EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(3), 95–110
https://doi.org/10.12912/27197050/199535
ISSN 2719–7050, License CC-BY 4.0

Received: 2024.12.20
Accepted: 2025.01.21
Published: 2025.02.01

Optimizing biochar application: Impact on soil chemical properties in spodosols and ultisols

Wahjuni Hartati[1*], Stella Serlyani[1], Syahrinudin[1], Triyono Sudarmadji[2]

[1] Silviculture Laboratory, Faculty of Forestry, Mulawarman University, Jl. Penajam Kampus Gunung Kelua, Samarinda, East Kalimantan, Indonesia
[2] Soil, Water Conservation and Climate Laboratory, Faculty of Forestry, Mulawarman University, Jl. Penajam Kampus Gunung Kelua, Samarinda, East Kalimantan, Indonesia
* Corresponding author's e-mail: wahjunihartati@fahutan.unmul.ac.id

ABSTRACT

This study examined the impact of biochar concentration variability and soaking duration in LOF on the chemical properties of Spodosols and ultisols. The biochar was applied at percentages of 0, 2, 5, 10, 20, 25, and 100%, with soaking times of 0, 1, 12, and 24 hours. The results indicated significant improvements in the soil pH, organic carbon, total nitrogen, phosphorus, potassium, and cation exchange capacity in both soil types. Applying biochar at the 100% application rate resulted in the most significant improvement in the soil chemical properties, but the application rate of 10–25% was optimal for agricultural soils, indicating economic feasibility and increased sustainability. The optimal dosage and soaking time varied for Spodosols; a 12-hour soaking period was best for pH improvement, whereas 24 hours maximized organic carbon and total nitrogen. In the ultisols, no soaking was necessary for the optimal pH, whereas 1 hour was ideal for organic carbon and total nitrogen. Available phosphorus and potassium were maximized at 24 hours for both soils. In the case of CEC, it was best improved, with 12 hours for Spodosols and 24 hours for ultisols. Thus, the results of this work demonstrated the effectiveness of individually selected biochar treatments for improving the soil pH, structure, and fertility, which is crucial for the sustainable use of soil in agriculture. Further studies should help confirm these results in long-term field tests and evaluate their economic feasibility for extensive applications.

Keywords: biochar, liquid organic fertilizer, soil chemical properties, spodosols, ultisol.

INTRODUCTION

Ultisols and spodosols can be problematic for crop planting and growth because of their inherent properties. Ultisols are primarily associated with low pH, low nutrient availability, high Al toxicity, and low cation exchange capacity. On the other hand, Spodosols are characterized by low soil pH, low nutrient values, and poor water-holding capacity. These properties reduce plant growth and agricultural yields in areas where these soils dominate.

The above-discussed studies have sought to overcome these soil limitations in different ways. Past practices, which include liming and the application of heavy fertilizers, have discouraged the achievement of low yields, high costs, or negative impacts on the natural environment. Consequently, more recent studies have focused on organic amendments; however, the use of organic amendments poses some challenges since no single solution can satisfy all the conditions of ultisols and spodosols.

In the search for improved and efficient methods of soil management, two of the potential options that have been hailed are biochar and liquid organic fertilizers. Biochar, produced through the pyrolytic conversion of organic compost, has demonstrated enhancements in both the physical and chemical characteristics of soil, including the cation exchange capacity (CEC), the concentration of organic carbon, and the soil's ability to modulate its pH levels (Singh et al., 2022). The research has demonstrated considerable potential for enhancing the accessibility of essential nutrients, particularly phosphorus; consequently, it is likely applicable to various soil classifications, including ultisols and Spodosols (Fernandes et al., 2018). However, the positive influence of biochar can change depending on the dose and type of soil in which it is used (Li et al., 2021).

Similarly, liquid organic fertilizers, particularly those produced from pineapple waste, have a constructive impact on the fertility of the soil, as well as the growth of plants (Sutikarini et al., 2023). These fertilizers can impact such chemical modifications of soil by increasing plant nutrient acquisition, thus changing the physical properties of the soil as well as the biomass and yield traits (Kaya et al., 2022). Research has shown that liquid fertilizers, specifically organic fertilizers, can improve the soil's biochemical and microbial status, which is good for the soil's overall health (Wu et al., 2020).

New studies have revealed that biochar and liquid organic fertilizers are favorable for individual plants. In accordance with earlier studies, the study by Gu et al. (2022) indicated that the effects of biochar use on the reaction of the soil increased, as did the water-holding capacity and rate of diffusion of nutrients in the rhizosphere. In the study by Lévesque et al. (2022), the effects of biochar on the number of nutritional microorganisms and bacterial diversity of growing media were noted. According to Zhivanov et al. (2020), the authors claimed that applying biochar remarkably improved phosphorus solubility. Concerning liquid organic fertilizers, Arthagama et al. (2021) reported changes in the chemical properties of growing media, plant growth, and physiological perturbation.

However, there is a dearth of information on the effects of biochar on the availability of liquid organic fertilizers, particularly when it is applied to problematic soils, namely, spodosols and ultisols. Most of the previous studies have addressed these amendments in isolation, and little is known about the impact of these compounds. This knowledge gap allows for identifying other mutualizing effects that could more effectively address the multiple constraints of these problematic soils.

Thus, the present study intends to fill this area of research by evaluating the physical and chemical changes in spodosols and ultisols in response to biochar application in combination with liquid organic fertilizers. To this end, this research aims to determine the extent of the treatment of these soils with various biochar concentrations and liquid organic fertilizer soaking times to establish the most suitable treatment regime for enhancing the fertility of the soils. This study reveals how these factors influence the pH of the soil, the amount of organic carbon and total nitrogen, the status of phosphorus and potassium, and the capacity for exchange and cation exchange. The novelty of this research lies in the ability to assess the chemical composition of spodosol and ultisol soils in terms of the effects of biochar and liquid organic fertilizers, both individually and in combination, which are currently unknown in the literature.

The knowledge gained in this study should be helpful for sustainable agriculture and environmental conservation. Therefore, this research contributes to enhancing the innovation of better practices involving biochar and liquid organic fertilizers to promote better soil health. Such knowledge might be more helpful for farmers and land owners struggling with managing ultisols and spodosols, as increasing crop yield and more efficient use of land resources in regions where these dominant soil types could be achieved.

MATERIAL AND METHODS

Study area

Growth media preparation, including arrangement and tests, was carried out at The Silviculture Laboratory, Soil Science and Forest Nutrition Research Group, Faculty of Forestry, Mulawarman University, Samarinda, Indonesia. This research was part of nursery seedling research on *Anthocepalus cadamba,* conducted before preparing the planting media. The research period included three months of observation, including the preparation of materials and equipment, the collection of spodosol and ultisol growth media samples, the generation of biochar and liquid organic fertilizers, the soaking of biochar with liquid organic fertilizers, the testing of samples in the laboratory, and the collection, processing, and analysis of data.

Procedure

Experimental design

The research design was a randomized complete block design with the biochar application rate set as the research factor and the duration of biochar soaking in liquid organic fertilizers set as the research block. Each block consisted of 3 units whose soil properties were observed. The biochar treatments (A) had six levels: 0%v (A0), 2%v (A2), 5%v (A5), 10%v (A10), 25%v (A25), and 100%v (A100). The soaking durations of the blocks (B) in the liquid organic fertilizers were four levels: without soaking (B0) and soaking for 1 hour (B1), 12 hours (B12), or 24 hours (B24). All these treatments were applied to the spodosol and ultisol growth media, which were tested separately.

The spodosol soil used for the planting media in this research was collected from nearby degraded spodosol soil 40 km northeast of Samarinda, specifically in the Muara Badak District, Kutai Kartanegara Regency, East Kalimantan. In contrast, the ultisols originated from Bukuan village, Palaran District, Samarinda city, East Kalimantan. These two soils were selected because of their very different textures. Spodosols have a coarse texture, whereas ultisols have a fine texture.

Biochar was manufactured using a retort production technique (shown in Figure 1). The source material consisted of wood from stems and branches of *Vitex pinnata*, which was collected as waste from nearby plantations. The process began by placing these materials into a sealed kiln drum to prevent oxygen from entering. The drum was initially heated using liquid natural gas as an external fuel source until the materials began releasing gases. At this point, the external fuel was cut off, and the process continued using only the gases emitted from the source material. The production was considered complete once these gases were fully depleted. The materials were maintained at peak temperatures between 400–500 °C for a period of 30–60 minutes. The chemical properties of the resulting biochar were analyzed according to methods described in research by Syahrinudin et al. (2019). The liquid organic fertilizers used in this work were derived from the anaerobic fermentation of vegetable wastes from the local traditional market. The vegetable scraps were chopped into approximately 1 cm pieces, put into a gunny sack, and placed in a composter tube. Sugarcane syrup, water, and EM4 bioactivator solution were then added. The ratio of water, EM-4, and sugarcane syrup was 15 liters:1 liter: 0.5 kg for every 5 kg of waste. The mixture was then stirred until evenly distributed, and the mouth of the sack was tied with a raffia string before finally closing the composite tube. The mixture was left to ferment for approximately 15 days before being harvested as a liquid organic fertilizer. The sack was opened daily to prevent the mixture's temperature from rising too high, disrupting the fermentation process, as the mixture's temperature was measured daily. The temperature of the mixture was maintained below 60 °C.

Biochar soaking treatment in liquid organic fertilizers

Before being soaked in fertilizer solution, the biochar was ground into powder, passed through a 2 mm sieve, and placed in bags (Figure 2). The bags containing biochar were put into containers used for soaking and then doused with fertilizer solution until the bags containing biochar were fully submerged. The samples were soaked for different durations (0 hours, 1 hour, 12 hours, and 24 hours). After being soaked for the predetermined time, the bags containing biochar were

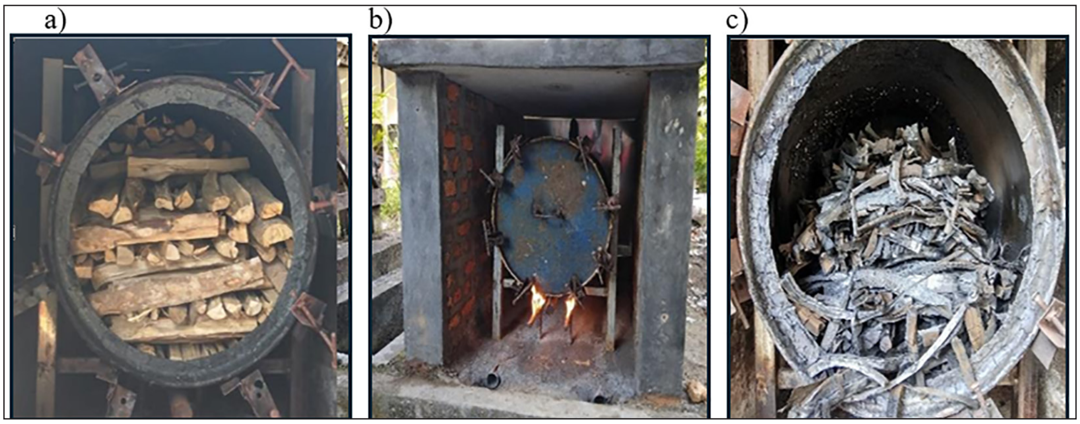

Figure 1. Making biochar using a closed double ring drum (retort): (a) the placement of wood in the double ring drum, (b) the combustion process, (c) biochar produced using the retort method

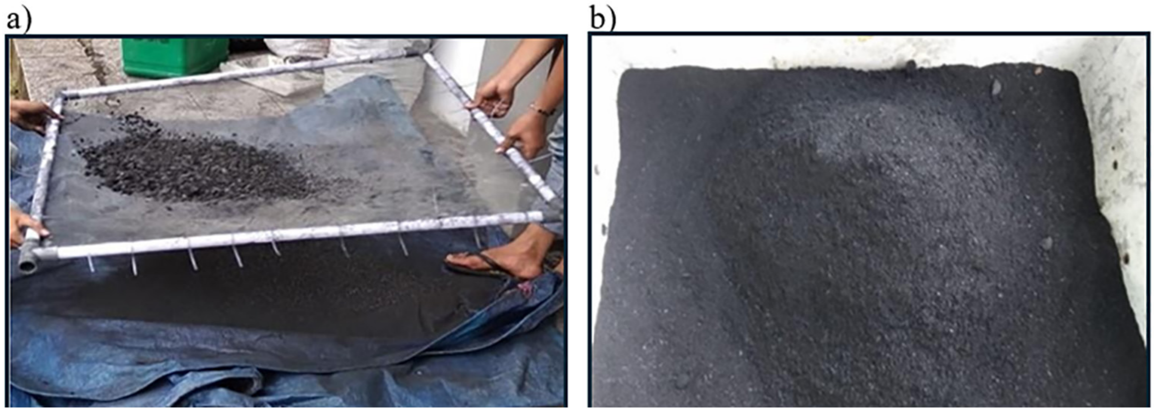

Figure 2. Biochar sieving before soaking in fertilizer solution: (a) biochar sieving, (b) sieved biochar; va, vl, l, m, h, and vh are very acidic, very low, low, moderate, high, and very high.

drained until the liquid organic fertilizers no longer dripped; the biochar was left overnight until it was ready to be applied to the growing media.

Biochar application to planting media

Before being applied to each planting medium (spodosols or ultisols), the volume of biochar soaked in liquid organic fertilizers for different durations was measured according to the predetermined concentration rate (0%v, 2%v, 5%v, 10%v, 25%v, or 100%v). The biochar concentration rate volume measurements were carried out in triplicate for each treatment for each planting medium. The concentration rate of biochar was calculated based on the volume of the polybags used, which were 10 cm in diameter and 15 cm in height. Furthermore, the biochar was mixed thoroughly with the planting media, put into polybags, and incubated for 1 week before samples were taken for laboratory testing. During the incubation period, the moisture content of the growing media was maintained by watering daily until the planting media appeared wet.

Data collection

In this study, the chemical properties measured were the soil acidity level (pH), organic C, total N, available P and K, CEC (cation exchangeable capacity), and EC (exchangeable cation) (Ca^{++}, Mg^{++}, K^{+}, Al^{+++}, and H^{+}). A total of 3 (three) planting media samples were taken from each group in each treatment and then composited, after which the chemical properties of the composite planting media samples were tested. The analysis methods for each soil chemical property are presented in Table 1.

Data analysis

The data collected in this research were tested and adjusted to a normal distribution (Rocha et al., 2019) using analysis of variance and mean difference tests with the help of SPSS software. To determine the effects of fundamental differences in variables due to treatment and interaction, the least significant difference (LSD) test was used (de Mendiburu, 2020).

Table 1. The analysis methods for each soil chemical property (Sulaeman et al., 2005)

Soil chemical properties	Soil analysis method
pH H_2O and KCl	Ratio of soil and solution (H_2O or KCl 1 N) = 1:3
Organic C	Walkley-Black dichromate method
Total N	Kjeldhal method
Available P and K	Bray I
CEC	It was determined by the calorimetric method, which is saturation with 1 N NH_4OAc at pH 7, followed by measurement using distillation and titration
EC (Ca^{++}, Mg^{++}, K^{+})	Saturation with 1 N NH_4OAc at pH 7.0
Al^{+++}	Saturation with 30% KCl, then followed by titration using 0.1 N HCl
H^{+}	Saturation with 30% KCl, then followed by titration using 0.02 N NaOH

RESULTS AND DISCUSSION

Chemical characteristics of the spodosols and ultisols

Table 2 comprehensively compares the chemical characteristics of the spodosols and ultisols. The data indicate that both soil types present very acidic pH values, with spodosols having a slightly higher pH in water (4.45) than ultisols (4.12). When measured in kcl, both soils have very similar pH values, with 3.80 for spodosols and 3.79 for ultisols. The organic carbon content significantly differed, with spodosols containing only 3.98% (high) organic carbon and ultisols containing 1.11% (low) organic carbon. The total nitrogen content also varies markedly, with spodosols accounting for a more significant percentage (0.69%) than ultisols (0.03%).

Regarding plant-available nutrients, spodosols have slightly higher phosphorus levels (13.37 ppm) than ultisols (11.46 ppm), although both are low. Potassium levels are moderate in both soils, with spodosols at 34.30 ppm and ultisols at 32.42 ppm. The CEC is significantly greater in ultisols (10.02 cmol kg^{-1}) than in spodosols (3.19 cmol kg^{-1}).

The EC also shows notable differences. Spodosols have very low levels of calcium (1.12 cmol kg^{-1}), magnesium (0.89 cmol kg^{-1}), and potassium (0.08 cmol kg^{-1}), whereas ultisols have slightly higher levels of calcium (1.84 cmol kg^{-1}) and magnesium (1.07 cmol kg^{-1}) but lower potassium (0.06 cmol kg^{-1}). Both soil types have very low levels of aluminum and hydrogen cations.

The pH values recorded for the Spodosols and Ultisols are consistent (Table 2) with those reported in earlier studies. Spodosols are characterized by their marked pH gradient, which varies from ultra to extremely acidic at the upper horizons (April et al., 2004). Ultisols, with pH values ranging from 4.5 to 5.5, are also more acidic, which affects the surface charge and nutrient solubility (Cáceres et al., 2010). These critical pH values are generally more significant than those for crop nutrient availability, especially phosphorus, suggesting that these soils may not support agricultural production effectively (Baquy et al., 2016).

Since ultisols contain small amounts of organic carbon, these soils are less fertile, and certain adjustments must be made to increase soil quality (Purwanto et al., 2023). The ultisols imply a slightly more significant potential for the support of plant growth while remaining relatively low. These outcomes underscore soil improvement's importance in improving organic matter's content and nutrient status (Moretti et al., 2017).

The total nitrogen content is thus higher in spodosols than in ultisols, which have very low values. These variations are essential for plant growth, especially nitrogen, since it is a nutrient. These deficiencies could be addressed by using organic fertilizers and incorporating biochar to improve the nitrogen content and fertility of the soil (Harahap et al., 2022). These differences in chemical properties affect aspects such as soil management and agricultural production between spodosols and ultisols. The pH of both soils is highly acidic, which hinders the release of essential

Table 2. Chemical characteristics of the spodosols and ultisols

Chemical properties	Units	Spodosols		Ultisols	
		Av.	Status	Av.	Status
pH (H_2O)	-	4.45	va	4.12	va
pH (KCl)	-	3.80	va	3.79	va
Organic C	%	3,98	h	1.11	l
Total N-	%	0.69	h	0.03	vl
P (P_2O_5)	ppm	13.37	l	11.46	h
K (K_2O)	ppm	34.30	m	32.42	m
CEC	cmol.kg^{-1}	3,19	vl	10.02	l
Ca^{++}	cmol.kg^{-1}	1.12	vl	1.84	l
Mg^{++}	cmol.kg^{-1}	0.89	l	1.07	l
K^{+}	cmol.kg^{-1}	0.08	vl	0.06	l
Al^{+++}	cmol.kg^{-1}	1.04	vl	6.16	l
H^{+}	cmol.kg^{-1}	0.06	-	0.38	-

nutrients such as phosphorus, which is very important for the growth of plants. Additives such as lime or biochar can increase the pH to those that are more suitable, thus increasing the nutrient solubility and quality of the soil (Yin et al., 2021).

The study's notably low levels of organic carbon suggest that adding organic matter can enhance soil structure and fertility. Integrating biochar and liquid organic fertilizers could elevate the organic carbon content, thereby improving the soil's physical appearance, structure, and microbial activity (Sutikarini et al., 2023). In addition, the cation exchange capacity of Spodosols is extremely low, which justifies the use of applied amendments to help with the cycle of essential nutrients. However, the somewhat higher CEC in ultisols indicates a lower but potentially more suitable ability of the soils to physically and chemically retain nutrients when augmented by biochar and organic sources of nutrients (Gu et al., 2022).

In conclusion, in the two soil types studied, namely, spodosols and ultisols, there was a significant improvement in pH levels and nutrient availability; hence, specific soil management strategies need to be implemented. Therefore, applying biochar and liquid organic fertilizer could be seen as the key approach for improving the chemical characteristics of these types of soils to improve the growth of plants and sustainable agriculture.

The impact of the biochar rate and soaking duration on the soil chemical properties of spodosols and ultisols biochar rate variability

Table 3 shows the analysis of variance for the effects of changes in biochar dosage on the chemical properties of the spodosols and ultisols. The study revealed a range of impacts on indicators such as pH, C-organic, N-total, P-available, K-available, and CEC. For pH, all the biochars and the higher dosages led to higher soil pH values for both soil types, with the ultisols being more responsive. The C-organic content increased significantly with increasing biochar dosage in the spodosols and ultisols. The total N content increased with increased biochar dosage, implying better nitrogen retention and availability. As expected, there was a significant increase in available phosphorus and potassium with increasing biochar levels due to increased nutrient availability. The CEC increased considerably in both soils, especially the Ultisols, indicating improved nutrient retention behavior.

The results of the ANOVA (analysis of variance) are consistent with those of previous studies (Table 3) that investigated the effects of biochar on soil characteristics. The higher soil pH with increasing biochar dosage confirms that biochar increases the soil pH, especially in ultisols and spodosols. These results corroborate other studies showing that applying biochar can increase organic matter in the soil by up to 40%, leading to better soil structure and fertility characteristics (Butnan et al., 2016).

This finding aligns with previous findings showing that biochar enhances nitrogen availability in the soil through increased microbial activity and reduced nitrogen leaching (Jing et al., 2020). The increased availability of phosphorus and potassium indicates that biochar can improve nutrient accessibility because nutrient adsorption on soil particles is reduced, and a direct nutrient source is provided (Asri, 2022). Moreover, biochar enhances the CEC, as the high surface area and functional groups enable better nutrient capture (Domingues et al., 2020).

The findings of this research also have considerable prospects for soil management and practical production. The increasing trend in the soil pH as influenced by biochar indicated that biochar could be used as a soil conditioner to improve the acidity of ultisols and spodosols and, in turn, improve their nutritional and crop-yielding capabilities. The increase in organic carbon content

Table 3. ANOVA of pH, EC, and soil nutrient element contents in spodosols and ultisols after biochar application

Source of variation	Parameter	pH (H_2O)	pH (KCl)	C-organic	N-total	P (P_2O_5)	K (K_2O)	CEC	Ca^{++}	Mg^{++}	K^+	Al^{+++}	H^+
				%		ppm		cmol kg^{-1}					
Rate of biochar (A)	F-prob	34.10	129.83	477.86	18,89	54.48	477.86	77.44	253.66	14.16	262.86	32.84	4.69
	P	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009
	Ultisols												
	F-prob	29.86	141.68	32.38	3.91	17.88	2.41	45.99	253.32	15.05	676.72	27.11	7.11
	P	0.000	0.000	0.000	0.018	0.000	0.086	0.000	0.000	0.000	0.000	0.000	0.001

with increasing biochar application rates suggests that this amendment can potentially enhance soil health and fertility, thus leading to sustainable agricultural production (Putra et al., 2023).

The changes in total N, P and available K suggested that the application of biochar increased the nutrient-holding capacity of the soil, thereby increasing plant nutrition and productivity. Overall, these studies present biochar as a promising and environmentally friendly option for synthetic supplements to improve nitrogen content in soil instead of chemical fertilizers (Günal et al., 2019).

Based on the observed change in the CEC with biochar application, adding biochar can help increase the nutrient stocks in the soil and thus lower nutrient losses. This is especially relevant for low-fixing capacity groups of soils, such as spodosols and ultisols, in which nutrient retention directly impacts soil productivity (Domingues et al., 2020). Therefore, the evidence from this study suggests that biochar is a significant additive for enhancing the chemical characteristics of soil for sustainable agricultural practices. Effect of biochar rate on chemical properties of spodosols and ultisols soils can be seen in Figure 3.

The duration of soaking of the biochar in the liquid organic fertilizers

Table 4 presents the ANOVA results for the effects of variations in the amount of biochar soaking in LOF on the soil chemical properties of the spodosols and ultisols. The analysis revealed that the soaking time significantly affects several parameters. In Spodosols, significant effects ($p < 0.05$) were observed for pH (H_2O), pH (KCl), total N, and P (P_2O_5). Organic C and K (K_2O) had no significant effect, with p-values of 0.202 each. For CEC, the effect was not substantial ($p = 0.185$). The levels of calcium (Ca), magnesium (Mg), potassium (K), and hydrogen (H) also varied significantly, with the most notable being Ca ($p = 0.049$) and H ($p = 0.046$).

In the ultisols, significant effects were observed for pH (H_2O), P (P_2O_5), K (K_2O), and CEC, with p values of 0.048, 0.003, 0.000, and 0.017, respectively. The organic C content showed a non-significant trend, with a p-value of 0.075. Similarly, total N and other cations (Ca, Mg, Al, and H) did not significantly affect the soaking time.

The significant increase in soil pH with increasing biochar soaking time in liquid organic fertilizers aligns with the findings of Mukhina et al. (2019), who reported short-term increases in soil pH following biochar application. This effect is crucial for acidic soils, including spodosols and ultisols, where improving the soil pH can improve nutrient availability and productivity (Zheng et al., 2020). An increase in pH might enable plants to absorb more nutrients and alleviate the problem of soil acidity, which provides evidence for the positive effects of the use of biochar-enriched fertilizers reported by Syahrinudin et al. (2019) and Liu et al. (2022).

The effect of biochar soaking time on organic carbon accumulation was relatively low. It was still associated with the biochar's inherent characteristics and the soil matrix's nature. This stands in juxtaposition with a finding highlighted by Putra (2023), who observed success in increasing the content of organic matter with biochar and noted that factors such as the type of biochar and conditions of the soil might also determine its results.

For nutrient elements/discriminated parameters such as total N, P (P_2O_5), and K (K_2O), the results indicate a fluctuating trend influenced by soaking time. It is supported by a higher total N content in the total N in spodosols, with studies implying that incorporating biochar increases nitrogen retention and decreases leaching (Xu et al., 2016). The relatively high P availability, especially in the ultisol, has been supported by Tessfaw et al. (2021), who reported improved phosphorus absorption due to reduced soil weight and better soluble P status due to biochar.

The results of this study indicate that the biochar soaking process variable with liquid organic fertilizer that has the most significant impact on the soil chemical characteristics is the soaking time in liquid organic fertilizers, where positive effects are observed on the pH, nutrients, and CEC values. These enhancements have significant implications for soil vitality and management, especially in soils such as spodosols and ultisols, which are acidic. This is where the modification of biochar soak time in organic fertilizers can be effective in helping to manage the pH level of soil and other nutrients, thus enhancing the productivity of crops as well as the health of the soil (Zheng et al., 2020). The increased availability of phosphorus and potassium with increasing biochar treatment indicates that specific biochar recipes could target the availability of various nutrients in the soil, helping to improve soil health and strongly supporting sustainable agriculture (Syahrinudin et al., 2019). This approach forms

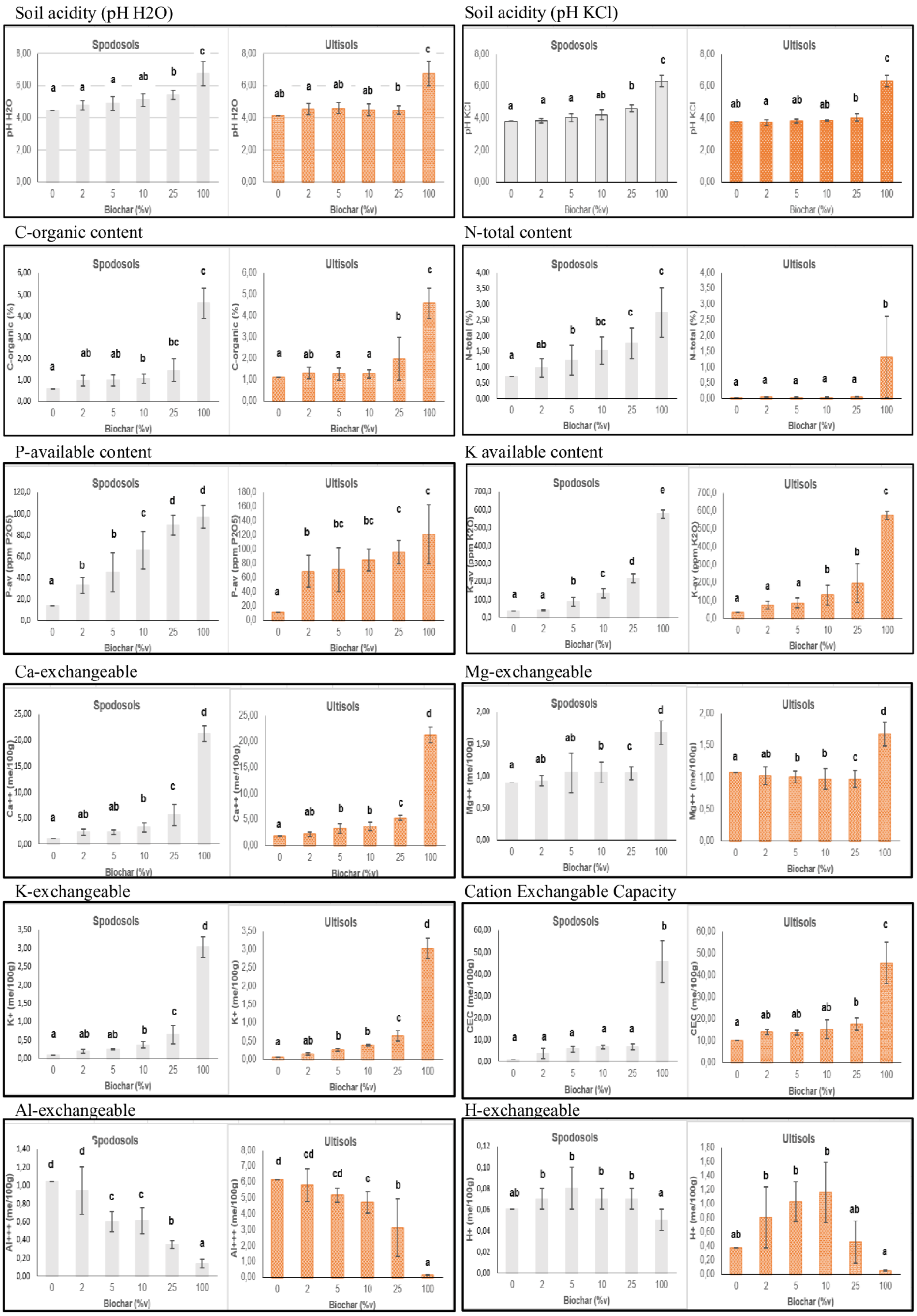

Figure 3. Rate of biochar effect on chemical properties of spodosols and ultisols soils; Points on the curve represent mean observation values while vertical lines represent their standard deviation; mean values with the same notation are not significantly different at α = 0.05

part of the larger plan of enhancing soil organic matter to support/ameliorate the environment through the reduced use of chemical fertilizers.

Nevertheless, such fluctuations in the changes in organic C content and other cations indicate that more studies are needed to ensure a detailed understanding and prediction of biochar behavior under various soil types and climate conditions and to fine-tune biochar recipes. Further experiments should refine these data together with the

Table 4. ANOVA of the effects of liquid organic fertilizer application on the pH, EC and soil nutrient contents of spodosols and ultisols

Source of variation	Parameter	pH (H_2O)	pH (KCl)	C-Organic	N-	P (P_2O_5)	K (K_2O)	CEC	Ca^{++}	Mg^{++}	K^+	Al^{+++}	H^+
				%		ppm		cmol kg^{-1}					
Soaking time duration biochar in in liquid organic fertilizers (B)	Spodosols												
	F-prob	9.18	8.87	1.74	7.41	6.49	1.74	1.83	3.32	2.36	2.91	2.06	3.39
	P	0.001	0.001	0.202	0.003	0.005	0.202	0.185	0.049	0.113	0.069	0.149	0.046
	Ultisols												
	F-prob	3.34	3.25	2.81	1.01	7.16	73.85	2.96	0.03	0.27	4.67	1.57	0.26
	P	0.048	0.052	0.075	0.416	0.003	0.000	0.066	0.993	0.846	0.017	0.238	0.853

effects of biochar intercalation on other organic and inorganic additives, contributing to the ultimate application of biochar for soil restoration and sustainable farming (Tessfaw et al., 2021).

Optimizing the chemical properties of spodosols and ultisols through treatment

Biochar rate treatment

Table 5 provides an overview of the chemical properties of spodosols and ultisols influenced by varying dosages of biochar. The minimum, maximum, and average values for each parameter are recorded. The pH (H2O) ranged from 4.45 to 6.75 in the Spodosols, whereas the pH (KCl) varied from 3.80 to 6.30. The organic carbon content (C-organic) increased significantly from 0.56% to 4.57%. The total nitrogen (N-total) content ranged from 0.69% to 2.73%. The amount of available phosphorus (P_2O_5) significantly increased from 13.37 ppm to 96.71 ppm. Available potassium (K_2O) varied from 34.30 ppm to 575.30 ppm. The cation exchange capacity (CEC) also notably increased from 0.91 cmol kg^{-1} to 45.55 cmol kg^{-1}.

In the Ultisols, the pH (H2O) ranged from 4.12–6.75, and the pH (KCl) ranged from 3.79–6.30. The organic carbon content increased from 1.11% to 4.57%. The total nitrogen content ranged from 0.03% to 1.32%. The amount of available phosphorus increased from 11.46 ppm to 120.77 ppm. Available potassium ranged from 32.42 ppm to 575.30 ppm. The CEC increased from 10.02 cmol kg^{-1} to 45.55 cmol kg^{-1}. The tendency of the increase in soil pH with increasing biochar application (Table 5) is consistent with the findings of Frimpong et al. (2021), who reported that

Table 5. Chemical properties of Spodosols and Ultisols as influenced by the dosage of biochar applied

Dosage of biochar (%v)	pH (H_2O)		pH (KCl)		C-organic %		N-total %		P (P_2O_5) ppm		K (K_2O) ppm		CEC cmol.kg^{-1}		Ca^{++} cmol.kg^{-1}		Mg^{++} cmol.kg^{-1}		K^+ cmol.kg^{-1}		Al^{+++} cmol.kg^{-1}		H^+ cmol.kg^{-1}	
	av	std	av	std	av	std	av	std	av	std	av	std	av	std	av	std	av	std	av	std	av	std	av	std
Spodosols																								
0	4.45^{a}	0.00	3.80^{a}	0.00	0.56^{a}	0.00	0.69^{a}	0.00	13.37^{a}	0.00	34.30^{a}	0.00	0.91^{a}	0.00	1.12^{a}	0.00	0.89^{a}	0.00	0.08^{a}	0.00	1.04^{d}	0.00	0.06^{ab}	0.00
2	4.78^{ab}	0.28	3.83^{a}	0.15	0.95^{ab}	0.24	0.97^{ab}	0.30	32.78^{b}	7.62	38.09^{a}	4.19	3.64^{a}	2.23	2.28^{ab}	0.54	0.92^{a}	0.08	0.19^{ab}	0.05	0.94^{d}	0.26	0.07^{b}	0.01
5	4.88^{b}	0.44	4.02^{a}	0.25	0.97^{ab}	0.26	1.21^{b}	0.47	45.17^{b}	18.27	85.54^{b}	24.47	5.47^{a}	1.49	2.33^{ab}	0.44	1.05^{a}	0.31	0.24^{ab}	0.02	0.60^{c}	0.11	0.08^{b}	0.02
10	5.09^{bc}	0.41	4.21^{b}	0.32	1.04^{b}	0.22	1.52^{bc}	0.45	65.81^{c}	17.49	133.32^{c}	25.90	6.60^{a}	0.87	3.23^{b}	0.93	1.05^{a}	0.16	0.37^{b}	0.10	0.61^{c}	0.14	0.07^{b}	0.01
25	5.43^{c}	0.27	4.58^{b}	0.22	1.45^{bc}	0.53	1.76^{c}	0.49	88.97^{d}	9.42	218.43^{d}	24.48	6.60^{a}	1.37	5.63^{c}	1.97	1.04^{a}	0.10	0.65^{c}	0.25	0.35^{b}	0.04	0.07^{b}	0.01
100	6.75^{d}	0.76	6.30^{c}	0.37	4.57^{c}	0.71	2.73^{c}	0.78	96.71^{d}	10.42	575.30^{e}	22.07	45.55^{b}	9.50	21.22^{d}	1.55	1.68^{b}	0.19	3.02^{d}	0.28	0.14^{a}	0.05	0.05^{a}	0.01
Ultisols																								
0	4.12^{a}	0.00	3.79^{ab}	0.00	1.11^{a}	0.00	0.03^{a}	0.00	11.46^{a}	0.00	32.42^{a}	0.00	10.02^{a}	0.00	1.84^{a}	0.00	1.07^{a}	0.00	0.06^{a}	0.00	6.16^{d}	0.00	0.38^{ab}	0.00
2	4.54^{a}	0.35	3.72^{a}	0.19	1.32^{ab}	0.27	0.05^{a}	0.01	68.86^{b}	21.92	74.66^{a}	22.30	14.12^{ab}	1.18	2.18^{ab}	0.47	1.02^{a}	0.14	0.15^{ab}	0.03	5.81^{cd}	1.02	0.81^{b}	0.43
5	4.59^{a}	0.35	3.82^{ab}	0.11	1.28^{a}	0.28	0.04^{a}	0.01	71.13^{bc}	30.99	86.50^{a}	28.35	13.78^{ab}	1.20	3.28^{b}	0.93	1.00^{a}	0.09	0.26^{b}	0.04	5.18^{cd}	0.44	1.03^{b}	0.28
10	4.49^{a}	0.36	3.86^{ab}	0.05	1.28^{a}	0.20	0.04^{a}	0.01	84.73^{bc}	15.52	131.40^{b}	53.56	15.26^{ab}	4.17	3.72^{b}	0.82	0.97^{a}	0.16	0.39^{b}	0.03	4.72^{c}	0.66	1.16^{b}	0.43
25	4.47^{a}	0.27	4.03^{b}	0.21	1.99^{b}	1.00	0.06^{a}	0.01	95.71^{c}	16.45	197.33^{b}	106.98	17.76^{b}	2.73	5.30^{c}	0.49	0.97^{a}	0.13	0.65^{c}	0.14	3.13^{b}	1.80	0.46^{ab}	0.30
100	6.75^{b}	0.76	6.30^{c}	0.37	4.57^{c}	0.71	1.32^{b}	1.29	120.77^{c}	41.19	575.30^{c}	22.07	45.55^{c}	9.50	21.22^{d}	1.55	1.68^{b}	0.19	3.02^{d}	0.28	0.14^{a}	0.05	0.05^{a}	0.01

Note: values followed by the same letter in a column are not significantly ($p < 0.05$) different.

soil biochar increases the soil's pH and organic carbon content – in the case of Spodosols and Ultisols, a dosage of 100% biochar resulted in the most significant increase in pH.

These increases in organic carbon content (Table 5) are well explained by the findings of the studies carried out by Bolan et al. (2021), which revealed that biochar improved the soil organic C stock and overall soil health. The large amount of organic C in the biochar treatment at the 100% dosage highlights the possibility of storing and enhancing the amount of organic C in the soil.

In the case of total N, the increase observed due to biochar application is consistent with the findings of Abbasi and Anwar (2015), who reported that biochar improves N nutrition by increasing nitrogen retention and availability. Thus, the best dose seems to be 100%, which positively affected the total N content, increased nitrogen mineralization, and decreased nitrogen leaching.

The increased P_2O_5 availability following biochar application supports Okebalama et al. (2022), who reported that biochar improved soil P accessibility. Compared with the control treatment, a dosage of 100% biochar improved soil P retention and availability to the most significant degree. The findings for potassium (K_2O) agree with those of Bao (2024) and Li et al. (2019), who reported that biochar enhances the potassium content in the soil. The available potassium content herein increased to the maximum value with 100% biochar due to the increase in the soil K content. The observed increase in cation exchange capacity with the application of biochar also confirms the work of Bishwakarma et al. (2022), where it was established that biochar optimizes the CEC because of the available surface area and functionalization. Concerning the effect of the biochar dosage on the CEC, the optimal value was 100%, which increased the CEC in both analyzed soils.

Based on the broad conclusions of this paper, numerous application factors have considerable impacts on soil concerning introductory biochar use in agriculture. Therefore, the increase in pH, organic carbon, nitrogen, phosphorus, potassium, and CEC values signifies that biochar is a substantial soil amendment for improving soil fertility and productivity. The biochar at the one hundred 100 full mark resulted in the most significant increase in all the parameters; hence, a relatively high biochar concentration increased the soil's fertility and nutrient value.

According to the results of the present study, only the most significant improvement in the soil, as reflected by its chemical characteristics, such as pH, organic carbon, total nitrogen, available phosphate, available potash, and cation exchange capacity, was obtained when the biochar was applied at a rate of 100%. This infers that if no soil or other growing media are included, then it is possible for 100% pure biochar to be used as an effective nursery media for seedlings. However, adequate additives for enhancing the soil's chemical properties should be between 10 and 25% biochar for agricultural soils with mixed soil. Notably, within this dosage limit, all the previously mentioned properties of biochar can be deemed valuable for improving the conditions within the ground. However, the degree of their manifestation would be best determined experimentally. Hence, for applying biochar on agricultural land or after using a soil mixture, a 10–25% dosage is optimal for enhancing the chemical nature of the soils and sustainable farming practices.

The observed changes in pH, organic carbon, and nutrient content and availability in the present study align with the results of other studies. Rogovska et al. (2014) established the ability of biochar to increase the chemistry of soil by increasing the pH as well as the carbon content present in the soil. However, to achieve the most significant improvement in the pH level, according to the study conducted by Frimpong et al. (2021), the application should be between 10% and 25% because it enhances the soil pH in spodosols and ultisols. This finding is further supported by Li et al. (2021) and Bolan et al. (2021), who reported that biochar application can strongly influence the organic carbon content of SOC and its stock. This study showed that applying 10–25% biochar is suitable for increasing organic carbon within soil types, resulting in improved soil quality and increased carbon storage.

The enhancements for total nitrogen align with Abbasi and Anwar (2015) and Nguyen et al. (2017). Among the Spodosols and Ultisols, 10–25% were the best for increasing the N-total, availability, and retention rates. The changes in available phosphorus in this study with biochar marginally increased; this finding corresponds with the studies conducted by Okebalama et al. (2022) and Zhang et al. (2022). Applying 10–25% improved the P availability; the results were similar for both soil types. The results corroborate Bao (2024) and Li et al. (2019), affirming that P availability increases the K content. The effective range of the nutrients that enhanced K solubility was 10–25%. According to Domingues et al. (2020) and Bishwakarma et al. (2022), CEC improvement with biochar is actual. In the case of Spodosols, the authors reported that the most effective concentration varied between 10 and 25% of the CEC enhancement.

The findings of this study provide relevant intervention solutions for soil management practices that seek to enhance soil health and fertility status. The desirable level of biochar application to increase Spodosols and Ultisols' properties is within 10–25% of the biochar solution, making it the most effective and realizable soil improvement method.

Soils made more alkaline using biochar will also benefit from improved nutrient access in the Spodosol and ultisol classes of soils, where the use of biochar is encouraged to improve crop yields (Rogovska et al. 2014; Frimpong et al., 2021). A better soil organic carbon status enhances the sustainability of the soil structure and fertility concerning the maintenance of intensive agriculture in addition to carbon sequestration (Li et al., 2021; Bolan et al., 2021). Ideal biochar doses in soils can increase the contents of hormone-like substances, nitrogen, phosphorus, and potassium, increasing plant nutrient uptake. It eventually reduces the use of chemical fertilizers for improved environmental management (Abbasi and Anwar, 2015; Nguyen et al., 2017; Okebalama et al., 2022; Zhang et al., 2022; Bao, 2024). The increase in the cation exchange capacity increases the nutrients and fertility of the soil, suggesting that biochar is a potent option for improving the productivity of the soil (Domingues et al., 2020; Bishwakarma et al., 2022).

Overall, the studies indicated that biochar can enhance the most important chemical characteristics of the soil. The suggested range of the biochar rate, 10–25%, also benefits from the optimality of the biochar application, standing at the same time for realistic economic feasibility and affordability for farmers and land stewards. The effect of rate of biochar on the chemical properties of Spodosols and Ultisols soils can be seen in Figure 3.

The duration of soaking of liquid organic fertilizer-treated biochar

Table 6 lists the chemical properties of the spodosols and ultisols influenced by the different soaking times of the biochar in the liquid organic fertilizer. The minimum, maximum, and average values for each parameter are recorded. In the spodosols, the pH (H_2O) ranged from 4.94 at 1 hour to 5.67 at 12 hours, with an average of 5.23, and the pH (KCl) ranged from 4.29 at 1 hour to 4.72 at 0 hours, with an average of 4.45. The C-organic content increased from 1.17% at zero h to 1.91% at 24 h, with an average of 1.59%. The N-total ranged from 1.03% at zero h to 1.83% at 24 h, with an average of 1.48%. In the Ultisols, the pH (H_2O) ranged from 4.46 at 1 hour to 5.08 at 0 hours, with an average of 4.82, and the pH (KCl) ranged from 4.07 at 1 hour to 4.33 at 12 hours, with an average of 4.25. The C-organic content ranged from 1.58% at zero h to 2.35% at one h, with an average of 1.92%. The N-total ranged from 0.08% at 12 hours to 0.55% at 1 hour, with an average of 0.26%. The spodosols' p-available

Table 6. Chemical properties of spodosols and ultisols as influenced by time in liquid organic fertilizer

Soaking time duration (hour)	pH (H_2O)		pH (KCl)		C-organic %		N-total %		P (P_2O_5) ppm		K (K_2O) ppm		CEC cmol.kg^{-1}		Ca^{++} cmol.kg^{-1}		Mg^{++} cmol.kg^{-1}		K^{+} cmol.kg^{-1}		Al^{+++} cmol.kg^{-1}		H^{+} cmol.kg^{-1}	
	av	std	av	std	av	std	av	std	av	std	av	std	av	std	av	std	av	std	av	std	av	std	av	std
Spodosols																								
0	5.33^{b}	0.49	4.72^{b}	0.50	1.17^{a}	0.59	1.03^{a}	0.17	45.83^{a}	14.13	194.85^{a}	100.85	8.96^{a}	6.81	5.55^{a}	3.70	1.10^{a}	0.19	0.71^{a}	0.54	0.54^{a}	0.16	0.06^{a}	0.006
1	4.94^{a}	0.31	4.29^{a}	0.42	1.67^{b}	0.73	1.33^{ab}	0.46	68.26^{b}	16.93	181.49^{a}	104.30	10.48^{a}	6.91	5.23^{a}	3.56	1.08^{a}	0.18	0.65^{a}	0.51	0.64^{a}	0.19	0.0^{a}	0.005
12	5.67^{c}	0.53	4.51^{ab}	0.54	1.61^{b}	0.83	1.73^{b}	0.43	56.53^{ab}	17.52	172.46^{a}	108.05	13.36^{a}	9.98	6.29^{a}	4.21	1.08^{a}	0.12	0.83^{a}	0.63	0.69^{a}	0.21	0.07^{ab}	0.006
24	4.97^{a}	0.32	4.30^{a}	0.44	1.91^{b}	0.84	1.83^{b}	0.42	57.92^{b}	18.07	174.52^{a}	97.88	13.06^{a}	10.04	6.80^{b}	3.83	1.23^{a}	0.13	0.85^{a}	0.57	0.57^{a}	0.16	0.08^{b}	0.007
Ultisols																								
0	5.08^{b}	0.53	4.32^{a}	0.56	1.58^{a}	0.50	0.30^{a}	0.31	49.81^{a}	14.528	147.11^{a}	105.54	16.85^{a}	4.94	6.34^{a}	3.49	1.11^{a}	0.19	0.72^{a}	0.54	4.20^{a}	1.17	0.6^{a}	0.3
1	4.46^{a}	0.40	4.07^{a}	0.45	2.35^{a}	0.67	0.55^{a}	0.61	75.66^{ab}	16.419	178.04^{ab}	103.03	17.54^{a}	5.19	6.25^{a}	3.34	1.11^{a}	0.18	0.68^{a}	0.51	4.48^{a}	1.13	0.7^{a}	0.2
12	4.92^{b}	0.67	4.33^{a}	0.56	1.83^{a}	0.77	0.08^{a}	0.06	81.31^{b}	19.528	187.72^{ab}	101.79	20.65^{a}	8.18	6.20^{a}	4.22	1.16^{a}	0.09	0.85^{a}	0.63	4.51^{a}	1.18	0.6^{a}	0.1
24	4.83^{b}	0.34	4.29^{a}	0.44	1.94^{a}	0.80	0.10^{a}	0.06	94.00^{b}	26.549	218.86^{b}	98.04	22.62^{a}	7.94	6.24^{a}	3.84	1.09^{a}	0.12	0.77^{a}	0.58	3.56^{a}	1.26	0.7^{a}	0.3

Note: values followed by the same letter in a column are not significantly ($p < 0.05$) different.

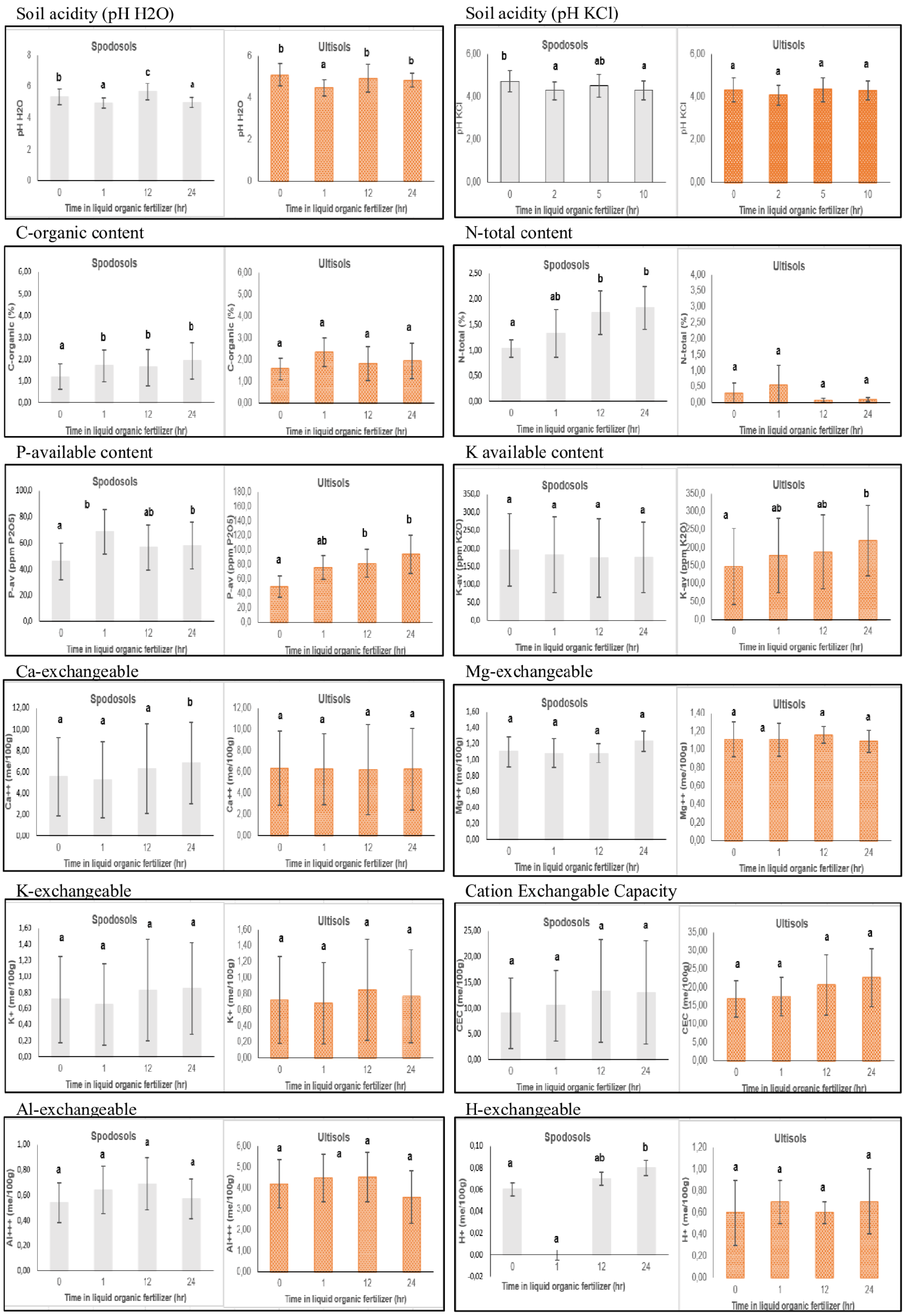

Figure 4. The effect of soaking time of biochar in liquid organic fertilizer on the chemical properties of spodosols and ultisols; Points on the curve represent mean observation values while vertical lines represent their standard deviation; mean values with the same notation are not significantly different at α = 0.05

(P_2O_5) concentrations ranged from 45.83 ppm at 0 hours to 68.26 ppm at 1 hour, with an average of 57.64 ppm. In the ultisols, the p-available (P_2O_5) concentration ranged from 49.81 ppm at 0 hours to 94.00 ppm at 24 hours, with an average of 75.70 ppm. The K-available (K_2O) in spodosols ranges from 172.46 ppm at 12 hours to 194.85 ppm at 0 hours, with an average of 180.83 ppm.

In the ultisols, the K-available (K_2O) content ranged from 147.11 ppm at 0 hours to 218.86 ppm at 24 hours, with an average of 182.93 ppm. The CEC of the spodosols ranged from 8.96 cmol.kg^{-1} at 0 hours to 13.36 cmol kg^{-1} at 12 hours, with an average value of 11.22 cmol kg^{-1}. In the ultisols, the CEC ranged from 16.85 cmol kg^{-1} at 0 hours to 22.62 cmol kg^{-1} at 24 hours, with an average value of 19.92 cmol kg^{-1}.

The optimal soaking times for improving various soil chemical properties align with findings from previous studies. Raden et al. (2017) suggested a 40-day soaking period for soil pH improvement. Still, this study indicated that for Spodosols, 12 hours resulted in the highest pH (5.67), whereas for ultisols, 0 hours resulted in the highest pH (5.08). Utami et al. (2021) reported that the organic carbon content increased with an increasing soaking period. In this study, the optimal soaking time for Spodosols was 24 hours (1.91%), whereas for ultisols, it was 1 hour (2.35%). Concerning total nitrogen, Listyarini and Prabowo (2020) highlighted a 40-day soaking period. However, this study revealed that 24 hours was optimal for Spodosols (1.83%), whereas 1 hour was optimal for ultisols (0.55%). The improvement in available phosphorus aligns with the findings of Norhalimah et al. (2022), who noted significant increases with specific soaking times. The optimal soaking time for the Spodosols was 1 hour (68.26 ppm), whereas for the ultisols, it was 24 hours (94.00 ppm). Concerning potassium availability, Zhang et al. (2017) reported that longer soaking times increase the K content. This study revealed that zero h was optimal for Spodosols (194.85 ppm), whereas 24 h was optimal for Ultisols (218.86 ppm). Prasetyo et al. (2021) highlighted improvements in CEC with longer soaking times. In this study, the optimal soaking time for Spodosols was 12 hours (13.36 cmol kg^{-1}), whereas for Ultisols, it was 24 hours (22.62 cmol kg^{-1}).

The findings shown here confirm that the soaking time in LOF influences systematic changes in biochar physical characteristics; therefore, the optimal soaking time for spodosols and ultisols is determined. Recommendations concerning the length of time the two soil samples should be soaked include 12 hours for spodosols and no soaking for ultisols to consider soil pH adjustment. Therefore, these studies indicate that an enhanced understanding of the best way to soak biochar could provide a way to improve methods for correcting soil acidity.

For WT slurries, longer soaking times (24 hours for spodosols and 1 hour for ultisols) are preferable regarding the organic carbon content. It shows that to increase the level of soil organic matter, increasing the time required for soaking is necessary. Consequently, the total nitrogen content was excellent at 24 hours of soaking for the spodosols, whereas it was most significant at one hour for the ultisols. The results below shed light on this issue by comparing various soil forms in response to biochar application.

For the available phosphorus, the optimal rate of decision-making was one hour for the spodosols but 24 hours for the ultisols. It means that the soaking period should be reviewed according to the type of nutrient in the soil for optimal uptake. The abovementioned hours of soaking for spodosols and 24 hours for ultisols help attain maximum potassium availability. It makes one conclude that some soils may require simple, practical applications to contain and stabilize contaminants effectively. In contrast, others may need more time to soak in order to enhance efficiency. The enhancement of the CEC was optimized at 12 hours for Spodosols and 24 hours for Ultisols. It highlights the importance of customizing biochar treatments to improve soil nutrient retention. The effect of soaking time of biochar in liquid organic fertilizer on the chemical properties of spodosols and ultisols can be seen in Figure 4

These findings provide valuable insights for optimizing biochar application in agriculture, promoting improved soil health and sustainable farming practices. Further research should focus on long-term field trials to validate these results and explore the economic feasibility of these treatments on a larger scale.

CONCLUSIONS

This study investigated the effects of biochar dosage and soaking time in liquid organic fertilizer (LOF) on the chemical properties of spodosols and ultisols. The results indicate that both biochar dosage and soaking time significantly influence soil pH, organic carbon content, nitrogen, phosphorus, potassium availability, and cation exchange capacity (CEC). Optimal biochar dosages of 25% were found to enhance soil pH, organic carbon content, nitrogen, phosphorus, potassium, and CEC in both spodosols and ultisols. The optimal soaking periods for soil improvement varied between spodosols and ultisols. Generally, spodosols require a longer soaking time to improve pH, organic carbon, and total nitrogen. However, for available phosphorus, no soaking is necessary, and available potassium reaches optimal levels without soaking. Conversely, ultisols typically reach optimal conditions with shorter soaking times or even no soaking for some parameters. For both, it is recommended to soak the biochar for 24 hours with LOF, which is expected to improve soil properties.

These findings highlight the importance of tailoring biochar application and soaking times to specific soil types and desired soil properties. The use of biochar as a soil amendment offers a sustainable strategy to improve soil health, enhance nutrient availability, and promote sustainable agricultural practices. Further research should focus on long-term field trials to validate these results and explore the economic feasibility of large-scale biochar applications

Acknowledgments

The authors would like to thank the Ministry of Research, Technology, and Higher Education of the Republic of Indonesia for funding the research.

REFERENCES

1. Abbasi, M. and Anwar, A. (2015). Ameliorating effects of biochar derived from poultry manure and white clover residues on soil nutrient status and plant growth promotion - greenhouse experiments. *Plos One 10*(6), e0131592, https://doi.org/10.1371/journal.pone. 0131592
2. April, R., Newton, R., Coles, L.T. (2004). Chemical properties of forest soils. In: *Encyclopedia of Forest Sciences*. Elsevier Inc, 329–343.
3. Arthagama, I., Dana, I. and Wiguna, P. (2021). Effect of various types of growing media and application of liquid organic fertilizer on the growth of dendrobium orchids. *International Journal of Biosciences and Biotechnology 8*(2): 54, https://doi.org/10.24843/ijbb. 2021. v08.i02.p07
4. Asri, F. (2022). Effects of biochar and fertilizer application on soil properties and nutrient status of lettuce. *Chilean Journal of Agricultural Research 82*(3), 469–483, https://doi.org/10.4067/s0718-58392022000300469.
5. Bao, Z. (2024). Long-term biochar application promoted soil aggregate-associated potassium availability and maize potassium uptake. *GCB Bioenergy 16*(4), https://doi.org/10.1111/gcbb.13134.
6. Baquy, A., Li, J., Xu, C., Mehmood, K., and Xu, R. (2016). Determination of critical ph and al concentration of acidic ultisols for wheat and canola crops. *Solid Earth Discuss*, https://doi.org/10.5194/se-2016-126
7. Bishwakarma, S., Khanal, B., Shriwastav, C., Dhakal, R., and Karkee, S. (2022). Impact of biochar and plastic mulch on soil properties in a maize field in nepal. *Archives of Agriculture and Environmental Science 7*(2): 241-245, https://doi.org/10.26832/24566632.2022.0702012
8. Blanco-Canqui, H. (2020). Does biochar improve all soil ecosystem services? *GCB Bioenergy 13*(2): 291–304, https://doi.org/10.1111/gcbb.12783
9. Bolan, N., Hoang, S., Beiyuan, J., Gupta, S., Hou, D., Karakoti, A., … and Zwieten, L. (2021). Multifunctional applications of biochar beyond carbon storage. *International Materials Reviews 67*(2): 150–200, https://doi.org/10.1080/09506608.2021.1922047
10. Butnan, S., Deenik, J., Toomsan, B., Antal, M., and Vityakon, P. (2016). Biochar properties influencing greenhouse gas emissions in tropical soils differing in texture and mineralogy. *Journal of Environmental Quality 45*(5): 1509–1519, https://doi.org/10.2134/jeq2015.10.0532
11. Caceres, L., Fuentes, R., Escudey, M., Fuentes, E., and Báez, M. (2010). Metsulfuron-methyl sorption/desorption behavior on volcanic ash-derived soils. effect of phosphate and ph. *Journal of Agricultural and Food Chemistry 58*(11): 6864–6869. https://doi.org/10.1021/jf904191z
12. de Mendiburu, F. (2020). Agricolae: *Statistical Procedures for Agricultural Research*. R package version 1.3-3. https://CRAN.R-project.org/package=agricolae
13. Domingues, R., Sánchez-Monedero, M., Spokas, K., Melo, L., Trugilho, P., Valenciano, M., … and Silva, C. (2020). Enhancing cation exchange capacity of weathered soils using biochar: feedstock, pyrolysis conditions and addition rate. *Agronomy 10*(6), 824. https://doi.org/10.3390/agronomy10060824
14. Fernandes, J., Chaves, L., Mendes, J., Chaves, I., and Tito, G. (2018). Soil chemical amendments and the macronutrients mobility evaluation in oxisol treated with biochar. *Journal of Agricultural Science 10*(10), 238, https://doi.org/10.5539/jas.v10n10p238
15. Frimpong, K., Abban-Baidoo, E., and Marschner, B. (2021). Can combined compost and biochar application improve the quality of a highly weathered coastal savanna soil. *Heliyon 7*(5), e07089. https://doi.org/10.1016/j.heliyon.2021.e07089
16. Gu, W., Wang, Y., Feng, Z., Wu, D., Zhang, H.,

Yuan, H., and Zhang, W. (2022). Long-term effects of biochar application with reduced chemical fertilizer on paddy soil properties and japonica rice production system. *Frontiers in Environmental Science 10*. https://doi.org/10.3389/fenvs.2022.902752

17. Günal, H., Bayram, Ö., Günal, E., and Erdem, H. (2019). Characterization of soil amendment potential of 18 different biochar types produced by slow pyrolysis. *Eurasian Journal of Soil Science (Ejss) 8*(4): 329–339, https://doi.org/10.18393/ejss.599760

18. Harahap, F., Arman, I., Harahap, N., Syawaluddin, F. and Yana, R. (2022). Provision of chicken manure and urea fertilizer on the chemical characteristics of Ultisol soil in Bilah Barat District. *International Journal of Science and Environment (Ijse) 2*(3): 98–103. https://doi.org/10.51601/ijse.v2i3.34

19. Jing, Y., Zhang, Y., Han, I., Wang, P., Mei, Q., and Huang, Y. (2020). Effects of different straw biochars on soil organic carbon, nitrogen, available phosphorus, and enzyme activity in paddy soil. *Scientific Reports 10*(1). https://doi.org/10.1038/s41598-020-65796-2

20. Kaya, E., Siregar, A., Matulessy, D., Hasan, M., and Akollo, A. (2022). Soil chemistry character, the N, P, and K uptake, and the growth and yield of corn (*Zea mays* L.) due to the application of ela sago palm waste compost and liquid organic fertilizer in ultisols. *Journal of Tropical Soils 27*(2), 49, https://doi.org/10.5400/jts.2022.v27i2.49-58

21. Levesque, V., Oelbermann, M., and Ziadi, N. (2022). Biochar in temperate soils: opportunities and challenges. *Canadian Journal of Soil Science 102*(1): 1–26. https://doi.org/10.1139/cjss-2021-0047

22. Li, M., Wang, Y., Liu, M., Liu, Q., Xie, Z., Li, Z., … and Chen, Y. (2019). Three-year field observation of biochar-mediated changes in soil organic carbon and microbial activity. *Journal of Environmental Quality 48*(3), 717–726, https://doi.org/10.2134/jeq2018.10.0354

23. Li, S., Ren, X., Yang, X., Ren, J., Wei, Z., Qin, Z. (2021). Biochar Application Rate Impacts Nutrient Availability and Phytoremediation Potential for Cdmium-Contaminated Soils. *Science of the Total Environment 774*, 145695, https://doi.org/10.1016/j.scitotenv.2021.145695

24. Listyarini, E., and Prabowo, Y. (2020). Effect of corncob biochar enriched with ammonium sulfate [(NH4)2SO4] on soil aggregate stability, several soil chemical properties, and corn plant growth. *Jurnal Tanah Dan Sumberdaya Lahan 7*(1): 101–108, https://doi.org/10.21776/ub.jtsl.2020.007.1.13 (in Indonesian).

25. Liu, M., Ma, S., Ma, Q., Song, W., Shen, M., Song, L., … and Wang, L. (2022). Biochar combined with organic and inorganic fertilizers promoted the rapeseed nutrient uptake and improved the purple soil quality. *Frontiers in Nutrition 9*, https://doi.org/10.3389/fnut.2022.997151

26. Moretti, S., Bertoncini, E., and Abreu-Junior, C. (2017). Carbon mineralization in soils irrigated with treated swine wastewater. *Journal of Agricultural Science 9*(3), 19, https://doi.org/10.5539/jas.v9n3p19

27. Mukhina, I., Rizhiya, E., Buchkina, N., and Balashov, E. (2019). Changes in soil conditions after application of biochar. *Iop Conference Series Earth and Environmental Science 368*(1), 012037, https://doi.org/10.1088/1755-1315/368/1/012037

28. Nguyen, T.T.N., Xu, C.Y., Tahmasbian, I., Che, R., Xu, Z., Zhou, X., Wallace, H.M., Bai, S.H., (2017). Effects of biochar on soil available inorganic nitrogen: A review and meta-analysis. *Geoderma 288*: 79–96, https://doi.org/10.1016/j.geoderma.2016.11.004

29. Norhalimah, A., Jumar, J., and NS, N. (2022). Effect of giving tofu dregs bokashi on phosphate dynamics in ultisols. *Agrotech Journal 7*(1): 1–6, https://doi.org/10.31327/atj.v7i1.1718

30. Okebalama, C., Asogwa, K., Uzoh, I., and Marschner, B. (2022). Impact of bambara seed residue biochar and npk on soil fertility, aggregate carbon and nitrogen concentrations and yield of cucumber. *Agro-Science 21*(2): 53–65, https://doi.org/10.4314/as.v21i2.6

31. Prasetyo, B. (2021). Mineralogical and chemical characteristics of Spodosols in toba highland, north sumatra. *Indonesian Journal of Agricultural Science 10*(2), 54, https://doi.org/10.21082/ijas.v10n2.2009.54-64

32. Purwanto, B., Hanudin, E., and Destri, E. (2023). Accumulation levels of available cu and cu absorption in corn in Ultisols and Alfisols after the addition of fly ash and organic materials. *Journal of Suboptimal Lands, 12*(1): 11–26, https://doi.org/10.36706/jlso.12.1.2023.617

33. Putra, M.O.P.S, Syahrinudin, Hartati, W., Kiswanto, Sudarmadji, T., Sofyan, F.P.M., and Hapsari, M.T. (2023). Enriched biochar enhances height growth performance of Anthocephalus cadamba on severely degraded Spodosols in East kalimantan. *Iop Conference Series Earth and Environmental Science 1282*(1), 012053, https://doi.org/10.1088/1755-1315/1282/1/012053

34. Raden, I., Fathillah, S., Fadli, M., and Suyadi, S. (2017). Nutrient content of liquid organic fertilizer (LOF) by various bioactivator and soaking time. *Nusantara Bioscience 9*(2): 209–213, https://doi.org/10.13057/nusbiosci/n090217

35. Rocha, J.V., Rocha, K.R., Klein, C., (2019). *Testing for Normality. In: McManus M. (eds) Pathological Conditions Associated with Pregnancy.* Springer

Protocols Handbooks. Humana Press, New York, NY. https://doi.org/10.1007/978-1-4939-8948-2_2

36. Rogovska, N., Laird, D.A., Rathke, S.J., Karlen, D.L., (2014). Biochar impact on Midwestern Mollisols and maize nutrient availability. *Geoderma* 230–231, 340–347, https://doi.org/10.1016/j.geoderma.2014.04.009
37. Singh, H., Northup, B., Rice, C., and Prasad, P. (2022). Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. *Biochar 4*(1), https://doi.org/10.1007/s42773-022-00138-1
38. Sulaeman, Suparto, Eviati. (2005). *Technical Guidelines for Chemical Analysis of Soil, Plants, Water, and Fertilizers.* Balai Penelitian Tanah, Badan Penelitian dan Pengembangan Pertanian, Departemen Pertanian, hlm. 45. [in Indonesian]
39. Sutikarini, S., Masulili, A., Suryani, R., Setiawan, S., and Mulyadi, M. (2023). Characteristics of pineapple waste as liquid organic fertilizer and its effect on ultisol soil fertility. *International Journal of Multi Discipline Science (Ij-Mds) 6*(1), 38, https://doi.org/10.26737/ij-mds.v6i1.3754
40. Syahrinudin, S., Hartati, W., Sudarmadji, T., Krisdianto, N., and Ibrahim, I. (2019). Biochar enriched with organic fertilizer improves the survival and growth rate of Anthocepalus cadamba seedlings planted on degraded Spodosols. *Biodiversitas Journal of Biological Diversity 20*(12), https://doi.org/10.13057/biodiv/d201237
41. Tessfaw, Z., Beyene, A., Nebiyu, A., Pikon, K., and Landrat, M. (2021). Short term effects of municipal solid waste compost, khat-derived biochar and cocomposted biochar on soil quality and faba bean yield and protein content, https://doi.org/10.21203/rs.3.rs-424999/v1
42. Utami, A., and Hidayat, B. (2021). Study of some chemical properties of ultisol soil applied by biochar and compos from some biomasses and incubation time. *Iop Conference Series Earth and Environmental Science 782*(4), 042040, https://doi.org/10.1088/1755-1315/782/4/042040
43. Wu, L., Zhao, F., He, X., Liu, H., and Yu, K. (2020). Increased organic fertilizer application and reduced chemical fertilizer application affect the soil properties and bacterial communities of grape rhizosphere soil. *Scientific Reports 10*(1), https://doi.org/10.1038/s41598-020-66648-9
44. Xu, G., Zhang, Y., Sun, J., and Shao, H. (2016). Negative interactive effects between biochar and phosphorus fertilization on phosphorus availability and plant yield in saline sodic soil. *Science of the Total Environment 568*: 910–915, https://doi.org/10.1016/j.scitotenv.2016.06.079
45. Yin, C., Schlatter, D., Kroese, D., Paulitz, T., and Hagerty, C. (2021). Responses of soil fungal communities to lime application in wheat fields in the pacific northwest. Frontiers in Microbiology 12, https://doi.org/10.3389/fmicb.2021.576763
46. Zhang, J., Zhang, Z., Shen G, Wang R, Gao L, Yanchen D, … and Zhang J. (2017). Tobacco growth responses and soil properties to rice-straw biochar applied on yellow–brown soil in central China. *Destech Transactions on Environment Energy and Earth Science*, (edep). https://doi.org/10.12783/dteees/edep2016/5907
47. Zhang, Y., Chen, T., Liao, Y., Luo, X., Li, G., Luo, J., Lin, Q., (2022). Biochar increases phosphorus availability in acidic soils: A review. *Pedosphere 32*(2): 175–190, https://doi.org/10.1016/S1002-0160(21)60064-5
48. Zheng, X., Song, W., Guan, E., Wang, Y., Hu, X., Liang, H., … and Dong J. (2020). Response in physicochemical properties of tobacco-growing soils and n/p/k accumulation in tobacco plant to tobacco straw biochar. *Journal of Soil Science and Plant Nutrition 20*(2): 293–305, https://doi.org/10.1007/s42729-019-00108-w
49. Zivanov, M., Seremesic S., Bjelic, D., Marinkovic, J., Vasin, J., Ninkov, J., … and Milic, S. (2020). Response of chemical and microbial properties to short-term biochar amendment in different agricultural soils. *Zbornik Matice Srpske Za Prirodne Nauke* (138): 61–69, https://doi.org/10.2298/zmspn2038061z