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Removal of glyphosate on Inceptisols ameliorated with biochar derived from young coconut waste

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ABSTRACT

Young Coconut Waste Biochar (YCWB) serves as an ameliorative agent that enhances soil quality and facilitates glyphosate removal, particularly in Inceptisols. This study aimed to evaluate the capacity of Inceptisols enhanced with YCWB to eliminate glyphosate, a commonly used herbicide. Inceptisols amended with 40 t ha^{-1} YCWB demonstrated an increased surface charge, improving soil properties such as acidity (pH), electrical conductivity (EC), cation exchange capacity (CEC), and soil organic matter (SOM). The adsorption capacity was determined to be 0.87 mg g^{-1} (or 870.27 mg kg^{-1}) at pH 5.07, under a glyphosate concentration of 100 mg L^{-1}. Glyphosate removal was facilitated by changes in functional groups, as indicated by Fourier-transform infrared spectroscopy (FT-IR), which showed reduced transmittance of O-H, C=C, C-O, C-H, and mineral groups. These modifications indicate an enhancement in the sorption capacity of Inceptisols treated with 40 t ha^{-1} YCWB. The glyphosate adsorption isotherms followed the sequence: Langmuir > Freundlich model, with performance ranking as soil + 40 t ha^{-1} YCWB > unamended soil (Inceptisols). The respective R^2 values were $R^2 = 0.9889 > R^2 = 0.9739$ for the Langmuir model and $R^2 = 0.9953 > R^2 = 0.9099$ for the Freundlich model, confirming a strong interaction relationship ($R^2 > 0.9$). This indicates that glyphosate removal occurs through simultaneous or alternating physical and chemical processes. Modifying the surface charge of Inceptisols using biochar-based amelioration technology derived from biomass waste, such as young coconut waste, is critical for improving glyphosate removal efficiency.

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1. INTRODUCTION

Unsustainable environmental management directly impacts ecosystem quality, particularly on agricultural land, leading to a decline in output quality. Effective agricultural environmental management begins with proper soil and crop inputs, including careful pesticide control. Pesticides must be used judiciously, as residues from active substances applied in agricultural areas can have harmful effects due to insufficient knowledge about proper dosage, timing, and application methods. The lack of management and control over the use of pesticides is evidenced by the results of research in Europe, which states that of 76 types of pesticides found, 83% are in the top soil, and even 53% of them leave residues of two or more active ingredients, and the highest concentration is glyphosate (Ahmad et al., 2024). A significant issue is the lack of awareness among farmers about the need to protect the environment from pesticide residue hazards, particularly glyphosate, a widely used herbicide (Sabran & Abas, 2021).

The annual global usage of glyphosate is estimated at 600,000–750,000 t, with projections suggesting an increase to 740,000–920,000 t by 2025 (Maggi et al., 2020). Glyphosate, also known as N-(phosphonomethyl) glycine or isopropylamine salt, is a systemic and non-selective herbicide. It is applied by spraying onto weed-infested soil surfaces, where it eventually enters water and soil systems. When glyphosate-contaminated soil is absorbed by plants, it can enter the food chain, posing a potential risk to human health. The World Health Organization (WHO) has identified

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glyphosate as potentially teratogenic and carcinogenic, with risks associated with its application and metabolite consumption in humans and cultivated plants (Costas-Ferreira et al., 2022). This contaminant's hydrophilic properties have resulted in its detection in surface water, effluents, groundwater, and agricultural products, particularly those in active agricultural areas. Although glyphosate is deemed relatively safe for human and aquatic health, its metabolite, aminomethylphosphonic acid (AMPA), is identified as significantly detrimental to both the aquatic ecosystem and human health upon exposure (Ogunbiyi et al., 2023).

Soil serves as a natural medium for absorbing dissolved pollutants, with its adsorption capacity influenced by clay content and soil organic matter. These two components contribute to the soil's adsorption capabilities. Inceptisols, a soil type frequently contaminated by pesticides, typically contain 14% clay and moderate organic matter concentrations (Muslim et al., 2020). This limits their ability to absorb significant amounts of pollutants. Consequently, biochar-based amelioration technology is used to enhance the adsorption capacity of Inceptisols for pesticides containing glyphosate. Diverse decontamination strategies involve the disintegration and dissolution of glyphosate into less harmful metabolites or its complete removal from soil, surface water, and drainage by both chemical and physical processes, including adsorption using biochar (Jia et al., 2020). Batch adsorption and isotherm studies were carried out to determine pH, reaction duration, and glyphosate dose. In addition, Langmuir and Freundlich adsorption isotherms were employed to calculate biochar equilibrium sorption values. The highest glyphosate absorption occurred at pH 4 and declined with increasing pH. The Freundlich model best fitted the equilibrium isotherm data, demonstrating that physisorption occurs on heterogeneous and amorphous biochar surfaces (Pereira et al., 2021).

Waste or biomass is pyrolyzed in environments with barely any oxygen to create biochar, which is a material rich in carbon (Ali et al., 2021). Biochar has numerous advantages, including negatively charged surfaces, functional groups, high specific surface area, big pore volume, and high cation exchange capacity (CEC) (Zhang et al., 2022). The physicochemical properties of biochar depend on the raw materials used and processing parameters such as technique, particle size, and temperature during pyrolysis (Ali et al., 2022).

Biochar derived from agricultural waste, such as young coconut waste, offers promising applications. Maulana et al. (2022) report that the Kon-Tiki method (deep-cone flame-curtain pyrolysis process) was used to pyrolyze young coconut waste biomass at 682 °C, yielding biochar with a yield ratio of 20.87% and an 81.27% water content. The biochar's properties included a pH of 10.82, liming potential of 5.50% $CaCO_3$, and proximate analysis values (38.80% moisture, 62.73% volatile matter, 19.50% ash, and 43.22% fixed carbon).

The biochar also exhibited a CEC of 45.71 Cmol kg^{-1}, cation bases (35.61 K and 13.13 Na-exch Cmol kg^{-1}), 0.035% inorganic carbon, and 1.43% organic carbon. Other analyses-

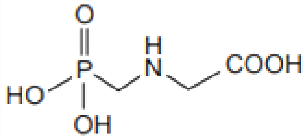


Figure 1. Chemistry arrangement of glyphosate (N-phosphonomethylglycine) (Patocka, 2018)

showed values such as 34.5% moisture, 57.77% volatile matter, 7.11% liming potential, and a particle size of less than 0.50 mm with a pH of 10.09. The optimal particle size for biochar is 0.5–2 mm (Lita et al., 2022). Young coconut waste biochar reduces environmental pollution from organic waste and offers sustainable potential for ameliorating soil. Research conducted by Kumari et al. (2016) proved that Birch wood biochar at the application of 10 t ha^{-1} and 50 t ha^{-1} increased the adsorption coefficient of glyphosate to 34% and 56%. According to the study Herviyanti et al. (2022) also found that rice husk biochar can improve the ability of Inceptisol in adsorbing glyphosate

The use of biochar from this under-researched material offers a diversified biochar material with dual functions as a soil ameliorant and pesticide adsorption agent, making an important contribution to sustainable tropical soil management. This study presents novelty in utilizing biochar derived from young coconut waste for ameliorating Inceptisols while enhancing the removal of glyphosate residues. The use of this underexplored biochar material offers a sustainable solution for organic waste management and tropical soil improvement, with significant relevance to mitigating pesticide impacts on the environment (Jagadeesh & Sundaram, 2023). This issue arises from the daily accumulation of ±7 tons of immature coconut waste in Padang, Indonesia, necessitating a solution.

Young Coconut Waste Biochar (YCWB) is a promising amelioration technology for improving the chemical characteristics of Inceptisols to enhance glyphosate adsorption. In the agricultural sector, this approach promotes sustainability. Soil and biochar, as geo-biosorbents, facilitate soil restoration and provide an economical solution while reducing the environmental impact of agricultural and industrial waste. This study aimed to evaluate the glyphosate removal capacity of Inceptisols from the horticultural production center of West Sumatra, Indonesia, ameliorated with young coconut waste biochar.

2. MATERIAL AND METHODS

The research was carried out in the Laboratory of Chemistry and Soil Fertility, Faculty of Agriculture, University of Andalas in Padang, Indonesia, from April to June 2021.

2.1. Soil samples and analyses

Soil samples were selected based on soil type and land use maps from the horticultural crop production center. The selected soil type belonged to the Inceptisols order (Fig. 2) and was collected from Sariak, Sungai Pua, Agam, West Sumatra, Indonesia, with GPS coordinates of 0°21’56’’ S and 100°24’0’’ E. Composite soil samples were taken from a depth of 0–20 cm, with three replications, and each sample weighed 1 kg per replication (Herviyanti et al., 2022).

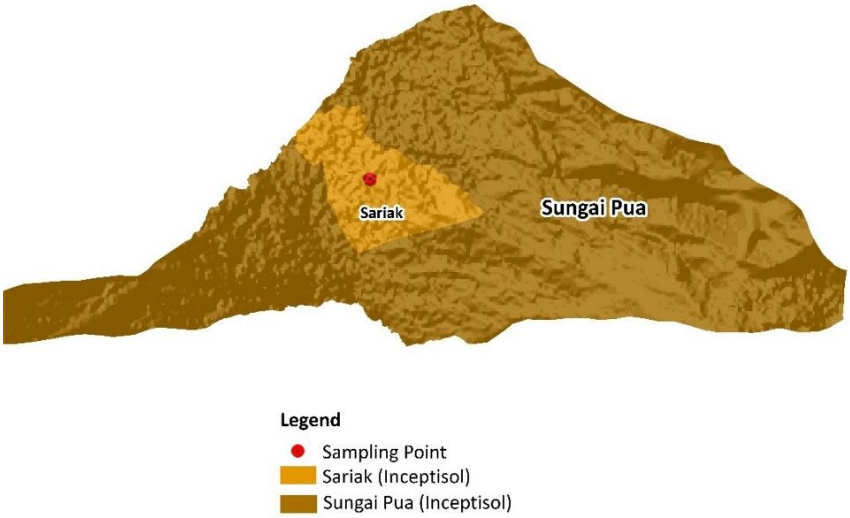


Figure 2. Map of soil types in Sariak district, Sungai Pua Agam Regency, West Sumatra, Indonesia

Table 1. Biochar derived from young coconut waste improves the surface charge change of Inceptisols

Soil	Clay	pH			Composition			
		H_2O	KCl	PZC	EC	Mineral	OM	CEC
	%		Unit		dS m^{-1}	%		Cmol kg^{-1}
Inceptisols	5.90	4.97	4.73	4.50	0.08	70.80	29.20	30.25
Inceptisols + 40 t ha^{-1} YCWB		5.93	5.00	4.07	0.15	60.87	39.13	55.11

Remarks: PZC = Point of zero charges; EC = Electrical conductivity; OM = Organic matter; CEC = Cation exchange capacity

The soil samples collected from the field were air-dried for a two-day period, thereafter pulverized, and separated through a 2-mm mesh. A 500 g absolute dry equivalent of the soil sample was weighed, mixed with 40 t ha^{-1} YCWB, and incubated for two weeks. After incubation, laboratory analyses were conducted. The soil analysis focused on evaluating surface charge activity for geo-biosorption (Inceptisols + YCWB) and sorption (Inceptisols alone) using the following parameters: clay content, pH (H_2O, KCl), point of zero charge (PZC), electrical conductivity (EC), cation exchange capacity (CEC), and mineral and organic matter (OM) composition (Maggi et al., 2020). The FTIR investigation utilized an ABB MB-3000 series spectrometer with a diamond internal reflection component (IRE) in absorbance mode. Spectral data were collected over a broad range from 485 to 8500 cm^{-1}, allowing for the detection of both mid- and near-infrared absorption bands. The instrument offers a high resolution of 0.7 cm^{-1}, with adjustable apodization resolution ranging from 1 to 64 cm^{-1} in 2 cm^{-1} increments, providing flexibility in spectral smoothing and detail preservation. A high signal-to-noise ratio of approximately 50,000:1 (RMS, 60 s, 4 cm^{-1}) ensures excellent spectral clarity. Signal digitization was carried out using a 24-bit analog-to-digital converter (ADC), ensuring high precision in data acquisition. The system demonstrates high stability, with short-term variability below 0.09%, temperature stability under 1% per °C, frequency repeatability better than 0.001 cm^{-1}, and frequency accuracy within 0.06 cm^{-1} at 1918 cm^{-1}.

2.2. Biochar production

Young coconut waste (*Cocos nucifera* L.) was chopped into pieces roughly 5 cm in size and dried for one week in the greenhouse of the Faculty of Agriculture, Andalas University, until the moisture level reached 18.20%. Biochar was then produced using the Kon-Tiki method, which employs a conical steel kiln with a top diameter of 100 cm, a height of 90 cm, a wall slope of 63.50°, and a capacity of 827 liters. Following pyrolysis, the resultant material was sprayed with water to stop the process of burning and then dried in an oven at 400°C for two days to guarantee homogeneous biochar water content. The biochar was next sieved utilizing an Electromagnetic Sieve Shaker EMS-8 with a 2.00 mm sieve to separate the particles by size (Lita et al., 2022; Maulana et al., 2022).

2.3. Glyphosate solution

Glyphosate solution was generated at five rates of concentration (0, 1, 5, 10, 50, and 100 mg L^{-1}) by dissolving the herbicide (Roundup) in 0.01 M calcium chlorite. To achieve a 100 mg L^{-1} glyphosate concentration, 0.19 mL of the herbicide was added to 750 mL of 0.01 M calcium chlorite. The 1, 5, 10, and 50 mg L^{-1} glyphosate solutions were prepared by adding 3.5, 17.5, 35, and 0.175 mL of the herbicide, respectively, to 0.5 L of 0.01 M calcium chlorite (Zhelezova et al., 2017).

2.4. Batch adsorption experiment

In a sealed 25 mL glass cylinder tube, 0.5 g of the adsorbent and 20 mL of glyphosate solution were mixed for the adsorption experiment in an isothermal test. Using glyphosate concentrations of 1, 5, 10, 50, and 100 mg L^{-1}, the mixture was agitated on a rotary shaker set to 250 rotations per minute (rpm) for 1 day at a room temperature of 25°C. After that, the samples were centrifuged (4000 rpm) for 30 minutes.

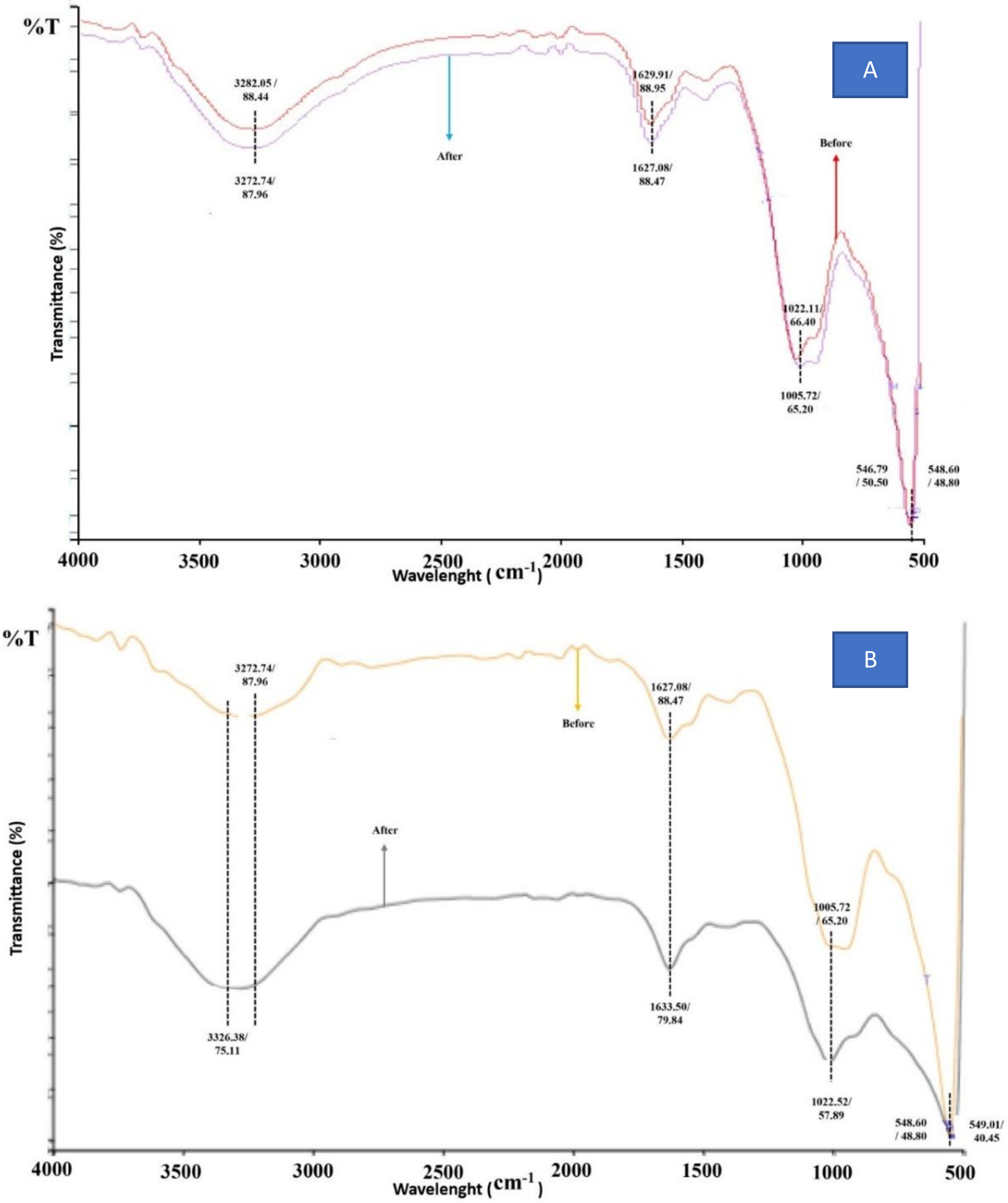


Figure 3. FT-IR spectra before and after adsorption, (A) Inceptisols and (B) Inceptisols ameliorated with YCWB

The pH of the filtrate and the equilibrium concentration of glyphosate left in the solution were measured using a UV-Vis spectrophotometer calibrated to 830 nm with a complexing agent (Yang et al., 2020). The adsorption capacity (Q_e) was calculated using Equation 1 to determine the total amount of glyphosate adsorbed by the various adsorbents.

$$Qe = \frac{(C0-Ce)*V}{m} \quad [1]$$

where Co (mg L^{-1}) indicates the initial glyphosate concentration and Ce (mg L^{-1}) equilibrium concentration after the adsorption process, m (g) indicates the mass of Inceptisol and Inceptisol + 40 t ha-1 YCWB, V (L) is the volume of the glyphosate solution, and Qe (mg kg^{-1}) is the adsorption capacity.

The experimental results were fitted to two isothermal models: Langmuir and Freundlich. The linearized forms of these models were used for the Freundlich (Eq. 2) and Langmuir (Eq. 3) adsorption isotherms (Chilev et al., 2022).

$$\text{Linear : } \log Q_e = \log K_F + n \log C_e \quad [2]$$

$$\text{Linear : } 1/Qe = 1/Kl*Qm * 1/Ce + 1/Qm \quad [3]$$

where Qm (mg kg^{-1}) is the amount of maximum adsorption capacity, KL is the Langmuir coefficient (L mg^{-1}), KF is the Freundlich affinity coefficient (mg Kg^{-1}) or adsorption capacity of the adsorbent, and n indicates a favorable adsorption process (n<1).

3. RESULTS

3.1. Characteristics of infrared spectroscopy

The FT-IR spectra obtained for Inceptisol and Inceptisol amended with 40 t ha^{-1} YCWB are shown in Figure 3 and Table 2. The application of 40 t ha^{-1} YCWB demonstrated its potential to improve the chemical characteristics of Inceptisol. The FT-IR spectrum of Inceptisol + 40 t ha^{-1} YCWB exhibited similar vibrations to those of Inceptisol; however, notable changes in transmittance were observed.

Table 2. Spectral band assignments of Inceptisol and Inceptisol ameliorated with YCWB, before and after adsorption

Before Adsorption		After Adsorption		
Soil	Soil + 40 t ha^{-1} YCWB	Soil	Soil + 40 t ha^{-1} YCWB	Description of Bond (Singh et al., 2017)
Wavenumbers / Transmittance (cm^{-1}/ %)				
3282.05/ 88.44	3270.11/ 91.07	3272.74/ 87.96	3326.38/ 75.11	v (OH) from sorbed water and hydrogen-bonded biochar –OH groups
1629.91/ 88.95	1628.93/ 88.83	1627.08/ 88.47	1633.50/ 79.84	H-O-H bending band of water v_2 mode and C=C: Alkene
1022.11/ 66.40	950.05/ 68.55	1005.72/ 65.20	1022.52/ 57.89	v (Si-O) from clay minerals associated with biochar
546.79/ 50.50	541.06/ 50.42	548.60/ 48.80	549.01/ 40.45	Mineral (e.g kaolinite, CaO, MgO, and others)

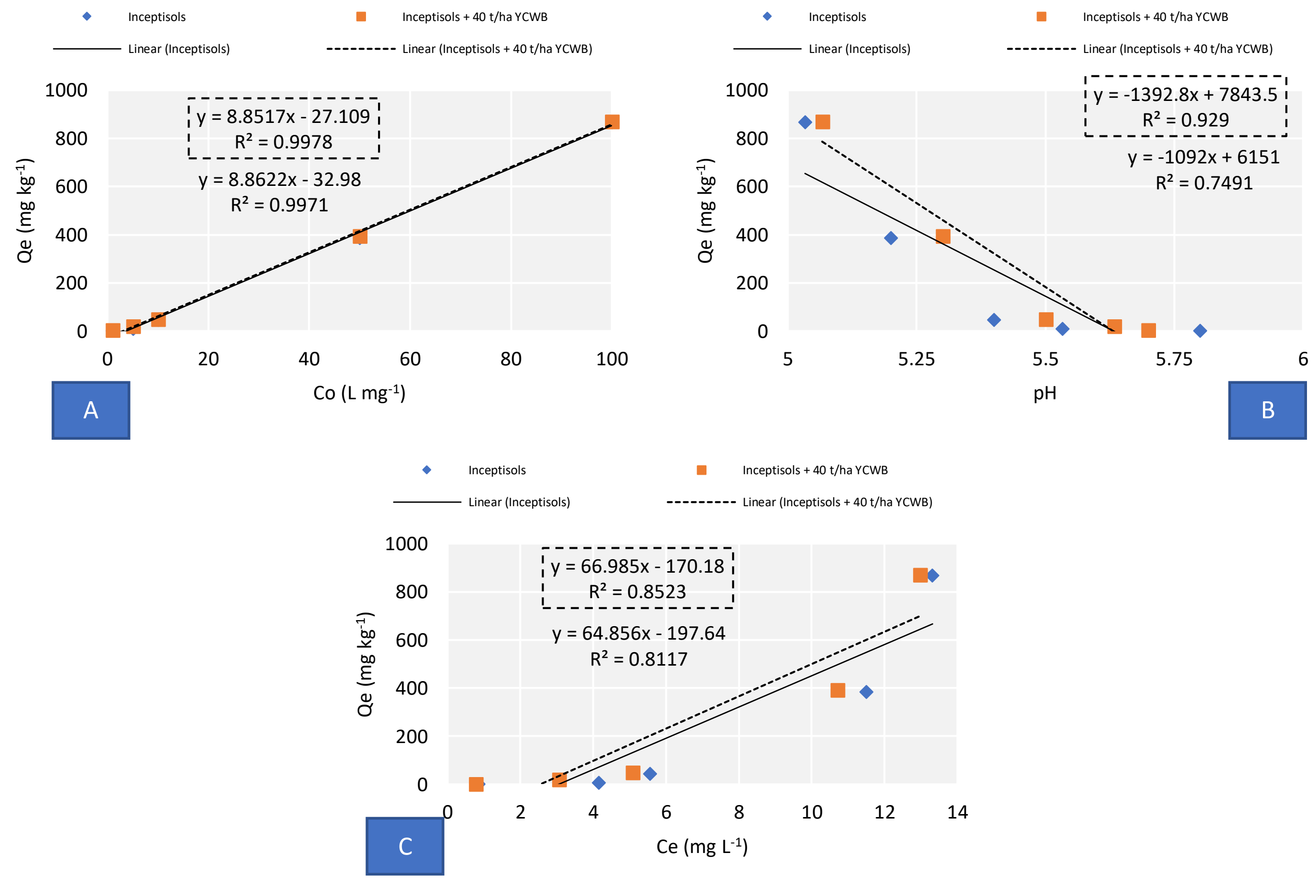


Figure 4. Linear plot of adsorption capacity with initial glyphosate concentration 1 to 100 mg L^{-1}. (A) pH adsorption (B) and equilibrium concentration (C_e) (C) on Inceptisol and Inceptisol + 40 t ha^{-1} YCWB

A decrease in transmittance was recorded in the absorption bands at 1629.91 cm^{-1}/88.95% to 1628.93 cm^{-1}/88.83% (H-O-H bending band of water, v_2 mode) and 546.79 cm^{-1}/50.50% to 541.06 cm^{-1}/50.42% (mineral), indicating an increase in adsorption capacity with the addition of 40 t ha^{-1} YCWB. Conversely, an increase in transmittance was observed in the absorption bands at 3282.05 cm^{-1}/88.44% to 3270.11 cm^{-1}/91.07% (v O-H from sorbed water and hydrogen-bonded biochar –OH groups) and 1022.11 cm^{-1}/66.40% to 950.05 cm^{-1}/68.55% (v (Si-O) from clay minerals associated with biochar).

Table 2 and Figures 3A and 3B further illustrate that the pesticide adsorption process influenced the changes in the absorption bands of the adsorbent during glyphosate adsorption. The FT-IR spectra of Inceptisol and Inceptisol + 40 t ha^{-1} YCWB exhibited a decrease in transmittance, indicating a significant increase in absorption intensity across several absorption bands, specifically in the v O-H from sorbed water and hydrogen-bonded biochar –OH groups; the H-O-H bending band of water (v_2 mode); C=C bonds within the solid carbon matrix of biochar; and the v (Si-O) from clay minerals associated with biochar and minerals.

3.2. Surface charge of Inceptisols ameliorated with biochar from young coconut waste

YCWB is utilized as an amelioration technology and adsorbent in glyphosate adsorption. The clay content of Inceptisol is 5.90%, which serves as the primary component influencing the surface charge of soil (Table 2). Clay minerals play a pivotal role in soil surface charge activity (Preocanin et al., 2016). Table 1 indicates the pH of Inceptisol in H_2O and KCl as 4.97 and 4.73, respectively. Following the application of 40 t ha⁻¹ YCWB, the pH was enhanced by 0.96, reflecting an enhancement in surface charge activity, which supports the soil's adsorption process. The ΔpH increased by 1.40 after the YCWB application, indicating a dominance of negative charges in the soil. A positive ΔpH value implies a prevalence of negative net charges in soil colloids, whereas a negative ΔpH reflects positive net charges (Herviyanti et al., 2022).

The soil's electrical conductivity (EC) increased from 0.08 to 0.15 dS m^{-1} after applying 40 t ha^{-1} YCWB. Biochar ash has many cations, and its incorporation into the soil will elevate soil salinity and induce a fast rise in soil EC (Khadem et al., 2021). The YCWB application also raised the soil's cation exchange capacity (CEC) by 24.86 Cmol kg^{-1} (Table 1). The robust adsorption of H^+ and OH^- ions affects the adsorption process by dissociating functional groups on the adsorbent's active sites, hence altering the kinetics and equilibrium properties of the reaction (Nayak et al., 2024). The increase in EC is associated with biochar's negative surface charge, enabling it to interact with single-charged ions in the soil, thus generating an external electric field (Tan et al., 2020). Changes in the electrochemical characteristics of clays, including their charge and composition, are directly affected by the quantity of aluminum hydroxy complexes present. The Al-hydroxy group, found in partially neutralized Al ion solutions used to coat clays, contributes to varying charge characteristics. The effect of interlayer quantities on the CEC also influences the zero charge point of each adsorbent during the adsorption process.

The mineral composition and soil organic matter (SOM) change with the integration of organic or inorganic materials through amelioration. The application of 40 t ha^{-1} YCWB on Inceptisol reduced ash content while increasing SOM by approximately 9.93%. Organic matter can influence soil pH and the zero-point charge through the ionization of organic compound functional groups. Surface charge activity is critical in the adsorption mechanism, as it determines the nature of the charge on the ameliorant surface at specific pH levels and its interaction with glyphosate. The analysis of pH values helps describe surface charge activity and the net positive or negative charge based on the ratio of soil pH in H_2O to pH in KCl (ΔpH). A positive ΔpH indicates a dominance of negative charges on the soil colloidal surface, whereas a negative ΔpH indicates a dominance of positive charges (Table 2).

3.3. Glyphosate adsorption behavior

The initial concentration of glyphosate (C_o) in this experiment decreases as the equilibrium concentration (C_e) is measured. The equilibrium concentration serves as a benchmark for determining the amount of glyphosate not adsorbed by Inceptisols and Inceptisols + 40 t ha^{-1} YCWB. As shown in Figure 4, the relationship between Q_e and C_o is directly proportional, with a stronger correlation observed for Inceptisols + 40 t ha^{-1} YCWB (R^2=0.9978) compared to Inceptisols (R^2=0.9971). Similarly, the relationship between Q_e and C_e also shows a stronger correlation for Inceptisols + 40 t ha^{-1} YCWB (R^2=0.8523) than for Inceptisols (R2=0.8117). Conversely, the relationship between Q_e and the glyphosate adsorption pH is inversely proportional, with Inceptisols + 40 t ha^{-1} YCWB (R^2=0.929) exhibiting a stronger correlation compared to Inceptisols (R^2=0.7491).

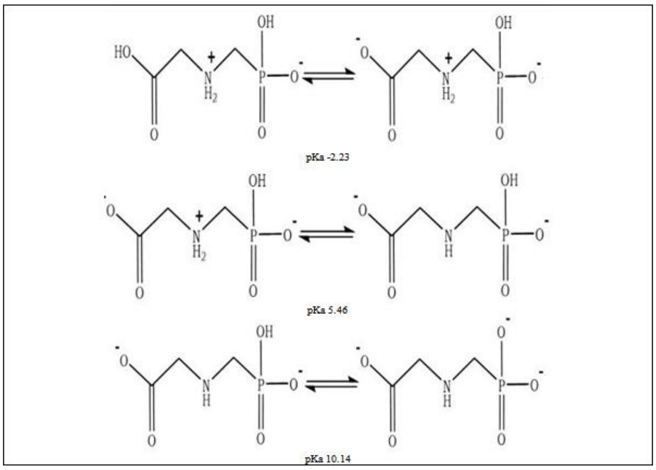


Figure 5. The ionic state of glyphosate as a function of pH (Wetzel et al., 2021)

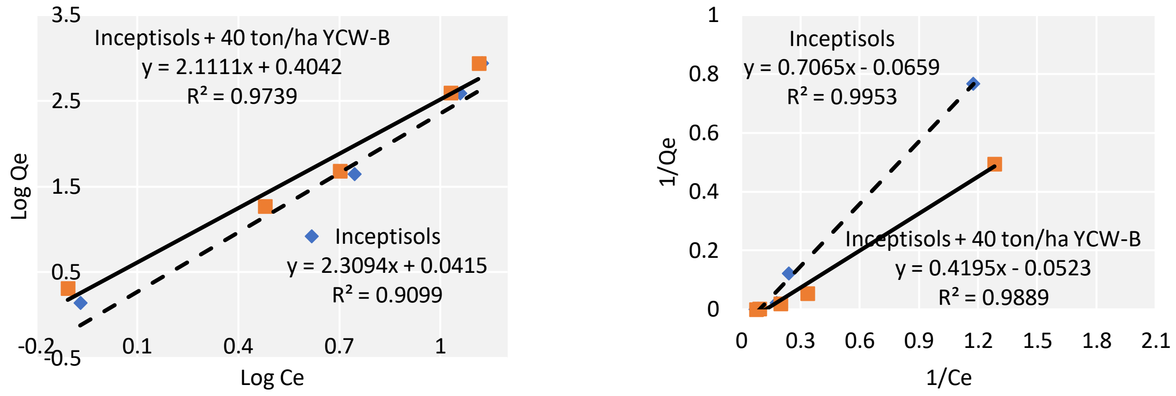
3.4. Adsorption isotherms

The R^2 value is used to determine which isotherm model best fits the linear model and is appropriate for the adsorption mechanism. Figure 6 and Table 3 display the parameters of the linear isotherm model. The R^2 values for the Freundlich and Langmuir linear models (Table 3) are comparable for both Inceptisol and Inceptisol + 40 t ha^{-1} YCWB. The R^2 values for each model can be arranged as follows: Langmuir (Fig. 6B) > Freundlich (Fig. 6A) for Inceptisol + 40 t ha^{-1} YCWB > Inceptisol, with R^2 = 0.9889 > R^2 = 0.9739 and R^2 = 0.9953 > R^2 = 0.9099, respectively. Figure 6B shows that the Langmuir linear model is dominated by the adsorption process of glyphosate in soil treated with Inceptisol + 40 t ha^{-1} YCWB, with Qm (19.12 mg kg^{-1}) and KL (0.15 L mg^{-1}) (Table 3).

In contrast, the Freundlich model (Fig. 6A) is dominated by the adsorption process of glyphosate in Inceptisol + 40 t ha^{-1} YCWB, with n (0.47) and KF (2.54). The mechanism of glyphosate adsorption in both treatments can be predicted using the Freundlich and Langmuir isotherms. The isotherm model with the closest R^2 value to 1 is best appropriate for the adsorption process. A higher R^2 value indicates a more accurate prediction model for the research being conducted (Ayawei et al., 2017).

4. DISCUSSION

The ability of soil to adsorb glyphosate is seen from the value of its adsorption capacity (Qe). The higher Qe value indicates an increase in adsorption that occurs in the soil, namely the soil ameliorated with YCWB. The low equilibrium concentration indicates an increasing adsorption capacity (Qe) for all treatments (Fig. 4C). This is due to the input of biochar as an ameliorant that can increase soil organic matter and can further increase PZC and CEC in Inceptisol. Organic matter and clay contain minerals and functional groups that can improve the negative charge on the soil.



(A) (B)

Figure 6. Freundlich (A) and Langmuir (B) isotherms for glyphosate adsorption with Inceptisols improved with YCWB

Table 3. Recapitulation of the Freundlich (A) and Langmuir (B) isotherms characteristics of glyphosate adsorption in Inceptisols ameliorated with YCWB

Models	Adsorben	Linear Parameters		
		n	K_F	Equational
Freundlich	Inceptisols	0.43	1.10	y = 2.3094x + 0.0415; R^2 = 0.9099
	Inceptisols + 40 t ha^{-1} YCWB	0.47	2.54	y = 2.1111x +0.4042; R^2 = 0.9739
		Q_m (mg kg^{-1})	K_L	Equational
Langmuir	Inceptisols	15.17	0.09	y = 0.7065x - 0.0659; R^2 = 0.9953
	Inceptisols + 40 t ha^{-1} YCWB	19.12	0.15	y = 0.4195x - 0.0523; R^2 = 0.9889

Remaks : Freundlich : [n = 1/b; $K_F = 10^a$] and Langmuir : [Q_m = 1/a; $K_L = (1/b)/Q_m$]

In the soil, biochar undergoes various oxidation processes that enhance oxygen-containing functional groups on the charcoal surface, such as phenol and carboxyl groups. As a result, biochar may have more glyphosate adsorption sites than fresh biochar. This explains how the incubation process of biochar in the soil causes variations in soil chemical characteristics, such as pH, CEC, and SOM (Table 2), as well as changes in functional groups before and after adsorption (Table 1 & Fig. 2). Biochar can enhance pH, CEC, and SOM due to an increase in negative charge provided by the OH and COOH groups and biochar's high carbon content (22–52%) (Domingues et al., 2020). This has a significant impact on the glyphosate adsorption capability in Inceptisol + 40 t ha^{-1} RHB (Herviyanti et al., 2022). The high frequency of soil + biochar interactions at higher levels of biochar application, including absorption sites in clay and amorphous oxides, plays an essential role in biochar + soil interactions in the glyphosate adsorption mechanism (Murtaza et al., 2023).

In the adsorption process, molecules or ions of the sorbate are bound by reactive particle surfaces, such as hydroxyl groups or other groups of the sorbent. Ions or pollutant molecules bind to the surface of soil particles via hydroxyl or other groups, either on the surface of mineral crystals, by organic substances, or through isomorphic substitution into the crystal structure or between crystal layers. During adsorption, the three phosphonate groups can form a surface complex and collaborate with OH, O, NH, and P with the adsorbent surface (Tévez & Afonso, 2015). This is influenced by the density of the adsorbent's active site (negative charges) and the specific surface area, which can influence glyphosate adsorption capacity. Adsorption may have increased due to an increase in surface area, and thus, the number of active sites (Adeyemo et al., 2017).

These negative charges bind with positive charges on glyphosate, resulting in electrostatic interactions or ionic bonding. Furthermore, this ability occurs due to biochar's high elemental content, wide specific surface area, multifaceted pore structure, and attraction to electricity (Ai et al., 2023; Du et al., 2023). The adsorption capacity of Inceptisol, which was ameliorated with 40 t ha^{-1} B-YWC, increased due to the role of biochar, which produces –OH (hydroxyl) groups capable of binding to amine groups in glyphosate. This is related to the decrease in pH (Fig. 4B) that occurred in the Inceptisol treatment ameliorated with YCWB, but the Qe value or adsorption capacity increased. this is because at low pH, the amine group can be protonated to -NH_3^+, thus giving glyphosate cationic properties. This group allows interaction with negatively charged soil surfaces (organic matter or clay).

The pH value of the glyphosate adsorption solution is particularly significant to examine, as it specifies the charge form of glyphosate. Glyphosate is a polar molecule influenced by pH, composed of three polar functional groups: carboxymethyl, amine, and phosphonomethyl, arranged linearly (Fig. 1) (Galicia-Andrés et al., 2021). Due to these groups, glyphosate is an ionic, highly polar molecule that is soluble in water (10.5 g L^{-1} at 20°C) with a log K_oW = 3.20. Glyphosate is a polyprotic acid with pKa values: 0.7, 2.2, 5.9, and 10.6, indicating that pH affects the molecule's speciation (Sidoli et al., 2016; Tzanetou & Karasali, 2022). Therefore, since glyphosate is amphoteric, the acidic condition shown when adsorption occurs indicates that the dominating charge is a positive charge due to protonation or the removal of hydrogen ions (H^+) from the soil solution. This protonation causes the glyphosate molecule to carry a positive charge. At low/acidic pH, there will be many H^+ protons attracted to NH_2 to form protonated amines (NH_3^+). The evidence of the interaction between adsorbent and adsorbate through hydrogen bonding and changes in chemical structure can be seen from the shift and change in intensity of the spectrum from before and after adsorption in Figure 3 and Table 2. Adsorption is indicated by a shift in frequency and a change in intensity in spectra (Şenol & Şimşek, 2020). Inceptisol ameliorated with YCWB 40 t ha^{-1} shows a shift and a greater change in intensity than the treatment of Inceptisol that is not ameliorated. therefore, through FTIR analysis, it strengthens the statement that YCWB can increase the ability of inceptisol to adsorb glyphosate.

Determining the behavior and strength of adsorption is done by finding the isotherm model that is suitable for the treatment through modeling with the Freundlich and Langmuir equations. The interaction strength of the Freundlich and Langmuir isotherms is strong, with R^2 > 0.9, indicating that both physical and chemical adsorption processes occur simultaneously or alternately. The adsorption process initially takes place on the soil pores' surface, where biochar gets trapped and subsequently undergoes a chemical reaction to cause adsorption. According to the Langmuir model, glyphosate and soil combine to form a monolayer during the period of adsorption. The soil surface is uniform, all sites are identical, and the heat of adsorption is independent of the closure of surface active sites (El Zrelli et al., 2021). The Freundlich model demonstrates that the heterogeneous soil surface produces a multilayer between glyphosate molecules and the soil surface. The adsorption process occurs when substances in the form of ions or compounds from the sorbate in a non-ionic solution are brought to the active or reactive sites of the particles or soil colloids. The thin layer of water that adheres to and surrounds the soil particles, as well as the space between layers or the hydrated part within the particles, is a location where the concentration of sorbate or ions is relatively low due to continuous adsorption.

The potential for environmental pollution by glyphosate is predicted from the value of the maximum adsorption (Qm) and the Langmuir coefficient (KL). The adsorption coefficient and maximum affinity determine how likely glyphosate is to pollute the environment by affecting its binding energy. The Qm and KL values for Inceptisol are lower than for Inceptisol + 40 t ha^{-1} YCWB, indicating that Inceptisol is more susceptible to environmental pollution when exceeding its maximum adsorption capacity. Therefore, it is necessary to add young coconut waste biochar. A lower affinity coefficient indicates lower bond energy in the herbicide, meaning more herbicide remains in the soil solution and is not adsorbed by soil colloids, resulting in increased mobility of glyphosate in aquatic systems and water sources.

5. CONCLUSION

At a glyphosate concentration of 100 mg L^{-1}, Inceptisols improved with 40 t ha^{-1}. YCWB increased their surface charge (pH, EC, CEC, and OM), with an adsorption capacity of 0.87 mg g^{-1} or 870.27 mg kg^{-1} at pH 5.07. Glyphosate removal was corroborated by changes in functional groups, where FT-IR analysis showed a reduction in transmittance of O-H, C=C, C-O, C-H, and mineral groups. This indicated a boost in the capacity to adsorb of Inceptisols amended with 40 t ha^{-1} YCWB. The glyphosate adsorption isotherms followed the sequence: Langmuir > Freundlich model, with soil + 40 t ha^{-1} YCWB > soil (Inceptisols), with respective values of R^2 = 0.9889 > R^2 = 0.9739 and R^2 = 0.9953 > R^2 = 0.9099. This confirms that the interaction relationship is very strong (R^2 > 0.9), indicating that the glyphosate removal process occurs simultaneously or alternately through both physical and chemical mechanisms. Modification of Inceptisol surface charge through biochar-based amelioration technology, using biomass waste (e.g., young coconut waste), is crucial in enhancing glyphosate removal capability.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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