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Ethno-agronomic Management of Horticultural Inceptisols under Monoculture and Polyculture Using Nagari Local Ameliorant Resource Formulations

Herviyanti[1*], An Nisa Mutiara Fathi[1], Irwan Darfis[1], M. Hafizh Ash Shiddiq[1], Defry Jonica Putri[1], Amsar Maulana[2] and Ridho Ryswaldi[3]

[1]Department of Soil Science and Land Resources, Faculty of Agriculture, Universitas Andalas, Padang, Indonesia; [2]Post-Doctoral Program of Faculty of Agriculture, Universitas Andalas, Padang, Indonesia; [3]Department of Management, Faculty of Economy and Business, Universitas Negeri Padang, Padang, Indonesia

[*]*Corresponding author:* herviyanti@agr.unand.ac.id

Abstract

Low soil surface charge and nutrient imbalances in Inceptisols threaten horticultural productivity in monoculture and polyculture systems. Ethno-agronomy management using local resources is expected to be a solution to these issues. The research aims to assess the effects of Nagari local ameliorant resource formulations (LARFs; bamboo biochar (BB), *Tithonia* green fertilizer (TGF), chicken manure (CM), and Agam compost (CA)) on surface charge and nutrients. A randomized complete block design (RCBD) was used to test 5 treatments: Control, LARF-I (BB + TGF + CM), LARF-II (BB + TGF + CA), conventional farming (CF), and Ministry of Agriculture Recommendations (MAR), with 3 replications, in Banuhampu, Agam. LARFs significantly improved soil surface charge properties (pH H_2O, electrical conductivity (EC), percentage of organic matter (%OM), and cation exchange capacity (CEC)) and macronutrient levels (organic C (OC), total N, available P, and exchangeable K) compared with the control and conventional farming. LARF-I excelled in pH H_2O, EC, %OM, and CEC under monoculture (+16–170%) and polyculture (+23–92%), outperforming CF by 11–157%. LARF-II led in OC (+91–112%) and total N (+37–441%), while LARF-I dominated available P (+122–328%) and exchangeable K (+60–78%). These enhancements increased crop nutrient uptake (N, P, and K) by up to 170% in string bean (monoculture) and broccoli (polyculture), with LARF-I achieving the highest overall increase. Yields increased most under LARF-II (string bean +33%, broccoli +74%, lettuce +70% compared to the control; 31–43% above CF), followed closely by LARF-I (+29–65% from the control; 21–29% above CF). These improvements enhanced soil fertility and nutrient availability, supporting better nutrient uptake and crop performance. LARFs promote sustainable restoration of soil fertility and support ethno-agronomic practices in horticulture.

Keywords: amelioration; macronutrient uptake; phosphate availability; soil surface charge; yield increase

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INTRODUCTION

Sustainable agriculture is a high priority due to problems such as land degradation, declining soil fertility, and climate change, especially in areas prone to natural disasters, such as Indonesia (Obaisi et al., 2024; Zhang and Zhang, 2025). Ethno-agronomy uses local resources and farmers' knowledge to help create farming systems that can withstand production challenges

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(Ramírez-García, 2019). In Nagari Pakan Sinayan, Banuhampu, Agam Regency, West Sumatra, horticultural farmers on Inceptisols rely on ethno-agronomic practices using local ameliorants to keep their crops productive. Inceptisols, commonly found in tropical upland regions, are crucial for food security because of their moderate soil development and strong support capacity for agriculture. However, they often deal with nutrient loss and reduced fertility under intensive use.

Inceptisols are young soils that are still similar to their parent material (Zu'amah et al., 2025) and commonly have low organic C, low pH, and limited N, P, and K, which restrict plant growth (Rizwan and Harahap, 2021; Rahmayuni et al., 2023). Inceptisols can exhibit higher fertility and near-neutral pH when farmers consistently use animal manure. For example, spinach and water spinach grown with duck manure have maintained consistent yields over many years (Lubis and Mukhlis, 2025). This proof highlights both the potential benefits and limitations of farmer-managed Inceptisols, where local organic inputs improve fertility, but physical problems like erosion and waterlogging can still occur (Lubis and Mukhlis, 2025). Given the widespread presence of Inceptisols in Indonesia, it is important to understand how local organic technologies influence their surface chemistry and nutrient levels for sustainable land management.

Soil surface properties form a crucial foundation of soil fertility and are essential for crop growth and nutrient absorption. The soil surface has electrical charge characteristics that promote the adsorption and exchange of nutrient ions from fertilizers, making it a key indicator of soil fertility, nutrient retention capacity, and buffering ability (Ma et al., 2025). In soils with variable charge components such as organic matter, biochar, and short-range-order minerals, surface charge behavior is highly dependent on pH. An important parameter that describes this behavior is the point of zero charge (PZC), the pH at which the net surface charge of soil particles is zero. The soil pH relative to the PZC influences whether cations or anions are retained more effectively, thereby affecting nutrient availability and leaching risk. In tropical Inceptisols, where pH tends to be acidic and organic amendments are frequently applied, shifts in PZC can notably alter surface charge characteristics. Nonetheless, data on PZC and its responses to locally applied organic amendments in Inceptisols are limited, especially within smallholder horticultural systems.

Nagari local ameliorant resource formulations (LARFs) combine bamboo biochar (BB), *Tithonia* green fertilizer (TGF), chicken manure (CM), and Agam compost (CA). These LARFs have been utilized to improve soil health, increase nutrient availability, and reduce dependency on external inputs (Herviyanti et al., 2023a). Biochar contributes fixed carbon and enhances the retention of water and nutrients (El-Naggar et al., 2024; Hussain et al., 2024; Khatun et al., 2024; Shyam et al., 2025). Organic inputs such as TGF, CM, and compost increase pH (Dayo-Olagbende et al., 2019), organic matter (Manea et al., 2024; Sparta et al., 2025), and macronutrient availability (Richa et al., 2020; Herviyanti et al., 2023b; Lucchetta et al., 2023; Almási et al., 2025; Suvendran et al., 2025) while supporting biological activity (Minkina et al., 2023; Moreira et al., 2024; Sarwari et al., 2024; Veettil et al., 2024; Vikas and Ranjan, 2024) in tropical soils.

The integrated use of biochar and organic manure has been shown to improve pH, organic C, total N, available P, and exchangeable K, Ca, and Mg, and enhance the chemical fertility of degraded tropical soils (Agbede and Oyewumi, 2022; Song et al., 2025). However, the specific effects of locally formulated combinations on surface-charge-related properties (e.g., pH, cation exchange capacity (CEC), and associated charge behavior) and macronutrient status in Inceptisols remain poorly documented.

Although these organic amendments are widely used, there remains limited scientific understanding of their combined effects on soil properties in specific soil types, such as Inceptisols. Especially, surface charge characteristics are a key factor affecting nutrient retention and availability. Additionally, detailed macronutrient dynamics under integrated organic treatments have not been sufficiently studied. This study, therefore, aimed to fill this knowledge gap by evaluating how the combination of bamboo biochar, *Tithonia diversifolia*, chicken manure, and compost affects soil surface charge properties, including the PZC and macronutrient availability in Inceptisols. The hypothesis was that LARFs would improve surface-charge-related properties and macronutrient availability in Inceptisols compared with the control. The research sought to generate new insights into sustainable soil-fertility management strategies adapted to tropical smallholder horticultural systems, thereby supporting productivity and environmental resilience.

MATERIALS AND METHOD

Study site and duration

The study was conducted from May to December 2024. It used a field plot in Nagari Pakan Sinayan, Banuhampu, Agam (100°22’01.6’’ E, 0°20’54.8’’ S; 1,027 m above sea level). Soil and plant nutrient analyses were performed in the Soil Chemistry and Fertility Laboratory of the Soil and Land Resources Department, Agriculture Faculty, Universitas Andalas. Oxide composition analyses of LARF-I (BB + TGF + CM) and LARF-II (BB + TGF + CA) were performed in the Chemistry Laboratory of the Mathematics and Natural Sciences Faculty, Universitas Negeri Padang, Indonesia. Proximate analysis followed ASTM D1762-8 standard methods, while oxide composition was determined using a PANalytical Epsilon 3XL Benchtop X-Ray Fluorescence (XRF) Spectrometer (Singh et al., 2017).

Figure 1 illustrates bed arrangement changes from prior planting (2022 to 2023) to current planting (2024). Minor plot rearrangements (each bed divided into two halves, one of which was merged with the half of the adjacent bed) were made by incorporating deliberate residuals (~5 to 8% post-mix) as a design feature simulating multi-year Nagari farming. Table 1 summarizes the history.

Experimental design

The experiment was arranged in a randomized complete block design with 5 treatments, each repeated 3 times. The plots measured 7 m^2 each and were cultivated under 2 systems: monoculture (string beans) and polyculture intercropping (lettuce and broccoli). The treatments consisted of combinations of locally produced soil amendments: bamboo biochar (BB), *Tithonia* green fertilizer (TGF), Agam compost (CA), and chicken manure (CM). The specific treatments applied are described in Table 2. LARF-I and LARF-II were chosen treatments from the 2022 to 2023 planting period based on Herviyanti et al. (2023a; 2024a; 2024b; 2025a); using a formula ameliorant dose of 10 tons ha^{-1} (Table 2).

Nagari LARF preparation

Ameliorants were prepared locally. BB was produced from *bambu betung* using the Kontiki pyrolysis method. TGF was made from chopped

Table 1. A summary of the history of the study site

Plot	Prior treatment (2022–2023)	Current use (2024)
A	Control	Polyculture
B	TGF + BB + CA + CM	Monoculture
C	TGF + BB + CM	Monoculture, polyculture
D	TGF + BB + CA	Monoculture, polyculture
E	BB + CA + CM	Monoculture
F	TGF + CA + CM	Monoculture
G	CF–CM (1.875 tons ha^{-1})	Polyculture
H	MAR–CM (10 tons ha^{-1})	Polyculture
I	No treatment	Monoculture, polyculture

Note: TGF = *Tithonia* green fertilizer; BB = Bamboo biochar; CA = Agam compost; CM = Chicken manure; MAR = Ministry of Agriculture Recommendations

30	29	28	27	26	25	24	23	22	21	20	19	18		17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
P I	P I	P I	P I	P H 3	P G 3	P A 3	P A 2	P G 2	P H 2	P G 1	P H 1	P A 1		P D 3	P C 3	P B 3	P E 3	P F 3	P D 2	P F 2	P C 2	P E 2	P B 2	P C 1	P D 1	P B 1	P F 1	P E 1	P I	P I

Note: P = Polyculture 2022-2023; A = Control; B = TGF + BB + CA + CM; C = TGF + BB + CM; D = TGF + BB + CA; E = BB + CA + CM; F = TGF + CA + CM; G = Conventional farming (CF) (CM = 1.875 ton ha^{-1}); H = MAR (CM = 10 ton ha^{-1}); I = No-treatment; 1, 2, 3 = Block

a.

30	29	28	27	26	25	24	23	22	21	20	19	18		17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
P G 3	P A 3	P C 3	P H 3	P D 3	P H 2	P C 2	P A 2	P G 2	P D 2	P C 1	P D 1	P H 1		P G 1	P A 1	M G 3	M A 3	M C 3	M H 3	M D 3	M H 2	M C 2	M A 2	M G 2	M D 2	M H 1	M D 1	M C 1	M A 1	M G 1

Note: P = Polyculture 2024; M = Monoculture 2024; A = Control; C = TGF + BB + CM; D = TGF + BB + CA; G = Conventional farming (CF); H = MAR; 1, 2, 3 = Block

b.

Figure 1. Bed arrangements of the 2022–2023 planting period (a) and the 2024 planting period (b)

Table 2. Description of the treatments used in the study

Treatment	Monoculture (M)	Polyculture (P)
Control (A)	No treatment	No treatment
LARF-I (B) ~ 10 tons ha^{-1}	5.2 kg BB + 11 kg TGF + 3 kg CM per plot	5.2 kg BB + 11 kg TGF + 3 kg CM per plot
LARF-II (C) ~ 10 tons ha^{-1}	5.2 kg BB + 11 kg TGF + 5.3 kg CA per plot	5.2 kg BB + 11 kg TGF + 5.3 kg CA per plot
Conventional (D) ~ M = 0.266 tons ha^{-1} CM P = 7.143 tons ha^{-1} CM : 2.429 tons ha^{-1} CA	187 g CM per plot	5 kg CM + 1.7 kg CA per plot
MAR (E) ~ M = 15 tons ha^{-1}; P = 20 tons ha^{-1}	10.5 kg CM per plot	14 kg CM per plot

Note: TGF = *Tithonia* green fertilizer; BB = Bamboo biochar; CA = Agam compost; CM = Chicken manure; MAR = Ministry of Agriculture Recommendations

Tithonia diversifolia plants harvested from Nagari Pakan Sinayan. CA originated from Acro Moris Family in Mato Aia Gadut, composed of a mixture of fermented animal feces and urine (horse, goat (fermented with urine), cow, and rabbit (fermented with urine)), fermented blood, ash from burned husk, biochar, dolomite, and *Trichoderma* spp. CM was collected from nearby chicken farms.

Soil sampling and analysis

Composite systematic sampling was conducted to collect a soil sample, in which soil samples from 6 points (upper, middle, and lower ends) of each raised-bed plot used in this study were collected and composited into a single representative sample. The sampling was conducted after 14 days of amendment incubation (Herviyanti et al., 2023a; 2024a; 2024b; Sajar et al., 2024). Analyses included soil pH, electrical conductivity (EC), mineral and organic matter compositions, and CEC. To be precise, pH was measured with a pH meter, EC was measured by the electrode method, mineral and organic matter compositions were measured by the dry-ash method, and CEC was determined by ammonium acetate leaching at pH 7 to evaluate changes in soil surface charge. The PZC was determined using Equation 1.

$$PZC = 2 \times pH_{KCl} - pH_{H_2O} \quad (1)$$

PZC indicates the pH where the net surface charge is zero, which affects nutrient adsorption and availability. Additional analyses of macronutrient availability were also conducted. Organic carbon (OC) was determined by the Walkley–Black method, total N was determined by the Kjeldahl method, available P was determined by the Bray I method, and exchangeable K was extracted with 1 M ammonium acetate at pH 7 and determined by flame atomic absorption spectrometry (AAS) (Darfis et al., 2023; Eviati et al., 2023).

Plant sampling and analysis

Plant samples were taken at mid-harvest. For string beans, 1-kg samples were collected; for broccoli and lettuce, 2 plants were sampled from each of the plot’s top, center, and bottom sections. The samples were wrapped in aluminum foil to minimize damage and then analyzed for N, P, and K using 96% H_2SO_4 and H_2O_2 digestion (Eviati et al., 2023). In addition, a record of harvests of these plants was kept to the end of the research period to obtain values of crop production yields.

Statistical analysis

The data collected were statistically analyzed using SPSS 23 for correlation analysis, Microsoft Excel 2016 for data compilation, and Statistic 8® for analysis of variance (ANOVA) and Duncan’s multiple-range test (DMRT). If ANOVA results indicate a significant effect, the DMRT is used as a post-hoc test to determine which group has a significantly different mean. Significance was assessed based on F-values–results are considered significant and marked with * when the calculated F exceeds the critical F-value at the 5% level, and are considered very significant and marked with ** when the calculated F exceeds the critical F-value at the 1% level.

RESULTS AND DISCUSSION

The proximate and oxide compositions of LARFs

The proximate and oxide compositions of LARF-I and LARF-II, presented in Figure 2, highlight key differences in the chemical makeup of the 2 formulas, which explains the influence on their soil amendment roles, arising from the presence of CM in LARF-I and CA in LARF-II. The proximate analysis showed that LARF-II had more moisture and volatile matter. In contrast, LARF-I had higher ash and fixed carbon.

The increased moisture and volatile matter in LARF-II align with those reported by Mujtaba et al. (2021), who state that compost generally has higher moisture content and more volatile components than other organic inputs. Research from Herviyanti et al. (2025b) found that adding more compost to the biochar formula improves its water-holding capacity. This is because biochar can spread water within its porous structure. Therefore, adding compost to LARF-II could boost its organic reactivity and promote earlier nutrient release during soil application.

In contrast, LARF-I's higher fixed carbon content and lower volatile matter suggest greater chemical stability and a higher carbon content. According to Ivanovski et al. (2022), higher fixed carbon is associated with greater thermal stability, longer residence time in soil, and higher energy content. That means LARF-I may provide greater long-term stability and carbon sequestration potential when used as a soil ameliorant. Additionally, the higher ash content in LARF-I indicates a greater mineral contribution, which can improve soil nutrient availability, especially for K, Ca, and Mg. These differences in composition emphasize the distinct roles of LARF-I and LARF-II. LARF-I offers more stable, long-lasting soil conditioning, while LARF-II may enhance quicker nutrient mineralization and microbial activity because of its less stable organic matter.

Overall, these findings demonstrate that adding chicken manure or compost to a biochar-*Tithonia* green fertilizer mixture is crucial for determining the chemical properties and potential agronomic outcomes of LARF. The balance between immediate nutrient availability (LARF-II) and long-term soil improvement (LARF-I) offers valuable flexibility for customizing soil

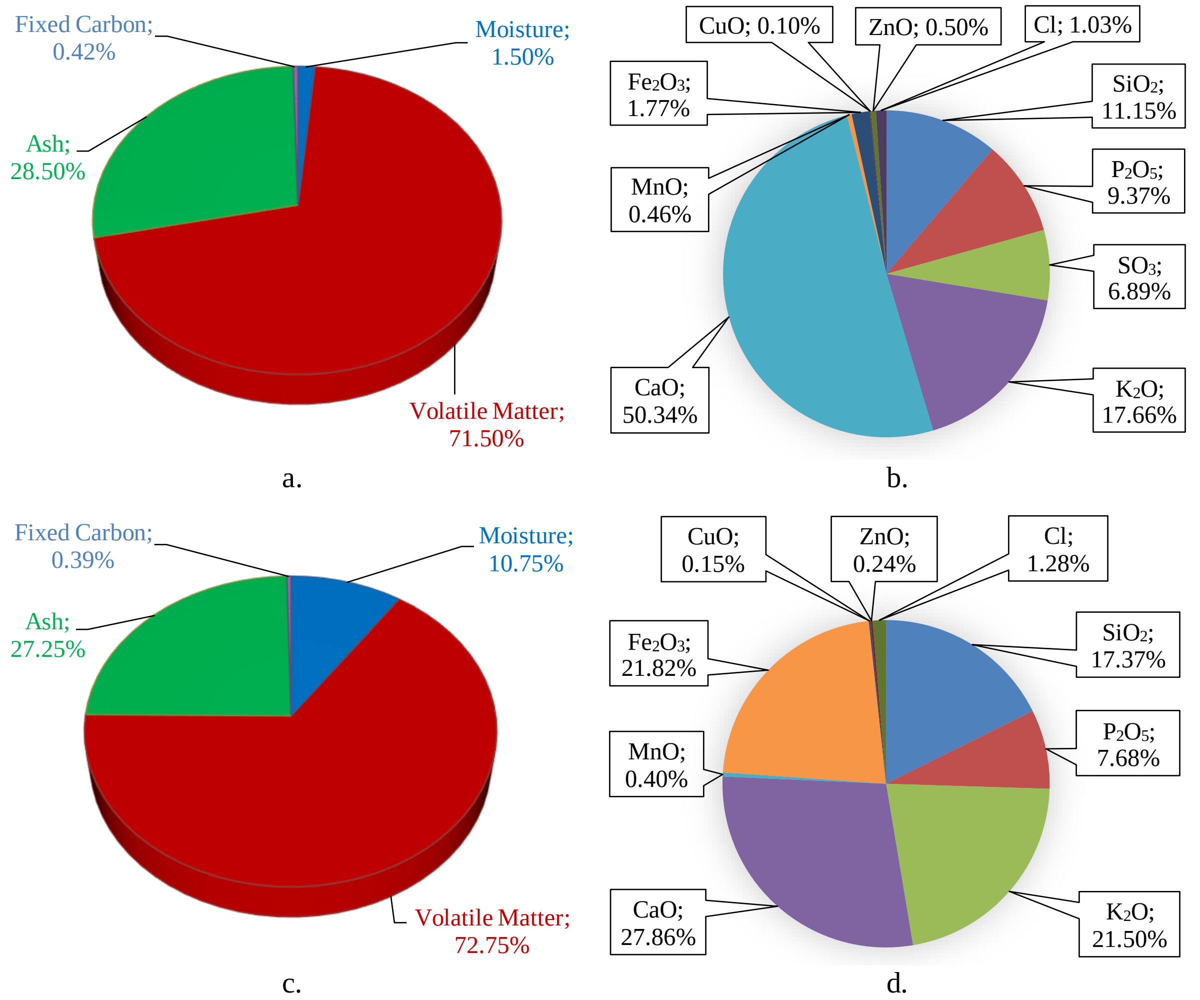

Figure 2. The proximate of LARF-I (a), oxide compositions of LARF-I (b), proximate of LARF-II (c), and oxide compositions of LARF-II (d)

amendment strategies to specific crop and soil needs.

The oxide compositions of LARF-I and LARF-II are presented in Figures 2b and 2d. These LARFs have different oxide compositions, where LARF-I has SO_3 and higher levels of P_2O_5, CaO, MnO, and ZnO. Meanwhile, LARF-II has no SO_3 but higher concentrations of SiO_2, K_2O, Fe_2O_3, CuO, and Cl. LARF-I has high CaO (50.34%) and P_2O_5 (9.37%) levels, probably coming from chicken manure, which is high in Ca and P, especially from poultry feed fortified for eggshell production (Chang et al., 2022). LARF-I is also higher with SO_3 content (6.89%), indicating a notable sulfur contribution, with chicken manure containing up to 5.76%, where it is the third dominant composition next to K and Ca (Prasetyo et al., 2024). Next, with higher ZnO and MnO in LARF-I, it is highlighted that chicken manure's micronutrients will enhance enzymatic functions and help plants tolerate stress.

Conversely, LARF-II has higher SiO_2 content (17.37%), a consequence of the rice husk ash present in the compost blend, as detailed in the Materials and Method section under "Nagari LARF preparation". Rice husk, known for its Si-rich composition, can contain up to 82.5% SiO_2 (Saeed et al., 2019). Furthermore, LARF-II has a very high Fe_2O_3 content (21.82%), potentially originating from the fermented animal blood incorporated into the compost used. Blood is used as a bioactivator for its high N; it also adds Fe, P, and K to the compost (Ginting, 2020).

The elevated levels of K_2O (21.50%) and Cl (1.28%) in LARF-II indicate the nutrient-rich, saline nature of the composted organic matter. In addition to supplying essential nutrients, the agronomic advantages are clear. LARF-I, which contains higher levels of Ca, P, S, and micronutrients, effectively enhances soil structure, promotes sustained fertility, and elevates micronutrient levels. On the other hand, LARF-II, with increased concentrations of Si, K, and Fe, improves stress tolerance and boosts photosynthetic efficiency. These variations in oxide content demonstrate how these formulations complement each other, each tailored for specific crop and soil management objectives.

The effect of LARF application on surface charge and macronutrients in Inceptisols

The LARF application was found to affect soil surface charge, thereby contributing to soil improvement. These effects, under monoculture and polyculture, are shown in Table 3. LARF-I showed the most significant changes in pH H_2O, EC, %OM, and CEC, significantly outperforming the control and CF. In monoculture, LARF-I reached pH H_2O of 5.60, EC of 0.54 dS m^{-1}, %OM of 32.10%, and CEC of 58.11 cmol kg^{-1}. Compared to the control (pH H_2O of 4.83, EC of 0.20 dS m^{-1}, %OM of 25.63%, and CEC of 48.17 cmol kg^{-1}), these figures represent increases, amounting to 15.94% (pH), 170% (EC), 25.24% (OM), and 20.46% (CEC), respectively. In polyculture, peaks were also observed in LARF-I, with pH H_2O of 5.63, EC of 0.48 dS m^{-1}, %OM of 24.63%, and CEC of 57.75 cmol kg^{-1}. Compared to the control (pH H_2O of 4.57, EC of 0.25 dS m^{-1}, %OM of 18.93%, and CEC of 40.80 cmol kg^{-1}), these figures correspond to increases of 23.19%, 92%, 30.11%, and 41.54%, respectively.

Compared with CF, LARF-I also showed higher values across both cropping systems. In monoculture, the pH H_2O, EC, and %OM increased by 14.99%, 157.14%, and 10.96%, respectively, compared to CF (pH H_2O of 4.87, EC of 0.21 dS m^{-1}, and %OM of 28.93%). In polyculture, LARF-I exceeded CF (pH H_2O 4.93, EC 0.30 dS m^{-1}, %OM 21.10%, and CEC 45.91 cmol kg^{-1}), representing increases by 14.20%, 60%, 16.73%, and 25.79%, respectively. Increases in soil pH, EC, and %OM directly increased negative charge, as indicated by an increase in soil CEC (Herviyanti et al., 2024c).

Tropical Inceptisols exhibit variable charges dominated by positive sites at low pH (< 5.0), limiting cation retention due to H^+ and Al^{3+} dominance on clay and low-OM colloids. BB in LARF-I supplied alkaline ash with 5.00–9.34% $CaCO_3$ (Herviyanti et al., 2022) and oxides that neutralize H^+ ions, raising pH and releasing base cations (Ca^{2+}, Mg^{2+}, and K^+) into the soil solution. This process subsequently increased EC and CEC by enhancing the negative surface charge on clay and OM colloids. Synergy with CM amplified this through ammoniacal nitrogen mineralization ($NH_4^+ \rightarrow OH^- + NO_3^-$) (Zhang et al., 2023), adding OM with carboxyl and phenolic groups that bind cations, thereby boosting CEC by 20–40%. These results align with those of Sajar et al. (2024) and Fauzan et al. (2025) regarding BB and CM combinations. Such results differ from single biochar applications at higher doses, such as 40 tons ha^{-1}, which show the highest increase in soil surface charge (Darfis et al., 2023).

Table 3. Changes in surface charge in Inceptisols ameliorated with LARFs in monoculture and polyculture cultivation systems

Treatment	pH (1:1)			EC	Composition		CEC
	H_2O	1 M KCl	PZC		Mineral	OM	
	unit			dS m^{-1}	%		cmol kg^{-1}
Monoculture							
Control	4.83[c]	4.37[c]	4.60	0.20[c]	74.37[a]	25.63[c]	48.17[b]
LARF-I	5.60[a]	5.17[a]	5.40	0.54[a]	67.90[c]	32.10[a]	58.11[a]
LARF-II	5.33[b]	5.03[ab]	5.20	0.38[b]	69.40[b]	30.60[ab]	56.66[a]
Conventional farming	4.87[c]	4.73[b]	4.80	0.21[c]	71.07[b]	28.93[b]	54.76[a]
MAR	5.23[b]	4.90[ab]	5.10	0.29[bc]	69.60[c]	30.40[ab]	56.12[a]
CV	2.42	3.54	8.01	17.58	1.91	4.55	3.73
Duncan's test	**	**	ns	**	**	**	**
SE	0.1	0.14	0.29	0.05	1.1	1.1	1.67
Polyculture							
Control	4.57[c]	4.47[c]	4.37	0.25[b]	81.07[a]	18.93[c]	40.80[c]
LARF-I	5.63[a]	4.93[b]	4.23	0.48[a]	75.37[c]	24.63[a]	57.75[a]
LARF-II	5.43[a]	5.30[a]	5.17	0.41[a]	76.03[c]	23.97[a]	52.16[ab]
Conventional farming	4.93[b]	4.70[b]	4.47	0.30[b]	78.90[ab]	21.10[b]	45.91[b]
MAR	5.07[b]	4.70[b]	4.33	0.32[b]	77.80[b]	22.20[ab]	48.19[b]
CV	3.54	4.03	11.36	11.71	1.90	6.67	7.50
Duncan's test	**	**	ns	**	**	**	**
SE	0.15	0.16	0.42	0.03	1.21	1.21	2.99

Note: Numbers in the same column followed by the same lowercase letter are not significantly (ns) different according to Duncan's test at the 5% (*) and 1% (**) levels. BB = Bamboo biochar; TGF = *Tithonia* green fertilizer; CM = Chicken manure; CA = Agam compost; MAR = Ministry of Agriculture recommendations; PZC = Point of zero charge; EC = Electrical conductivity; OM = Organic matter; CEC = Cation exchange capacity; CV = Coefficient of variance; SE = Standard error; n = 15 samples per experiment

Additionally, as shown in Figure 2, LARF-I had a higher ash content, which would support increased soil base cations and thereby alter soil EC. Because of biochar's alkalinity and $CaCO_3$ content, weakly bound nutrients were released into the soil solution, which increased the soil pH, EC, and CEC (Chintala et al., 2014; Piash et al., 2016). Negative charge shift improves nutrient availability, supports macronutrient uptake, and enhances horticultural yields.

When the increases in soil surface charge in the polyculture and monoculture plots were compared, most monoculture plots showed greater changes than the polyculture plots. As stated in the methods section regarding the bed arrangement history, monoculture plots had a history of previous LARF applications, which contained BB, TGF, CM, and CA. In contrast, polyculture plots had a history of prior control, CF, and MAR applications, which involved no treatments other than CM. It may be that the effects of previous applications of ameliorants, which partly remained in the monoculture system, were retained in the current planting period. According to Mon et al. (2024b), the effect of combining biochar with organic fertilizers, such as chicken manure, persists after 1 year of application. There were increases of approximately 2.6% and 5.9% in pH in low-fertility soils, followed by significant rises in soil EC in medium- and low-fertility soils.

Changes in the main macronutrients of soils ameliorated by LARFs are shown in Figure 3. LARF-II produced the highest OC and total N values, while LARF-I excelled in available P and exchangeable K, all being significant compared to the control. In the control, the OC, total N, available P, and exchangeable K were 1.53%, 0.24%, 48.89 ppm, and 0.82 cmol(+) kg^{-1} under monoculture, and 1.65%, 0.57%, 57.41 ppm, and 0.61 cmol(+) kg^{-1} under polyculture, respectively. LARF-II increased OC to 3.25% in monoculture (+112.42%) and 3.16% in polyculture (+91.52%), while total N reached 1.30% (+441.17%) and 0.78% (+36.84%) under monoculture and polyculture, respectively. In contrast, LARF-I achieved the highest available P and exchangeable K, reaching 209.43 ppm (+328.37%) and 1.31 cmol(+) kg^{-1} (+59.76%) under monoculture, and 127.38 ppm (+121.88%) and 1.09 cmol(+) kg^{-1} (+78.69%) under polyculture, compared to the control.

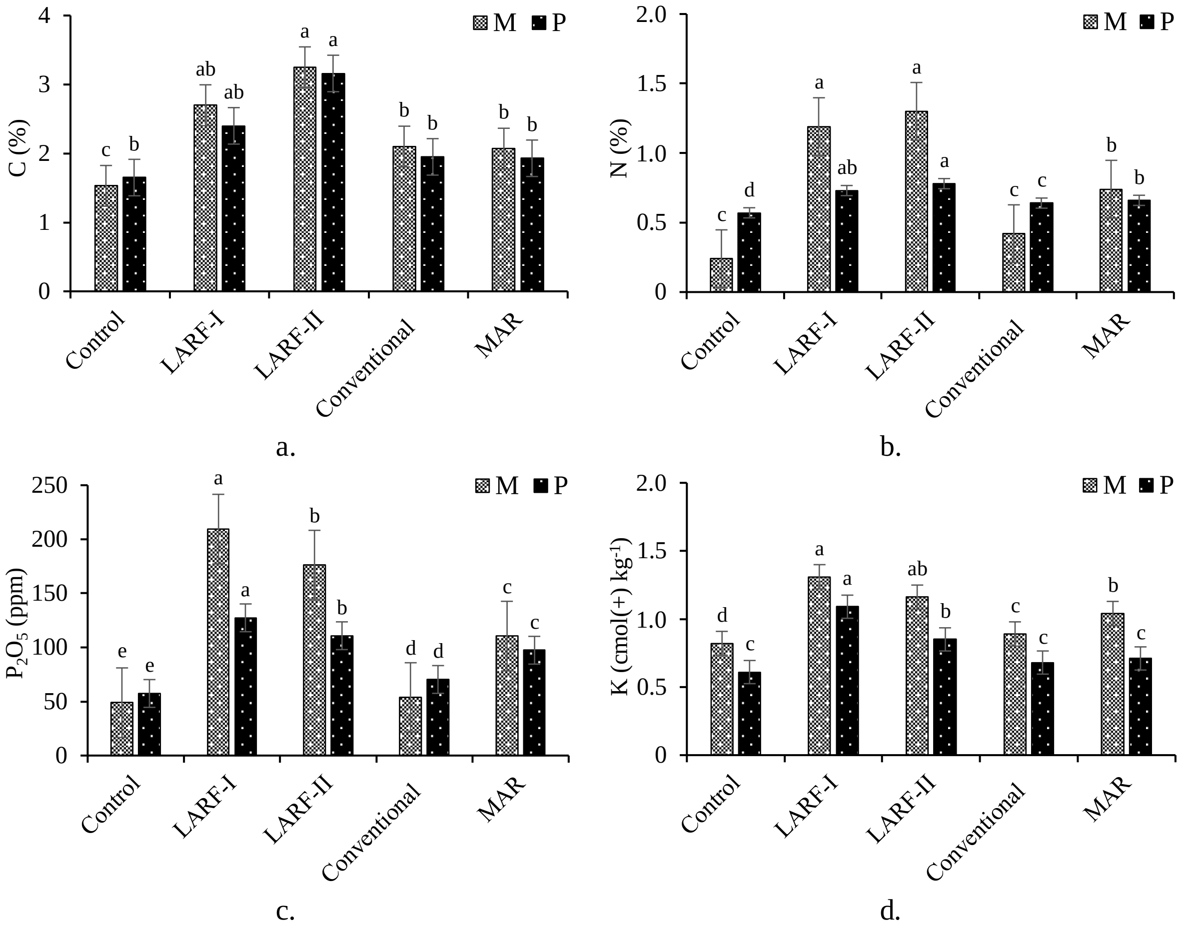

Figure 3. Main macronutrients, organic C (a), total N (b), available P (c), and exchangeable K (d) in Inceptisols ameliorated with LARFs in monoculture (M) and polyculture (P) cultivation systems

Note: Bars with the same lowercase letter are not significantly (ns) different according to Duncan's test at the 5% (*) and 1% (**) levels

The increase in soil surface charge (Table 3) raised the availability of macronutrients. These improvements stemmed from the distinct nutrient profiles of the components of the organic ameliorants. For example, CA consisted of rabbit manure fermented with its urine, with high levels of OC and total N. Prajanti et al. (2023) found that rabbit urine had the highest percentage of OC (79.54%) and total N (1.89%), followed by rabbit manure (64.33% OC and 1.47% total N), compared with goat manure (50.98% OC and 1.44% total N) and topsoil (45.98% OC and 1.29% total N). According to the study by Li et al. (2022), when rabbit manure is composted, N, P, and K increase from their initial levels (the largest increase of 18.4% was recorded).

Incorporating biochar in the formulation will help retain these nutrients and increase their availability. This mirrors the findings of Widowati et al. (2024), who reported that biochar application at 45 tons ha^{-1} increased N, P, and K availability by 23–70%, 75–451%, and 36–421%, respectively. Another study by Mon et al. (2024a) found that differences in the manures applied affected the nutrients added to the soil, even though the same amounts of ameliorants and fertilizers were used across all treatments. CA and CM have different high-nutrient levels depending on their origins, with the former often higher in C and N. At the same time, the latter is richer in P and K (Ksheem et al., 2015). These nutrients will remain available longer in the soil when biochar is included in the formula, as biochar becomes more porous over time, increasing its surface area (Mon et al., 2024b).

Chemically, it may increase the surface functional groups (e.g., hydroxyl, carboxyl, and phenolic) that trap nutrients, thereby prolonging their retention. Confirmed by Ouyang et al. (2024), biochar's surface retains nutrients through functional groups such as O–H (~3.407 cm^{-1}, carboxyl/phenolic hydroxyl), C–H (~2.885 cm^{-1}, aliphatic), and C=O/C=C (~1,710 cm^{-1}), primarily via electrostatic attraction. When the ζ-potential drops significantly between pH 3 and 5, it facilitates the retention of NH_4^+, K^+, and P complexes, along with π–π interactions. This is evidenced by shifts in FT-IR C peaks from 1.575 to 1.598 cm^{-1} and changes in XPS C–O binding energies from 286.58 to 286.35–286.45 eV, which collectively reduce leaching in this acidic range. Consequently, incorporating TGF, CA, or CM into the biochar formulation effectively decreases nutrient leaching and extends nutrient availability for plants.

The effect of LARFs on nutrient uptake and yields

Nutrient uptake by crops in soil ameliorated with LARF under monoculture (string beans) and polyculture (broccoli, lettuce) systems is shown in Table 4. The LARF-I application demonstrated the highest increases in N, P, and K across all crops, significantly outperforming the control. In string beans, LARF-I increased N to 5.93% (control: 4.11%; +44.28%), P to 0.027% (control: 0.010%; +170%), and K to 0.37% (control: 0.28%; +32.14%). In broccoli, N, P, and K reached 8.87% (control: 6.30%; +40.79%), 0.104% (control: 0.053%; +96.23%), and 1.02% (control: 0.70%; +45.71%), respectively.

Similarly, in lettuce, LARF-I increased N to 6.16% (control: 3.92%; +57.14%), P to 0.085% (control: 0.034%; +150%), and K to 0.80% (control: 0.51%; +56.86%). Most of these effects were nearly identical to LARF-II. In string beans, LARF-II resulted in increases in N to 5.41%, P to 0.020%, and K to 0.34%, corresponding to increases of +31.63%, +100%, and +21.43%, respectively, compared to the control. In broccoli, LARF-II increased N, P, and K to 8.40%, 0.087%, 0.95%, representing increases of +33.33%, +64.15%, and +35.71%, respectively. In lettuce, nutrient concentrations reached 5.51% N, 0.063% P, 0.78% K, corresponding to increases of 40.56% N, 85.29% P, and 52.94% K, compared with the control.

Improvements in soil surface charge and macronutrient availability affected nutrient uptake by crops. The combined application of BB, TGF, and CM (LARF-I) significantly enhanced the uptake of N, P, and K by string beans, broccoli, and lettuce, compared to the control. Among the three crops, lettuce showed the greatest increases in nutrient uptake, with 57.14% N, 150% P, and 56.86% K, followed by string beans and broccoli. These improvements were observed consistently in both monoculture and polyculture farming systems, demonstrating the broad effectiveness of LARF-I resulted from the synergistic action of the ameliorant components: chicken manure provides abundant readily available N, P, and K; TGF offers quick-decomposing organic matter rich in macronutrients; and bamboo biochar, though relatively low in nutrients by itself, helps reduce nutrient loss with its porous structure and high surface area enhance CEC and facilitate the absorption and retention of essential nutrients such as ammonium, potassium, and phosphate ions in the root zone, thereby increasing their availability to crops over time.

Although BB has a different nutrient profile from manure-based biochar, it still enhances

Table 4. Nutrients of crops in monoculture and polyculture cultivation systems on Inceptisols ameliorated with local ameliorant resource formulations

Treatment	Monoculture			Polyculture					
	String beans			Broccoli			Lettuce		
	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)	N (%)	P (%)	K (%)
Control	4.11^{c}	0.010^{c}	0.28^{d}	6.30^{c}	0.053^{d}	0.70^{c}	3.92^{c}	0.034^{b}	0.51^{c}
LARF-I	5.93^{a}	0.027^{a}	0.37^{a}	8.87^{a}	0.104^{a}	1.02^{a}	6.16^{a}	0.085^{a}	0.80^{a}
LARF-II	5.41^{ab}	0.020^{ab}	0.34^{b}	8.40^{ab}	0.087^{b}	0.95^{ab}	5.51^{ab}	0.063^{ab}	0.78^{ab}
Conventional farming	4.76^{c}	0.013^{b}	0.30^{c}	7.84^{b}	0.073^{c}	0.81^{b}	4.76^{b}	0.036^{b}	0.64^{bc}
MAR	4.57^{b}	0.014^{b}	0.31^{c}	8.03^{b}	0.080^{b}	0.85^{b}	5.27^{b}	0.041^{b}	0.73^{ab}
CV	7.46	31.99	3.27	5.50	8.34	9.51	7.90	29.98	11.05
Duncan's test	**	*	**	**	**	**	**	*	**
SE	0.300	0.004	0.010	0.540	0.010	0.070	0.330	0.010	0.060

Note: Numbers in the same column followed by the same lowercase letter are not significantly (ns) different according to Duncan's test at the 5% (*) and 1% (**) levels. BB = Bamboo biochar; TGF = *Tithonia* green fertilizer; CM = Chicken manure; CA = Agam compost; MAR = Ministry of Agriculture recommendations; CV = Coefficient of variance; SE = Standard error; n = 15 samples per experiment fertilizer usage efficiency. This aligns with the findings of Piash et al. (2025), who reported that biochar retained up to 76.4% nitrogen from the original material, a figure much higher than that retained by hydrochar (37.4%) and compost (36.2%). It showed that biochar can retain nutrients. Although bamboo biochar may not directly supply high nutrient levels, it likely supports nutrient conservation and gradual release when combined with nutrient-rich organic amendments such as *Tithonia* and chicken manure. The significant rise in P uptake under LARF-I is also attributed to its higher P_2O_5 content (as shown in Figure 2), which increases the available P in the soil.

In line with Zhang et al. (2024), applying green manure and biochar, either individually or in combination, boosts N, P, and K uptake by 18 to 60% in continuous cropping systems. This improvement mainly results from increased soil nutrient availability and more effective alignment with plant growth requirements. In summary, LARF-I shows strong potential to enhance soil fertility and crop yields by combining fast-release nutrients, high nutrient retention, and organic matter inputs, which support both immediate crop nutrition and long-term soil health, offering a sustainable alternative to conventional fertilization.

The crop yields shown in Figure 4 demonstrate that both LARF treatments significantly increased the productivity of string beans, broccoli, and lettuce compared to the control. LARF-II consistently showed the highest yields: string beans, 20.10 kg plot^{-1} (control: 15.07 kg plot^{-1}; +33.38%); broccoli, 11 kg plot^{-1} (control: 6.33 kg plot^{-1}; +73.78%); and lettuce, 3.60 kg plot^{-1} (control: 2.12 kg plot^{-1}; +69.81%). In comparison, LARF-I achieved 19.37 kg string beans plot^{-1} (+28.53%), 10.47 kg broccoli plot^{-1} (+65.40%), and 3.03 kg lettuce plot^{-1} (+42.92%). Both LARF treatments also achieved higher yields than conventional farming (CF: 15.40 kg of string beans, 8.13 kg of broccoli, and 2.51 kg of lettuce per plot). LARF-II increased productivity by +30.52%, +35.30%, and +43.43% for each crop, while LARF-I improved yields by +25.78%, +28.78%, and +20.72% for string beans, broccoli, and lettuce, respectively.

The enhancement in surface charge and macronutrient availability boosts crop yields. Soil provides the nutrients the crop needs, promotes better growth, and increases yields. Combining Nagari local resources such as biochar, *Tithonia* green fertilizer, compost, and chicken manure increases crop productivity, with the highest productivity in LAFR-II, followed by LARF I. The improved performance of LARF-II results from its balanced composition, which boosts both surface charge and nutrient availability. Situmeang et al. (2018) reported that combining biochar with compost significantly boosted corn yields, achieving a high relative agronomic efficiency (RAE 119.69%) and a strong economic return (IBCR 1.27).

Similarly, Rassem and Elzobair (2024) reported that applying biochar and chicken manure to sandy soils increase about 62 to 64% in pea yield. The synergistic interaction between these components explains the positive effects:

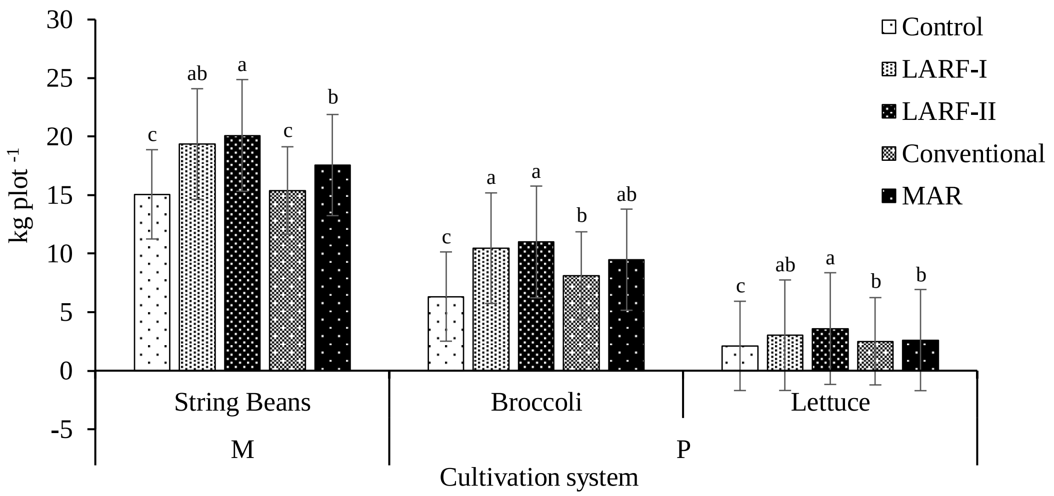

Figure 4. Crop yields in monoculture (M) and polyculture (P) systems on Inceptisols ameliorated with LARFs

Note: Bars sharing the same lowercase letter are not significantly (ns) different based on Duncan's test at the 5% (*) and 1% (**) levels biochar improves soil structure, water retention, and nutrient-holding capacity, while TGF, which decomposes quickly, fixes nitrogen effectively, and promotes rapid biomass growth. These effects are further supported by compost and chicken manure, which supply readily available nutrients and stimulate microbial activity. Together, all of these advantages boost root development and nutrient uptake, leading to higher biomass and yields. Finally, integrated organic amendments, such as LARF-II, offer a promising approach to sustainably increase crop productivity, particularly in nutrient-deficient and low-fertility soils.

CONCLUSIONS

This study demonstrates that LARFs notably improve soil surface charge and macronutrient availability in Inceptisols. LARF-I raised pH H_2O (16 to 23%), EC (92 to 170%), %OM (25 to 30%), CEC (20 to 42%), available P (122–328%), and exchangeable K (60–79%) compared to the control. Meanwhile, LARF-II performed better in OC (91–112%) and total N (37–441%). These improvements boosted nutrient uptake (up to +170% N, P, K) and yields (LARF-II: +33% string bean, +74% broccoli, +70% lettuce compared to the control; 31 to 43% above CF). This integration provides cost-effective fertility management for tropical smallholder horticulture, balancing short-term nutritional needs with long-term soil health. Scaling via farmer training and subsidies could restore Sumatra's degraded soils. Future long-term trials and tailored LARF selection are recommended.

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DECLARATION OF GENERATIVE AI USE

The authors used Perplexity.ai as an AI-assisted tool to improve the text's readability and language quality and to address reviewer comments during manuscript revision. All suggestions generated by the tool were carefully reviewed, edited, and validated by the authors. The authors take full responsibility for the accuracy and integrity of the manuscript.

REFERENCES

Agbede, T. M., & Oyewumi, A. (2022). Benefits of biochar, poultry manure, and biochar–poultry manure for improvement of soil properties and sweet potato productivity in degraded tropical agricultural soils. *Resources, Environment and Sustainability*, *7*, 100051. https://doi.org/10.1016/j.resenv.2022.100051

Almási, C., Veres, Z., Demeter, I., Orosz, V., Tóth, T., Mansour, M. M., ... & Makádi, M. (2025). From wastewater to soil amendment: A case study on sewage sludge composting and the agricultural application of the compost. *Water*, *17*(13), 2026. https://doi.org/10.3390/w17132026

Chang, H. C., Chou, P. Y., Cheng, M. P., Hsiao, T. H., Lo, K. Y., & Wang, S. L. (2022). Phosphorus conversion during anaerobic digestion of high-calcium chicken manures and phosphorus recovery as struvite. *Journal of Environmental Chemical Engineering*, *10*(3), 107615. https://doi.org/10.1016/j.jece.2022.107615

Chintala, R., Mollinedo, J., Schumacher, T. E., Malo, D. D., & Julson, J. L. (2014). Effect of biochar on chemical properties of acidic soil. *Archives of Agronomy and Soil Science*, *60*(3), 393–404. https://doi.org/10.1080/03650340.2013.789870

Darfis, I., Maulana, A., Prasetyo, T. B., Lita, A. L., & Herviyanti. (2023). Surface charge characteristics of Inceptisols ameliorated with biochar from young coconut waste. *International Conference on Sustainability Agriculture and Biosystem (ICSAB 2022)*, *1182*(1), 012034. https://doi.org/10.1088/1755-1315/1182/1/012034

Dayo-Olagbende, G. O., Ewulo, B. S., & Akingbola, O. O. (2019). Combined effects of tithonia mulch and urea fertilizer on soil physico-chemical properties and maize performance. *Journal of Sustainalble Technology (JoST)*, *10*(1), 86–93. Retrieved from https://www.researchgate.net/publication/335527891

El-Naggar, A., Jiang, W., Tang, R., Cai, Y., & Chang, S. X. (2024). Biochar and soil properties affect remediation of Zn contamination by biochar: A global meta-analysis. *Chemosphere*, *349*, 140983. https://doi.org/10.1016/j.chemosphere.2023.140983

Eviati, Sulaeman, Herawaty, L., Anggria, L., Usman, Tantika, H. E., Prihatini, R., & Wuningrum, P. (2023). *Petunjuk teknis analisis kimia tanah, tanaman, air, dan pupuk* (3rd ed.). Ministry of Agriculture of the Republic of Indonesia. Retrieved from https://repository.pertanian.go.id/server/api/core/bitstreams/77f52e6b-6a13-48bc-96d1-d6a35025d793/content

Fauzan, M. I., Tumanggor, J. A. E., Arafat, S., Safitri, D., Irawan, A. F., & Arini, D. I. D. (2025). Enhancing saline soil fertility through biochar and organic manure combinations: An incubation study. *Journal of Ecological Engineering*, *26*(9), 82–95. https://doi.org/10.12911/22998993/204560

Ginting, N. (2020). Utilization of blood meal, slaughterhouse waste and bio gas slurry into fertilizer. *Indonesian Journal of Agricultural Research*, *3*(2), 105–115. https://doi.org/10.32734/injar.v3i2.4267

Herviyanti, H., Maulana, A., Fathi, A. N. M., Monikasari, M., Kasim, M., Ryswaldi, R., ... & Refdi, C. W. (2024a). Effects of local resource-based ameliorant residues on chemical properties of Inceptisols and green bean production (*Phaseolus vulgaris* L.). *Malaysian Journal of Soil Science*, *28*, 105–116. Retrieved from https://www.msss.com.my/mjss/Full%20Text/vol28/V28_09.pdf

Herviyanti, H., Maulana, A., Fathi, A. N. M., Monikasari, M., Nursyam, E. A., Putri, A. M. I., ... & Refdi, C. W. (2024b). The residual of ameliorant formulation from local resources on chemical properties of Inceptisols and production of green bean (*Phaseolus vulgaris* L.). *IOP Conference Series: Earth and Environmental Science*, *1315*(1), 012035. https://doi.org/10.1088/1755-1315/1315/1/012035

Herviyanti, H., Maulana, A., Habazar, T., Noer, M., Lita, R. P., Refdi, C. W., ... & Monikasari, M. (2023a). Application of local resource-based amelioration technology on the chemical properties of Inceptisols in monoculture and polyculture cultivation systems. *IOP Conference Series: Earth and Environmental Science*, *1160*(1), 012025. https://doi.org/10.1088/1755-1315/1160/1/012025

Herviyanti, H., Maulana, A., Harianti, M., Lita, A. L., Prasetyo, T. B., Juwita, P., … & Yasin, S. (2024c). Effect of glyphosate contamination on surface charge change and nutrients of degraded Inceptisols ameliorated with sub-bituminous coal. *Journal of Degraded and Mining Lands Management*, *11*(2), 5135–5145. https://doi.org/10.15243/jdmlm.2024.112.5135

Herviyanti, H., Maulana, A., Lita, A. L., Prasetyo, T. B., & Ryswaldi, R. (2022). Characteristics of biochar methods from bamboo as ameliorant. *IOP Conference Series: Earth and Environmental Science*, *959*(1), 012036. https://doi.org/10.1088/1755-1315/959/1/012036

Herviyanti, H., Maulana, A., Monikasari, M., & Darfis, I. (2025b). Characteristics of Nagari organic fertilizer from biochar and closed-house chicken litter compost formulations based on local resource waste. *IOP Conference Series: Earth and Environmental Science*, *1571*(1), 012012. https://doi.org/10.1088/1755-1315/1571/1/012012

Herviyanti, H., Mutiara Fathi, A. N., Amalia, F., Guspita, A., Maulana, A., & Darfis, I. (2025a). Residual effect of local resources ameliorant formulation on surface charge change of Inceptisol in the second growing season. *IOP Conference Series: Earth and Environmental Science*, *1469*(1), 012032. https://doi.org/10.1088/1755-1315/1469/1/012032

Herviyanti, Maulana, A., Lita, A. L., Fathi, A. N. M., Monikasari, M., Amalia, F., ... & Refdi, C. W. (2023b). Approximate of C/N ratio for ameliorant formulations from local resources in horticultural production centers, Banuhampu Agam. *IOP Conference Series: Earth and Environmental Science*, *1182*(1), 012031. https://doi.org/10.1088/1755-1315/1182/1/012031

Hussain, R., Kumar, H., Bordoloi, S., Jaykumar, S., Salim, S., Garg, A., ... & Sreedeep, S. (2024). Effect of biochar type and amendment rates on soil physicochemical properties: Potential application in bioengineered structures. *Advances in Civil Engineering Materials*, *13*(1), 1–20. https://doi.org/10.1520/ACEM20200102

Ivanovski, M., Goricanec, D., Krope, J., & Urbancl, D. (2022). Torrefaction pretreatment of lignocellulosic biomass for sustainable solid biofuel production. *Energy*, *240*, 122483. https://doi.org/10.1016/j.energy.2021.122483

Khatun, M., Hossain, M., & Joardar, J. C. (2024). Quantifying the acceptance and adoption dynamics of biochar and co-biochar as a sustainable soil amendment. *Plant Science Today*, *11*(2), 307–317. https://doi.org/10.14719/pst.3242

Ksheem, A. M., Bennett, J. M. L., Antille, D. L., & Raine, S. R. (2015). Towards a method for optimized extraction of soluble nutrients from fresh and composted chicken manures. *Waste Management*, *45*, 76–90. https://doi.org/10.1016/j.wasman.2015.02.011

Li, R., Hao, H., Sun, H., Wang, L., & Wang, H. (2022). Composted rabbit manure as organic matrix for manufacturing horticultural growing media: Composting process and seedling effects. *Sustainability*, *14*(9) 5146. https://doi.org/10.3390/su14095146

Lubis, K. S., & Mukhlis. (2025). Soil quality evaluation of Inceptisol based on the alberta card (Case study of horticultural land in Titi Papan, Medan Deli District). *Jurnal Online Pertanian Tropik*, *12*(03), 20–026. https://doi.org/10.32734/jpt.v12i3.22370

Lucchetta, M., Romano, A., Alzate Zuluaga, M. Y., Fornasier, F., Monterisi, S., Pii, Y., ... & Gaiotti, F. (2023). Compost application boosts soil restoration in highly disturbed hillslope vineyard. *Frontiers in Plant Science*, *14*, 1289288. https://doi.org/10.3389/fpls.2023.1289288

Ma, R., Yu, N., Zhao, S., Kou, T., & Jiao, N. (2025). Effects of long-term maize/peanut intercropping and phosphorus application on soil surface electrochemical properties and crop yield. *Frontiers in Agronomy*, *7*, 1535871. https://doi.org/10.3389/fagro.2025.1535871

Manea, E. E., Bumbac, C., Dinu, L. R., Bumbac, M., & Nicolescu, C. M. (2024). Composting as a sustainable solution for organic solid waste management: Current practices and potential improvements. *Sustainability*, *16*(15), 6329. https://doi.org/10.3390/su16156329

Minkina, T., Sushkova, S., Delegan, Y., Bren, A., Mazanko, M., Kocharovskaya, Y., ... & Ranjan, A. (2023). Effect of chicken manure on soil microbial community diversity in poultry keeping areas. *Environmental Geochemistry and Health*, *45*(12), 9303–9319. https://doi.org/10.1007/s10653-022-01447-x

Mon, W. W., Toma, Y., & Ueno, H. (2024a). Combined effects of rice husk biochar and organic manures on soil chemical properties and greenhouse gas emissions from two different paddy soils. *Soil Systems*, *8*(1), 32. https://doi.org/10.3390/soilsystems8010032

Mon, W. W., Toma, Y., & Ueno, H. (2024b). Residual effects of rice husk biochar and organic manure application after 1 year on soil chemical properties, rice yield, and greenhouse gas emissions from paddy soils. *Soil Systems*, *8*(3), 91. https://doi.org/10.3390/soilsystems8030091

Moreira, B., Gonçalves, A., Pinto, L., Prieto, M. A., Carocho, M., Caleja, C., & Barros, L. (2024). Intercropping systems: An opportunity for environment conservation within nut production. *Agriculture*, *14*(7), 1149. https://doi.org/10.3390/agriculture14071149

Mujtaba, G., Hayat, R., Hussain, Q., & Ahmed, M. (2021). Physio-chemical characterization of biochar, compost and co-composted biochar derived from green waste. *Sustainability (Switzerland)*, *13*(9), 4628. https://doi.org/10.3390/su13094628

Obaisi, A. I., Adegbeye, M. J., Meléndez, J. H., de Jesús, J. A. C., Velarde, E. D. A., & Mariezcurrena-Berasain, M. A. (2024). Management of natural resource and sustainable agriculture. *Handbook of Climate Change Mitigation and Adaptation* (pp. 1–41). Springer New York. https://doi.org/10.1007/978-1-4614-6431-0_133-2

Ouyang, E., Zhang, R., Fu, W. J., Zhao, R., Yang, H., Xiang, H., & He, W. (2024). Facile synthesis of bamboo biochar for efficient adsorption of quinolone antibiotics: Effects and mechanisms. *ACS Omega*, *9*(49), 48618–48628. https://doi.org/10.1021/acsomega.4c07479

Piash, M. I., Hossain, Md. F., & Parveen, Z. (2016). Physico-chemical properties and nutrient content of some slow pyrolysis biochars produced from different feedstocks. *Bangladesh Journal of Science*, *29*(2), 111–122. https://doi.org/10.3329/bjsr.v29i2.32327

Piash, M. I., Itoh, T., Abe, K., & Iwabuchi, K. (2025). Superior nutrient recovery and release by chicken manure-derived biochar over hydrochar and compost for soil fertilization. *Geoderma Regional*, *40*, e00906. https://doi.org/10.1016/j.geodrs.2024.e00906

Prajanti, S. D. W., Litaay, C., Widiatningrum, T., Amelia, D. R., & Daud, D. (2023). Application of rabbit urine and manure based fertilizer on the growth of arabica and robusta coffee seedlings. *Biosaintifika*, *15*(3), 441–449. https://doi.org/10.15294/biosaintifika.v15i3.48027

Prasetyo, T. B., Maulana, A., Monikasari, M., Andestopano, A., Darfis, I., Pratama, I., ... & Herviyanti, H. (2024). Chemical characteristics of chicken litter waste in closed-house system. *International Journal on Advanced Science Engineering Information Technology*, *14*(3), 1026–1034. https://doi.org/10.18517/ijaseit.14.3.19700

Rahmayuni, E., Anwar, S., Nugroho, B., & Indriyati, L. T. (2023). Characteristics of soil chemical properties associated with Inceptisols in various land use in Jasinga, Bogor. *Journal of Tropical Soils*, *28*(3), 89–97. https://doi.org/10.5400/jts.2023.v28i3.89-97

Ramírez-García, A. G. (2019). Ethnoagronomy and sustainable community development. *Indian Journal of Science and Technology*, *12*(14), 1–8. https://doi.org/10.17485/ijst/2019/v12i14/121168

Rassem, A. M., & Elzobair, K. A. (2024). The effects of biochar and chicken manure on the growth and yield of pea in sandy soil. *Bani Waleed University Journal of Humanities and Applied Sciences*, *9*(5), 360–367. https://doi.org/https://doi.org/10.58916/jhas.v9i5

Richa, Kumar, V., Singh, J., & Sharma, N. (2020). Poultry manure and poultry waste management: A review. *International Journal of Current Microbiology and Applied Sciences*, *9*(6), 3483–3495. https://doi.org/10.20546/ijcmas.2020.906.410

Rizwan, M., & Harahap, F. S. (2021). Provision of urea fertilizer and chicken manure on chemical characteristics of Inceptisol soil in Pangkatan District. *Jurnal Pertanian Tropik*, *8*(3), 215–221. https://doi.org/10.32734/jopt.v8i3.8226

Saeed, A. A. H., Harun, N. Y., & Nasef, M. M. (2019). Physicochemical characterization of different agricultural residues in Malaysia for bio char production. *International Journal of Civil Engineering and Technology (IJCIET)*, *10*(10), 213–225. Retrieved from https://iaeme.com/Home/article_id/IJCIET_10_10_023

Sajar, S., Setiawan, A., & Tri Anzani, A. (2024). Effect of various biochar materials and levels of chicken manure fertilizer on soil chemical, growth and yield of soybean (*Glycine max* L Merrill). *International Journal of Research and Review*, *11*(8), 279–293. https://doi.org/10.52403/ijrr.20240830

Sarwari, A., Abdieva, G. Zh., Hassand, M. H., Mohammad, U. K., & Niazi, P. (2024). Role of microbial communities in compost and plant growth: Structure and function. *European Journal of Theoretical and Applied Sciences*, *2*(2), 23–37. https://doi.org/10.59324/ejtas.2024.2(2).03

Shyam, S., Ahmed, S., Joshi, S. J., & Sarma, H. (2025). Biochar as a soil amendment: Implications for soil health, carbon sequestration, and climate resilience. *Discover Soil*, *2*(1), 18. https://doi.org/10.1007/s44378-025-00041-8

Singh, B., Camps-Arbestain, M., & Lehmann, J. (2017). *Biochar: A guide to analytical methods*. CSIRO Publishing. Retrieved from https://books.google.co.id/books?hl=id&lr=&id=ieRrDgAAQBAJ&oi=fnd&pg=PP1&dq=Biochar%E2%80%AF:+a+guide+to+analytical+methods&ots=zDDP_l_AB2&sig=SeoV9WE3V6f6YZqMzbCv42TNCX8&redir_esc=y#v=onepage&q=Biochar%E2%80%AF%3A%20a%20guide%20to%20analytical%20methods&f=false

Situmeang, Y. P., Adnyana, I. M., Subadiyasa, I. N. N., & Merit, I. N. (2018). Effectiveness of bamboo biochar combined with compost and NPK fertilizer to improved soil quality and corn yield. *International Journal on Advanced Science, Engineering and Information Technology*, *8*(5), 2241–2248. https://doi.org/10.18517/ijaseit.8.5.2179

Song, J., Zhang, H., Kumar, A., Chang, F., Yu, R., Zhang, X., ... & Li, Y. (2025). Combined organic ameliorants is benefits for improving ecosystem multi-functionality in saline soils. *Industrial Crops and Products*, *230*, 121068. https://doi.org/10.1016/j.indcrop.2025.121068

Sparta, A., Hamdani, S., Yuwariah, Y., & Wulandari, E. (2025). The role of *Tithonia diversifolia* in sustaining crop productivity in acid soils. *Bulgarian Journal of Agricultural*

Science, *31*(1), 50–60. Retrieved from https://www.agrojournal.org/31/01-07.pdf

Suvendran, S., Acevedo, M. F., Smithers, B., Walker, S. J., & Xu, P. (2025). Soil fertility and plant growth enhancement through compost treatments under varied irrigation conditions. *Agriculture*, *15*(7), 734. https://doi.org/10.3390/agriculture15070734

Veettil, A. V., Rahman, A., Awal, R., Fares, A., Melaku, N. D., Thapa, B., … & Woldesenbet, S. (2024). Transforming soil: Climate-smart amendments boost soil physical and hydrological properties. *Soil Systems*, *8*(4), 134. https://doi.org/10.3390/soilsystems8040134

Vikas, & Ranjan, R. (2024). Agroecological approaches to sustainable development. *Frontiers in Sustainable Food Systems*, *8*, 1405409. https://doi.org/10.3389/fsufs.2024.1405409

Widowati, Wilujeng, R., Nurhidayati, & Indrayatie, E. R. (2024). Improvement of N, P, and K availability of post-brick mining soil to increase maize yield by applying different types of biochar. *Journal of Degraded and Mining Lands Management*, *11*(2), 5319–5327. https://doi.org/10.15243/jdmlm.2024.112.5319

Zhang, H., Zhang, X., Chen, M., Deng, X., Pei, Y., Zhang, J., ... & Yang, S. (2023). Biochar can improve absorption of nitrogen in chicken manure by black soldier fly. *Life*, *13*(4), 938. https://doi.org/10.3390/life13040938

Zhang, M., Liu, Y., Gu, X., Wei, Q., Liu, L., & Gou, J. (2024). Green manure rotation combined with biochar application improves yield and economic stability of continuous cropping of peppers in southwest China. *Plants*, *13*(23), 3387. https://doi.org/10.3390/plants13233387

Zhang, M., & Zhang, B. (2025). Policymaking issues: Sustainable management of natural resources. *Management of Natural Resources - Relevance, Issues and Constraints [Working Title]* (pp. 1–19). Intechopen. http://doi.org/10.5772/intechopen.1008943

Zu’amah, H., Handayani, C. O., Dewi, T., Arianti, F. D., Beti, J. A., Jufri, A., ... & Syamsiyah, J. (2025). The potential of biochar and compost from sugarcane bagasse on growth, yield, nutrient uptake of shallot, and properties of an Inceptisol. *Journal of Degraded and Mining Lands Management*, *12*(3), 7559–7569. https://doi.org/10.15243/jdmlm.2025.123.7559