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Enhanced Glyphosate Adsorption in Inceptisols Ameliorated with Compostchar Derived from Closed-House Chicken Litter

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ABSTRACT

Glyphosate contamination in horticultural land, particularly in Inceptisols with low adsorption capacity, necessitates effective amelioration strategies using closed-house chicken litter (CHCL). This study evaluated the adsorption capacity of CHCL-derived compostchar in ameliorated Inceptisols using a completely randomized design (CRD) with three replicates and batch equilibrium methods modeled by the Freundlich and Langmuir isotherms. Compostchar application significantly enhanced soil quality and glyphosate capacity. Incorporation of biochar improved chemical stability and physical properties, as indicated by reduced volatile matter (VM) and increased bound carbon, ash content, pH, electrical conductivity (EC), and cation exchange capacity (CEC). Compared to 15% biochar, the 80% CHCL + 20% biochar-CHCL formulation exhibited superior performance, producing a more stable aromatic carbon structure, improved pore distribution, and a higher density of active sites in increased maximum adsorption capacity (6248.36 mg g^{-1}) and consistently high sorption efficiency (≈70–92%) across concentrations. Additionally, compostchar application increased soil pH by 0.75, point of zero charge (PZC) 0.40, and EC by 0.13 dS m^{-1} compared to the control. These findings indicate a synergistic enhancement of physicochemical interactions between soil-ameliorant and glyphosate. Thus, the 80% CHCL + 20% biochar formulation is suggested as a successful method to enhance soil quality and pesticide retention.

1. INTRODUCTION

One of the most popular herbicides in contemporary agriculture is glyphosate, mainly due to its broad-spectrum efficacy, rapid action, and relatively low cost. Since the introduction of glyphosate-tolerant crops, global use of this herbicide has increased significantly, making it the dominant weed control tool in agricultural systems worldwide [1]. Glyphosate is thought to have a moderate half-life; however, soil factors, including pH, organic matter, microbial activity, and mineralogy, greatly influence how quickly it breaks down [2]. In soils with low organic carbon, such as tropical Inceptisols, glyphosate can persist longer and exhibit increased mobility, raising concerns about potential groundwater contamination [3]. This challenge highlights the importance of soil amelioration approaches that can enhance glyphosate uptake and transformation while improving overall soil quality. Inceptisols are one of the most widespread soil orders in tropical countries such as Indonesia and are characterized by minimal horizon development, low soil organic matter content, moderate cation exchange capacity (CEC), and structural instability [4].

These characteristics make Inceptisols susceptible to agrochemical contamination due to their limited capacity to retain organic pollutants. Although glyphosate binds strongly to Fe and Al oxides, low organic matter content and weak aggregation reduce the adsorption capacity of Inceptisols, especially under high rainfall conditions that are common in tropical climates [5]. Increasing the organic matter content and physicochemical properties of the soil through organic amendments is essential to improve glyphosate retention and reduce environmental risks. Compost and biochar have been extensively explored as soil ameliorants to improve soil structure, nutrient availability, and contaminant adsorption. Compost increases microbial activity, enhances nutrient content, and improves CEC, while biochar provides a stable carbon-rich matrix with a large surface area and functional groups that can strongly adsorb pesticides [6].

The integration of compost and biochar formulated in the composting process supplies labile nutrients and microbial populations, while biochar contributes to structural stability and strong adsorption capacity. The combination of compost and biochar into a single composite material (compostchar) has received increasing attention due to its synergistic effects on soil improvement and contaminant adsorption [7]. However, limited nutrient availability and relatively low biological activity limit its effectiveness alone. In contrast, compost is rich in readily available nutrients and an active microbial community but is prone to rapid mineralization and lacks structural stability [8]. The combination of these two materials creates a functional composite in which biochar acts as a stable matrix that retains nutrients and provides a habitat for microorganisms, while compost contributes labile organic matter and abundant functional groups, which are essential for chemical adsorption mechanisms. This synergistic interaction enhances the CEC, improves soil pH buffering, and increases the abundance of reactive sites, significantly enhancing the adsorption of organic contaminants such as glyphosate [9].

The integration of compost and biochar into a composite material (compostchar) is an effective approach to improving soil quality and remediating contaminants through synergistic interactions. Compost provides labile nutrients and an active microbial community, while biochar provides high surface area, structural stability, and strong adsorption capacity [8]. Individually, biochar is limited by low nutrient availability, while compost is prone to rapid mineralization. Integrating the two overcomes these constraints, as biochar acts as a stable matrix that enhances nutrient retention and microbial habitat, while compost contributes labile organic matter and oxygen-containing functional groups that promote adsorption processes [7]. Biochar can effectively absorb pesticides such as glyphosate due to its porous structure and diverse functional groups [10, 11]. Conversely, compost has been associated with increased pesticide degradation through stimulation of microbial activity and provision of a nutrient-rich environment for biodegradation [12]. This synergy improves key soil properties, including CEC, pH buffering, and reactive adsorption sites, thereby enhancing the retention of organic contaminants such as glyphosate [9].

Closed-house chicken litter (CHCL) systems are a promising feedstock due to their high nutrient content and mineral-rich composition, which supports the formation of functional groups and consistent biochar quality. One of the most promising raw materials for compost and biochar production is chicken litter, especially from modern poultry farming systems in closed houses. CHCL contains N, P, organic C, and high levels of mineral-rich ash, making it an ideal substrate for composting and pyrolysis [13]. Given the rapid growth of chicken litter waste poses a significant environmental challenge if not properly managed. Converting this waste into compost is a sustainable strategy for turning waste into a resource that is in line with the principles of the circular economy and provides potential material for soil improvement and contaminant remediation [14].

Biochar adsorbs pesticides through electrostatic interactions and surface complexation, while compost enhances biodegradation through microbial activity. Despite extensive studies on biochar and compost for pesticide remediation, their applications have been largely investigated in isolation, with limited attention to their integration as a single composite material. Existing studies predominantly emphasize either the adsorption capacity of biochar or the microbial-driven degradation facilitated by compost, leaving the synergistic interactions within compost char systems insufficiently understood. In particular, the mechanisms governing glyphosate retention, such as ligand exchange, hydrogen bonding, and electrostatic interactions, remain poorly elucidated in composite matrices that simultaneously involve physicochemical and biological processes. Moreover, there is a notable lack of studies conducted under tropical soil conditions, especially in Inceptisols characterized by low organic matter and weak adsorption capacity. This study investigates compostchar derived from CHCL as a multifunctional amendment, aiming to elucidate the coupled adsorption–biodegradation mechanisms and evaluate its effectiveness in enhancing glyphosate retention in tropical soils. This work provides new insights into the design of integrated soil amendments while offering a sustainable strategy for agricultural waste valorization and pesticide mitigation. Therefore, this study aimed to systematically evaluate the physicochemical characteristics and adsorption performance of compostchar derived from CHCL. Specific indicators assessed included pH, CEC, elemental composition, and functional group abundance. Glyphosate adsorption capacity was analyzed using equilibrium isotherm models (Langmuir and Freundlich). Furthermore, the effectiveness of compostchar was examined under tropical Inceptisol conditions to evaluate its potential for soil surface charge changes.

2. MATERIAL AND METHODS

This research was conducted based on laboratory analysis from April to October 2025 at the Soil Chemistry and Fertility Laboratory, Department of Soil Science and Land Resources, Faculty of Agriculture, and the Central Laboratory, Andalas University, West Sumatra, Indonesia.

2.1 Compostchar production

The raw material used to make biochar-enriched compost is CHCL systems obtained from a broiler farm in Payakumbuh, West Sumatra, Indonesia. The CHCL is then air-dried and sieved through a 2 mm sieve. The fine fraction is used as the primary composting material, while the coarse fraction is used as the raw material for char production. The char process involves placing the CHCL used to make biochar in an oven. The temperature is set at 250 °C for 60 minutes through the torrefaction process. Once all the raw materials have been burned to form char, they are removed from the oven and slowly doused with water until the flames are extinguished and the smoke is gone. The char is then calculated and weighed according to the formulation requirements. Compost is made by mixing the CHCL and biochar from CCW (B-CHCL) according to the specified formula: 95% CHCL + 5% B-CHCL; 90% CHCL + 10% B-CHCL; 85% CHCL + 15% B-CHCL, and 80% CHCL + 20% B-CHCL.

Composting involves 200 g of *Tricoderma* sp. per 5 kg of raw material as a decomposer and 1 liter of sugarcane juice as molasses, which are mixed thoroughly in a composting container. The composting process was carried out in a simple reactor consisting of a used polypropylene (PP) paint bucket with a capacity of approximately 25 kg that had been cleaned and dried to remove residual contaminants. The inside of the container was lined with black polyethylene (PE) plastic with a thickness of approximately 0.05–0.1 mm to minimize direct interaction with the container walls and maintain humidity and temperature stability. The reactor was operated under semi-aerobic conditions with a modified bucket cover by adding aeration holes with a diameter of approximately 0.5–1 cm on the top and sides of the container (3 points), which were covered with fine-pored nylon gauze (mesh < 1 mm) to allow gas exchange without the entry of external contaminants. The container was placed in a controlled environment (25 ℃), protected from rain and direct sunlight, and periodically stirred every 7 days to maintain homogeneity and oxygen distribution. This system design allows for consistent control of key parameters such as temperature and pH, thus supporting a stable and reproducible decomposition process at the laboratory scale. Mature compost is characterized by a blackish color resembling humus, a fine or crumbly texture, a stable temperature, and an odorless appearance.

The compost is ready for harvest, air-dried, and samples are taken for chemical analysis in the laboratory. Laboratory analysis in determining the characterization of compostchar to be carried out includes: proximate, pH, electrical conductivity (EC), cation exchange capacity (CEC), C in/organic, total N, and ratio C/N. The oxide composition was analyzed using X-ray fluorescence (XRF; Bruker S6 Jaguar) on samples that had been dried at 60–70 ℃ to constant weight, then ground and homogenized (2 mm~10 mesh). Functional group identification was performed using Fourier Transform Infrared Spectroscopy (FTIR; Shimadzu Tracer-100) with spectrum recording in the range of 4000–400 cm^{-1}. Surface morphology and elemental composition analysis were performed using a Scanning Electron Microscope equipped with Energy Dispersive X-ray (SEM-EDX; Carl Zeiss EVO 10), where the dried samples were mounted on an aluminum stub using carbon tape and coated with a thin conductive layer (Au/Pd) via sputter coating to enhance conductivity. Observations were made at an acceleration voltage of 10–20 kV [15].

2.2 Soil samples and analysis

Soil samples were collected from Nagari Sariak, Sungai Pua, Agam, West Sumatra, Indonesia, with GPS coordinates 0°21′56″ S and 100°24′0″ E. Composite soil samples were taken from a depth of 0–20 cm, with three replicates, and each sample weighed 1kg per replicate [16]. Soil samples collected from the field were air-dried for two days, then ground and sieved through a 2 mm sieve. A total of 500 g of the absolute dry equivalent of the soil sample was weighed, mixed with 40 tons ha^{-1} of selected compostchar, and incubated for two weeks. After incubation, laboratory analysis was performed. Soil analyses evaluated surface charge properties relevant to sorption in Inceptisols amended with compostchar, including pH (H_2O and KCl), point of zero charge (PZC), EC, mineral composition, organic matter (OM) content, and CEC [17].

2.3 Glyphosate solution

Glyphosate solutions were prepared at five concentration levels (1000, 2000, 3000, 4000, and 5000 mg L^{-1}) by dissolving the herbicide (Roundup 480 SL) in 0.01 M $CaCl_2$. Glyphosate concentrations of 5000–1000 mg L^{-1} were calculated by dissolving 1.4, 1.1, 0.8, 0.6, and 0.3 mL of Roundup 480 SL into a 100 mL volumetric flask containing 0.01M $CaCl_2$, respectively [18].

2.4 Glyphosate adsorption

Glyphosate adsorption focused on isothermal adsorption using the batch equilibrium method. The adsorbent, 0.5 g of Inceptisols ameliorated with 40 ton ha^{-1} compostchar, was weighed and mixed with 20 mL of glyphosate solution with a concentration of 1000-5000 mg L^{-1} in a 25 mL measuring cylinder. Isothermal adsorption was carried out for a contact time of 1 × 24 hours using a rotary shaker at 300 rpm and a temperature of 25 ℃ in a laminar flow chamber. The adsorption pH was determined after the contact time at each concentration. The equilibrium filtrate concentration of glyphosate was measured using HPLC with a C18 column at 25 ℃ with an injection volume of 20 µL at a wavelength of 200 nm with a mobile phase consisting of distilled water and acetonitrile. The adsorbed glyphosate was calculated using Eqs. (1)-(3) [5].

$$Q_e = \frac{(C_0 - C_e)V}{m} \tag{1}$$

$$R = \frac{(Co-Ce)}{Co} \times 100\% \tag{2}$$

$$K_d = \frac{Qe}{Ce} \tag{3}$$

where, C_0 (mg L^{-1}) = initial adsorbate concentration; C_e (mg L^{-1}) = equilibrium concentration; R (%) = removal efficiency; Qe (mg g^{-1}) = adsorption capacity; m (g) = mass of adsorbent and V (L) = solution volume; R = adsorption efficiency (%) and K_d = adsorption coefficient (L g^{-1}).

The adsorption isotherm model used consists of a two-parameter isotherm model (the Freundlich and Langmuir). The adsorption isotherm model uses a non-linear model (Eqs. (4) and (5)) [19].

$$Qe = K_F C_e^{1/n} \tag{4}$$

$$Qe = \frac{Q_m K_L C_e}{1 + K_L C_e} \tag{5}$$

where, C_e (mg L^{-1}) = equilibrium concentration; Q_e (mg g^{-1}) = adsorption capacity; K_F = Freundlich adsorption capacity constant; K_L = Langmuir constant (L mg^{-1}), and Q_m = maximum adsorption capacity (mg g^{-1}).

2.5 Data analysis

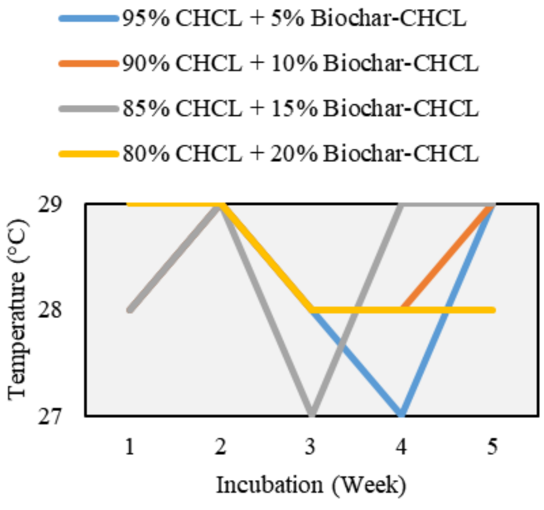
The batch equilibrium method was used to explain the mechanism for determining the application and stability of the adsorption process. The soil analyses were subjected to statistical analysis using software (Microsoft Excel 2016 and SPSS 23). Statistical analyses were performed using one-way analysis of variance (ANOVA), followed by Duncan's multiple range test (DMRT) as a post hoc procedure when significant effects were detected. Differences among treatment means were evaluated at two significance levels, $\alpha = 0.05$ and $\alpha = 0.01$. Results were considered significant at $p < 0.05$ and highly significant at $p < 0.01$, denoted by * and **, respectively. These annotations indicate the level of statistical significance among treatment means as determined by ANOVA and subsequent DMRT.

3. RESULTS AND DISCUSSION

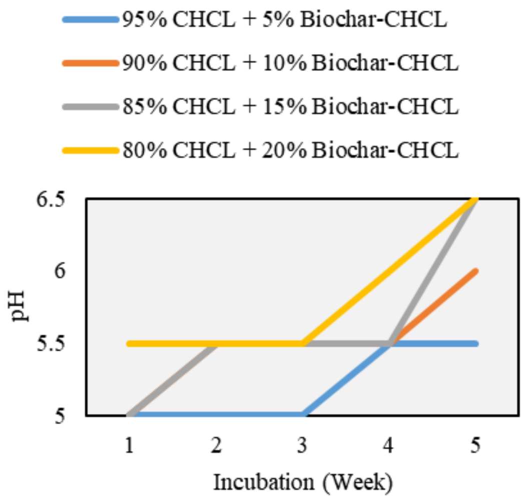
3.1 Characteristics of compostchar from closed-house chicken litter

The temperature in the CHCL systems composting formulation with the addition of biochar at various concentrations (5–20%) was in the range of 27–29 °C for five weeks. This pattern indicates that the process took place in the mesophilic phase without reaching the thermophilic phase (40–60 °C), which is usually required for intensive decomposition and pathogen inactivation. This stable and low temperature may be due to low microbial activity, relatively stable initial materials, lack of aeration, or suboptimal humidity. The increase in temperature during composting is highly dependent on microbial activity and physical conditions such as aeration and moisture. The temperature does not increase, and the biological decomposition process proceeds slowly. Furthermore, biochar itself is biologically inert and does not contribute to temperature increase, so differences in biochar concentration did not show a significant effect on temperature patterns [20].

Failure to reach the thermophilic phase (>45–55 °C) during CHCL composting in a closed greenhouse system indicates that the metabolic heat generated by microorganisms is insufficient to offset heat loss from the system. This condition is generally associated with a low initial C/N ratio due to the high nitrogen content of CHCL (Figures 1 and 2), which reduces microbial metabolic efficiency and increases nitrogen loss through ammonia volatilization. Furthermore, excess moisture, low porosity, limited aeration due to material compaction, and small pile volume can accelerate heat loss and inhibit temperature accumulation. Improperly formulated additives, such as biochar, also affect substrate balance and oxygen transfer. In particular, biochar is relatively resistant to biodegradation, which can reduce the intensity of initial decomposition and reduce peak temperatures when dosages are too high. Failure to reach the thermophilic phase has direct implications for the quality of the resulting compost. Lower temperatures generally reduce the efficiency of biological sanitation, slow the degradation of resistant organic compounds such as lignocellulose, and prolong the composting time. As a result, the final product potentially has high residual biological activity, an unstable C/N ratio, a greater risk of phytotoxicity, and a higher likelihood of pathogens than compost that has reached the optimal thermophilic phase. However, these conditions can also provide the advantage of better nitrogen retention due to lower NH_3 losses at moderate temperatures [21].



(a)



(b)

Figure 1. Temperature (a) and pH (b) profiles during composting of closed-house chicken litter (CHCL) systems under different formulations

All composting formulations showed an initial value of around pH 5, then gradually increased to pH 6–6.5 at the end of incubation. This pattern is consistent with the normal composting process, where the pH tends to be low in the early phase due to the formation of organic acids by microbes and increases as these acids degrade and more alkaline compounds such as ammonia are formed. The slightly higher pH increase with 20% biochar is consistent with the characteristics of biochar, which is generally alkaline and capable of increasing the buffering capacity in compost. Therefore, it can be concluded that biochar affects pH stabilization but not temperature. Overall, the composting process in this study took place at a low level of biological activity, but showed a tendency towards chemical stability through an increase in pH, although it did not reach optimal maturation as indicated by the thermophilic phase.

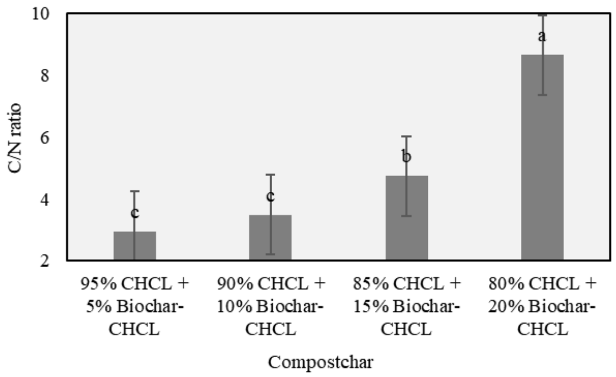


Figure 2. The C/N ratio of compostchar from closed-house chicken litter (CHCL) systems

Numbers followed by the same lowercase letter are not significantly different (ns) according to Duncan's test at the 5% (*) and 1% (**) levels.

The C/N ratio of CHCL-based compostchar showed an increasing trend with increasing biochar proportion, from 3.0 (95% CHCL + 5% biochar) to 8.7 (80% CHCL + 20% biochar) (Figure 2). The relatively low C/N ratio values in all formulations indicate a very advanced level of decomposition and a high content of available mineral nitrogen. The increase in the C/N ratio with the addition of biochar can be explained by the contribution of stable carbon (recalcitrant carbon) from biochar, which is resistant to microbial decomposition, thereby increasing the total carbon fraction without a commensurate increase in nitrogen. However, all C/N values (<10) were still below the optimal range of compost maturity (10–20), indicating that the material was highly mature but potentially experiencing nitrogen loss through volatilization or low immobilization. The addition of biochar tends to increase the C/N ratio and improve carbon stability in the compost system [22].

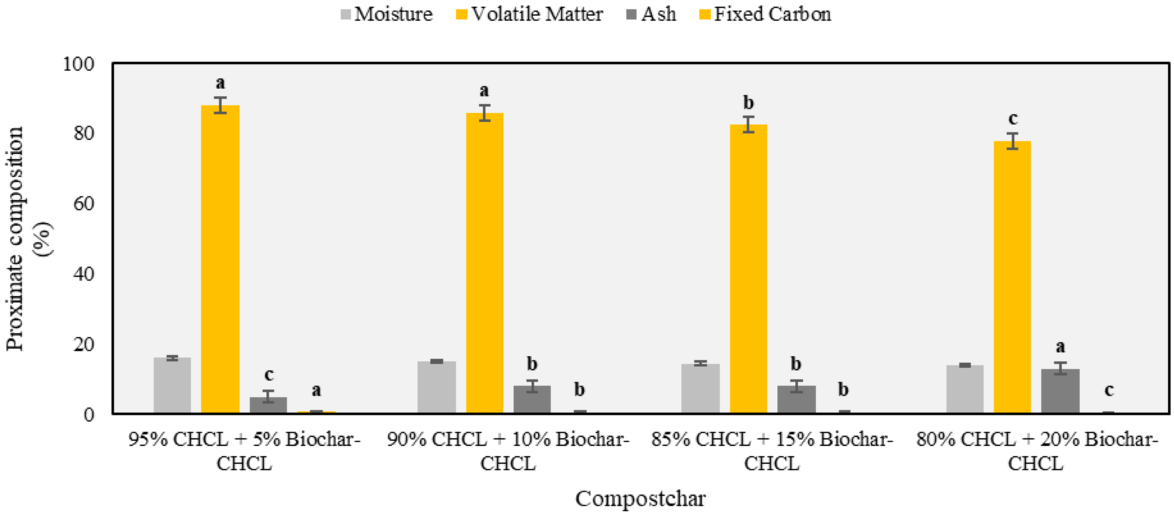


Figure 3. Proximate composition of compostchar from closed-house chicken litter (CHCL) systems
Numbers followed by the same lowercase letter are not significantly different (ns) according to Duncan's test at the 5% (*) and 1% (**) levels.

Proximate composition shows changes in the characteristics of compostchar from CHCL due to the addition of biochar in various formulations. An increase in biochar composition from 5% to 20% caused a decrease in moisture content from 16.00% to 14.00% (Figure 3). This low moisture content indicates that biochar helps reduce total moisture due to its porous yet relatively hydrophobic nature, thereby not retaining large amounts of water and producing more stable compostchar during storage. Volatile matter (VM) also decreased significantly and consistently from 88.09% to 77.90% as the biochar dose increased. This decrease indicates increased thermal stability and a decrease in easily decomposable organic components, an important characteristic in high-quality compost and biochar. Biochar itself is known to have low VM, so its presence reduces the volatility of the mixture [23].

The ash content, on the other hand, showed a significantly different condition, increasing from 5% to 13% in the formulation with 20% biochar. This increase reflects the addition of inorganic minerals, which are naturally high in livestock waste-based biochar [24]. High ash content can also increase the capacity of compostchar as a soil conditioner because it enriches nutrients. Meanwhile, the fixed carbon (FC) value decreased slightly from 0.69 to 0.54. Although biochar is generally known to be rich in stable carbon, this decrease may be due to the characteristics of the biochar used, which likely originated from a low-temperature pyrolysis process, resulting in lower FC than the original CHCL organic material. The decrease in FC may also be due to an increase in the mineral fraction (ash), resulting in a relative decrease in the proportion of stable carbon. The decrease in moisture and VM indicates that the greater the proportion of biochar, the more stable the compostchar becomes, both chemically and biologically. Meanwhile, the increase in ash confirms the role of biochar in enriching minerals in the final product, which is important for improving soil fertility. The composition of 80% CHCL + 20% biochar provides the best formulation for stability and mineral content, making it suitable for use as a soil amendment with long-term ability to improve soil quality, nutrient retention, and carbon stability.

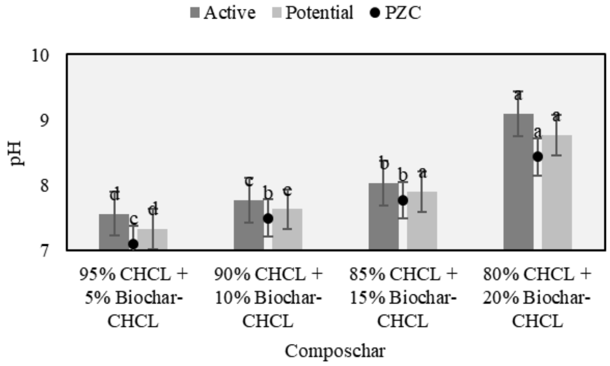


Figure 4. The pH of compostchar from closed-house chicken litter (CHCL) systems
Numbers followed by the same lowercase letter are not significantly different (ns) according to Duncan's test at the 5% (*) and 1% (**) levels.

The pH of compostchar showed a significant increase as the proportion of biochar increased, with pH of the H_2O rising from 7.57 (5% biochar) to 9.10 (20% biochar), while pH of KCl and PZC showed a similar pattern (Figure 4). This increase confirms that biochar from chicken manure has highly alkaline properties and provides a strong liming effect in the compost system, thereby increasing the pH of the H_2O and buffer capacity. Biochar from poultry litter generally has a high pH (≈9–10) due to its high ash and base mineral content [25]. Furthermore, the increase in PZC from 7.10 to 8.43 due to the addition of biochar shifts the surface charge of compostchar to a more alkaline condition, which can affect cation and anion adsorption when applied to soil. Biochar from poultry manure increases pH, compost stability, and surface charge buffering capacity [26]. The integration of biochar-CHCL in chicken litter compost significantly alters its chemical properties towards a more alkaline and stable condition.

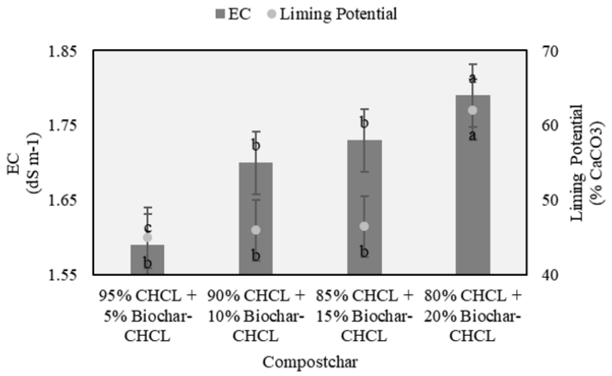


Figure 5. Electrical conductivity (EC) and liming potential of compostchar from closed-house chicken litter (CHCL) systems

Numbers followed by the same lowercase letter are not significantly different (ns) according to Duncan's test at the 5% (*) and 1% (**) levels.

The EC value of compostchar showed a significant increase as the proportion of biochar increased, from 1.59 to 1.79 dS m^{-1}, indicating a higher content of dissolved salts due to the contribution of alkali and base minerals from biochar (Figure 5). The EC in this range is still considered safe for soil application and reflects a high ionic charge that can support microbial activity and nutrient availability [27]. Meanwhile, the liming potential of compostchar increased significantly, especially in the 80% CHCL + 20% biochar-CHCL formulation, reaching 62.10% $CaCO_3$, which indicates a stronger acid neutralization capacity due to the ash content, base cations, and alkali functional groups from biochar (Figure 4). This increase in liming potential confirms that the combination of chicken litter compost–biochar can function as an effective soil conditioner to raise the pH of acidic soils, such as Inceptisols, and improve overall soil fertility.

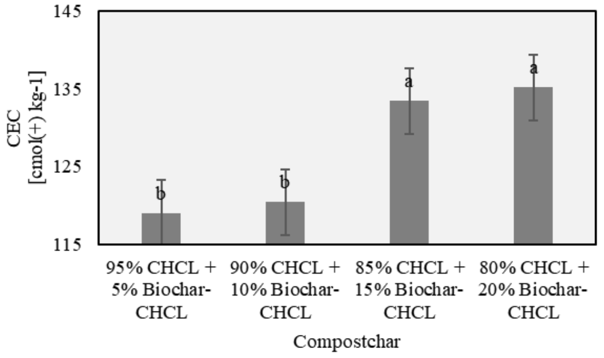


Figure 6. The cation exchange capacity (CEC) of compostchar from the closed-house chicken litter (CHCL) systems

Numbers followed by the same lowercase letter are not significantly different (ns) according to Duncan's test at the 5% (*) and 1% (**) levels.

The CEC of compostchar from CHCL increases with the proportion of biochar in the formulation, from 119.00 cmol(+) kg^{-1} at 5% biochar to 135.17 cmol(+) kg^{-1} at 20% biochar-CHCL. The addition of biochar contributes positively to the CEC of compost, mainly because biochar from chicken manure usually has high ash content, high porosity, and the potential for negative charge formation that develops during the composting and surface oxidation processes. Biochar can increase CEC in organic mixtures through two main mechanisms: (a) increased specific surface area and cation adsorption sites, and (b) the development of negatively charged functional groups (carboxyl, phenolate) during the aging or composting process [28]. In addition, the formulation of chicken litter rich in humic organic matter with structurally stable biochar supports the formation of organo-mineral complexes, which further increases the nutrient retention capacity of NH_4^+, K^+, Ca^{2+}, and Mg^{2+}. The addition of up to 20% biochar significantly improved the ability of compostchar to retain cations (Figure 6).

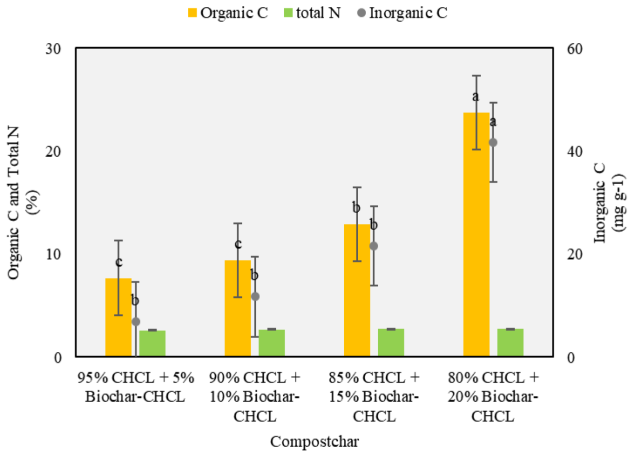


Figure 7. Inorganic carbon, organic carbon, and total N in compostchar derived from closed-house chicken litter (CHCL) systems

Numbers followed by the same lowercase letter are not significantly different (ns) according to Duncan's test at the 5% (*) and 1% (**) levels.

Increasing the proportion of biochar in the CHCL formulation significantly increases the organic and inorganic C. In the 95% CHCL + 5% biochar formulation, organic C is 7.67%, but increases sharply to 23.76% in the formulation with a 20% biochar proportion (Figure 7). This increase is in line with the properties of biochar, which is rich in aromatic carbon and has a high fraction of stable carbon, thereby increasing the organic carbon content in compostchar. Biochar is also known to enrich total carbon through its resistant aromatic structure that is not easily degraded, thereby improving the quality of the material as a long-term soil conditioner [29]. Inorganic C also increased significantly, from 6.9% in the 5% biochar proportion to 41.7% in the 20% biochar proportion. This increase may originate from carbonate minerals that are commonly formed during the biomass pyrolysis process and are more commonly found in livestock waste-based biochar [30]. High inorganic carbon content contributes to pH buffering capacity and helps improve soil chemistry, especially in acidic soils. Meanwhile, total N increased slowly from 2.60% to 2.75% as the biochar dose increased. Although the increase is not as significant as that of carbon, because ammonium and nitrate are adsorbed in its pores, biochar helps retain nitrogen [31]. Biochar is known to reduce nitrogen loss through volatilization and denitrification, thereby helping to maintain N availability in compostchar. The combination of increased organic C and total N indicates the potential for compostchar formation with a more ideal C/N ratio, supporting material stability. The formulation of 80% CHCL + 20% biochar showed the most significant increase in both organic and inorganic carbon, as well as better nitrogen stability.

The formulations 85% CHCL + 15% biochar-CHCL and 80% CHCL + 20% biochar-CHCL have relatively similar main element compositions, but there are important variations, especially in macro-microelements (Figure 8). These variations reflect changes in inorganic composition influenced by the addition of biochar, which generally increases carbon content but can decrease the proportion of mineral oxides per total mass [32]. The P_2O_5 oxide decreased from 1.43 to 0.98% when the biochar composition was increased from 15% to 20% biochar-CHCL. This decrease may occur because biochar typically has a lower P content than the ash fraction of chicken litter. A decrease in P is often found due to the dilution effect when the organic/carbon fraction increases [33].

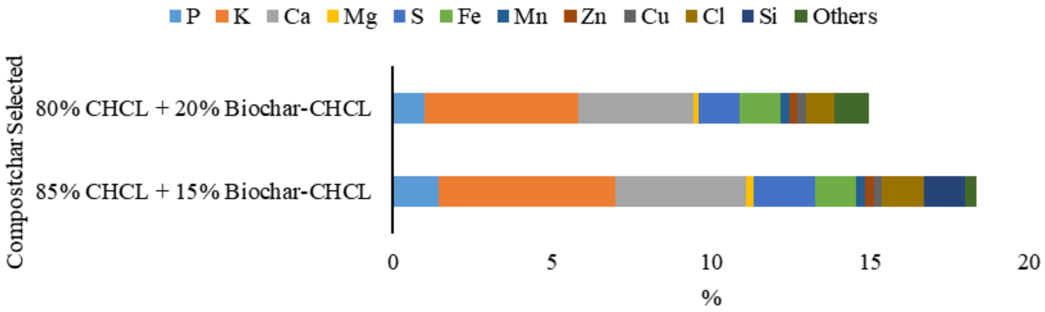


Figure 8. Oxide composition of compostchar from closed-house chicken litter (CHCL) systems selected by X-ray fluorescence (XRF)

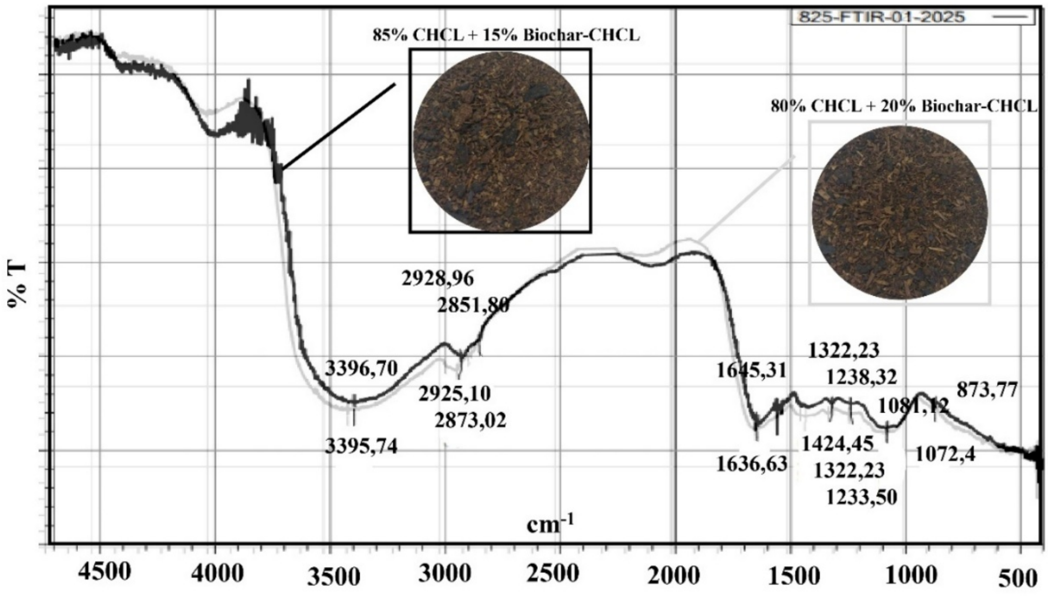


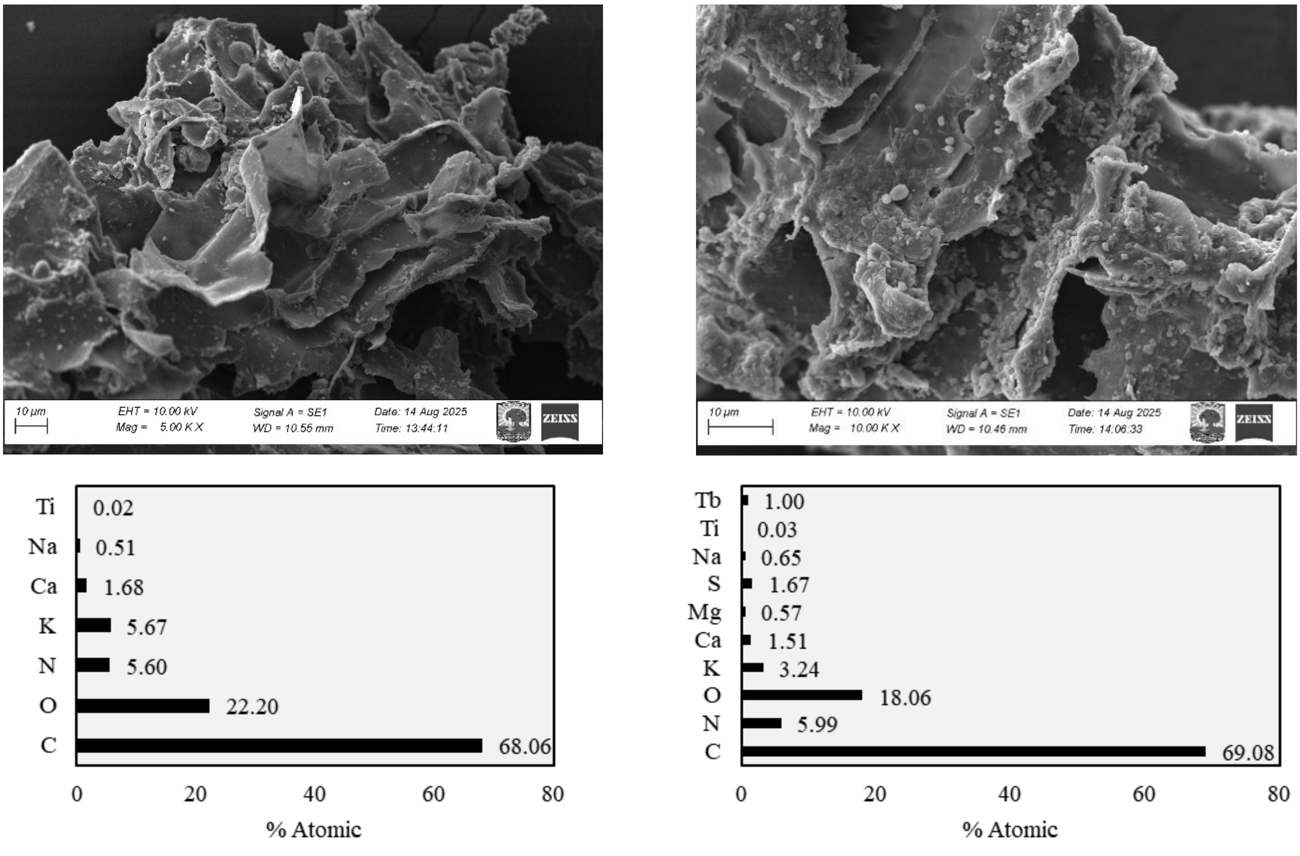
Figure 9. Functional groups of compostchar from closed-house chicken litter (CHCL) systems selected by Fourier transform infrared spectroscopy (FTIR)

The K also showed a decrease from 5.54 to 4.84%. The K is often present in the form of soluble minerals, and its presence decreases as the percentage of biochar increases, which has a lower K concentration than raw chicken litter or combustion ash. The CaO oxide decreased from 4.11 to 3.62%. In chicken litter, Ca is usually high due to the use of lime/calcitic supplements in chicken feed. When biochar is added, the total Ca mass decreases because the Ca concentration in biochar tends to be lower or more bound in a stable aromatic carbon structure [34]. The MgO oxide decreased from 0.27 to 0.17%, following the pattern of other macroelements. Mg in litter usually comes from chicken feed and mineral ash. This decrease is consistent with the addition of biochar, which generally has minimal Mg content [35]. The SO_3 oxide also decreased from 1.91 to 1.29%. The S in litter is usually associated with proteins and organic sulfur compounds, and can be transformed into sulfides or sulfates during pyrolysis. The decrease in S content indicates that the added biochar may have lost more S during the high-temperature pyrolysis process [36].

The composition of oxides such as Fe_2O_3, Mn_2O_3, ZnO, and CuO showed very little change between the two formulations, indicating that the addition of biochar in the range of 5% had a relatively insignificant effect on these micro-mineral groups. This is because biochar and chicken litter have relatively stable micro-mineral content that is not easily volatile at pyrolysis temperatures of 300–500 °C. A fairly clear decrease occurred in Cl oxide, from 1.31 to 0.89%. The Cl is an element that is easily volatile during the heating process, so that an increase in the proportion of biochar usually reduces the Cl content because most of the Cl in organic material will evaporate during pyrolysis [37]. A significant increase occurred in several other oxides, from 0.37 to 1.09%. This may indicate that biochar contributes to unclassified minor oxides (e.g., Al_2O_3, or other trace minerals), or the presence of relative concentrations due to a reduction in macroelements. An increase in the fraction of minor oxides is often observed in lignocellulosic biochar [38].

The FTIR spectrum at 85% CHCL + 15% biochar-CHCL and 80% CHCL + 20% biochar-CHCL shows a comparison of different functional group characteristics (Figure 9). Differences in biochar composition appear to affect the intensity and a slight shift in absorption bands (band shifting), especially in the main functional group region. The strong band in the 3395–3397 cm^{-1} region is characteristic of the stretching vibration of the O–H group of hydroxyl compounds, bound water, or phenolic groups, commonly found in biochar and pyrolyzed organic materials. Peaks in the 2925–2928 cm^{-1} and 2851–2873 cm^{-1} regions indicate the presence of aliphatic C–H stretching vibrations, reflecting the hydrocarbon chain structure of biomass residues that have not been completely degraded. Meanwhile, the band at 1636–1645 cm^{-1} is related to C=O or aromatic C=C stretching vibrations, which indicate the contribution of aromatic components in biochar, usually increasing with the addition of biochar fractions due to their more aromatic nature.

The bands in the range of 1424, 1322, 1233–1238 cm^{-1} indicate C–O, C–H bending groups, and potential phenolic or carboxylate groups, which are often indicators of biochar surface reactivity that plays a role in adsorption. The peak at 1072–1081 cm^{-1} corresponds to Si–O or C–O–C vibrations, commonly found in biochar with silicate mineral content or lignocellulose residues. The lowest band around 873 cm^{-1} indicates substituted aromatic groups or aromatic C–H deformation. The addition of biochar from 15% to 20% appears to increase the intensity of bands associated with aromatic groups and functional oxygen, reflecting an increase in the diversity of active groups on the material surface. Biochar brings more complex chemical components into the CHCL mixture, potentially increasing adsorption capacity and chemical reactivity through the presence of more dominant phenolic, carboxylate, and aromatic groups.



(I) (II)

Figure 10. Morphology of compostchar from closed-house chicken litter (CHCL) systems selected: (I) 85% CHCL + 15% biochar-CHCL and (II) 80% CHCL + 20% biochar-CHCL by Scanning Electron Microscope equipped with Energy Dispersive X-ray (SEM-EDX)

The SEM images show the complex morphological structure of composites with high porosity and irregular surfaces (Figure 10). In 85% CHCL + 15% biochar-CHCL, the surface appears to be dominated by large hollow structures and relatively thin walls. These macro to meso-sized cavities are generally formed as a result of the decomposition of organic matter and partial pyrolysis, which produces an irregular carbon network. This porous structure is known to play an important role in increasing the water retention capacity and adsorptive surface of biochar [39]. The surface in the image appears “cleaner,” indicating a lower biochar fraction, so the intensity of mineral microparticle or ash formation is still limited. Conversely, at 80% CHCL + 20% biochar-CHCL, the surface appears rougher and denser with many small granular particles attached to the pore walls. The presence of these fine grains reflects an increase in inorganic mineral content and carbon residue from biochar in the mixture composition. Biochar generally carries silicate particles, phosphates, microcrystalline aromatic carbon, and light metals left over from the biomass pyrolysis process [40].

The more heterogeneous texture and layered surface in the image indicate that the addition of 20% biochar produces material with a more developed surface area and higher adsorption capacity, especially for heavy metals and organic compounds. This type of morphology is also often associated with increased carbon stability and nutrient binding capacity due to its surface rich in oxygen and mineral functional groups [41]. These differences indicate that increasing the biochar fraction from 15% to 20% significantly modifies the microstructure of the compostchar, where 85% CHCL + 15% biochar-CHCL is more dominated by natural voids from the former organic tissue, while 80% CHCL + 20% biochar-CHCL showed a more compact structure, rich in mineral particles, and had a textured surface with mineral-carbon aggregate attachment.

The EDX analysis provides an overview of the elemental composition on the surface of the compostchar, showing significant differences between the two formulations (Figure 10). In 85% CHCL + 15% biochar-CHCL, carbon (C) dominates with a value of 68.06%, accompanied by oxygen (O) at 22.20%. This C–O dominance reflects a higher organic material content, with biochar contributing to the aromatic carbon structure, but not significantly due to its relatively low fraction. The N content of 5.60% indicates that nitrogen from chicken manure, residual protein, and amide compounds is still relatively available in the compost. The presence of nutrients such as K (5.67%), Ca (1.68%), and Na (0.51%) indicates a moderate contribution of minerals from litter and biochar, potentially increasing the agronomic value of compostchar as a soil conditioner. The content of minor metals such as Ti (0.02%) is natural and usually comes from soil or poultry feed.

In 80% CHCL + 20% biochar-CHCL, the carbon percentage increased to 69.08%, in line with the increase in the biochar fraction, which is rich in aromatized carbon. The oxygen content decreased significantly to 18.06%, indicating that the carbon structure became more stable and contained fewer reactive oxygen groups, a characteristic of biochar with higher carbonization levels. The N increased slightly to 5.99%, indicating that this mixture can retain nitrogen better or has a larger surface area for attaching N compounds. Potassium abundance decreased to 3.24%, indicating that K minerals tend to decrease in concentration in mixtures with higher biochar content, possibly due to dilution of K-rich litter composition. Other elements, such as Mg (0.57%), S (1.67%), and Tb (1.00%), appeared in 80% CHCL + 20% biochar-CHCL, indicating the contribution of additional minerals from biochar or the heterogeneity of the raw materials. The presence of sulfur and magnesium increases the potential of compostchar as a secondary nutrient source for soil, while the presence of trace elements (Tb and Ti) indicates complex mineral properties commonly found in litter-based biochar.

Comparison of the two samples shows that an increase in biochar from 15% to 20% increased total carbon, reflecting a more dominant and stable biochar structure. A decrease in oxygen indicates a higher degree of carbonization and better chemical stability. Variations in nutrients, especially K, Mg, and S, can affect soil fertility. The emergence of additional minor minerals indicates higher heterogeneity in the formulation with 20% biochar. The 20% biochar formulation produces compostchar with higher carbon, lower oxygen, and more complex minerals, making it more stable, more potentially functional as biochar, and having higher agronomic and adsorbent value.

3.2 Surface charge on Inceptisols ameliorated with compostchar selected from closed-house chicken litter systems

The application of compostchar significantly increased the pH of Inceptisols (Table 1). This increase in pH is significant because Inceptisols are generally acidic with surface charges that depend on pH. When the pH increased by 0.45 and 0.75, respectively, compared to the control, this indicated that more functional groups on soil colloids underwent deprotonation, resulting in higher negative charges.

Table 1. Surface charge on Inceptisols ameliorated with compostchar from closed-house chicken litter (CHCL) systems

Compostchar Selected	**pH**			**EC, dS m^{-1}**	**Composition**		**CEC, cmol(+) kg^{-1}**
	H_2O	**1 M KCl**	**PZC**		**Mineral, %**	**OM, %**	
Soil	5.15 b	5.00 b	4.83 b	0.14 b	66.00	34.00	62.38
Soil - 40 tons ha^{-1} compostchar selected I	5.60 ab	5.40 a	5.20 a	0.23 a	63.70	36.30	77.22
Soil - 40 tons ha^{-1} compostchar selected II	5.90 a	5.70 a	5.23 a	0.27 a	62.00	38.00	74.42
CV (%) - Duncan's Test	4.57*	1.66**	2.93*	12.43**	2.71^{ns}	4.79^{ns}	10.33^{ns}
SE	0.21	0.07	0.12	0.02	1.41	1.41	6.02

Note: Numbers in the same column followed by the same lowercase letter are not significantly different (ns) according to Duncan's test at the 5% (*) and 1% (**) levels, I = 85% CHCL + 15% Biochar-CHCL, II = 80% CHCL + 20% Biochar-CHCL, CHCL = closed-house chicken litter, PZC = point of zero charge, EC = electrical conductivity, OM = organic matter, CEC = cation exchange capacity, SE = standard error, n = 9 samples.

Compostchar can raise soil pH through the contribution of carbonates, base cations, and alkaline surfaces. Meanwhile, the PZC in compostchar is in the range of 5.20–5.23, slightly lower than the pH of H_2O and KCl. A decrease in PZC indicates that the soil surface becomes more easily negatively charged at lower pH. This shift can be attributed to the presence of oxidized oxygen groups in compostchar and the contribution of degraded organic matter that introduces variable charge sites. Biochar with high oxygen content tends to lower soil PZC [42]. EC increased significantly in compostchar applications, especially at a compostchar dose of 20%, which reached 0.27 dS m^{-1} (Table 1). This increase in EC indicates that compostchar enriches the soil with soluble cations, which can act as charge balancers in negatively charged soil colloids. The availability of these base cations supports aggregate stabilization and enhances electrostatic interactions on the soil surface, which in turn strengthens the development of permanent and variable negative charges [43].

Soil organic matter (OM) also increased after compostchar application, from 34% in the control soil to 36–38% in compostchar (Table 1). Conversely, mineral composition decreased with compostchar application. This increase in OM not only added organic charge sites but also increased water retention and soil pH buffering capacity. Organic matter is known to contribute significantly to charge variables due to the diversity of functional groups. The increase in OM through compostchar strengthens the shift in surface charge towards a dominance of negative charges at field pH. The CEC showed an increase in compostchar, especially in the CHCL + 20% biochar-CHCL composition, which reached 74.42 cmol(+) kg^{-1}. This confirms that compostchar improves the colloidal properties of Inceptisols through an increase in permanent and variable negative charges. Overall, these findings indicate that compost char based on CHCL is an effective ameliorant for improving surface charge, CEC, and the chemical status of Inceptisols, which generally have fertility problems. The potential of biochar-compost as a builder of negative charge and a long-term soil quality enhancer [44].

3.3 Equilibrium adsorption characteristics of glyphosate adsorption with Inceptisols ameliorated with compostchar selected from closed-house chicken litter systems in solution

The equilibrium adsorption characteristics of glyphosate on Inceptisols soil showed a consistent response to increases in initial concentration (C_0) and remediation using compostchar from closed-house chicken litter (CHCL) systems selected (Table 2). Increases in C_0 (1000–5000 mg L^{-1}) were followed by increases in equilibrium concentration (C_e) and adsorption capacity (Q_e), reflecting an increase in the driving force for diffusion, approaching saturation of active sites. The highest Q_e value was recorded for selected compostchar II (182.59 mg g^{-1}), higher than that of the control soil (170.81 mg g^{-1}), indicating that the addition of compostchar significantly increased retention capacity. This increase is associated with an increase in the presence of oxygen functional groups, which play a role in interactions with glyphosate through hydrogen bonding and complexation [45].

The high adsorption efficiency (%R) (≈70–92%) indicates that the system has good retention capacity even at high concentrations. In untreated soil, the R value tends to decrease at the highest concentrations, indicating a limited number of active sites and increased competition among adsorbate molecules. In contrast, the compostchar, particularly Selected II, maintained high efficiency (>89%) at nearly all concentration levels, indicating improved stability of the adsorption system. Biochar and compost increase surface heterogeneity and the dispersion of adsorption energy, which can improve pesticide adsorption capability [46].

The distribution coefficient (K_d) values, ranging from 0.10 to 0.52 L g^{-1}, indicate an increase in relative affinity following the modification process, although the trend is not entirely linear. The highest K_d value for selected charcoal I (0.52 L g^{-1}) suggests the existence of an optimum point between the number of active sites and the adsorbate concentration. This variation confirms that the adsorption mechanism does not fully follow a simple linear model, but is governed by a combination of physisorption mechanisms and weak chemical interactions such as hydrogen bonding and complexation with metal cations [47].

The change in solution pH from an initial acidic condition (4.3–4.9) to a higher pH after adsorption (up to ~5.3) in the compostchar indicates the contribution of the material's alkalinity in modifying the reaction environment. This increase in pH can increase the degree of glyphosate dissociation and the negative charge on the adsorbent surface, thereby strengthening interactions through cation bridging and metal complexation mechanisms. Previous studies have shown that glyphosate adsorption is strongly influenced by pH due to changes in molecular speciation and the adsorbent's surface charge [48]. Amelioration of Inceptisols with compostchar, particularly selected II, significantly increased the equilibrium capacity (Q_e), adsorption efficiency, and system stability at various concentration levels. This improvement was not only quantitative (number of adsorption sites) but also qualitative through modification of surface chemistry. Environmental implications include reduced mobility and the potential for glyphosate leaching into groundwater.

Isothermal adsorption analysis showed that glyphosate sorption on Inceptisols and ameliorated soil could be satisfactorily described by the Freundlich and Langmuir models (R^2 = 0.99 for all treatments), indicating that the adsorption process involves heterogeneous surface interactions along with limited site saturation behavior (Figure 11 and Table 3). According to the Freundlich model, the untreated soil showed an adsorption intensity (n) of 0.89 and a K_F value of 0.4966, while the addition of 40 t ha^{-1} compostchar substantially modified the adsorption intensity. The selected compostchar I and II increased n to 2.56 and 2.38, respectively, while the K_F values numerically decreased to 4.3×10^{-5} and 7.79×10^{-4} (Figure 11(a) and Table 3). An increase in n values (>1) indicates more favorable adsorption and a lower concentration dependence after addition, suggesting that compostchar produces additional reactive domains with a higher affinity for glyphosate.

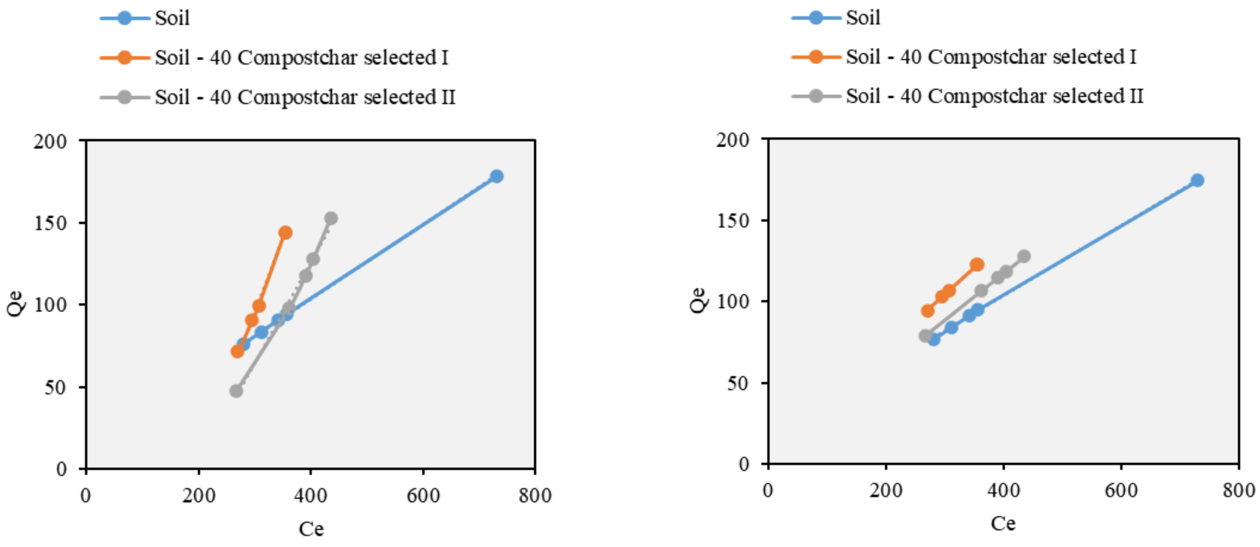
This increase is generally attributed to the physicochemical characteristics of compostchar, including increased specific surface area, larger pore volume, and the presence of oxygen-containing functional groups such as hydroxyl (–OH), carboxyl (–COOH), and carbonyl (C=O) groups. These surface functionalities can interact with glyphosate through hydrogen bonding, ligand exchange, electrostatic attraction, and surface complexation involving glyphosate's phosphonate groups [19]. Furthermore, compostchar materials generally have a well-developed micro- and mesoporous structure that enhances retention through pore filling and van der Waals interactions. The lower C/N ratio in mature compostchar may also indicate greater organic matter stabilization and increased aromatic carbon condensation, which increases the resistance of the active adsorption surface.

The relatively small difference between compostchar selected I and II further suggests that the raw material composition and degree of carbonization significantly influence adsorption performance. Materials with a higher degree of carbonization typically exhibit greater surface area and porosity but fewer polar functional groups, shifting the adsorption mechanism from chemical interactions to physical sorption [49]. Consequently, the balance between these two mechanisms determines the overall adsorption efficiency of glyphosate. Soil pH also plays a significant role in regulating glyphosate sorption because glyphosate is an amphoteric molecule with multiple pKa values, causing its specificity to vary with environmental pH. Compost-based additives are generally alkaline and can increase soil pH, thereby making the soil and compostchar surfaces more negatively charged. Under such conditions, electrostatic repulsion between negatively charged surfaces and glyphosate anions can reduce adsorption affinity, despite an increase in total adsorption capacity due to the presence of additional adsorption sites [48]. This phenomenon may explain why soils treated with compostchar exhibit a change in the Freundlich constant while maintaining favorable adsorption intensity.

Table 2. Equilibrium adsorption characteristics of glyphosate adsorption with Inceptisols ameliorated with compostchar selected from closed-house chicken litter systems in solution

Adsorbent	pH Solution	C_0, mg L^{-1}	C_e, mg L^{-1}	pH Adsorption	Q_e, mg g^{-1}	R, %	K_d, L g^{-1}
Soil	4.9	1000	280.71	5.2	28.77	71.93	0.10
	4.8	2000	311.78	5.1	67.53	84.41	0.22
	4.7	3000	342.20	5.0	106.31	88.59	0.31
	4.6	4000	356.14	4.9	145.75	91.10	0.41
	4.3	5000	729.76	4.2	170.81	85.40	0.23
Soil - 40 tons ha^{-1} compostchar selected I	4.9	1000	269.78	5.2	29.21	73.02	0.11
	4.8	2000	295.92	5.1	68.16	85.20	0.23
	4.7	3000	306.90	5.1	107.72	89.77	0.35
	4.6	4000	354.56	4.9	145.82	91.14	0.41
	4.3	5000	354.70	4.9	185.81	92.91	0.52
Soil - 40 tons ha^{-1} compostchar selected II	4.9	1000	267.42	5.3	29.30	73.26	0.11
	4.8	2000	361.71	5.3	65.53	81.91	0.18
	4.7	3000	390.50	5.2	104.38	86.98	0.27
	4.6	4000	404.39	5.2	143.82	89.89	0.36
	4.3	5000	435.36	5.1	182.59	91.29	0.42

Note: CHCL = closed-house chicken litter, I = 85% CHCL + 15% Biochar-CHCL, II = 80% CHCL + 20% Biochar-CHCL, C_0 = initial concentration of the adsorbate, C_e = equilibrium concentration, Q_e = adsorption capacity, R = removal efficiency, K_d = coefficient of adsorption.



(a)

(b)

Figure 11. Non-linear of glyphosate adsorption on isothermal models, (a) the Freundlich and (b) Langmuir, with Inceptisols ameliorated with compostchar selected from closed-house chicken litter (CHCL) systems in solution

Table 3. Isothermal adsorption of glyphosate on non-linear models, the Freundlich and Langmuir, with Inceptisols ameliorated with compostchar selected from closed-house chicken litter systems in solution

Adsorbents	Isothermal			R^2
	A. Freundlich			
	n	K_F (mg g^{-1}) (L mg^{-1})^n	1/n	
Soil	0.89	0.49656	1.12	0.99
Soil - 40 tons ha^{-1} compostchar selected I	2.56	0.00004	0.39	0.99
Soil - 40 tons ha^{-1} compostchar selected II	2.38	0.00078	0.42	0.99
Adsorbents	**B. Langmuir**			**R^2**
	Q_m (mg g^{-1})	**K_L (L mg^{-1})**	**$^*R_L$**	
Soil	865.66	0.00035	0.52	0.99
Soil - 40 tons ha^{-1} compostchar selected I	2941.24	0.00012	0.74	0.99
Soil - 40 tons ha^{-1} compostchar selected II	6248.36	0.00005	0.88	0.99

Note: CHCL = closed-house chicken litter, I = 85% CHCL + 15% Biochar-CHCL, II = 80% CHCL + 20% Biochar-CHCL, and $^*R_L = 1/[1+(K_L \times C_0)]$.

Furthermore, adsorption heterogeneity in ameliorated soils likely arises from the presence of multiple adsorption domains, including mineral surfaces, humified organic matter, and the pyrolyzed carbon matrix. Competition between glyphosate and structurally similar anions, such as phosphate, can also suppress adsorption efficiency by occupying the same ligand exchange sites on Fe/Al oxides and clay minerals [50]. The addition of compostchar significantly increased glyphosate retention capacity in Inceptisols while creating a more complex and heterogeneous adsorption environment.

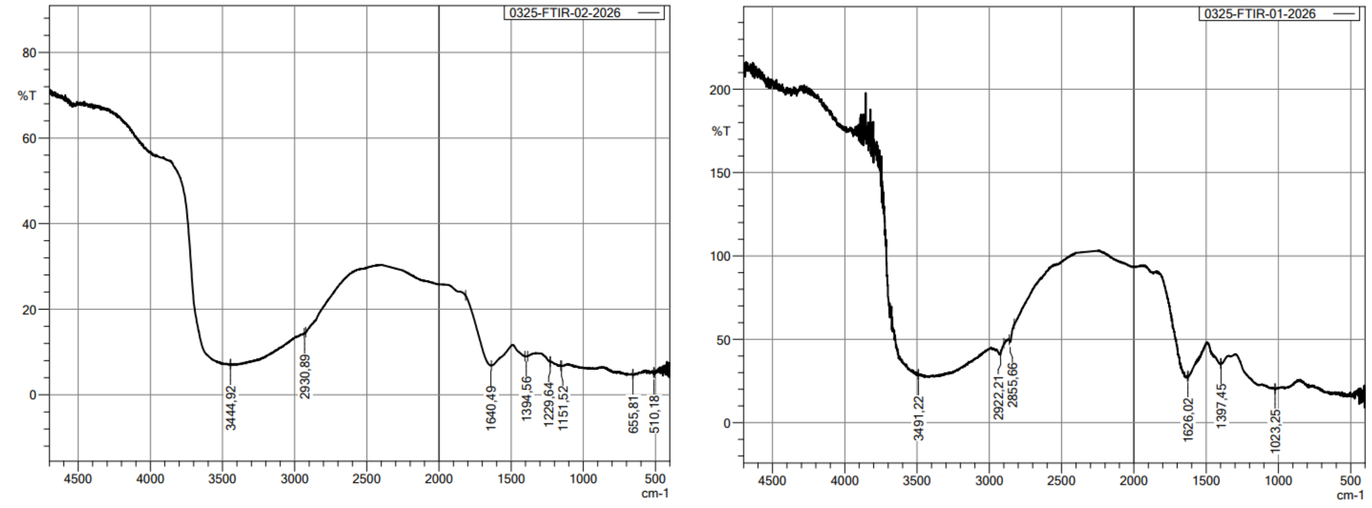
The Langmuir model further demonstrated a significant increase in maximum adsorption capacity after compostchar addition. The monolayer adsorption capacity (Q_m) increased from 865.66 mg g^{-1} in untreated soil to 2941.24 mg g^{-1} in compostchar selected I and 6248.36 mg g^{-1} in compostchar selected II, indicating a several-fold increase in the number of available adsorption sites (Figure 11(b) and Table 3). This substantial increase confirms that compostchar application significantly enhances the retention potential of Inceptisols against glyphosate. This increase is generally attributed to the development of a porous structure, increased specific surface area, and the introduction of additional reactive functional groups derived from the composted and carbonized organic matter [5].

The Langmuir affinity constant (K_L) ranged from 0.000048 to 0.000346 L mg^{-1}, with the highest values recorded in untreated soil and the lowest values observed with compostchar addition. Although the total adsorption capacity increased substantially, the average bond strength per adsorption site decreased. In other words, compostchar generated many new adsorption sites, but many of these sites were energetically weaker than the naturally high-affinity sites present in untreated soil. Such behavior is characteristic of porous carbonate adsorbents, where adsorption is often governed by pore filling, hydrogen bonding, van der Waals forces, and nonspecific electrostatic interactions rather than strong chemisorption processes [10].

The inverse relationship between adsorption capacity and affinity further indicates a broader and more heterogeneous distribution of adsorption energy after material addition. Rather than highly localized high-energy binding domains, glyphosate sorption in soil treated with charcoal compost likely occurs through a combination of physisorption and weak surface complexation. Given the amphoteric and pH-sensitive nature of glyphosate, the strength of adsorption is strongly influenced by soil pH and surface charge state. Therefore, the dominant retention mechanism in treated soil is likely related to hydrogen bonding and complexation with Fe/Al oxides or oxygen-containing functional groups, rather than irreversible covalent bonding [50].

The dimensionless separation factor (R_L) ranged from 0.52 to 0.88 for all treatments, remaining within the favorable adsorption region ($0 < R_L < 1$), confirming that glyphosate sorption is thermodynamically favorable under all conditions. However, the progressive increase in R_L from untreated soil (0.52) to selected compostchar II (0.88) indicates that adsorption becomes more linear and less strongly irreversible as the total capacity increases. Practically, selected compostchar II provided the highest overall glyphosate retention capacity, while untreated soil exhibited a stronger site-specific affinity but a much lower total sorption capacity.

A combined Freundlich and Langmuir model showed that compostchar addition significantly altered the adsorption behavior of Inceptisols by increasing surface heterogeneity, expanding the number of available sorption sites, and significantly increasing glyphosate retention. Among all ameliorated soils, selected compostchar II demonstrated the best overall performance, suggesting that optimized compostchar properties can serve as an effective strategy to reduce glyphosate mobility and leaching risk in agricultural soils.



(a) (b)

Figure 12. Functional groups before and after glyphosate adsorption with Inceptisols ameliorated with the best selected compostchar (80% CHCL + 20% Biochar-CHCL) in solution

FTIR spectrum analysis showed significant changes in functional groups before and after glyphosate adsorption by Inceptisols ameliorated with compostchar (80% CHCL + 20% biochar-CHCL). Before adsorption, eight main peaks were identified reflecting the presence of functional groups such as –OH (~3444 cm^{-1}), aliphatic C–H (~2931 cm^{-1}), C=O (~1640 cm^{-1}), and C–O and P–O (~1151–1229 cm^{-1}). After adsorption, the number of peaks decreased to six with a significant wavenumber shift, for example, in the region of ~1037–1262 cm^{-1}, indicating the involvement of the phosphonate (P–O) group of glyphosate in the interaction process with the adsorbent surface (Figure 12). This shift confirms the existence of a chemisorption mechanism through the formation of a complex between the phosphate group of glyphosate and metal oxides (Fe/Al), which are commonly found in Inceptisols [50]. In addition, the peak shift in the hydroxyl region from ~3444 cm^{-1} to ~3491 cm^{-1} and changes in the band ~1640 cm^{-1} indicate the involvement of hydrogen bonds between the –OH groups of the compostchar surface and the polar groups of glyphosate. A significant increase in the intensity of the C–H band (~2922 cm^{-1}) after adsorption indicates the accumulation of organic compounds from glyphosate on the adsorbent surface, which strengthens the suspicion of hydrophobic interactions and the contribution of the aromatic carbon fraction of biochar from CHCL. On the other hand, a small shift in the band ~1397 cm^{-1} indicates a possible electrostatic interaction between the carboxylic and amine groups of glyphosate with the charged surface. The adsorption mechanism of glyphosate in the compost-char-ameliorated Inceptisols system involves a combination of physical and chemical interactions, including chemisorption through complexation with soil minerals, hydrogen bonding, and electrostatic interactions, as confirmed by this shift in the FTIR spectrum. Using compostchar might potentially reduce herbicide contamination in the soil environment because it not only boosts the adsorption capacity by increasing the surface area but also provides active functional groups that help bind pollutants forcefully and steadily.

Although this study demonstrates robust adsorption performance toward glyphosate, a significant limitation is the use of relatively high initial glyphosate concentrations compared to concentrations typically detected in natural soils, surface waters, and agricultural runoff, where environmental levels are generally several orders of magnitude lower. Such high experimental concentrations are typically used to facilitate isotherm modeling, determining maximum sorption capacity under controlled laboratory conditions. However, adsorption behavior at high concentrations may not fully represent the mechanisms operating in realistic environmental exposure scenarios, where sorption often occurs with low surface coverage, stronger competition with co-existing ions, and more heterogeneous binding dynamics. Consequently, the very high sorption capacities reported here should be interpreted primarily as indicators of comparative material performance rather than direct predictions of field-scale removal efficiency. Nonetheless, the observed improvements following the addition of compostchar remain mechanistically relevant, as increased surface functional groups, mineral interactions, and pore availability are also expected to enhance glyphosate retention at lower concentrations. Therefore, future studies should validate these findings under environmentally relevant glyphosate levels, multi-solute systems, and dynamic soil conditions to better assess real-world applicability.

4. CONCLUSIONS

Amelioration of Inceptisols using CHCL-based compostchar significantly improved soil quality and glyphosate adsorption capacity. The integration of biochar into the compostchar formulation plays a significant role in improving the chemical stability and physical properties of the material, as indicated by a decrease in VM content and an increase in bound carbon, ash, pH, EC, and CEC. These improvements directly impact the increase in surface charge and the availability of active functional groups that control the adsorption process. Compared to the formulation containing 15% biochar, the composition of 80% CHCL + 20% biochar provides more optimal performance in increasing material stability and adsorption capacity. The proportion of 20% biochar produces a more developed aromatic carbon structure, better pore distribution, and a higher density of active sites, thus increasing adsorption efficiency and capacity more consistently. This is reflected in the increase in maximum adsorption capacity (6248.36 mg g^{-1}) and sorption efficiency (≈70–92%) that remains high at various concentrations. Compostchar application to Inceptisols also significantly increased pH by 0.75 units, PZC by 0.40 units, and EC by 0.13 dS m^{-1} compared with the control. This evidence demonstrates a synergistic strengthening of the interaction between the soil-ameliorant and glyphosate through complex physicochemical mechanisms. The 80% CHCL + 20% biochar formulation is suggested as a successful method to enhance soil quality and pesticide retention.

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