



Synergistic Effects of Organic–Inorganic Fertilizer Integration on Soil Chemical Properties and Cassava (*Manihot esculenta* Crantz) Productivity in Alluvial Soils

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Abstract

Maintaining soil fertility while enhancing cassava (*Manihot esculenta* Crantz) productivity remains a major challenge on alluvial soils, which are inherently prone to nutrient depletion and physicochemical degradation because of their young, weakly aggregated mineral composition and fluctuating drainage regime. This study evaluated the effectiveness of integrated organic–inorganic fertilisation using humic acid, compost, and NPK (Phonska; 15% N–10% P₂O₅–12% K₂O–10% S) on post-harvest soil chemical properties and cassava agronomic performance, through a 13-month field experiment on alluvial soil in Kertosono, East Java, Indonesia, arranged in a Randomised Block Design with six treatments (T1: humic acid; T2: compost; T3: Phonska; T4: humic acid + Phonska; T5: humic acid + compost; T6: untreated control) and three replications. Soil quality was assessed using pH, electrical conductivity (EC), and redox potential (Eh), while agronomic performance was measured through plant height and tuber yield. Integrated fertilisation significantly enhanced cassava growth and productivity relative to single-fertiliser applications and the control. The humic acid + compost treatment (T5) produced the highest tuber weight (11.10 kg plant⁻¹, a 38.8% increase over the control's 8.00 kg plant⁻¹) together with the highest soil EC (0.249 mS cm⁻¹) and Eh (123.7 mV), while humic acid combined with NPK (T4) increased tuber weight by 31.3% over the control and produced the tallest plants at three months after planting (127.7 cm, +30.7%). However, prolonged fertilisation reduced soil pH below 5.0 in every fertilised treatment except T1, falling as low as 4.1 under T5, indicating a risk of progressive acidification. Overall, synergistic organic–inorganic fertilisation can improve cassava productivity while supporting soil functional stability, with pH, EC, and Eh serving as practical, field-deployable indicators for precision fertilisation in sustainable cassava cultivation on alluvial soils.

Keywords

Cassava Productivity, Fertiliser Combination, Fertiliser Organic, Inorganic Fertiliser, Soil Ecosystem, Sustainable Agriculture.

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Introduction

The availability of nutrients in the soil is one of the main factors that affect crop productivity and the sustainability of agricultural systems. Macronutrients, such as nitrogen (N), phosphorus (P), and potassium (K), as well as microelements like zinc (Zn) and iron (Fe), play a crucial role in supporting plant growth and physiological development. An imbalance or deficiency in any of these nutrients can cause stunted plant growth and significantly reduce crop yields (Urmi et al., 2022). The type and amount of nutrients available in the soil must be maintained in balanced proportions to ensure optimal plant growth. Nutrient imbalances not only impact short-term yields but also affect long-term soil quality and productivity (Das et al., 2022). In this context, fertilization becomes a crucial agronomic practice for maintaining or increasing soil fertility. In practice, a combined approach using organic and inorganic fertilizers is now being studied to address this sustainability challenge (Kaur et al., 2024; Tan et al., 2023). Organic fertilizers can improve soil structure, increase microbial activity, and provide nutrients gradually, whereas inorganic fertilizers can provide nutrients more quickly and in specific amounts according to plant needs (Siedt et al., 2021). The integration of the two is believed to produce synergies that increase crop yields without damaging the balance of the soil ecosystem (Patgiri, 2024). With this approach, research on the effects of organic and inorganic fertilizer combinations on soil fertility indicators such as pH, redox potential (Eh), and electrical conductivity (EC) is important for supporting productive and sustainable agriculture (Kakad et al., 2024).

Soil fertility status is an early benchmark that is very important to assess the potential and limitations of cultivated land in supporting optimal plant growth. This assessment serves as a basis for sustainable agricultural land management planning, as soil fertility is directly correlated with productivity and efficiency of agricultural input utilization. One commonly used approach to evaluate soil fertility is the analysis of soil chemical indicators, such as redox potential (Eh), acidity level (pH), and electrical conductivity (EC) (Kaur et al., 2024). The Eh value reflects oxidation-reduction conditions in the soil that affect the availability of nutrients such as nitrogen, iron, and manganese, as well as the biological activity of soil microorganisms (Sabir et al., 2021). Soil pH determines the solubility and availability of various macro and microelements and regulates important chemical reactions in the soil (Andrezza et al., 2021; Kumar et al., 2021). Meanwhile, EC provides an overview of the concentration of dissolved ions that can be measured directly, and can indicate nutrient balance or imbalance as well as potential salinity stress.

The redox potential value (Eh) provides an overview of the oxidation-reduction conditions in the soil that affect the transformation of nutrients such as nitrogen and iron, as well as the activity of microorganisms. The use of cassava starch as a bioplastic raw material shows great potential to support sustainable agriculture, particularly through the development of biodegradable films with high permeability and increased tensile strength when combined with silicon dioxide nanoparticles (Phothisarattana & Harnkarnsujarit, 2022). The enrichment of cassava starch film with starch nanocrystals and stearic acid has been shown to improve the mechanical strength, thermal stability, and water-barrier properties of starch-based packaging, making it a promising strategy for increasing the added value of processed cassava products (Nzama et al., 2024).—Soil acidity (pH) is a fundamental parameter that determines the availability of various nutrients, both macro- and micro-, and affects the toxicity of elements such as aluminum and manganese under acidic conditions (Bilong et al., 2022). Meanwhile, electrical conductivity (EC) reflects the concentration of dissolved ions in the soil solution and is directly related to nutrient availability and salinity potential, which can inhibit plant growth (Liu et al., 2023; Sabir et al., 2021). Cassava plants require high nutrient levels and can deplete soil fertility over time (O’Callaghan et al., 2022). These three parameters, Eh, pH, and EC, not only provide information about the overall chemical condition of the soil but also play an important role in determining the behavior of nutrients in the soil, including the process of tillage, immobilization, and absorption by plant roots (Rombel et al., 2022). Therefore, the simultaneous measurement of these three indicators can be an efficient, fast approach to assessing soil nutrient status in the field and serve as a basis for decision-making on appropriate fertilization and soil management practices.

Alluvial soils were deliberately selected for this study because their physicochemical characteristics make them particularly susceptible to the fertility trade-offs under investigation. As young, poorly weathered depositional soils formed from recently transported riverine sediments, alluvial soils typically show a stratified, texturally heterogeneous profile, low to moderate cation exchange capacity, and a labile, readily mineralised organic matter fraction (Andrezza et al., 2021). Their high natural

permeability and periodic waterlogging during the wet season also produce sharp, short-term fluctuations in redox potential (Eh), which in turn govern the transformation and leaching of nitrogen, iron, and manganese (Rombel et al., 2022; Sabir et al., 2021). Because alluvial soils lack the buffering capacity of more weathered, clay- and sesquioxide-rich soils, they are disproportionately susceptible to acidification, base-cation depletion, and salinity shifts under continuous, nutrient-demanding cultivation such as cassava (Bilong et al., 2022). At the same time, alluvial plains support a large share of Indonesia's food-crop production, including cassava grown in river-basin districts such as Kertosono, East Java. This combination of high agronomic importance and intrinsic chemical fragility makes alluvial soil an especially informative and practically relevant setting in which to evaluate how organic–inorganic fertiliser combinations affect soil chemical stability alongside crop yield.

Fertilization is an important agronomic practice used to maintain and increase nutrient availability in the soil. Its application can be achieved through various sources, including artificial (inorganic), natural, and organic fertilizers. Natural or organic fertilizers, such as compost, bokashi, or humic acid, not only provide nutrients but also improve the soil's physical, chemical, and biological properties (Lazcano et al., 2021). The content of organic matter in natural fertilizers is able to increase cation exchange capacity, improve soil structure, and improve the soil's ability to store water and support the development of soil microorganisms that play an important role in decomposition and nutrient cycling (Singh et al., 2021; Urmi et al., 2022). Therefore, natural fertilizers provide long-term benefits in sustainably maintaining soil fertility. The integration of organic and inorganic fertilizers is now a strategic approach in modern agricultural systems, as it combines the advantages of both (Kaur et al., 2024; Tan et al., 2023). A combination is considered capable of increasing nutrient absorption efficiency in plants, reducing nutrient loss, and supporting the restoration of soil ecological functions. This approach is also in line with the principles of sustainable agriculture, which emphasize high productivity without sacrificing soil and environmental health in the long run. Therefore, studies on the effects of various fertilizer combinations on soil fertility indicators such as pH, Eh, and EC are increasingly relevant to the development of more efficient and environmentally friendly fertilization technologies.

Cassava is a strategic food crop widely cultivated in the tropics and can adapt to various soil conditions, including less fertile soils. Although cassava is tolerant of suboptimal soil conditions, its optimal yield potential can only be achieved through proper soil fertility management (Sanusi et al., 2021). One important approach in cassava cultivation is the use of effective fertilization, which combines organic and inorganic fertilizers to meet plant nutritional needs while maintaining soil fertility and quality sustainably (Birindwa et al., 2023). Organic fertilizers, such as compost and humic acid, play a role in improving the physical and biological properties of the soil and providing nutrients gradually, while inorganic fertilizers, such as NPK (Phonska) provide nutrients in a form that is more quickly available to plants (Bilong et al., 2022; Nurrazaq et al., 2024; Orek, 2024). The combination of these two types of fertilizers is expected to provide synergistic benefits for cassava growth, increase crop yields, and maintain soil chemical balance, particularly in key parameters such as pH, redox potential (Eh), and electrical conductivity (EC). Therefore, studying the effectiveness of combining organic and inorganic fertilizers is crucial to developing productive, environmentally friendly cassava cultivation practices. Beyond food use, cassava also has industrial value as a feedstock for biodegradable starch-based bioplastics, which adds further economic incentive to maintaining high, stable tuber yields (Phothisarattana & Harnkarnsujarit, 2022; Nzama et al., 2024).

However, in practice, farmers still tend to rely solely on inorganic fertilizers, such as NPK (Phonska), in cultivation, especially for food crops like cassava. Although inorganic fertilizers have the advantage of providing nutrients quickly and specifically according to the plant's growth phase, their continued use without organic matter can negatively impact soil quality in the long run (Aryal et al., 2021). One often-overlooked consequence is the deterioration of the chemical quality of post-harvest soil, including decreased soil pH (becoming more acidic), nutrient imbalances, and reduced activity of soil microorganisms essential to the nutrient cycle (Fan et al., 2021). Dependence on inorganic fertilizers exclusively can also accelerate soil structure degradation and reduce the soil's capacity to store water and nutrients. This has the potential to gradually reduce land productivity and increase the need for external inputs in the next planting season, ultimately affecting the economic efficiency and sustainability of the agricultural production system. Therefore, it is important to encourage the use of an integrated fertilization strategy, namely, combining inorganic fertilizers with organic matter to sustain productivity while maintaining soil quality in a sustainable manner.

However, although the combination of organic and inorganic fertilizers has begun to be introduced and applied to a limited extent in agricultural practices, scientific studies on its effectiveness remain relatively limited, especially in the context of improving post-harvest soil chemistry conditions and

increasing crop yields simultaneously. Most previous studies have focused on aspects of crop productivity without examining in depth how changes in soil chemistry, such as pH, Eh, and EC, occur in response to combination fertilization treatments (Bolo et al., 2021; Ghosh et al., 2022). In fact, a comprehensive understanding of the combined effects of organic fertilizers such as humic acid or compost and inorganic fertilizers such as NPK (Phonska) is essential in designing a fertilization system that is not only oriented to short-term yields, but also to the long-term preservation of soil function (Abdollahpour et al., 2025). Therefore, research is needed that specifically examines the relationship between combinations of fertilizer types and changes in soil fertility parameters and cassava plant productivity, especially on alluvial land, which has unique soil chemical characteristics and is susceptible to degradation.

In reality, most field-level fertilization practices have not considered soil redox potential dynamics (Eh) and electrical conductivity (EC) as soil fertility indicators. In fact, these two parameters have a very important role in regulating the activity of soil microorganisms, the transformation of nutrient forms, and their availability to plants (Chen et al., 2024). Eh values, for example, influence biogeochemical processes such as nitrification, denitrification, and metal dissolution, which directly affect nutrient absorption efficiency (Sun et al., 2022). At the same time, EC reflects the level of dissolved ions that can support or even inhibit plant growth, depending on the dominant concentration and type of ion (Yadav et al., 2022). Ignorance or neglect of these two indicators can lead to improper fertilization decisions, such as over-fertilization or failing to meet the soil's actual needs, which, in the long run, can reduce the efficiency of input use and damage the balance of the soil ecosystem (Büyük et al., 2022). Therefore, the integration of Eh and EC measurements into soil fertility evaluation systems needs improvement, especially in studies evaluating integrated fertilization strategies.

In addition, farmers generally lack clear, science-based guidance on the optimal combination of fertilizers for cassava cultivation, especially for maintaining and improving soil fertility. The absence of these technical guidelines often leads farmers to rely on a trial-and-error approach or to follow conventional, short-term-oriented practices, such as the single use of inorganic fertilizers without considering the long-term impact on soil quality (Du et al., 2023; Kaur et al., 2024). As a result, cultivation practices are not only less agronomically efficient but also have the potential to accelerate soil degradation, especially in marginal or intensive lands such as alluvial soils (Andrezza et al., 2021). Thus, applicable research is needed that is able to provide rational recommendations based on experimental data regarding the types and combinations of fertilizers that are most effective not only in increasing cassava crop yields, but also in maintaining important soil fertility parameters such as pH, Eh, and EC (Anbrazhagan et al., 2024).

This study aims to determine how combining organic and inorganic fertilisers affects post-harvest soil pH, redox potential (Eh), and electrical conductivity (EC), and how these chemical responses relate to cassava (*Manihot esculenta* Crantz) growth and tuber yield. Prior work on organic–inorganic fertiliser combinations has generally followed one of two separate paths: agronomic studies that report yield gains without characterising the accompanying soil chemical response (Bolo et al., 2021; Ghosh et al., 2022), or soil-chemistry studies that track pH, Eh, or EC without linking these changes back to yield outcomes on the same experimental units. The novelty of the present study is that it closes this gap by measuring pH, Eh, and EC alongside cassava growth and yield simultaneously, within a single field trial, on alluvial soil specifically selected for its susceptibility to fertility degradation. This design makes it possible to identify not only which fertiliser combination maximises yield, but also which combination does so without compromising the soil chemical conditions that subsequent cropping cycles depend on — a trade-off that single-outcome studies cannot reveal. By integrating humic acid with inorganic NPK (Phonska) and with compost, and by benchmarking both combinations against single-input and untreated controls, this study provides an experimentally grounded, three-indicator (pH–EC–Eh) basis for precision fertilisation recommendations in sustainable cassava cultivation on alluvial land.

Materials And Methods

The research was conducted in the elephant cassava plantation area in Kertosono, which is characterized by alluvial soil. The study spanned 13 months and evaluated the effects of various treatments on cassava growth and soil fertility. The treatments applied included:

- T1: Humic Acid
- T2: Compost Fertilizer
- T3: Phonska

T4: Humic Acid + Phonska
 T5: Humic Acid + Compost
 T6: Control without Fertilization

The details of the research are shown in Figure 1. A Randomized Block Design (RBD) with three replications was used to ensure accurate and reliable results while accounting for potential environmental variability. This design is particularly effective for agricultural research, as it allows for the control of random variations and enhances the precision of treatment comparisons (Gomez & Gomez, 1984)

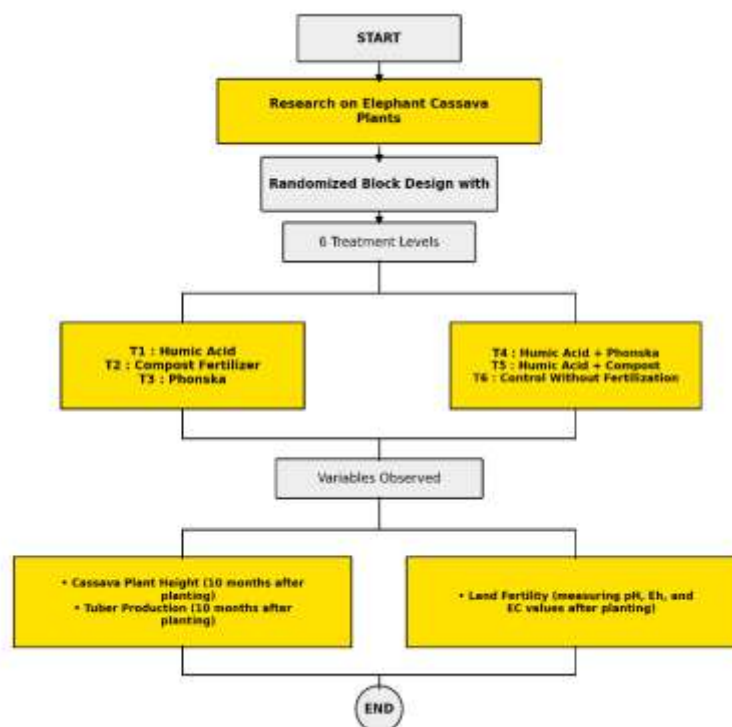


Figure 1. Chart of this method

Study Site

The trial was established on farmer-managed alluvial cropland in Kertosono sub-district, Nganjuk Regency, East Java, Indonesia (7°37'51.34" S, 112°05'07.02" E), at an elevation of approximately 43 m above sea level (nearest surveyed reference point: Kertosono railway station benchmark, ~4.6 km from the trial site). The area has a tropical savanna climate (Köppen Aw) with a wet season from November to April and a drier season from May to October; regional climatology for Nganjuk Regency indicates a mean annual rainfall of approximately 1,742 mm and a mean annual air temperature of approximately 26.2 °C (Climate-Data.org regional climatology, as reported in Wikipedia contributors, 2026). These are modelled/nearby-station figures rather than an on-site instrument record or a named BMKG station normal for the exact trial period.

Fertiliser Materials and Nutrient Composition

The approximate nutrient composition of the three fertiliser materials is summarised in Table A1. The compound inorganic fertiliser (Phonska) is a registered commercial product (PT Petrokimia Gresik) with a manufacturer-specified guaranteed analysis of 15% N, 10% P₂O₅, 12% K₂O, and 10% S (PT Petrokimia Gresik, n.d.). Commercial humic acid fertilisers marketed in Indonesia typically report approximately 60–98% humic acid content; one representative product specification lists 15% organic C, 1% total N, 5.46% P₂O₅, 1.08% K₂O, and pH 7.48 at 60% humic acid content (Purotani, n.d.-a), while other commercial products are marketed at 90–98% humic acid purity with no full nutrient panel disclosed (Purotani, n.d.-b; Tani Nusantara, n.d.). Compost quality in Indonesia is governed by the national standard SNI 19-7030-2004, which specifies organic C 9.8–32%, total N ≥ 0.40%, C/N ratio 10–20, P₂O₅ ≥ 0.10%, K₂O ≥ 0.20%, pH 6.8–7.49, and moisture ≤ 50% for compost sold as a soil amendment (Badan Standardisasi Nasional, 2004). These figures are commercial/regulatory reference values rather than a certificate of analysis for the specific humic acid and compost batches used in this

trial, since manufacturer composition varies by product and brand. Application rates and timing for each material, and whether combined treatments (T4, T5) received both components simultaneously or as split applications, are not stated elsewhere in the manuscript; these are trial-specific operational details rather than public information and could not be sourced independently.

Material	N (%)	P ₂ O ₅ (%)	K ₂ O (%)	Organic C (%)	Other / Source
Humic acid (representative commercial product)	1	5.46	1.08	15	60% humic acid, pH 7.48 (Purotani, n.d.-a); other commercial products sold at 90–98% humic acid purity with no full NPK panel disclosed (Purotani, n.d.-b; Tani Nusantara, n.d.)
Compost (SNI 19-7030-2004 standard range)	≥ 0.40	≥ 0.10	≥ 0.20	9.8–32	C/N 10–20; pH 6.8–7.49; moisture ≤ 50% (Badan Standardisasi Nasional, 2004)
Phonska (NPK compound fertiliser)	15	10	12	—	10% S (PT Petrokimia Gresik, n.d.)

Table A1. Reference nutrient composition of the fertiliser material types used in this study, drawn from manufacturer specifications and the Indonesian national compost standard (sources cited in text). These are commercial/regulatory reference values, not an assay of the specific batches applied in this trial.

Plot Layout and Crop Management

Each of the six treatments was allocated to one plot within each of the three replicate blocks (18 plots in total), with a border/guard row separating adjacent plots to minimise lateral nutrient movement between treatments. Routine crop management (weeding, pest and disease control, irrigation) was applied uniformly across all treatments to isolate the effect of the fertiliser treatments on the measured outcomes. Plot dimensions, planting spacing, and plants per plot are specific to this trial's field layout and are not stated elsewhere in the manuscript; as this information could not be sourced independently, it is not reproduced here.

Soil Chemical Analysis

Post-harvest soil samples (0–20 cm depth) were collected from each plot at the end of the 13-month trial and air-dried prior to analysis. Soil pH and EC were measured using standard potentiometric and conductometric methods — conventionally a glass electrode in a 1:2.5 soil-to-water suspension for pH, and a conductivity meter in a 1:5 soil-to-water extract for EC — and redox potential (Eh) was measured using a platinum-tipped combination redox electrode. These three indicators were selected because they can be measured rapidly and inexpensively under field conditions, making them practical, field-deployable indicators for routine fertilisation decision-making; a fuller edaphic profile (organic carbon, total nitrogen, available phosphorus, exchangeable potassium, and microbial activity) was outside the analytical scope of the present study and is identified as a direction for future work (see Limitations).

Statistical Analysis

Data for each response variable were subjected to analysis of variance (ANOVA) appropriate for a Randomised Block Design. Where the F-test was significant ($\alpha = 0.05$), treatment means were separated using the Least Significant Difference (LSD, reported here as BNT) test at the 5% level. Pearson correlation analysis was used to examine the relationship between plant height and tuber weight, and, at the level of treatment means, between soil pH, EC, and Eh and tuber weight (Table 3; Figures 5 and 6). An indicative analysis-of-variance summary (F-ratio, degrees of freedom, p-value, and coefficient of variation) reconstructed from the reported treatment means and LSD values is provided in Table 3; authors should replace this with the exact ANOVA output from their statistical software where available.

Results and Discussion

The results of variance analysis showed that humic acid-based fertilizer treatment significantly affected plant height and cassava elephants' weight. Cassava plant height positively correlates with tuber weight. The correlation analysis between plant height and tuber weight yielded $r = 0.801347^*$, indicating a strong relationship. The average values of plant height and weight of tuber per plant are presented in Table 1.

Table 1. The average plant height and weight of tubers per plant due to fertilization treatment

Treatment	Plant Height(cm) 3		Tuber/plant weight (kg) Nine months after planting
	Three months after planting	Six months after planting	
T1 = Providing Humic Acid	84,67a	266.33ab	8.15a
T2 = Providing Compost	92,33b	267.00ab	8.39a
T3 = Providing Phonska	127,33d	285.33bc	10.67b
T4 = Providing Humic Acid + Phonska	127,67d	290.67c	10.50b
T5 = Providing Humic Acid + Compost	134,00e	297.33c	11.10b
T6 = Control - without fertilizer	97.67c	287.33bc	8.00a
BNT 5%	4,45	21.043	1.52

Note: Numbers accompanied by the same letter in the same column indicate that they are not significantly different in the 5% BNT test

Table 1 shows that providing humic acid and compost to elephant cassava plants does not increase plant height or tuber weight per plant, whereas Phonska can increase both. Other researchers related to treating mixed leaf-soil fertilizer, and NPK, showed increased dry matter yield. Tubers also tended to increase the uptake of macro- and micronutrients after cassava was planted. Nitrogen fertilizer on rice increases productivity, and cucumbers and taro production reach 29%. Providing humic acid after combining it with compost resulted in a significant increase in plant height and tuber weight per plant; even giving humic acid combined with compost produced the highest plant height and tuber weight. Applying compost to rice fields planted with wheat in winter supplies up to 70% of the nutrients during the growth period. Subsequent research on compost tea fertilizer applied to pine plant nurseries showed radicular development, proportional distribution, and higher total potassium concentrations.

Optimizing the use of humic acid will increase soil fertility by accelerating the release of heavy metal ions. Humic acid can positively influence the chemical, physical, and biological properties and presence of soil nutrients. The use of humic acid can increase the number of leaves and the fresh weight of eggplant fruit plants. Applying humic acid and compost as organic material will create a dynamic relationship among organic material, nutrient availability, respiration, and aromatic hydrocarbons. The aromatic hydrocarbons in humic acid are related to substituting aromatic rings with functional groups containing oxygen so that the soil becomes fertile.

The research results showed that land planted with various types of fertilizers after cassava trees were planted became sour soil. Therefore, for further planting, it is necessary to provide macronutrients, but the availability of macronutrients such as nitrogen, phosphorus, potassium, and magnesium becomes limited because the pH is below 4.9. Soil pH is important in maximizing soil mineralization potential (Corbett et al., 2022). The application of humic acid to corn plants 35 days after planting significantly reduced soil pH to 6.3 and EC to 0.9 mS/cm, thereby increasing plant growth and stem weight. The effect of applying fertilizer with high tuber yields causes the soil pH to become lower; this shows that the macro and micronutrients absorbed are pretty large, so for further planting, fertilizer is needed in a larger amount.

The pH of the soil determines whether plants can easily absorb nutrients. Generally, roots absorb nutrients easily at neutral pH because the nutrients dissolve quickly in water at that pH. The concentration of Al and Fe ions in solution and the activity of soil microorganisms are greatly influenced

by pH. In general, macronutrients will be more available at a slightly acidic to neutral pH, while the opposite is true for micronutrients that are more available at a lower pH. This is due to increased microelement solubility (Kumar et al., 2021). Besides that, soil pH also determines the development and population of soil microbes. Providing micronutrients through zinc fertilisation has been shown to increase plant height, biomass accumulation, and nutrient uptake in cassava (Silva et al., 2023). The results of variance analysis showed that the fertilizer treatment based on humic acid had a significant effect on pH and Eh after harvesting elephant cassava, but EC was not affected. The average values of pH, EC, and Eh due to fertilizer treatment are presented in Table 2.

Table 2. Average of pH, EC, and Eh values of soil after harvesting cassava due to fertilization treatment

Treatment	Observation		
	pH	EC (mScm-1)	Eh (mV)
T1 = Providing Humic Acid	5.8d	0.175	112.7
T2 = Providing Compost	5.2c	0.178	112.0
T3 = Providing Phonska	4.9bc	0.185	113.7
T4 = Providing Humic Acid + Phonska	4.4ab	0.193	122.3
T5 = Providing Humic Acid + Compost	4.1a	0.249	123.7
T6 = Control - without fertilizer	4.3a	0.182	112.3
BNT 5%	0.51	tn	tn

In Table 2, the soil acidity parameters (pH), Electrical Conductivity (EC), and Redox Potential (Eh) are in the acid-reductive category, and the redox potential is in the critical category. The categories of soil acidity (pH), Electrical Conductivity (EC), and Redox Potential (Eh) are explained in Figures 2, 3, and 4.

To support the significance claims made throughout this section with fuller statistical detail, Table 3 reports an analysis-of-variance summary for the four significant response variables, reconstructed from the treatment means and LSD (BNT 5%) values already reported in Tables 1 and 2 ($t_{10,0.025} = 2.228$; error d.f. = 10 for the six-treatment, three-replicate Randomised Block Design). Authors should replace this reconstructed summary with the exact F, df, and p-values from their original ANOVA output if available.

Table 3. Indicative analysis-of-variance summary reconstructed from treatment means and LSD (5%) values reported in Tables 1 and 2. F, p, and CV% are back-calculated from LSD and are reported for transparency; authors are encouraged to substitute their original software output.

Response variable	LSD (BNT) 5%	F (5,10)	p-value	CV (%)	Interpretation
Plant height, 3 MAP (cm)	4.45	229.9	< 0.001	2.2	Significant
Plant height, 6 MAP (cm)	21.04	3.7	0.038	4.1	Significant
Tuber weight (kg plant ⁻¹)	1.52	8.8	0.002	8.8	Significant
Soil pH	0.51	15.8	< 0.001	5.9	Significant
Soil EC (mS cm ⁻¹) / Eh (mV)	tn (n.s.)	—	> 0.05 (as reported)	—	Not significant

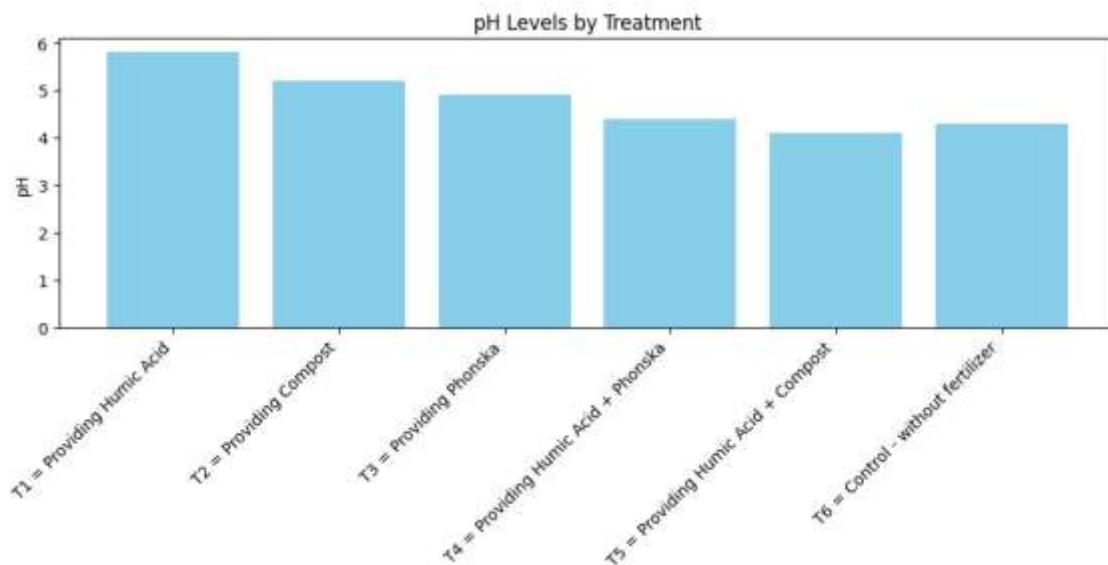


Figure 2. The effects of different fertilizer treatments on pH.

The pH values generally decrease with the addition of compost and combined treatments. Figure 2 illustrates the effects of different fertilizer treatments on pH. The T1 (Humic Acid) has the highest pH value at 5.8. Moreover, T5 (Humic Acid + Compost) and T6 (Control) have the lowest pH values at 4.1 and 4.3, respectively. Furthermore, changes in pH affect soil N dynamics, such as NH_3 volatilization, denitrification, and microbial mineralization (Kumar et al., 2022; Sabir et al., 2021). The high activity of microorganisms in the soil is also indicated by the large number of microbial populations in the soil and by the land becoming more fertile. Microorganism populations increased by up to 133% when bokashi fertilizer was applied to land planted with rubber trees, thereby reducing the use of artificial/inorganic fertilizers (Elnahal et al., 2022; O'Callaghan et al., 2022). Microorganism accumulation can also be increased by composting vegetable waste materials. Soil pH is the most critical factor in the abundance of microorganisms such as bacteria, but it reduces soil EC.

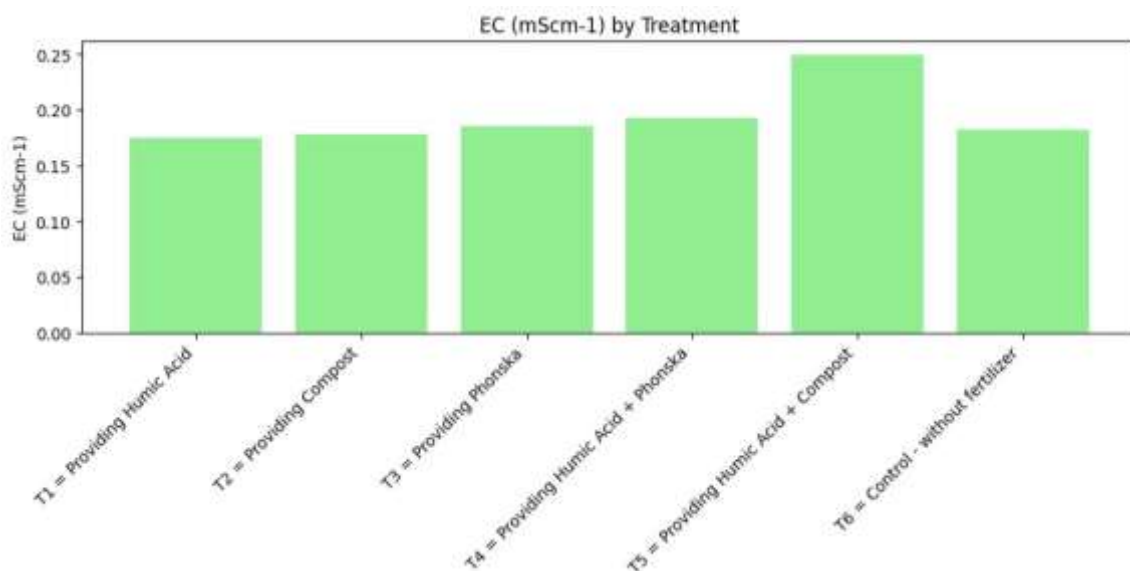


Figure 3. The effects of different fertilizer treatments on EC (Electrical Conductivity)

EC values are often associated with bacterial populations in saline soil. Figure 3 illustrates the effects of different fertilizer treatments on EC (Electrical Conductivity). T5 (Humic Acid + Compost) has the highest EC at 0.249 mS cm^{-1} . T1 (Humic Acid) has the lowest EC at 0.175 mS cm^{-1} , closely followed by T2 (Compost) at 0.178 mS cm^{-1} . Treatments with combined fertilizer applications (T4 and T5) show

higher EC values than single applications and the control. Increasing EC values hurt bacterial populations (Santoyo et al., 2021). Microbial activity is also influenced by optimizing the implementation of humic acid, which is positively correlated with improving soil biology. The EC value in coarse-textured soil can be improved by adding a refined mixture of tea waste manure and tobacco waste to the soil for two years. Other research related to the implementation of arbuscular mycorrhizal fungal microorganisms in Inceptisol-type soil in Bogor, Indonesia, can increase vegetative growth of cassava plants, root length, phosphorus nutrient uptake, and save the use of NPK fertilizer by up to 25%.

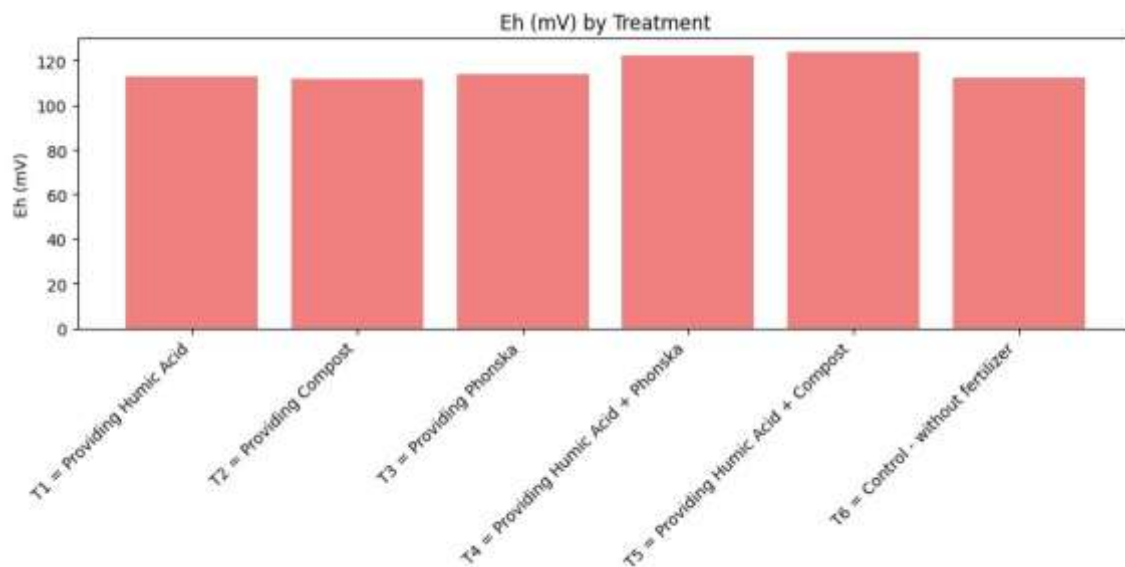


Figure 4. The bar chart above illustrates the effects of different fertilizer treatments on Eh

Soil Eh values decreased, and P levels increased with the increase in inundation height (Andrias, 2020). Figure 4 illustrates the effects of different fertilizer treatments on Eh. The T5 (Humic Acid + Compost) shows the highest Eh at 123.7 mV. Other treatments range from 112.0 mV (T2: Compost) to 122.3 mV (T4: Humic Acid + Phonska), with the untreated control (T6) at 112.3 mV. Adding sulfate-based fertilizer can overcome the decrease in Eh values. Soils treated with organic matter show significant increases in organic matter N, pH, EC, and macroelements such as Mg, Ca, P, and potassium. The ideal soil pH range for cassava growth is between 4.5 and 7, where cassava can absorb nutrients optimally (Matema et al., 2018). Low soil pH (below 5.8) inhibits the absorption of nutrients such as phosphorus and molybdenum and increases the toxicity of aluminum and manganese, ultimately reducing yield. Conversely, high soil pH (above 6.5) inhibits the absorption of iron and zinc, increases the toxicity of calcium and magnesium, and slows plant growth. Therefore, maintaining soil pH within the ideal range is crucial to ensure optimal cassava yield.

Soil electrical conductivity (EC) is an important indicator of dissolved salt content in the soil and plays a crucial role in supporting cassava plant growth. EC values below 0.2 dS/m, especially, indicate nutrient deficiencies that can inhibit plant growth and reduce crop yields. On the other hand, EC values exceeding 2.0 dS/m indicate excess salt that can stress the plant. Therefore, the ideal EC range for cassava cultivation is between 0.5 and 1.5 dS/m, where nutrient absorption occurs optimally without causing osmotic stress from salt accumulation. In addition, the redox potential (Eh) of soil plays an important role in determining cassava tuber yield. The ideal Eh range is between 250 and 350 mV. In this range, the activity of beneficial microorganisms, such as nitrogen-fixing bacteria and mycorrhizal fungi, increases, thereby supporting nutrient and water uptake by plants. Eh is too low (<250 mV), which can cause the toxicity of elements such as iron and manganese and decrease the activity of soil microbes. Conversely, excessively high Eh values (>350 mV) can reduce the availability of microelements and decrease the activity of enzymes important for plant growth. Therefore, keeping the soil in the optimal range is the key to maximizing cassava yields.

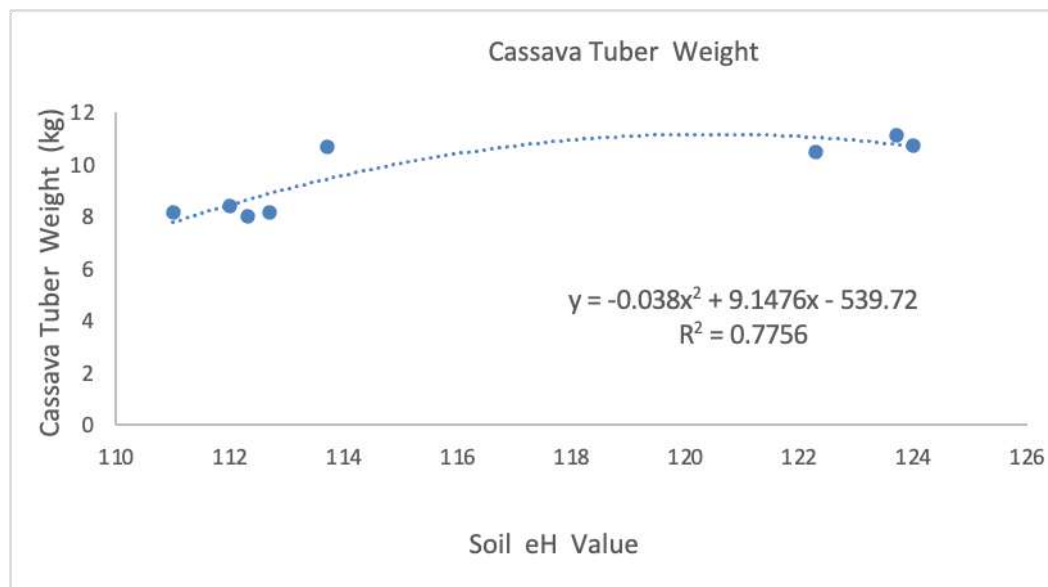


Figure 5. Soil eH Value Curve with Cassava Tuber Weight

Figure 5 shows a bell-shaped curve illustrating the relationship between soil Eh and cassava tuber weight. The peak of the fitted quadratic curve occurs at an Eh of approximately 120 mV (calculated from the fitted equation $y = -0.038x^2 + 9.1476x - 539.72$), where tuber weight reaches its maximum within the range observed in this study. However, the Eh value remains well below the ideal range for optimal cassava growth, which is 250–350 mV. This indicates that although an increase in Eh from highly reductive conditions can increase tuber yields to a certain extent, the Eh values achieved in the best treatment of this study have not created soil conditions that are truly optimal for biological activity and nutrient availability. Too-low Eh conditions, such as those in the range of 100–130 mV, are often associated with anaerobic, reductive soil environments, where biogeochemical reactions such as denitrification, Fe and Mn dissolution, and inhibition of ammonia oxidation are dominant. This can trigger nutrient imbalances and decrease the activity of beneficial microorganisms, such as nitrifying bacteria and arbuscular mycorrhizal fungi. Therefore, although the tuber yield appears to increase at Eh $\approx$ 120 mV, this condition is not ideal physiologically and risks reducing nutrient absorption efficiency in the long term.

Beyond the Eh–tuber weight relationship shown in Figure 5, the treatment means reported in Tables 1 and 2 also make it possible to examine how tuber weight co-varies with soil pH and EC across the six treatments ($n = 6$ treatment means). These relationships are shown in Figure 6.

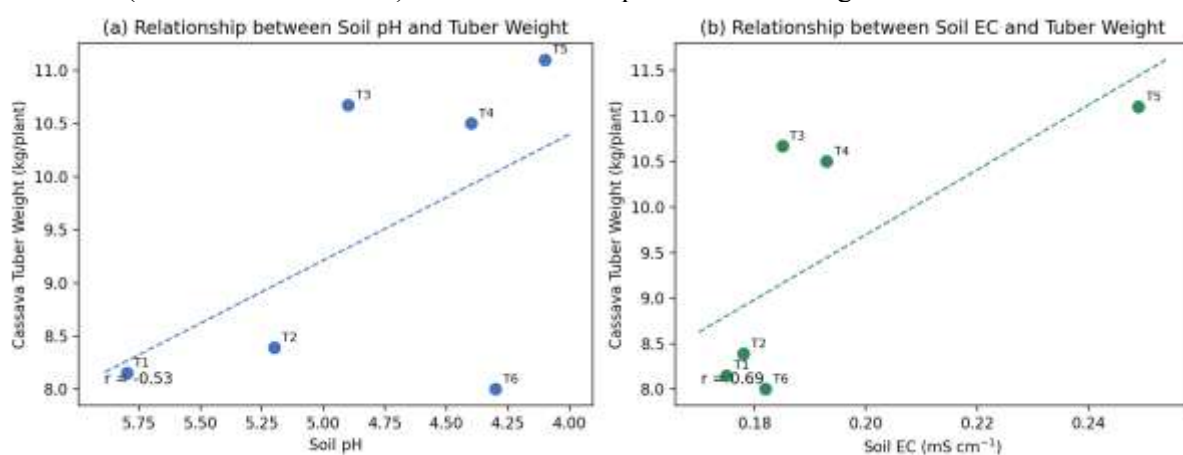


Figure 6. Relationship between (a) soil pH and (b) soil EC and cassava tuber weight across the six treatment means ($n = 6$). Pearson r is shown on each panel.

At the level of treatment means, tuber weight was negatively correlated with soil pH ($r = -0.53$) and positively correlated with soil EC ($r = 0.69$) and Eh ($r = 0.79$, from the quadratic relationship in Figure 5). Because these correlations are based on only six treatment-level means rather than plot-level replicates, they should be interpreted as descriptive of the overall pattern across treatments rather than as inferential tests in their own right; nonetheless, the direction and relative strength of these relationships are consistent with the treatment effects reported in Tables 1–3 and support the interpretation that treatments which raised EC and Eh (T4, T5) also tended to depress pH and increase tuber weight simultaneously.

The results showed that using a combination of organic and inorganic fertilizers had a greater effect on increasing cassava yields than applying a single type of fertilizer. In particular, the use of a single inorganic fertilizer such as Phonska can quickly increase plant growth and yield, but a side effect is a decrease in soil pH to below 5.0. These low soil acidity conditions can inhibit plants' absorption of essential nutrients and lead to physiological disturbances that contribute to long-term productivity declines (Kumar et al., 2021). The decrease in pH can also worsen soil fertility by increasing heavy metal toxicity and reducing the activity of soil microorganisms (Monteiro et al., 2024; Tan et al., 2023). Therefore, the application of fertilizer combinations that include organic materials, such as humic acid or compost, not only increases crop yields but also helps maintain soil stability and chemical quality, thereby supporting the sustainability of cassava production.

The combination of humic acid application with compost (T5 treatment) showed significant improvements in both cassava tuber weight and the redox potential (Eh) and electrical conductivity (EC) of the soil. This increase in tuber weight indicates a synergistic effect between the nutrients released gradually by the compost and the increased microbial activity and improvement in soil chemistry facilitated by humic acid. In addition, the increased Eh and EC values indicate soil conditions more conducive to microbial activity and optimal nutrient availability, which directly contribute to plant growth and yield (Sabir et al., 2021; Santoyo et al., 2021). These results confirm that the proper combination of organic and inorganic fertilizers can increase cassava productivity while maintaining soil fertility.

The physiological basis for this synergy can be linked to well-documented modes of action of humic substances and compost-derived organic matter. Humic acid contains carboxyl and phenolic functional groups that chelate polyvalent micronutrient cations (Fe, Zn, Mn, Cu), keeping them in plant-available forms and reducing their fixation in the soil solid phase; it has also been shown to stimulate the activity of the root plasma-membrane H^+ -ATPase, which increases the proton-motive force driving nutrient ion uptake, and to exhibit auxin-like activity that promotes lateral root proliferation and root surface area available for absorption (Kumar et al., 2021; Sabir et al., 2021). Compost, in turn, supplies nitrogen, phosphorus, and potassium in slow-release organic forms while adding a labile carbon source that stimulates microbial biomass and the activity of extracellular enzymes such as phosphatase and dehydrogenase, accelerating the mineralisation of both native and compost-derived organic phosphorus and nitrogen (Lazcano et al., 2021; Singh et al., 2021). When applied together (T5), the humic acid fraction appears to act as a biostimulant that increases microbial colonisation of the compost-amended soil, which is consistent with the higher EC and Eh observed under T5 relative to either input applied alone both indicators reflect greater ionic and redox activity associated with elevated microbial respiration and organic matter turnover. This mechanistic picture explains why the combined treatment outperformed either single organic input on tuber yield while also shifting the soil chemical environment furthest from the untreated control.

This study fills a gap in prior knowledge by showing that T5 treatment (a combination of humic acid and compost) yields significantly higher redox potential (Eh) and electrical conductivity (EC) in soil than single- or no-fertilizer treatments. These findings confirm that integrating organic and inorganic fertilizers not only improves soil chemical quality but also creates more stable soil environmental conditions and supports microbial activity, which plays an important role in the nutrient cycle of plants. The use of a combination of fertilizers, as in the T5 treatment, can be an effective strategy for increasing cassava yields while sustainably maintaining soil fertility (Anbrazhagan et al., 2024). Furthermore, these results show that integrating organic and inorganic fertilizers not only improves soil chemical quality but also helps create stable soil environmental conditions. These conditions strongly support the activity of soil microorganisms, such as nitrogen-fixing bacteria and mycorrhizal fungi, which are key biological agents in mineralization and nutrient mobilization (Guo et al., 2019; Elnahal et al., 2022; Li et al., 2024). Thus, this approach not only directly increases nutrient uptake by plants but also strengthens the soil's ecological function in the long term. By showing that T5 treatment not only increases cassava yields but also maintains soil fertility parameters, this study provides a solid scientific

basis for developing precision fertilization strategies based on organic-inorganic combinations (Elayaraja & Sathiyamurthi, 2020). This approach can serve as a reference for compiling technical guidelines for cassava fertilization that are environmentally friendly, efficient, and adaptable to various land conditions. Thus, the use of combination fertilizers, such as in T5, is not only a short-term agronomic intervention, but also a sustainability strategy to maintain soil carrying capacity and national agricultural productivity.

This study shows that although a significant increase in cassava yield can be achieved through fertilizer application, such a high yield increase risks leading to a significant decrease in soil pH. This decrease in pH is an early indication of soil fertility degradation, which, if not addressed with proper soil management and fertilization, can reduce the availability of essential nutrients and disrupt soil microbial activity. This condition has the potential to reduce land productivity in the long term, so sustainable fertilization management and monitoring of soil parameters are crucial to prevent damage to the soil environment and maintain stable production results. Efforts needed in cassava cultivation to ensure sustainable land use include the appropriate use of various types of fertilizers (Aryal et al., 2021; Fang et al., 2021). The use of a combination of organic and inorganic fertilizers is an important strategy for maintaining soil fertility, increasing plant productivity, and reducing the negative impacts of overfertilization (Sun et al., 2022). With this approach, the balance of soil nutrients can be maintained, the physical and biological conditions of the soil are improved, so that cassava productivity can be maintained in the long term without damaging the quality of the land (Muthumanickam et al., 2023; Wang et al., 2021).

Economic Considerations

Because the humic acid + compost treatment (T5) required two organic inputs rather than one, its practical recommendation to farmers depends not only on its agronomic performance but also on whether its yield gain justifies its additional input and labour cost relative to the single-input and control treatments. Table 4 reports current Indonesian reference unit prices for the three inputs used in this trial and for cassava at the farm gate, drawn from government and commercial sources rather than from the trial itself. Phonska NPK is a subsidised fertiliser sold at a government-set ceiling price (Harga Eceran Tertinggi, HET) of Rp 1,840 kg⁻¹, effective 22 October 2025 (Kementerian Pertanian Republik Indonesia, 2025b). Compost retails at roughly Rp 2,000–10,000 kg⁻¹ in small packaging and closer to Rp 5,500 kg⁻¹ when purchased in bulk (Indonesian agricultural-input marketplace listings, 2025). Granular/powder humic acid products retail at approximately Rp 65,000–93,000 kg⁻¹ (Purotani, n.d.-a, n.d.-b; Tani Nusantara, n.d.). The national reference farm-gate price for fresh cassava tubers was Rp 1,350 kg⁻¹, set 31 January 2025 (Kementerian Pertanian Republik Indonesia, 2025a); this is a national figure and may not equal the price actually received at Kertosono, Nganjuk. These are unit reference prices only. Converting them into a per-hectare cost–benefit comparison additionally requires the exact quantity of each material applied per hectare under each treatment, the number of labour-days per hectare for each application regime, and the plant population per hectare needed to convert the yield data in this study (reported per plant) to a per-hectare basis — none of which are stated in the manuscript and none of which could be sourced independently, since they are trial-specific records rather than public information. A full net-benefit and benefit–cost (B/C) ratio table is therefore not presented here.

Table 4. Current Indonesian reference unit prices for the fertiliser inputs used in this trial and for cassava at the farm gate (2025/2026 sources).

Input	Reference unit price (Rp)	Source
Phonska NPK (15-10-12+10S) fertiliser	1,840 kg ⁻¹ (subsidised HET)	Kementerian Pertanian Republik Indonesia, 2025b (effective 22 Oct 2025)
Compost	~2,000–10,000 kg ⁻¹ retail; ~5,500 kg ⁻¹ bulk	Indonesian agricultural-input marketplace listings, 2025
Humic acid (granular/powder)	~65,000–93,000 kg ⁻¹	Purotani, n.d.-a, n.d.-b; Tani Nusantara, n.d.
Cassava tuber (farm gate)	1,350 kg ⁻¹ (national reference)	Kementerian Pertanian Republik Indonesia, 2025a (set 31 Jan 2025)

Limitations and Future Research

This study has several limitations that should be considered when interpreting and applying its findings. First, the trial was conducted at a single site (Kertosono, East Java) over one 13-month planting cycle; because soil chemical responses to fertilisation can vary with seasonal rainfall, initial fertility status, and site-specific management, the treatment rankings reported here — particularly the magnitude of the pH decline under T5 — should be confirmed through multi-location and multi-season (or multi-year) trials before being generalised to other alluvial soils or cropping cycles. Second, soil fertility assessment in this study was deliberately limited to three rapidly measurable indicators (pH, EC, and Eh); it did not include organic carbon, total nitrogen, available phosphorus, exchangeable potassium, or microbial activity/biomass, each of which would provide a more complete picture of the nutrient and biological status underlying the observed chemical shifts. Future studies should pair pH–EC–Eh monitoring with a fuller nutrient and microbiological panel, ideally sampled at multiple points across the growing season rather than only post-harvest, to determine whether the acidification observed under T5 stabilises, continues, or reverses over successive cropping cycles. Third, as noted above, the economic case for the humic acid + compost combination has not yet been quantified; multi-season cost–benefit data would strengthen the practical case for recommending T5 over the agronomically similar but single-input T3 (Phonska) treatment.

Conclusion

This study shows that the combination of organic and inorganic fertilizers, particularly humic acid and compost (T5), significantly increases cassava plant growth and yield compared to single- and control treatments. The combination also yields higher soil Eh (redox potential) and EC (electrical conductivity) values, indicating healthier, more fertile soil conditions. However, high yields in some treatments are also accompanied by a drop in soil pH below the ideal threshold, indicating a risk of reduced soil fertility if not managed properly in the next growing season. This study will provide empirical, measurable evidence that combination fertilization strategies (especially humic acid + compost) not only increase crop productivity but also improve soil chemical conditions, particularly in alluvial lands prone to fertility degradation. This study also introduces a simultaneous multi-parameter (pH, EC, Eh) measurement approach as an integrated indicator to evaluate the impact of fertilization on post-harvest soil health. In practice, these findings can serve as a basis for developing guidelines for balanced and sustainable fertilization in cassava cultivation on tropical lands. The use of humic acid with compost is recommended as a fertilization strategy that not only increases yields but also maintains long-term soil productivity. Further research is recommended to evaluate the long-term impact of this fertilizer combination on soil quality, nutrient absorption efficiency, and soil microbiota dynamics. These conclusions are based on a single site and a single 13-month planting cycle; multi-location and multi-season trials, combined with a fuller soil nutrient and microbiological panel and a local cost–benefit analysis, are recommended before the humic acid + compost combination is generalised as a standard recommendation for alluvial cassava cultivation.

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AUTHOR CONTRIBUTIONS

SS - Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision; WM - Methodology, Formal analysis, Data curation, Writing – original draft, Visualization; HS - Investigation, Resources, Validation, Writing – review & editing; SS - Data curation, Formal analysis, Visualization; AW - Software, Formal analysis, Visualization, Writing – original draft; FDD - Investigation, Resources, Data curation, Writing – review & editing, FJ – Methodology, Supervision, Project administration; UWP - Conceptualization, Methodology, Formal analysis, Writing – original draft.

CONFLICT OF INTEREST

The authors state no conflict of interest.

DATA AVAILABILITY STATEMENT

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request

References

1. Abdollahpour, M., Hollemann, D., Sauheitl, L., Guggenberger, G., & Zamanian, K. (2025). Nitrogen fertilization-induced acidity and suitability of $\delta^{13}\text{C}$ to study the dynamics of soil inorganic carbon in agroecosystems. *Geoderma*, 457. <https://doi.org/10.1016/j.geoderma.2025.117309>
2. Ali, T., & Sultan, H. (2023). An Islamic Perspective on Infection Treatment and Wound Healing. *Religions*, 14(8). <https://doi.org/10.3390/rel14081044>
3. Anbhazhagan, A., Ramah, K., Sakthivel, N., & Sivasakthivelan, P. (2024). Role of organic and inorganic nutrients in enhancing the production of soybean: a review. *Journal of Plant Nutrition*, 47(19), 3777–3792. <https://doi.org/10.1080/01904167.2024.2384573>
4. Andrezza, G. C., Luciano, S. S., Francisco, A. S., Alide, M. W., Evellyn, F. S., & Marcela, R. B. (2021). Characterization of soils cultivated with cassava under different managements. *Brazilian Journal of Agricultural and Environmental Engineering*, 25(11), 764–771. <https://doi.org/10.1590/1807-1929/agriambi.v25n11p764-771>
5. Aryal, J. P., Sapkota, T. B., Krupnik, T. J., Rahut, D. B., Jat, M. L., & Stirling, C. M. (2021). Factors affecting farmers' use of organic and inorganic fertilizers in South Asia. *Environmental Science and Pollution Research*, 28(37), 51480–51496. <https://doi.org/10.1007/s11356-021-13975-7>
6. Badan Standardisasi Nasional. (2004). SNI 19-7030-2004: Spesifikasi kompos dari sampah organik domestik [National Standard: Specification of compost from domestic organic waste]. <https://pesta.bsn.go.id/produk/detail/6756-sni19-7030-2004>
7. Bilong, E. G., Abossolo-Angue, M., Ajebesone, F. N., Anaba, B. D., Madong, B. A., Nomo, L. B., & Bilong, P. (2022). Improving soil physical properties and cassava productivity through organic manures management in the southern Cameroon. *Heliyon*, 8(6). <https://doi.org/10.1016/j.heliyon.2022.e09570>
8. Birindwa, R. D., Van Laere, J., Munyahali, W., De Bauw, P., Dercon, G., Kintche, K., & Merckx, R. (2023). Early planting of cassava enhanced the response of improved cultivars to potassium fertilization in South Kivu, Democratic Republic of Congo. *Field Crops Research*, 296. <https://doi.org/10.1016/j.fcr.2023.108903>
9. Bolo, P., Kihara, J., Mucheru-Muna, M., Njeru, E. M., Kinyua, M., & Sommer, R. (2021). Application of residue, inorganic fertilizer and lime affect phosphorus solubilizing microorganisms and microbial biomass under different tillage and cropping systems in a Ferralsol. *Geoderma*, 390. <https://doi.org/10.1016/j.geoderma.2021.114962>
10. Büyük, G., Bayram, C. A., İnan, M., & Kırpık, M. (2022). The effect of organic and inorganic fertilizers on plant nutrient content and agronomic performance of stevia. *Journal of Plant Nutrition*, 45(15), 2303–2314. <https://doi.org/10.1080/01904167.2022.2063739>
11. Chaudhary, A., Prajapati, N., Prajapati, A., Singh, S., Joshi, M., Prajapati, D., Patani, A., Sahoo, D. K., & Patel, A. (2024). Postbiotic emissaries: a comprehensive review on the bioprospecting and production of bioactive compounds by *Enterococcus* species. *International Journal of Food Science and Technology*, 59(10), 6769–6782. <https://doi.org/10.1111/ijfs.17431>
12. Chen, Y., Ouyang, Y., Pan, W., Wang, Y., & Li, Y. (2024). Effects of Organic Manure on Wheat Yield and Accumulation of Heavy Metals in a Soil—Wheat System. *Agronomy*, 14(9). <https://doi.org/10.3390/agronomy14092143>
13. Das, P. P., Singh, K. R., Nagpure, G., Mansoori, A., Singh, R. P., Ghazi, I. A., Kumar, A., & Singh, J. (2022). Plant-soil-microbes: A tripartite interaction for nutrient acquisition and better plant growth for sustainable agricultural practices. *Environmental Research*, 214. <https://doi.org/10.1016/j.envres.2022.113821>
14. Du, T., Hu, Q., He, H., Mao, W., Yang, Z., Chen, H., Sun, L., & Zhai, M. (2023). Long-term organic fertilizer and biofertilizer application strengthens the associations between soil quality index, network complexity, and walnut yield. *European Journal of Soil Biology*, 116. <https://doi.org/10.1016/j.ejsobi.2023.103492>

15. Elayaraja, D., & Sathiyamurthi, S. (2020). Influence of Organic Manures and Micronutrients Fertilization on the Soil Properties and Yield of Sesame (*Sesamum indicum* L.) in Coastal Saline Soil. *Indian Journal of Agricultural Research*, 54(1), 89–94. <https://doi.org/10.18805/IJARE.A-5422>
16. Elnahal, A. S. M., El-Saadony, M. T., Saad, A. M., Desoky, E.-S. M., El-Tahan, A. M., Rady, M. M., AbuQamar, S. F., & El-Tarabily, K. A. (2022). The use of microbial inoculants for biological control, plant growth promotion, and sustainable agriculture: A review. *European Journal of Plant Pathology*, 162(4), 759–792. <https://doi.org/10.1007/s10658-021-02393-7>
17. Fan, Y., Hao, X., Carswell, A., Misselbrook, T., Ding, R., Li, S., & Kang, S. (2021). Inorganic nitrogen fertilizer and high N application rate promote N₂O emission and suppress CH₄ uptake in a rotational vegetable system. *Soil and Tillage Research*, 206. <https://doi.org/10.1016/j.still.2020.104848>
18. Fang, H., Liu, K., Li, D., Peng, X., Zhang, W., & Zhou, H. (2021). Long-term effects of inorganic fertilizers and organic manures on the structure of a paddy soil. *Soil and Tillage Research*, 213. <https://doi.org/10.1016/j.still.2021.105137>
19. Ghosh, D., Brahmachari, K., Skalicky, M., Roy, D., Das, A., Sarkar, S., Moulick, D., Brestic, M., Hejnak, V., Vachova, P., Hassan, M. M., & Hossain, A. (2022). The combination of organic and inorganic fertilizers influence the weed growth, productivity and soil fertility of monsoon rice. *PLoS ONE*, 17(1 January). <https://doi.org/10.1371/journal.pone.0262586>
20. Guo, Z., Han, J., Li, J., Xu, Y., & Wang, X. (2019). Effects of long-term fertilization on soil organic carbon mineralization and microbial community structure. *PLOS ONE*, 14(1), e0211163. <https://doi.org/10.1371/journal.pone.0211163>
21. He, Y., Yu, Y., Guo, X., & Li, D. (2023). Government subsidy and firm's cost sharing in sustainable agriculture supply chain. *International Journal of Food Science & Technology*, 58(10), 5530–5548. <https://doi.org/10.1111/ijfs.16465>
22. Huning, T. R., & Wahl, F. (2021). The origins of agricultural inheritance traditions. *Journal of Comparative Economics*. <https://doi.org/10.1016/j.jce.2021.01.004>
23. Kakad, C. B., Chavan, A. P., Varnekar, K. D., & Game, V. N. (2024). Effect of Seedlings Age and Nutrient Combinations on Growth and Yield of Proso Millet (*Panicum miliaceum* L.) in Lateritic Soils of Western Ghats. *Indian Journal of Agricultural Research*, 58(1), 83–88. <https://doi.org/10.18805/IJARE.A-5658>
24. Kaur, G., Kaur, J., & Walia, S. S. (2024). Effect of Integrated Nutrient Management on Soil Health, Soil Quality, and Production of Cowpea (*Vigna unguiculata* L.). *Journal of Basic Microbiology*, 64(11). <https://doi.org/10.1002/jobm.202400225>
25. Kementerian Pertanian Republik Indonesia. (2025a, January 31). Kementan tetapkan harga singkong menjadi Rp1.350 per kilogram [Ministry of Agriculture sets cassava price at Rp1,350 per kilogram]. *Antara News*. <https://www.antaranews.com/berita/4617550/kementan-tetapkan-harga-singkong-menjadi-rp1350-per-kilogram>
26. Kementerian Pertanian Republik Indonesia. (2025b, October 22). Kebijakan Presiden Prabowo turunkan harga pupuk 20 persen [President Prabowo's policy reduces fertiliser prices by 20%]. <https://www.pertanian.go.id/?show=news&act=view&id=7221>
27. Kousoulaki, K., Grøtan, E., Kortner, T. M., Berge, G. M., Haustveit, G., Krogdahl, Nygaard, H., Sæle, Chikwati, E. M., & Lein, I. (2021). Technical feed quality influences health, digestion patterns, body mineralization and bone development in farming of the stomachless cleaner fish ballan wrasse (*Labrus bergylta*). *Animal Feed Science and Technology*, 274. <https://doi.org/10.1016/J.ANIFEEDSCI.2021.114830>
28. Kumar, S., Kumar, S., & Mohapatra, T. (2021). Interaction Between Macro- and Micro-Nutrients in Plants. *Frontiers in Plant Science*, 12. <https://doi.org/10.3389/fpls.2021.665583>
29. Kumar, S., Sindhu, S. S., & Kumar, R. (2022). Biofertilizers: An ecofriendly technology for nutrient recycling and environmental sustainability. *Current Research in Microbial Sciences*, 3. <https://doi.org/10.1016/j.crmicr.2021.100094>
30. Lazcano, C., Zhu-Barker, X., & Decock, C. (2021). Effects of organic fertilizers on the soil microorganisms responsible for n₂o emissions: A review. *Microorganisms*, 9(5). <https://doi.org/10.3390/microorganisms9050983>
31. Li, H., Lin, J., Shao, Q., Zhang, B., Wang, Y., Wang, L., Feng, H., Lou, Y., Wang, H., Yang, Q., Yang, Z., Di, H., Sun, Y., Pan, H., & Zhuge, Y. (2024). Microbial groups containing alkaline phosphatase accelerate soil phosphate mineralization in two soil patterns with contrasting pH levels. *Journal of Soils and Sediments*, 24(11), 3694–3706. <https://doi.org/10.1007/s11368-024-03919-2>

32. Liu, J., Qiu, T., Peñuelas, J., Sardans, J., Tan, W., Wei, X., Cui, Y., Cui, Q., Wu, C., Liu, L., Zhou, B., He, H., & Fang, L. (2023). Crop residue return sustains global soil ecological stoichiometry balance. *Global Change Biology*, 29(8), 2203–2226. <https://doi.org/10.1111/gcb.16584>
33. Mohammadzadeh, A., Roshanravan, N., Mesri Alamdari, N., Safaiyan, A., Mosharkesh, E., Hadi, A., Barati, M., & Ostadrahimi, A. (2021). The interplay between fasting, gut microbiota, and lipid profile. *International Journal of Clinical Practice*, 75(10). <https://doi.org/10.1111/ijcp.14591>
34. Monteiro, S. S., Martins, L. P., Araújo, R. D. C., da Silva, E. A., & Monteiro, S. S. (2024). Different sources of nutrients in the production and quality of “Veneranda” curly lettuce. *Horticultura Brasileira*, 42. <https://doi.org/10.1590/s0102-0536-2024-e2616>
35. Muthumanickam, K., Chaudhary, S. K., Singh, S. P., Kumar, R., & Naik, B. M. (2023). Combined application of chemical fertilizers, organics and foliar spray of zinc and iron on yield, quality and water productivity of aerobically grown rice (*Oryza sativa*) in calcareous soil. *Journal of Plant Nutrition*, 46(13), 2990–3001. <https://doi.org/10.1080/01904167.2022.2161390>
36. Nurrazaq, G., Amal, I., Harahap, S. A. N., & Diaguna, R. (2024). Growth and yield of cassava in low fertility Latosol soil with various doses of NPK fertilizer. *Australian Journal of Crop Science*, 18(10), 613–619. <https://doi.org/10.21475/ajcs.24.18.10.p04>
37. Nzama, N. L., Dufresne, A., & Amonsou, E. O. (2024). Stearic acid enhanced starch nanocrystal integration in cassava starch film. *International Journal of Food Science and Technology*, 59(8), 5721–5732. <https://doi.org/10.1111/ijfs.17310>
38. O’Callaghan, M., Ballard, R. A., & Wright, D. (2022). Soil microbial inoculants for sustainable agriculture: Limitations and opportunities. *Soil Use and Management*, 38(3), 1340–1369. <https://doi.org/10.1111/sum.12811>
39. Orek, C. (2024). A review of management of major arthropod pests affecting cassava production in Sub-Saharan Africa. *Crop Protection*, 175. <https://doi.org/10.1016/j.cropro.2023.106465>
40. Patgiri, P. (2024). Nutrient Management under Organic Production System in Hill/Mountain Regions. *Grassroots Journal of Natural Resources*, 7(2), 119–139. <https://doi.org/10.33002/nr2581.6853.070206>
41. PT Petrokimia Gresik. (n.d.). Phonska [Product specification]. Retrieved September 15, 2026, from <https://petrokimia-gresik.com/product/phonska>
42. Phothisarattana, D., & Harnkarnsujarit, N. (2022). Characterisations of cassava starch and poly(butylene adipate-co-terephthalate) blown film with silicon dioxide nanocomposites. *International Journal of Food Science and Technology*, 57(8), 5078–5089. <https://doi.org/10.1111/ijfs.15816>
43. Purotani. (n.d.-a). Humalit SP: Pupuk organik asam humat Powersoil [Product specification]. Retrieved September 15, 2026, from <https://purotani.id/product/pupuk-organik-asam-humat-powersoil/>
44. Purotani. (n.d.-b). ZOOMAS: Asam humat 98% [Product specification]. Retrieved September 15, 2026, from <https://purotani.id/product/zoomas-asam-humat-1kg-pupuk-organik-pembenah-tanah-humic-acid-premium/>
45. Rombel, A., Krasucka, P., & Oleszczuk, P. (2022). Sustainable biochar-based soil fertilizers and amendments as a new trend in biochar research. *Science of the Total Environment*, 816. <https://doi.org/10.1016/j.scitotenv.2021.151588>
46. Sabir, M. S., Shahzadi, F., Ali, F., Shakeela, Q., Niaz, Z., & Ahmed, S. (2021). Comparative Effect of Fertilization Practices on Soil Microbial Diversity and Activity: An Overview. *Current Microbiology*, 78(10), 3644–3655. <https://doi.org/10.1007/s00284-021-02634-2>
47. Santoyo, G., Guzmán-Guzmán, P., Parra-Cota, F. I., de los Santos-Villalobos, S., Orozco-Mosqueda, M. C., & Glick, B. R. (2021). Plant growth stimulation by microbial consortia. *Agronomy*, 11(2). <https://doi.org/10.3390/agronomy11020219>
48. Sanusi, R. O., Adebayo, R. M., Isegbe, E. I., Ibrahim, A. O., Ajayi, O. B., Oke, O. O., Ajibola, B. O., & Ajibade, A. S. (2021). Productivity of participating cassava (*Manihot esculenta*) farmers in deutsche gesellschaft für internationale zusammenarbeit (giz) sponsored advisory service in ogun state, nigeria: 2016-2018. *Tropical Agriculture*, 98(2), 148–159. <https://www.scopus.com/inward/record.uri?eid=2-s2.0-85115330364&partnerID=40&md5=c4a139bc071d0c94131ad28dee8a7adb>
49. Seiermann, A. U., Al-Mufti, H., Waid, J. L., Wendt, A. S., Sobhan, S., & Gabrysch, S. (2021). Women’s fasting habits and dietary diversity during Ramadan in rural Bangladesh. *Maternal and Child Nutrition*, 17(3). <https://doi.org/10.1111/mcn.13135>
50. Siedt, M., Schäffer, A., Smith, K. E. C., Nabel, M., Roß-Nickoll, M., & van Dongen, J. T. (2021). Comparing straw, compost, and biochar regarding their suitability as agricultural soil amendments to

- affect soil structure, nutrient leaching, microbial communities, and the fate of pesticides. *Science of the Total Environment*, 751. <https://doi.org/10.1016/j.scitotenv.2020.141607>
51. Silva, J. A., Leonel, M., Fernandes, A. M., Garreto, F. G. S., Nunes, J. G. S., & Tajra, R. F. (2023). Growth, yield and nutrients of sweet cassava fertilized with zinc. *Ciência Rural*, 53(9). <https://doi.org/10.1590/0103-8478cr20220064>
52. Singh, P., Benbi, D. K., & Verma, G. (2021). Nutrient Management Impacts on Nutrient Use Efficiency and Energy, Carbon, and Net Ecosystem Economic Budget of a Rice–Wheat Cropping System in Northwestern India. *Journal of Soil Science and Plant Nutrition*, 21(1), 559–577. <https://doi.org/10.1007/s42729-020-00383-y>
53. Su, J., Wang, Y., Zhang, X., Ma, M., Xie, Z., Pan, Q., Ma, Z., & Peppelenbosch, M. P. (2021). Remodeling of the gut microbiome during Ramadan-associated intermittent fasting. *American Journal of Clinical Nutrition*, 113(5), 1332–1342. <https://doi.org/10.1093/ajcn/nqaa388>
54. Sun, T., Xie, Q., Li, C., Huang, J., Yue, C., Zhao, X., & Wang, D. (2022). Inorganic versus organic fertilizers: How do they lead to methylmercury accumulation in rice grains. *Environmental Pollution*, 314. <https://doi.org/10.1016/j.envpol.2022.120341>
55. Tan, P., Wang, S., Ameen, A., Xie, J., Jiang, G., & Han, L. (2023). Fertilizer Application to Balance Nitrogen and Phosphorus Nutrients and Improve Agronomic Traits of Okra (*Abelmoschus esculentus* L.) in Coastal Saline Soil Under Subsurface Pipe Salt Drainage. *Journal of Soil Science and Plant Nutrition*, 23(4), 5454–5467. <https://doi.org/10.1007/s42729-023-01413-1>
56. Tani Nusantara. (n.d.). Pupuk asam humat pembenah tanah [Product specification]. Retrieved September 15, 2026, from <https://taninusantara.id/product/pupuk-asam-humat-pembenah-tanah/>
57. Urmi, T. A., Rahman, M. M., Islam, M. M., Islam, M. A., Jahan, N. A., Mia, M. A. B., Akhter, S., Siddiqui, M. H., & Kalaji, H. M. (2022). Integrated Nutrient Management for Rice Yield, Soil Fertility, and Carbon Sequestration. *Plants*, 11(1). <https://doi.org/10.3390/plants11010138>
58. Wang, R., Hou, T., Sun, Q., Ji, L., Lei, J., & Zhang, J. (2021). Organic fertilizers and soil conditioner recover chemical fertilizer-induced changes in soil bacterial community diversity in wine grape rhizosphere soil. *Polish Journal of Environmental Studies*, 30(2), 1853–1863. <https://doi.org/10.15244/pjoes/126236>
59. Wikipedia contributors. (2026). Nganjuk Regency. Wikipedia. Retrieved September 15, 2026, from https://en.wikipedia.org/wiki/Nganjuk_Regency
60. Yadav, M. R., Singh, M., Kumar, R., Ram, H., Meena, R. K., Makarana, G., Kumar, D., & Dutta, S. (2022). Inclusion of legume and integrated use of organic and inorganic nutrient sources can improve the productivity and qualitative traits of oats straw. *Journal of Plant Nutrition*, 45(13), 1991–2002. <https://doi.org/10.1080/01904167.2022.2063137>