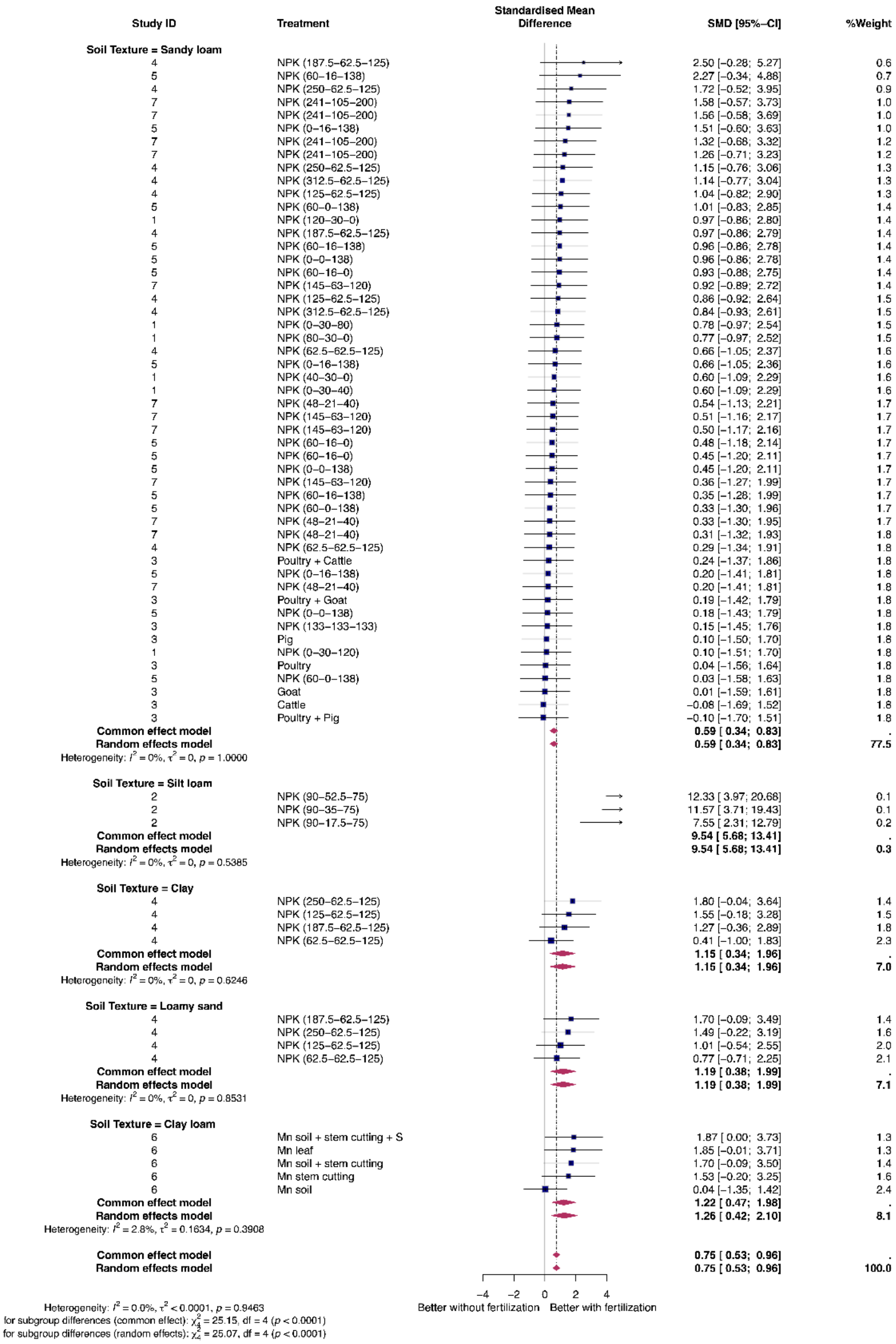

Figure 7. Forest plot of fertilization studies in cassava production, sup-grouped by soil textures.

DISCUSSION

Our systematic review screened 85 studies on cassava production, of which 39 (46%) examined fertilizer application effects on yield. Only seven of these fertilization studies met our inclusion criteria for meta-analysis. Given that cassava is a crop harvested from underground and the majority of cassava cultivation occurs in African regions with low soil fertility, it is reasonable that research has focused on soil contexts, particularly applying fertilization to improve soil fertility. To evaluate the effectiveness of fertilization across comparable studies, we performed a meta-analysis examining its impact on cassava yield.

Our meta-analysis revealed that an overall moderately positive effect of fertilizer application on cassava yield, with heterogeneity approaching zero at a statistically significant level (Fig. 4). The existing studies consistently demonstrate that fertilizer application enhances cassava yield in a similar manner across different research contexts, such as varying fertilizer types, soil textures, and planting regions.

Effectiveness of different fertilizer types on cassava yield

Our subgroup analyses by fertilizer types revealed significant differences in the effectiveness of various fertilizer types on cassava yield, as reflected by their distinct effect size. Micronutrients demonstrated the highest effect size, followed by macronutrients and organic fertilizers, showing the lowest effect (Table 2).

Micronutrients. Fertilization with micronutrients showed a notably greater positive influence on cassava yield compared to macronutrients and organic fertilizers. However, this finding should be interpreted cautiously as it was based on a single study on Manganese with relatively few treatments ($N = 5$) and samples ($n = 20$), whereas macronutrient data were derived from six studies with substantially more treatments ($n = 55$) and samples ($n = 356$). The limited data for micronutrients might have influenced the magnitude of the observed effect.

Despite the limited sample size in our meta-analysis, emerging research supports the potential of micronutrient fertilization for substantial yield improvements. Specifically, manganese fertilization through foliar spraying or treating stem cuttings with manganese solutions before planting effectively increased fresh root yield, shoot yield, and the number of roots by 516%, 227%, and 319% respectively, compared to control treatments (Marchi et al., 2020). These findings suggest that micronutrient deficiencies, particularly manganese, may be significant but underrecognized constraints to cassava productivity, especially in intensively cultivated areas where soil micronutrient depletion or limited bioavailability is more likely to occur (Howeler, 2001; Marchi et al., 2020).

Macronutrients. Chemical fertilizers containing macronutrients (both NPK combinations and individual nutrients) demonstrated a greater positive influence on cassava yield compared to organic fertilizers. This superior performance can be attributed to the precise nutrient composition of chemical fertilizers. Commercial fertilizers contain exact ratios of nutrients, typically expressed as percentages of N, P, and K, allowing farmers to supply just the right amounts needed by cassava plants. Additionally, these fertilizers are sold in dry form, maximizing their nutrient concentration while minimizing water content, which enhances their effectiveness (Howeler & Maung Aye, 2014).

Multi-location trials across Africa and Asia consistently reported significant yield gains with NPK application, with increases ranging depending on application rates (Carsky & Toukourou, 2005; Kaweewong et al., 2013; Aliyu et al., 2019). Nitrogen fertilizer enhances overall plant growth, increases the efficiency of photosynthesis, and boosts the leaf area index (LAI), leading to higher yields, with fresh root yields (Kaweewong et al., 2013).

Phosphorus is often a limiting nutrient in savanna soils, and its improved acquisition is crucial for increasing crop yields (Aliyu et al., 2019). Withholding phosphorus from a complete fertilizer regime resulted in significant yield reductions (Carsky & Toukourou, 2005). In low phosphorus conditions, co-application of phosphorus fertilizer with arbuscular mycorrhizal fungal (AMF) inoculants can reduce phosphorus fertilizer requirements while maintaining statistically similar root fresh yields to full phosphorus application (Aliyu et al., 2019).

Potassium deficiency is often the main limiting factor when cassava is grown continuously without potassium fertilizer, with withholding potassium leading to significant yield reductions (Carsky & Toukourou, 2005; Howeler, 2001). This wide range in response rates underscores the importance of site-specific nutrient management, as the magnitude of yield response depends heavily on initial soil fertility status and the specific nutrients limiting production in each location.

Organics. In contrast, organic fertilizers showed the lowest effect size with a confidence interval that included zero (– 0.04, 0.57), suggesting their impact might not be statistically significant in some contexts. Several factors can explain this limited effectiveness. According to Howeler & Maung Aye (2014), while manure provides valuable secondary nutrients and improves soil structure and water-holding capacity, it contains relatively small amounts of the macronutrients (N, P, K) that crops need in larger quantities. Furthermore, the nutrient composition of organic fertilizers cannot be tailored to the specific requirements of cassava and varies considerably depending on their source, animal feed, and storage methods. This variability likely contributed to their less consistent performance compared to chemical fertilizers in enhancing cassava yield.

However, it is important to note that organic fertilizers provide benefits beyond immediate yield increases. Research indicates that organic amendments such as poultry or cattle manure and compost improve soil organic carbon content and contribute to long-term soil health maintenance (Cadavid et al., 1998; Odedina et al., 2012; Pypers et al., 2012). Single applications of organic manure significantly increased soil Na, K, Mg, and CEC, available P, Zn, and organic matter compared to control treatments (Odedina et al., 2012). The addition of organic and organo-mineral fertilizers increased cassava tuber weight and biomass production (Odedina et al., 2012).

While their immediate effect on cassava yield may be lower than that of chemical fertilizers, organic inputs play a crucial role in sustainable production systems by enhancing soil physical and biological properties over time. Mulch applications significantly reduced soil temperatures, increased soil organic carbon, and improved levels of K, P, Ca, and Mg in the soil while maintaining soil pH near its initial value (Cadavid et al., 1998).

Relationship between soil texture and fertilizer efficiency

Soil texture plays a fundamental role in determining fertilizer efficiency for cassava cultivation, with different soil types exhibiting markedly distinct responses to nutrient applications. The subgroup analyses revealed striking variations in fertilizer responsiveness across soil textures, with silt loam demonstrating an exceptionally high fertilizer response, substantially exceeding the responses observed in clay loam, loamy sand, clay, and sandy loam soils (Table 2). This remarkable variation underscores the critical importance of soil physical properties in governing fertilizer use efficiency for cassava production. The differential responses across soil textures can be attributed to three interconnected mechanisms (physical, chemical, and biological processes) that collectively influence nutrient availability and plant uptake.

Physical properties and nutrient retention. Soil texture directly affects pore size distribution, water retention, and drainage characteristics, which in turn influence nutrient mobility and accessibility (Chaem-Ngern et al., 2020; Xie et al., 2020). Silt loam soils, with silt as the dominant component, possess an optimal balance of small pores that effectively retain water and nutrients while maintaining adequate drainage and aeration for root development (Wang et al., 2022). This dual advantage enables silt loam to combine the benefits of both fine and coarse-textured soils. Cassava performs optimally in well-structured, loose soils that promote oxygen availability, prevent root rot, and enhance overall productivity (Fasinmirin & Reichert, 2011). In contrast, sandy and loamy sand soils, characterized by low cation exchange capacity (CEC) and poor nutrient retention capacity, experience significant leaching losses of applied fertilizers, particularly potassium (K) and nitrogen (N), resulting in reduced fertilizer use efficiency and lower cassava yields compared to finer-textured soils (Chaem-Ngern et al., 2020; Xie et al., 2020).

Chemical properties and cation exchange. The chemical composition of soil texture classes fundamentally determines their capacity to retain and supply nutrients to plants. Silt loam soils benefit from moderate clay and organic matter content, which confers high cation exchange capacity, ensuring that applied NPK fertilizers remain plant-available rather than being lost through leaching processes (Wang et al., 2022). The superior nutrient retention in finer-textured soils such as sandy clay loam and loam enables more effective utilization of fertilizer inputs compared to coarse-textured soils (Pongsivapai et al., 2016; Xie et al., 2020). Conversely, heavy clay soils, while possessing high nutrient retention capacity, may hold water too tightly and impede root penetration or restrict oxygen supply, potentially limiting nutrient uptake efficiency (Fasinmirin & Reichert, 2011).

Biological interactions and root development. Well-structured loam soils create favorable conditions for vigorous root system development and support beneficial symbiotic relationships with microorganisms, particularly mycorrhizal fungi, which enhance nutrient uptake capacity (Wang et al., 2022). The biological activity in these soils further contributes to nutrient cycling and availability. In contrast, coarse sandy soils not only allow rapid nutrient leaching but also provide less favorable conditions for beneficial microbial associations, further reducing fertilizer efficiency.

This comprehensive understanding of soil texture-fertilizer interactions provides a foundation for developing site-specific nutrient management strategies that optimize both fertilizer efficiency and cassava productivity while considering the inherent limitations and advantages of different soil types.

Regional variation in fertilizer response

Geographical and environmental differences between planting regions significantly impact the efficiency of fertilizer use in increasing cassava yields. The subgroup analyses revealed notable disparities in the effectiveness of fertilizer application on cassava yield. The strongest effect was observed in South America, followed by Southeast Asia, with Africa showing a relatively lower effect size. Despite these differences, heterogeneity remained minimal, indicating consistent responses within each region (Table 2). These differences were likely due to contrasting soil fertility levels, dominant nutrient limitations, and management practices across regions.

In South America, cassava was primarily cultivated on acidic and nutrient-depleted soils such as Ultisols, Alfisols, and Oxisols, which were often severely deficient in phosphorus (Pellet & El-Sharkawy, 1993; Howeler, 2012). This marked nutrient limitation likely contributed to the high responsiveness of cassava to fertilization in this region, particularly when phosphorus was applied. Moreover, cassava was commonly integrated into mixed farming systems when fertilizer use may be prioritized when resources were available, further enhancing the observed effect size. Despite cassava's adaptability to marginal soils, studies suggested that without external inputs, yield remained suboptimal, which created a greater relative gain when fertilizers were introduced (Henry & Hershey, 2001; Howeler, 2012)

In Southeast Asia, the soils, mainly Ultisols, Inceptisols, and Alfisols, were relatively more fertile compared to South America, and phosphorus deficiency was less widespread (Howeler, 2012). Nevertheless, cassava showed a strong yield response to nitrogen and potassium in this region, especially in intensively cultivated areas of China and Vietnam (Howeler, 2012). The higher effect size in Southeast Asia can be attributed to regionally targeted fertilizer regimes that address specific nutrient demands, coupled with more developed infrastructure and extension services that support the adoption of fertilizers.

Conversely, in Africa, particularly in West Africa, cassava was grown across diverse soil types with significant variability in fertility. Continuous cultivation without adequate replenishment had led to widespread potassium deficiency, which was considered the primary limiting nutrient in many cassava-growing areas (Howeler, 2012; Ezui et al., 2016). Despite the observed deficiency, the effect size of fertilization in Africa was the lowest among the regions. The lowest effect size might reflect suboptimal fertilizer application rates, limited access to appropriate nutrient formulations, and economic constraints faced by smallholder farmers, which reduced the effectiveness of fertilizer use in practice (Fermont et al., 2009; Howeler, 2012; Ezui et al., 2016).

Additionally, Africa accounted for the majority of included studies (48 out of 67 treatments), which may introduce a distributional bias in the overall effect size, as underperformance in this region can disproportionately influence the pooled average. In contrast, fewer studies from South America and Southeast Asia, despite showing higher responsiveness, may not fully capture the potential of well-managed fertilization practice in those contexts.

Geographical conditions may indeed affect cassava yield through several combined factors. However, the large effect size observed in South America may not definitively demonstrate that this region has superior fertilizer response compared to the other regions, given that the effect size is derived from a limited number of studies. However, South America continues to represent a region where cassava demonstrates substantial responsiveness to fertilization interventions, likely due to the specific soil-plant-environment interactions that have evolved in these acidic, nutrient-depleted soils.

CONCLUSION

This systematic review and meta-analysis indicated that research on cassava production has predominantly focused on nutrient management interventions to improve yields. The aggregated evidence suggests that fertilizer application provides only modest overall yield gains, with minimal effect sizes for organic inputs. By contrast, inorganic fertilizers, especially those supplying phosphorus, tended to have clearer positive impacts on cassava yields. However, these yield responses varied markedly across soil types and regions, implying that local soil fertility and environmental conditions strongly modulate fertilization outcomes.

A critical limitation of this study is that only seven studies met our inclusion criteria for meta-analysis. This small sample size reflects both the scarcity of standardized cassava fertilization research and our rigorous selection requirements for cross-study comparison. Consequently, our findings should be interpreted with appropriate caution, particularly when extrapolating to regions or conditions underrepresented in the available literature. While our robust methodological approach helps ensure the reliability of our conclusions, the limited evidence base inherently constrains the statistical power and generalizability of our results.

This meta-analysis identified a major obstacle in the lack of standardized statistical reporting in agricultural studies. Few studies reported complete statistical details (means, standard deviations, and sample sizes), hindering robust cross-study comparisons and the ability to conduct a fully comprehensive meta-analysis. Despite the observed benefits of targeted fertilization, particularly phosphorus supplementation, the evidence base remains constrained by inconsistent data reporting and context-dependent results. To address these issues, we recommend that future research adopt standardized statistical reporting practices and explore region-specific fertilizer management approaches. Such improvements would enhance data synthesis and guide more effective fertilization recommendations tailored to local conditions in cassava production.

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