Open Journal of Soil Science, 2026, 16(6), 101-120
https://www.scirp.org/journal/ojss
ISSN Online: 2162-5379
ISSN Print: 2162-5360

Carbonized Rice Hulls as a Climate-Smart Soil Amendment for Coffee Production in Mbozi District, Tanzania

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How to cite this paper: Mlengera, N., Katunzi, A., Mng'ong'o, M., Mvile, B., Nyabwisho, K., Kazungu, S. and Khafa, B. (2026) Carbonized Rice Hulls as a Climate-Smart Soil Amendment for Coffee Production in Mbozi District, Tanzania. *Open Journal of Soil Science*, **16**, 101-120.
https://doi.org/10.4236/ojss.2026.166006

Received: May 18, 2026
Accepted: June 27, 2026
Published: June 30, 2026

Abstract

Declining soil fertility is a major constraint to coffee productivity in the Southern Highlands of Tanzania. This study assessed the impact of carbonized rice hull (CRH) amendments on soil properties in coffee-based systems of Mbozi district. Soil samples from four villages (Nsenga, Iyula, Nambinzo, Halungu) were collected at two depths (0 - 30 cm, 30 - 60 cm) before and after CRH application. Parameters measured included pH, electrical conductivity, moisture, organic carbon, macronutrients (N, P, S), exchangeable bases (K, Mg, Ca), micronutrients (Fe, Mn, Zn), and cation exchange capacity (CEC). Results showed marked improvements in soil moisture (3.4 - 7.0% to 8.3 - 18.2%) and organic carbon (0.53 - 1.97% to 0.79 - 2.30%), with Iyula recording the highest gains. Phosphorus and zinc concentrations increased significantly, enhancing fertility essential for coffee growth. Although mild acidification occurred in some sites, CEC improved notably, especially in Iyula (up to 22.74 Cmol/kg), indicating stronger nutrient-holding capacity. Site-specific differences were evident: Iyula soils were near-neutral and fertile, while Halungu soils remained acidic with low CEC, requiring corrective measures. Overall, CRH demonstrated strong potential to restore soil health, improve nutrient availability, and enhance resilience of smallholder coffee systems. Findings highlight CRH as a climate-smart amendment, though site-specific strategies remain vital for optimizing outcomes.

Keywords

Carbonized Rice Hull, Cation Exchange Capacity, Climate-Smart Soil Amendment, Integrated Soil Fertility Management

1. Introduction

Coffee is one of Tanzania's most important cash crops, contributing significantly to household income, national export earnings, and rural livelihoods [1]. However, declining soil fertility has been identified as a major constraint to coffee productivity in many growing regions of the country [2]. The soils of Tanzania are highly diverse, ranging from Cambisols and Acrisols to Ferralsols, many of which are characterized by low nutrient reserves and increasing acidity [3]. Soil acidity, in particular, has emerged as a critical challenge, with approximately 14% of Tanzania's cropland classified as acidic, leading to reduced nutrient availability and crop yields [4]. Studies have shown that acidic soils can reduce production efficiency of staple crops by up to 40%, underscoring the urgency of soil management interventions [5].

Fertilizer use remains a cornerstone of soil fertility management. Inorganic fertilizers provide readily available nutrients that can significantly boost yields, but their high cost and limited accessibility constrain widespread adoption among smallholder farmers [6]. Integrated Soil Fertility Management (ISFM) approaches, which combine organic amendments with inorganic inputs, have been promoted as a sustainable strategy to enhance nutrient availability, improve soil structure, and increase long-term productivity [7]. Organic amendments such as manure and carbonized rice husk (CRH) contribute to soil organic matter, improve water retention, and enhance microbial activity, though their nutrient release is slower and less synchronized with crop demand [8].

Soil chemical properties such as pH, organic carbon, nitrogen, phosphorus, and sulfur are critical determinants of crop response to fertilization [9]. Neutral to slightly acidic soils (pH 6 - 7) generally favor nutrient availability, while strongly acidic soils (pH < 5.5) limit phosphorus uptake and micronutrient balance [10]. Organic carbon plays a central role in soil fertility by improving nutrient cycling and microbial activity, whereas nitrogen, phosphorus, and sulfur are essential macronutrients for plant growth and yield formation [11]. Variability in these parameters across villages underscores the importance of site-specific soil fertility management.

The study aimed to enhance soil fertility, boost land productivity, improve moisture retention, and minimize soil erosion in coffee farming systems that face multiple abiotic, biotic, and socio-economic challenges. It was implemented through CRH technology alongside other soil amendments, both recognized as climate-smart practices designed to increase productivity in coffee production. Due to inherently poor soil conditions, communities engaged in coffee farming often struggle with poverty, food insecurity, and malnutrition. In Mbozi district, coffee remains the most viable crop, yet its sector suffers from low yields driven by biotic, abiotic, and socio-economic constraints [1]. Key abiotic limitations include declining soil fertility, recurring drought, frost, inadequate soil moisture, high humidity, and unpredictable rainfall. Biotic pressures such as coffee berry disease (CBD), coffee leaf rust (CLR), and insect pests further reduce productivity. Yields are also hampered by reliance on traditional, long-maturing local varieties that no longer adapt well to shortened growing seasons. Developing high-yielding, stable varieties resistant to major biotic and abiotic stresses, while meeting end-user needs, is therefore a priority for sustainable improvement. Combining these improved varieties with climate-smart practices and management strategies such as CRH interventions and fertilizer micro-dosing offers strong potential to significantly raise coffee yields [12].

In this context, evaluating the agronomic and economic performance of different fertilization strategies including inorganic fertilizer, manure, and CRH provides critical insights for sustainable coffee production in Tanzania. Such studies contribute to regional training on climate smart technologies and soil health management, which emphasizes improved fertilizer access, integrated soil fertility management, and long-term soil health restoration [13]. Given the increasing stresses and variability of abiotic, biotic, and socio-economic factors intensified by climate change, a new approach is required one that embraces environmental variability and risk rather than assuming uniform conditions. The integrated soil fertility management is essential, fostering synergies between natural resource management and crop production [14].

Therefore, this study evaluated the effectiveness of integrated soil fertility management practices including CRH, animal manure, and industrial fertilizers in improving soil fertility, moisture conservation, and coffee productivity under variable biotic, abiotic, and socio-economic factors exacerbated by climate change. These interventions were designed as adaptive innovations stress-tolerant, synergistic, locally customizable, and resilient to unexpected variability while drawing on local knowledge, institutions, and comparative advantages. Specifically, the study sought to assess: (i) the soil fertility status of coffee fields before and after CRH application, (ii) the effectiveness of combining animal manure (AM) with CRH in improving soil fertility, (iii) the role of CRH in conserving soil moisture within coffee production systems, and (iv) the yield potential, income gains, and benefit-cost ratios associated with different soil amendment treatments.

2. Materials and Methods

2.1. Description of the Study Sites

This research was carried out in Mbozi district, situated in the Southern Highlands of Tanzania. The district was chosen because of its long-standing tradition of cultivating arabica coffee and the on-going initiatives, since 2005, to distribute improved coffee varieties to farmers. Geographically, Mbozi lies between 8˚45'0" S and 32˚45'0" E. It shares boundaries with Chunya district to the North, Mbeya urban and Ileje districts to the East, Zambia to the South, and Rukwa region to the West (**Figure 1**). The district's elevation ranges from 900 to 2750 meters above sea level. Annual rainfall varies between 1350 mm and 1550 mm, while temperatures range from 20˚C to 28˚C. Mbozi is well known for food crop production, including maize, sorghum, finger millet, sweet potatoes, Irish potatoes, beans, and groundnuts. In addition, cash crops such as coffee, sunflower, and sesame are widely cultivated.

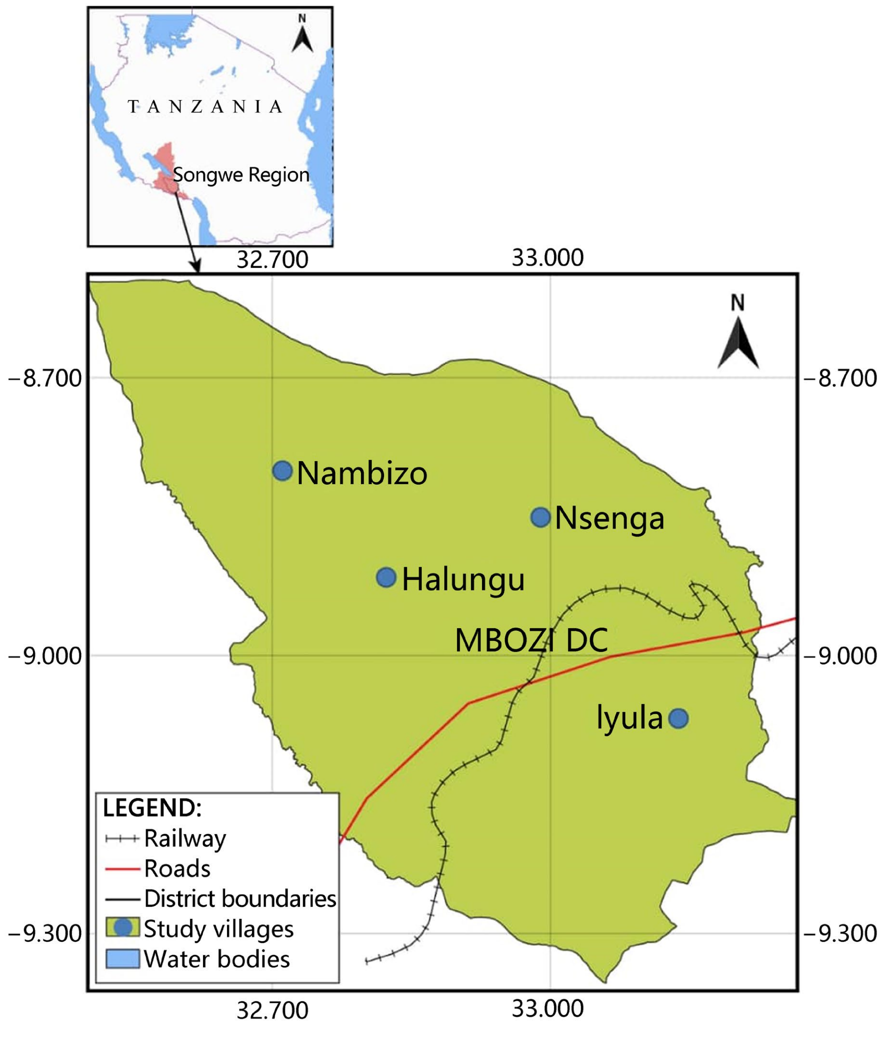

Figure 1. The map showing the study areas.

2.2. Steps to Prepare Carbonated Rice Hulls

First, ignite the fire inside the rice husk burner (**Figure 2**). Spread the rice husks evenly across the bottom of the burner. During the charring process, the husks should be carefully stirred to ensure uniform burning under controlled fire, preventing them from turning completely into ash.

Figure 2. Rice husk burner (written consent to publish was obtained from the participant).

2.3. Soil Sampling and Analytical Procedures before and after CRH Application

Soil samples were systematically collected from coffee fields in four villages of Mbozi district Iyula, Nambinzo, Nsenga, and Halungu both before CRH (B CRH) and after CRH (A CRH) application to capture treatment effects (Figure 3). In each village, samples were taken at two depths: 0 - 30 cm (topsoil), representing the plough layer for shallow-rooted crops, and 30 - 60 cm (subsoil), representing the rooting zone for deeper crops. This stratified sampling approach ensured that both nutrient-rich surface layers and deeper horizons were assessed for treatment responses. Composite sub-samples were prepared by mixing soil cores collected randomly within representative coffee plots to minimize bias. The sub-samples were air-dried, gently crushed, and passed through a 2-mm sieve to remove coarse fragments before laboratory analysis.

A comprehensive set of soil fertility parameters was measured to evaluate the impact of CRH. These included soil pH, electrical conductivity (EC), organic carbon (OC), total nitrogen (N), extractable phosphorus (P), and sulfur (S). Exchangeable bases such as potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) were determined alongside micronutrients including iron (Fe), manganese (Mn), and zinc (Zn). Soil fertility indices such as cation exchange capacity (CEC), exchangeable acidity, and exchangeable aluminum were also assessed to provide a holistic understanding of soil chemical dynamics. The distinction between B CRH samples, which provided baseline soil fertility conditions prior to intervention, and A CRH samples, which reflected post-treatment changes in nutrient availability, moisture retention, and soil structure, was central to the experimental design.

By replicating analyses across villages and soil depths, the study ensured reliability and robustness of results. This methodological rigor allowed for quantification of CRH-induced improvements and identification of site-specific constraints, thereby providing a strong basis for evaluating CRH as a climate-smart soil amendment for coffee production systems in Mbozi district.

Figure 3. Soil collection in coffee field (written consent to publish were obtained from the participants some being authors of the manuscript).

2.4. Experimental Design and Treatment Structure

Multi-location field trials were conducted across diverse coffee-growing ecologies in Mbozi district to capture variability in soil and environmental conditions. The experiments were laid out using a randomized complete block design (RCBD) to minimize experimental error and ensure statistical reliability. Three soil amendment types were applied that included Bio-char (16 tha^{-1}), Manure (12.5 tha^{-1}), and Inorganic fertilizers (310 kg Nha^{-1} and 200 kg Pha^{-1}). [15]-[17]. Four treatments were tested: (i) animal manure (20%) combined with carbonized rice hulls (CRH) (80%), (ii) CRH alone (100%), (iii) animal manure (50%) combined with CRH (50%), and (iv) the recommended inorganic fertilizer (IF) serving as the control benchmark. Each treatment was replicated three times per village/location, thereby strengthening the robustness of the data and allowing for meaningful comparisons across villages and soil depths.

The RCBD arrangement ensured that local variations in soil fertility, moisture, and micro-climatic conditions were accounted for, while the replication across sites enhanced the reliability of treatment effects. Treatments involving CRH were designed to evaluate its role both as a standalone amendment and in combination with animal manure, reflecting integrated soil fertility management practices. The inclusion of inorganic fertilizer provided a comparative standard against conventional practices. Placement of CRH and fertilizer inputs was carefully managed to reflect farmer practices while maintaining experimental rigor (**Figure 4**). This design allowed for the assessment of CRH's effectiveness in improving soil fertility, nutrient retention, and coffee productivity under real-world smallholder conditions.

Figure 4. CRH (left) and industrial fertilizer (right) placement in coffee trials in the study areas (written consent to publish were obtained from the participants).

3. Results and Discussion

3.1. Physical Chemical Soil Parameters Studied

The analysis of soil pH across the four study sites; Nsenga, Iyula, Nambinzo, and Halungu reveals distinct spatial variability in soil acidity (**Figure 5**). Nsenga, Halungu and Nabinzo exhibit relatively medium acidity soils, with pH values of approximately 5.5 to 5.9. In contrast, Iyula demonstrates consistently higher pH values, ranging from 6.7 to 6.8, with a median of 6.75, indicating very slightly acidity compared to the other sites. Acceptable pH for arabica which is grown in the study sites is in the range of 5.2 - 6.5. The narrow ranges observed within each site suggest stable soil chemistry locally, though the differences between sites highlight the influence of environmental and geological factors.

These findings carry important implications for agricultural productivity and soil management. Acidic soils, such as those observed in Nsenga, Halungu, and Nambinzo, are known to limit the availability of essential nutrients like phosphorus, calcium, and magnesium, while increasing the solubility of potentially toxic elements such as aluminum. Such conditions can negatively impact crop growth and yield unless corrective measures, such as liming, are applied to raise soil pH and improve nutrient availability [18]. Conversely, Iyula's near-neutral soils provide more favorable conditions for crop development, as nutrient availability and microbial activity are generally optimized in soils with pH values closer to neutrality. This suggests that Iyula may require fewer amendments to sustain high levels of productivity compared to the other sites.

The observed variability underscores the importance of site-specific soil management interventions. Uniform approaches across regions may fail to address localized constraints, particularly in areas with acidic soils. Tailored interventions, informed by soil pH monitoring, can enhance nutrient cycling, improve crop resilience, and support sustainable agricultural practices [19]. These results align with broader findings in the literature, which emphasize that soil pH is a critical determinant of nutrient availability, microbial activity, and overall crop performance [20]-[22].

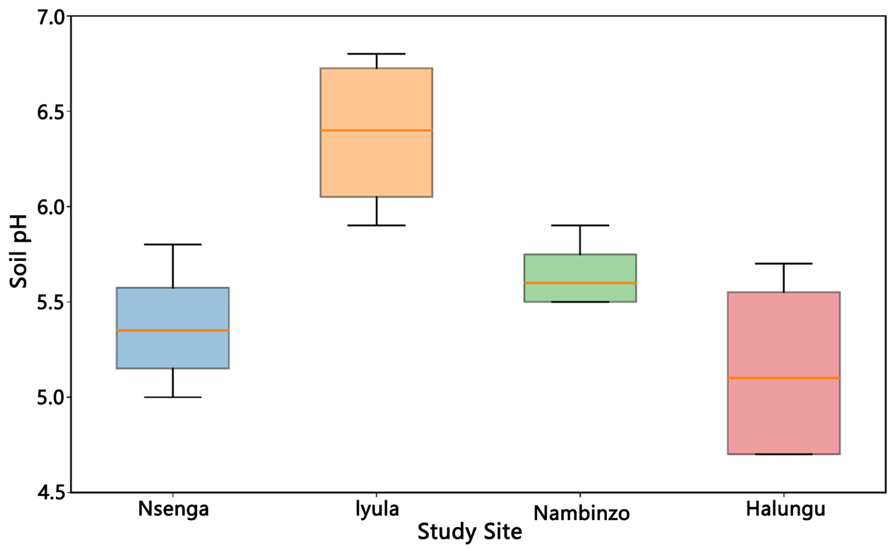

Figure 5. The soil pH among the studied coffee farms in four villages before CRH application.

The analysis of soil properties across Nsenga, Iyula, Nambinzo, and Halungu villages reveal clear contrasts in fertility potential and constraints (**Table 1**). Iyula consistently stands out as the most fertile site, with near-neutral pH values (6.7 - 6.8 under B CRH and 5.9 - 6.1 under A CRH), higher organic carbon (up to 2.3%), and elevated nutrient concentrations, particularly phosphorus (up to 14.04 mg/kg) and magnesium (up to 14.4 cmol/kg). These conditions are highly favorable for crop growth, as nutrient availability and microbial activity are optimized in soils closer to neutrality [23]. The high moisture content observed under A CRH further enhances Iyula's suitability for sustained agricultural productivity.

In contrast, Halungu emerges as the most constrained site. Soils here are strongly acidic (pH as low as 4.7 under A CRH), with low calcium (as little as 0.68 cmol/kg) and generally reduced nutrient levels compared to other sites. Such conditions are known to limit nutrient uptake and increase aluminum toxicity risks, which can impair root development and crop yields [24]. Nsenga and Nambinzo occupy intermediate positions: both exhibit moderately acidic soils (pH 5.0 - 5.9), with variable nutrient profiles. Nsenga shows relatively low organic carbon and phosphorus, while Nambinzo demonstrates higher potassium and magnesium levels but still requires pH correction for optimal productivity.

Overall, the comparative analysis underscores the importance of site-specific soil management interventions. Iyula may require minimal intervention to sustain productivity, while Halungu demands significant corrective measures such as liming and balanced fertilization to overcome acidity and nutrient deficiencies. Nsenga and Nambinzo, though less constrained, would also benefit from targeted amendments to optimize nutrient availability. These findings reinforce the broader consensus in soil science that managing pH and organic matter is central to improving crop performance and ensuring long-term soil health [20] [25] [26].

Table 1. The chemical soil fertility parameters analyzed from studied soils before and after experimentation with CRH at various soil depth (top 0 - 30 and sub soil 30 - 60) in various coffee farms among studied villages in Mbozi district.

S/N	Village	Soil depth (cm)	Treatment	pH	E.C	MC	OC	N	P	S	K	Mg	Ca
1	Nsenga	30 - 60	B CRH	5.80	0.09	4.50	0.53	0.05	6.70	2.90	1.10	12.80	3.20
2	Nsenga	0 - 30	B CRH	5.50	0.09	3.60	0.91	0.08	5.90	3.90	1.30	7.60	3.20
3	Iyula	0 - 30	B CRH	6.70	0.09	5.80	1.60	0.14	7.90	6.30	0.90	12.60	7.20
4	Iyula	30 - 60	B CRH	6.80	0.08	6.40	1.10	0.10	9.10	6.70	1.03	10.97	6.40
5	Nambinzo	0 - 30	B CRH	5.70	0.16	3.40	1.30	0.11	5.80	4.80	0.90	6.80	8.60
6	Nambinzo	30 - 60	B CRH	5.90	0.06	5.30	0.60	0.05	6.10	5.70	1.30	8.70	2.30
7	Halungu	0 - 30	B CRH	5.50	0.07	7.00	1.20	0.10	5.90	4.40	1.10	6.70	1.80
8	Halungu	30 - 60	B CRH	5.70	0.13	5.30	1.97	0.17	6.30	2.10	1.10	8.40	2.60
9	Nsenga	30 - 60	A CRH	5.00	0.24	8.30	0.98	0.09	5.84	6.70	0.84	7.70	2.10
10	Nsenga	0 - 30	A CRH	5.20	0.18	9.50	0.79	0.08	3.70	3.80	0.73	10.72	2.98
11	Iyula	0 - 30	A CRH	5.90	0.20	18.20	2.30	0.19	14.04	5.47	1.14	14.40	7.20
12	Iyula	30 - 60	A CRH	6.10	0.14	16.60	1.70	0.15	13.04	6.40	1.16	12.60	6.80
13	Nambinzo	0 - 30	A CRH	5.50	0.17	12.60	1.45	0.13	8.60	4.10	1.18	8.20	2.30
14	Nambinzo	30 - 60	A CRH	5.50	0.13	12.40	1.12	0.09	4.90	7.20	0.94	10.30	3.50
15	Halungu	0 - 30	A CRH	4.70	0.27	10.70	1.87	0.17	3.80	4.90	1.10	1.95	0.68
16	Halungu	30 - 60	A CRH	4.70	0.20	14.30	1.25	0.12	4.96	7.01	1.04	4.70	1.05

Table 2. Micronutrient concentrations (Fe, Mn, Zn) and Cation exchange capacity (CEC) across villages, soil depth and treatments.

S/N	Village	Soil depth (cm)	Treatment	Fe (ppm)	Mn (ppm)	Zn (ppm)	CEC (Cmol/kg)
1	Nsenga	30 - 60	B CRH	330.50	276.00	0.49	17.10
2	Nsenga	0 - 30	B CRH	328.40	287.40	1.10	12.10
3	Iyula	0 - 30	B CRH	20.70	235.90	6.30	20.70
4	Iyula	30 - 60	B CRH	18.40	1.40	292.60	18.40
5	Nambinzo	0 - 30	B CRH	16.30	0.70	226.10	16.30
6	Nambinzo	30 - 60	B CRH	12.30	0.00	313.70	12.30
7	Halungu	0 - 30	B CRH	9.60	0.00	370.50	9.60
8	Halungu	30 - 60	B CRH	12.10	17.50	271.60	12.10
9	Nsenga	30 - 60	A CRH	177.50	295.60	5.60	10.64
10	Nsenga	0 - 30	A CRH	190.70	299.90	3.80	14.43
11	Iyula	0 - 30	A CRH	164.90	265.80	17.70	22.74
12	Iyula	30 - 60	A CRH	159.30	260.20	9.50	20.56
13	Nambinzo	0 - 30	A CRH	169.80	294.40	6.23	11.68
14	Nambinzo	30 - 60	A CRH	181.20	301.80	3.80	14.74
15	Halungu	0 - 30	A CRH	188.40	237.80	6.30	3.73
16	Halungu	30 - 60	A CRH	171.50	276.80	2.95	6.79

The assessment of micronutrient concentrations (Fe, Mn, Zn) and cation exchange capacity (CEC) across Nsenga, Iyula, Nambinzo, and Halungu reveals pronounced site-specific differences in soil fertility (**Table 2**). Iron (Fe) levels were highest in Nsenga under B CRH (328 - 330 ppm), while Iyula, Nambinzo, and Halungu recorded much lower values under the same treatment (as low as 9.6 - 20.7 ppm). Under A CRH, Fe concentrations were more evenly distributed (159 - 190 ppm), suggesting that treatment influenced Fe availability. Manganese (Mn) followed a similar pattern, with Nsenga consistently recording high values (276 - 299 ppm), while Nambinzo and Halungu under B CRH showed extremely low or absent Mn (0 - 17 ppm), indicating potential deficiencies. Zinc (Zn) concentrations varied widely: Halungu under B CRH showed the highest levels (370.5 ppm), followed by Nambinzo (226 - 313 ppm) and Iyula (6.3 - 292 ppm depending on depth and treatment). Nsenga, however, exhibited comparatively low Zn values (0.49 - 5.6 ppm), suggesting possible Zn deficiency risks.

Cation exchange capacity (CEC), a key indicator of nutrient retention, ranged from very low values in Halungu under A CRH (3.73 - 6.79 cmol/kg) to relatively high values in Iyula (up to 22.74 cmol/kg). Nsenga and Nambinzo showed intermediate CEC values (10.64 - 17.10 cmol/kg), reflecting moderate nutrient-holding capacity. These results highlight that while Iyula soils are generally balanced and fertile, Halungu soils are constrained by low Mn under B CRH and critically low CEC in A CRH, limiting their ability to retain nutrients. Nsenga soils are Fe- and Mn-rich but Zn-poor, while Nambinzo soils are Zn-rich but Mn-deficient, indicating imbalances that could affect crop nutrition.

Overall, the comparative analysis underscores the importance of site-specific soil management interventions. Iyula stands out as the most balanced and fertile site, Nsenga is Fe-rich but Zn-poor, Nambinzo is Zn-rich but Mn-deficient, and Halungu is the most constrained due to low Mn and poor nutrient retention capacity. These findings reinforce the broader consensus that micronutrient balance and CEC are critical determinants of crop productivity, long-term soil health and ecosystem integrity [20] [27].

The soil pH distributions across four villages; Nsenga, Iyula, Nambinzo, and Halungu under two treatments, B CRH and A CRH were illustrated in **Figure 6**. Soil pH values ranged between 5.0 and 6.75, reflecting moderately acidic conditions typical of many tropical soils. Across most villages, treatment A CRH consistently produced higher median soil pH values compared to treatment B CRH, suggesting that A CRH exerted a stronger alkalizing effect. This trend was particularly evident in Nsenga and Iyula, where the orange box plots (A CRH) were positioned above the blue plots (B CRH), indicating a clear upward shift in soil pH. In Nambinzo, the difference between treatments was less pronounced, with overlapping ranges, while in Halungu, treatment A CRH again showed a higher median but with greater variability, as reflected in the wider interquartile range.

These findings suggest that treatment A CRH generally improved soil chemical conditions by reducing acidity, though the magnitude of change varied across villages. The observed variability highlights the influence of site-specific factors such as baseline soil properties, organic matter content, and local management practices on treatment effectiveness. From an agronomic perspective, raising soil pH closer to neutral is beneficial for nutrient availability, particularly phosphorus and molybdenum, while reducing toxicities associated with aluminum and manganese [28] [29]. Therefore, the consistent upward shift under A CRH indicates its potential as a more effective amendment for improving soil fertility in coffee farming systems. However, the heterogeneity observed, especially in Halungu, underscores the need for localized soil management interventions and further site-specific evaluation before broad recommendations can be made. Overall, the results demonstrate that treatment A CRH holds promise for ameliorating soil acidity and enhancing crop productivity, but its adoption should be guided by village-level soil characteristics to ensure optimal outcomes.

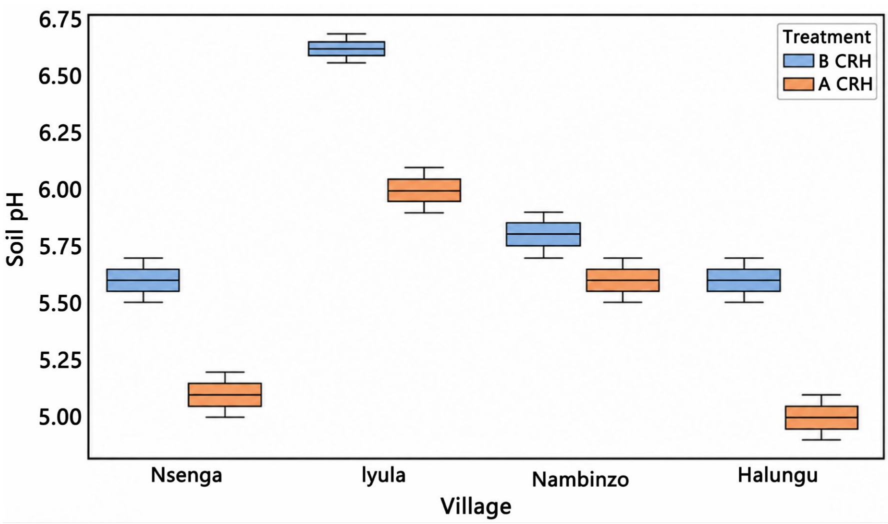

Figure 6. The box plot comparison of soil pH levels across four villages (Nsenga, Iyula, Nambinzo, and Halungu) under two treatments, B CRH (blue) and A CRH (orange).

3.1.1. Soil Moisture Content under Different Treatments across Villages

The distribution of soil moisture content across four villages of Nsenga, Iyula, Nambinzo, and Halungu under two treatments, B CRH and A CRH were presented in (**Figure 7**). Moisture content values varied across locations, but a consistent trend emerged: treatment A CRH generally resulted in higher median moisture content compared to treatment B CRH. This pattern was evident in Nsenga and Iyula, where the orange box plots (A CRH) were positioned above the blue plots (B CRH), indicating improved soil water retention. In Nambinzo, the difference between treatments was less pronounced, with overlapping ranges, while Halungu showed a clear advantage for A CRH, though with greater variability, suggesting heterogeneous soil responses within the village.

These results demonstrate that treatment A CRH enhanced soil moisture retention relative to B CRH, which is agronomically significant given the importance of soil-water availability for crop growth and resilience under variable rainfall conditions. The higher moisture content under A CRH implies that this treatment may improve soil structure or organic matter interactions, thereby reducing water loss and increasing water-holding capacity. However, the variability observed, particularly in Halungu, highlights the influence of site-specific factors such as soil texture, organic matter content, and micro-climatic conditions on treatment performance. From a practical and theoretical perspective, improved soil moisture retention can enhance crop establishment, reduce drought stress, and contribute to more stable yields [30]-[32]. Thus, while A CRH appears to be a more effective amendment for improving soil water dynamics, its adoption should be tailored to local soil and environmental conditions to maximize benefits [33]. Overall, the findings suggest that A CRH holds promise as a strategy for enhancing soil moisture management, but further site-specific evaluations are necessary to refine recommendations for coffee farmers across diverse agro-ecological settings.

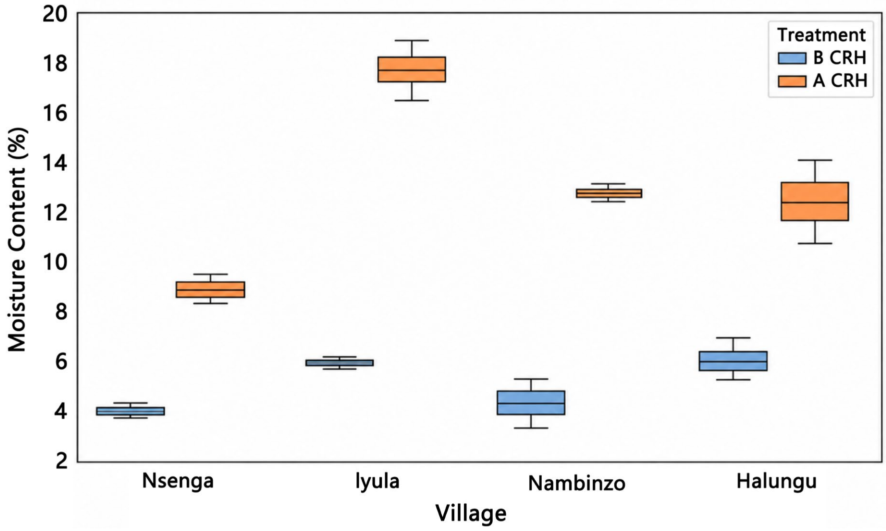

Figure 7. Soil moisture content (%) across four villages (Nsenga, Iyula, Nambinzo, and Halungu) under two treatments, B CRH (blue) and A CRH (orange).

Effect of CRH treatments on soil organic carbon in four Tanzanian villages

The soil organic carbon (%) across four villages of Nsenga, Iyula, Nambinzo, and Halungu under two treatments, B CRH and A CRH were depicted in **Figure 8**. Organic carbon values ranged between 0.6 - 2.0%, indicating generally low to moderate levels of soil organic matter. In most cases, treatment A CRH resulted in higher median organic carbon compared to treatment B CRH, suggesting that A CRH was more effective in enhancing soil organic matter. This effect was most pronounced in Nsenga and Iyula, where the A CRH plots were clearly elevated relative to B CRH. In Nambinzo, the difference between treatments was minimal, with overlapping distributions, while Halungu showed a distinct increase under A CRH but with wider variability, pointing to heterogeneous soil responses.

These findings indicate that A CRH generally improved soil organic carbon relative to B CRH, which is significant for soil fertility and sustainability. Higher organic carbon levels contribute to better soil structure, increased microbial activity, and improved nutrient cycling, all of which are critical for crop productivity [34] [35]. The variability observed, particularly in Halungu, underscores the role of local soil characteristics, land-use history, and Micro-climatic conditions in influencing treatment outcomes. From an agronomic perspective, increasing soil organic carbon is essential for enhancing water retention, reducing erosion, and supporting long-term agricultural resilience [36] [37]. Thus, while A CRH appears to be a more effective amendment for improving soil organic matter, its application should be adapted to site-specific conditions to maximize benefits. Overall, the results suggest that A CRH holds promise as a strategy for strengthening soil health and promoting sustainable coffee farming systems, though further localized studies are warranted to refine recommendations across diverse agro-ecological contexts.

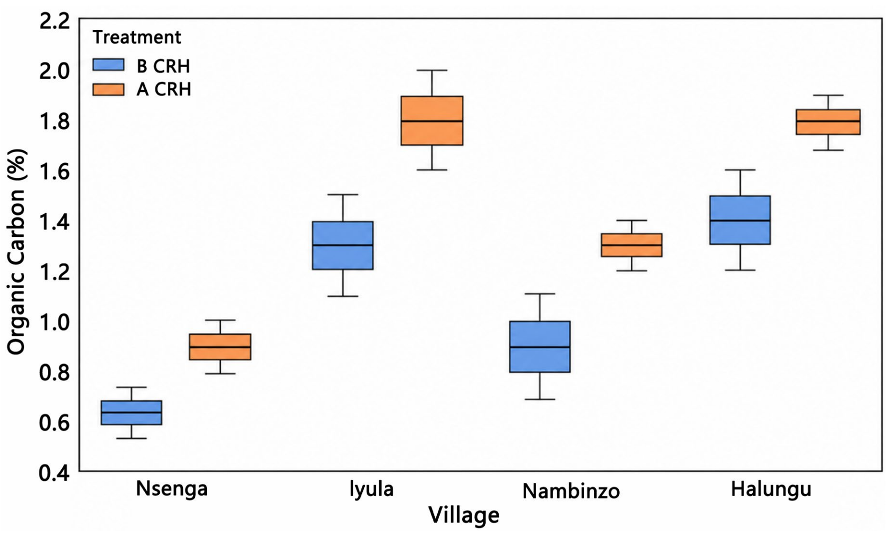

Figure 8. Soil organic carbon (%) across four villages (Nsenga, Iyula, Nambinzo, and Halungu) under two treatments, B CRH (blue) and A CRH (orange).

3.1.2. Effect of CRH Treatments on Soil Nitrogen, Phosphorus, and Sulfur in Four Tanzanian Villages

In general, treatment A CRH resulted in higher nutrient concentrations than treatment B CRH, indicating a positive impact on soil fertility management (**Figure 9**). For total nitrogen, A CRH consistently raised nitrogen levels across villages, with particularly strong effects observed in Nsenga and Iyula. Phosphorus also showed improvement under A CRH, though the extent of increase varied among villages, with some overlap between treatments suggesting site-specific responses. Sulfur levels followed a similar pattern, with A CRH producing higher values overall, though Halungu exhibited greater variability, reflecting heterogeneous soil conditions.

These outcomes suggest that A CRH enhances soil nutrient availability, which is critical for coffee growth and sustainable production. Elevated nitrogen supports vegetative development, increased phosphorus improves root growth and energy transfer, and higher sulfur contributes to protein synthesis and plant health [38]. The variability across villages highlights the influence of local soil properties, land-use history, and microclimatic conditions on treatment effectiveness.

Agronomically, the consistent upward trend in nutrient levels under A CRH indicates its potential as a more effective soil amendment [39]. However, the differences among sites emphasize the need for localized recommendations and adaptive management to optimize benefits. The findings demonstrate that A CRH can improve soil nutrient status and support sustainable coffee farming systems, though further site-specific studies are required to refine its application across diverse agro-ecologies.

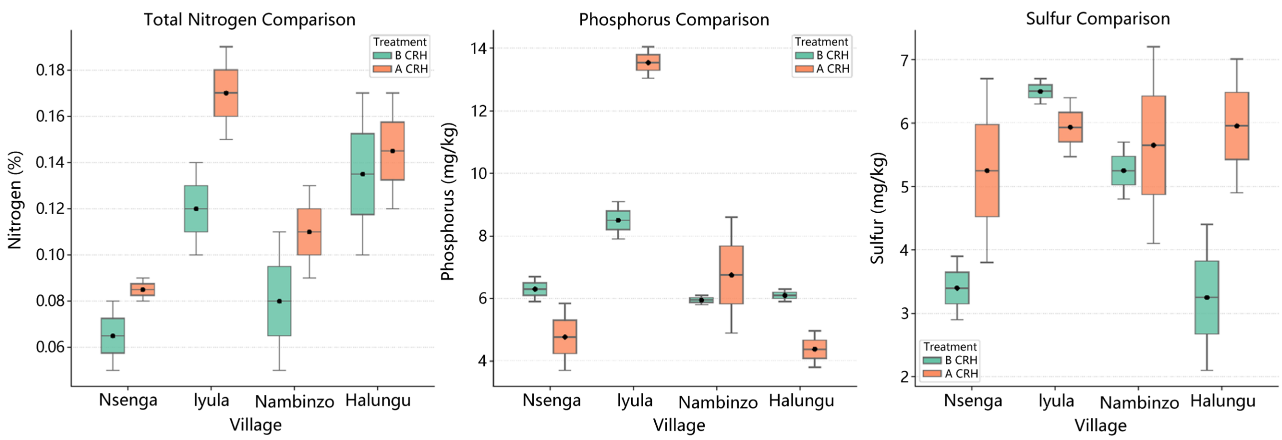

Figure 9. Comparison of soil nutrient levels (total nitrogen, phosphorus, and sulfur) across four villages (Nsenga, Iyula, Nambinzo, and Halungu) under two treatments, B CRH (green) and A CRH (orange).

3.2. Effect of CRH, Manure, and Industrial Fertilizer Treatments on Coffee Yield in Trial Plots

The highest yield was obtained under industrial fertilizer, reaching close to 1.4 t ha^{-1}, which was significantly greater than all other treatments (**Figure 10**). The combined application of 50% CRH and 50% manure produced the second-highest yield, suggesting that integrated nutrient management can partially substitute for industrial fertilizer. Treatments with higher proportions of CRH (20% manure + 80% CRH and CRH only) resulted in comparatively lower yields, both averaging below 0.8 t ha^{-1}, and were nearly equal in performance.

These findings highlight the strong yield advantage of industrial fertilizer, which provides readily available nutrients that support rapid coffee growth and higher productivity. However, the relatively good performance of the 50% CRH + 50% manure treatment indicates that organic-inorganic integration can enhance nutrient supply and soil health, while reducing reliance on costly industrial inputs. The lower yields under CRH-dominant treatments suggest that nutrient release from CRH is slower and less synchronized with crop demand, limiting short-term productivity.

Nonetheless, CRH may contribute to long-term soil fertility through organic matter accumulation and improved soil structure. From a sustainability perspective, while industrial fertilizer maximizes yield, integrated approaches such as CRH-manure combinations may offer a balance between productivity, cost-effectiveness, and soil health improvement [40] [41]. Further research on nutrient release dynamics and long-term soil benefits of CRH is warranted to optimize its role in coffee production systems.

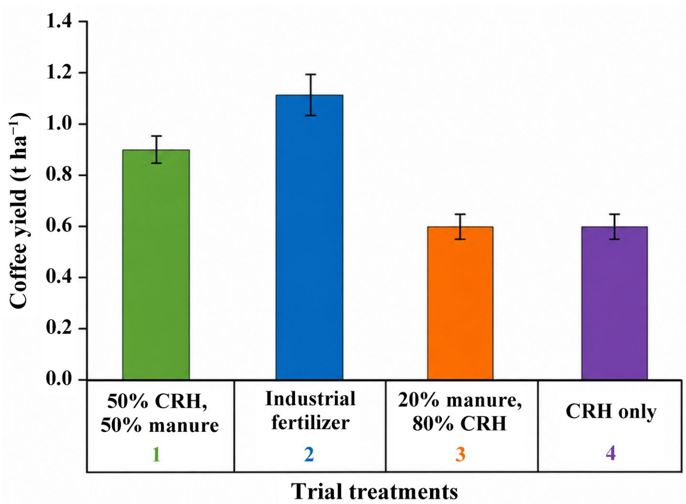

Figure 10. Coffee yield (t ha^{-1}) under four fertilization treatments: 50% CRH + 50% manure, industrial fertilizer, 20% manure + 80% CRH, and CRH only.

Comparative analysis of coffee yield and economic viability of CRH, manure, and inorganic fertilizer treatments

The highest yield was achieved under inorganic fertilizer (1124 kg ha^{-1}), which translated into the greatest income (TZS 5,955,433) and the most favorable B/C ratio of 2.4 (**Table 3**). This indicates that inorganic fertilizer provided the most efficient nutrient supply, resulting in superior productivity and profitability. The integrated treatment of 50% CRH + 50% manure produced a moderate yield (868 kg ha^{-1}) and income (TZS 4,600,400), with a B/C ratio of 1.7. Although lower than inorganic fertilizer, this treatment still demonstrated economic viability, suggesting that combining organic and inorganic sources can balance productivity with soil health benefits.

By contrast, treatments dominated by 80% CRH + 20% manure and CRH only produced substantially lower yields (575 and 595 kg ha^{-1}, respectively) and incomes (TZS 3,047,500 and 3,153,500). Their B/C ratios (1.2 and 1.3) were marginally above break-even, reflecting limited profitability. These results suggest that while CRH contributes to soil organic matter and long-term fertility, its nutrient release is slower and less synchronized with crop demand, thereby constraining short-term yield performance.

The findings demonstrate that inorganic fertilizer remains the most effective option for maximizing coffee yield and profitability. However, the integrated use of CRH and manure offers a promising alternative by improving economic returns while potentially enhancing soil quality and sustainability [42]. Treatments relying heavily on CRH alone are less profitable in the short term, but may still play a role in long-term soil fertility management. This underscores the importance of site-specific nutrient management interventions that balance immediate productivity with sustainable resource use.

Table 3. Coffee yield, income, costs, and benefit-cost ratios under different fertilization treatments.

S/No	Treatments	Yield t/ha	Income (TZS)	Production cost (TZS)	B/C ratio
1.	50% CRH & 50% Manure	868	4,600,400	2,645,962	1.7
2.	Inorganic fertilizer	1124	5,955,433	2,489,955	2.4
3.	80% CRH & 20% Manure	575	3,047,500	2,482,955	1.2
4.	CRH only	595	3,153,500	2,377,455	1.3
	Grand Mean	**790**	**4,189,208**	**2,499,081**	**1.7**

4. Conclusion and Recommendations

This study revealed that fertilization strategies significantly influenced both soil fertility parameters and coffee yield across sites. Inorganic fertilizer consistently produced the highest yields and profitability, underscoring its efficiency in supplying readily available nutrients. However, integrated approaches such as the combination of 50% CRH and 50% manure achieved moderate yields with economically viable benefit-cost ratios, demonstrating their potential to balance productivity with long-term soil health improvement. Treatments dominated by CRH alone resulted in lower yields and marginal profitability, reflecting the limitations of slow nutrient release in meeting crop nutrient demands, though they may contribute to soil organic matter accumulation over time. Soil acidity in Nsenga and Halungu constrained nutrient availability, highlighting the need for corrective measures such as liming, while Iyula's near-neutral pH provided favorable conditions for crop growth. Based on these findings, it is recommended that farmers adopt integrated fertility management practices that combine CRH and manure with inorganic fertilizers to optimize both yield and sustainability. Policymakers should support such approaches through extension services, training, and incentives to reduce reliance on costly industrial inputs while promoting soil health. Furthermore, site-specific soil management strategies are essential, particularly in acidic regions, to ensure effective nutrient utilization. Long-term trials are also needed to evaluate the cumulative benefits of CRH on soil fertility and yield sustainability across diverse agro-ecological zones. Together, these measures can enhance coffee productivity, improve profitability, and contribute to sustainable agricultural development in Tanzania.

Acknowledgements

The research team is thankful for the financial support from TARI through own source activities that made implementation of the research experiment possible. Authors are also, grateful to the Regional, Districts, Wards and Village Offices for the research clearances and support received throughout the study.

Author Contributions

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Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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