Coffee Husk Biochar: A Sustainable Amendment for Soil Acidity Mitigation and Carbon Sequestration — A Review

Abstract

Coffee husks are the most abundant biomass waste generated by coffee processing plants. Converting this waste into biochar is an emerging and promising approach for reclaiming acidic soils and enhancing carbon sequestration. This paper provides an overview of the characteristics of coffee husk biochar (CHB) and its effects on soil properties, liming and agronomic potential, and environmental impacts. Application of CHB produced at different pyrolysis temperatures and application rates increased soil pH, organic carbon, and the availability of P, K^+, and Ca^{2+} in acidic soils, while significantly reducing exchangeable acidity and the concentrations of Al^{3+} and H^+. The high ash content of CHB, together with the presence of $KHCO_3$ and $CaCO_3$, contributes to its strong liming potential in acidic soils. Furthermore, CHB produced at moderate pyrolysis temperatures (350–550 °C) exhibited high cation exchange capacity (CEC), indicating its potential to improve soil nutrient retention, reduce greenhouse gas emissions, and enhance carbon sequestration, thereby reducing dependence on agricultural lime. Overall, this review synthesises current knowledge on the effects of CHB on soil properties and highlights its potential role in mitigating soil acidity and climate change. The findings provide valuable insights for researchers, practitioners, and farmers seeking sustainable strategies to improve acidic soils using CHB. However, as most existing studies have been conducted under controlled conditions, further research across diverse soil types and agroecological zones is required to fully understand the long-term impacts and practical applicability of CHB.

Keywords: C sequestration; soil acidity; biomass; pyrolysis; biochar

Introduction

Soil acidity is a serious agricultural constraint that directly affects soil physicochemical properties, crop productivity, and human health (Kalkhoran et al., 2019; Yadav et al., 2020). Globally, more than 50% of potentially arable soils are affected by acidity (Kochian et al., 2004). In Ethiopia, soil acidity affects over 43% of agricultural land (Agegnehu et al., 2021), with approximately 80% of Nitisols and Luvisols classified as strongly acidic (pH 4.5–5.5) (Eyasu, 2016). The severity and spatial extent of soil acidity have continued to increase in Ethiopia, particularly in the Sidama region. High rainfall, intensive leaching of basic cations, removal of crop residues, and the continuous use of nitrogen- and sulfur-based fertilisers are major factors exacerbating soil acidity (Kalkhoran et al., 2019). Elevated concentrations of H^+, Al^{3+}, and Mn^{2+} in acidic soils severely reduce crop productivity and pose risks to food safety (Briffa et al., 2020). In addition, low availability of essential nutrients such as P, Ca^{2+}, K^+, and Mg^{2+} further constrains plant growth in acidic soils (Briffa et al., 2020; Cui et al., 2020).

To address this challenge, Ethiopia has launched a national acid soil reclamation strategy aimed at supplying agricultural lime in a timely, sustainable, and cost-effective manner (Ali et al., 2023c). However, the high costs associated with purchasing, transporting, mixing, and applying large quantities of lime (up to 20 q ha^{-1}) often discourage farmers and impose significant financial burdens. In this context, the conversion of agro-industrial wastes into biochar represents a promising alternative, offering dual benefits of soil acidity amelioration and climate change mitigation (Liu et al., 2014). Biochar application enhances carbon sequestration and reduces greenhouse gas emissions (Agegnehu et al., 2017; Yu et al., 2019; Ayaz et al., 2021). Moreover, the high ash content of biochar, together with its oxides, carbonates, silicates, and surface functional groups (e.g., carboxylic and phenolic groups), contributes significantly to the neutralisation of soil acidity (Das et al., 2021a).

Ethiopia is the largest producer of highland Arabica coffee (*Coffea arabica* L.) in Africa (Tefera and Tefera, 2014). During the 2020/2021 growing season, more than seven million smallholder farmers produced approximately 5,847,895.69 tonnes of coffee cherries from an area of 856,591.99 ha (Motebayenore, 2022). In the same year, the Sidama region alone produced 50,454.44 tonnes of coffee cherries from 73,030.04 ha. These figures indicate that an equivalent proportion of coffee husk is generated from each tonne of coffee cherries and is often dumped into the surrounding environment, causing serious environmental pollution. Converting this waste into coffee husk biochar (CHB) through pyrolysis offers a climate-smart and resilient agricultural solution (Filho et al., 2021). Application of CHB represents an affordable alternative for smallholder farmers to ameliorate soil acidity (Yazhini et al., 2020), enhance carbon sequestration, reduce atmospheric CO_2 concentrations, and improve soil fertility and crop productivity (Lehmann et al., 2021; Bolan et al., 2021). However, only a limited number of

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studies have examined the effects of CHB on soil properties, and most existing research has been conducted under controlled laboratory or simulated conditions.

Therefore, this review aims to highlight the potential agricultural benefits of CHB and to raise awareness among researchers, farmers, and extension services. The overarching objective of this review is to critically analyse recent advancements in the use of CHB to improve soil fertility, enhance crop yields, promote soil carbon sequestration, and explore its potential role in large-scale climate change mitigation.

Methods and Materials

Data collection and synthesis

For this review, a systematic literature search was conducted using Google Scholar with multiple relevant keywords. Both research and review articles were considered, with particular emphasis on publications containing the term *"coffee husk biochar."* The selected studies were further screened based on their reporting of: (a) biochar production conditions and physicochemical characteristics of coffee husk biochar (CHB); (b) the effects of CHB on the properties of acidic soils; and (c) the environmental and agronomic benefits associated with CHB application. After organising the extracted data and selected parameters, the effects of CHB on various soil chemical properties were analysed and compared between CHB-amended and unamended acidic soils.

Figure 1. Biochar production process (Vicky *et al.,* 2022)

Coffee husk biochar production

Commented [MY2]: Add mass balance information describing the biochar production process from coffee husk.

Slow and fast pyrolysis are the most commonly used techniques for producing biochar for agricultural applications (Brewer et al., 2012). In fast pyrolysis, dry biomass is heated very rapidly (approximately 1000 °C s^{-1}) in the absence of oxygen, with a very short residence time in the reactor (about 2 s). In contrast, slow pyrolysis involves the gradual heating of biomass at rates of 1–20 °C min^{-1} under oxygen-limited conditions, with residence times ranging from several hours to days (Dutta and Mahanta, 2012). The primary objective of fast pyrolysis is to maximise bio-oil production, whereas slow pyrolysis is designed to maximize biochar yield.

Biochar properties such as specific surface area, porosity, pH, and ash content generally increase with increasing pyrolysis temperature (Tomczyk et al., 2020). As pyrolysis temperature rises, hydrogen and oxygen relative to carbon (H/C and O/C ratios) decrease due to volatilisation of labile organic compounds, promoting the formation of inorganic phases, particularly carbonates (Bakshi et al., 2020). At lower pyrolysis temperatures (<300 °C), biochars retain higher concentrations of carboxylic and phenolic functional groups, which contribute to pH buffering capacity (Tomczyk et al., 2020).

Biochars produced at moderate temperatures (300–550 °C) typically exhibit intermediate H/C and O/C ratios, partial carbonisation, and moderate specific surface area. These characteristics make them suitable for soil amendment applications, as they enhance nutrient availability, improve soil fertility, and contribute to carbon sequestration (Saha et al., 2020). In contrast, biochars produced at higher temperatures (550–700 °C) are dominated by well-carbonised, stable aromatic carbon structures, characterised by low H/C ratios, reduced contents of N, P, and S, and a larger specific surface area (Chan and Xu, 2009). Such biochars are particularly effective when long-term carbon sequestration is the primary objective.

Consequently, coffee husk biochar produced at an optimal pyrolysis temperature range of 450–550 °C, characterised by low hydrophobicity, high ash content, elevated pH, and high specific surface area, is considered highly suitable for improving soil nutrient retention and enhancing the liming potential of acidic soils (Domingues et al., 2017; Ghorbani et al., 2022).

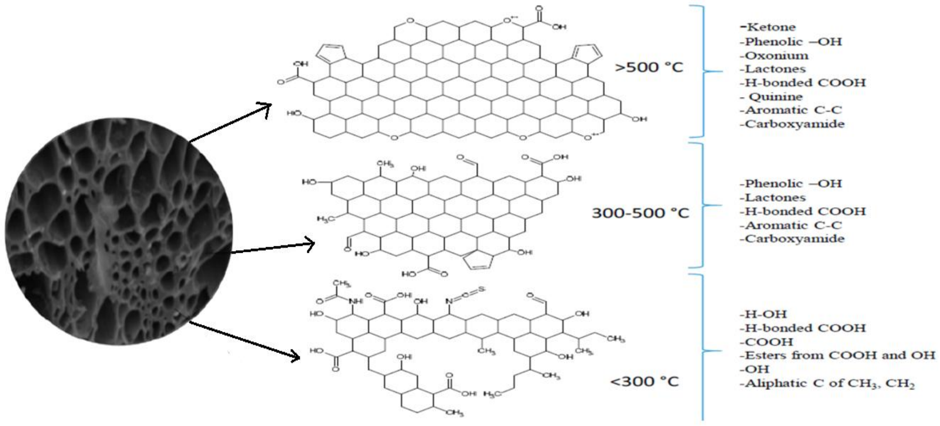

Figure 2. Functional groups on the biochar surface at different pyrolysis temperatures (Tusar *et al.,* 2023)

Characteristics of coffee husk

Coffee husk is the primary by-product generated by coffee processing plants and is composed of approximately 39.2% cellulose, 12.6% hemicellulose, 23.3% lignin, 11.6% extractives, and 9.5% ash by weight (Nguyen et al., 2023). From an agricultural perspective, lignin acts as a slow-release source of nutrients and supports sustainable plant growth by improving soil structure and enhancing nutrient availability (Lu et al., 2021). In addition, coffee husk contains substantial elemental constituents within its lignocellulosic matrix, including 51.28% C, 41.23% O, 4.78% K, 1.23% Ca, 0.34% Mg, 0.29% Fe, 0.54% S, and 0.03% Si (Nguyen et al., 2023) (Figure 2).

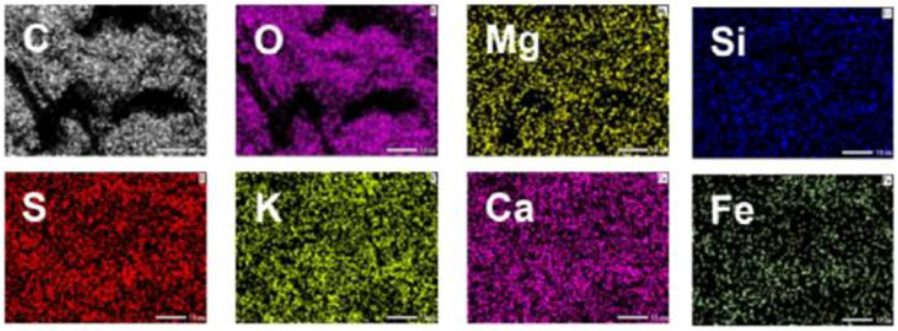

Figure 3. Elemental mapping of coffee husks (Nguyen *et al.,* 2023).

Characteristics of coffee husk biochar

Following pyrolysis, ash content and fixed carbon increased, whereas volatile matter decreased significantly with increasing pyrolysis temperature (450–750 °C) (Figure 1). Gilles et al. (2023) reported a significant reduction ($p < 0.05$) in coffee husk biochar (CHB) yield from 38.7% to 30.3% at 350 °C and from 38.4% to 32.0% at 550 °C, respectively. Increasing pyrolysis temperature also led to a marked increase in organic carbon content, ranging from 16.45% to 58.66%, primarily due to the thermal decomposition and volatilisation of labile organic compounds (Table 1). Total carbon content increased by 60.5%, 61.3%, and 66.0%, while H/C and O/C ratios decreased to 0.78, 0.71, and 0.29, and 0.24, 0.23, and 0.11, at pyrolysis temperatures of 350, 450, and 750 °C, respectively (Domingues et al., 2017).

The increase in aromaticity and the reduction in hydrophilic character of CHB with increasing pyrolysis temperature are primarily attributed to dehydration reactions and the progressive removal of oxygen- and hydrogen-containing functional groups (Gilles et al., 2023). Fourier transform infrared (FTIR) spectra confirmed the presence of aromatic C=C stretching, $–CH_2$ bending, and aromatic C–H bending vibrations at approximately 1600, 1400, and 885 cm^{-1}, respectively, in CHB (Domingues et al., 2017). In contrast, raw coffee husk biomass exhibited characteristic absorption bands corresponding to O–H stretching from water or phenolic groups (3200–3400 cm^{-1}), C–H stretching (2920–2885 cm^{-1}), and C–O stretching of aliphatic functional groups (≈1030 cm^{-1}) associated with cellulose, hemicellulose, and methoxyl groups of lignin (Domingues et al., 2017). Overall, these results indicate that increasing pyrolysis temperature promotes the formation of inorganic functional groups, such as carbonates, oxides, and silicates, leading to a corresponding increase in ash content and enhanced alkalinity of CHB (Waqas et al., 2018).

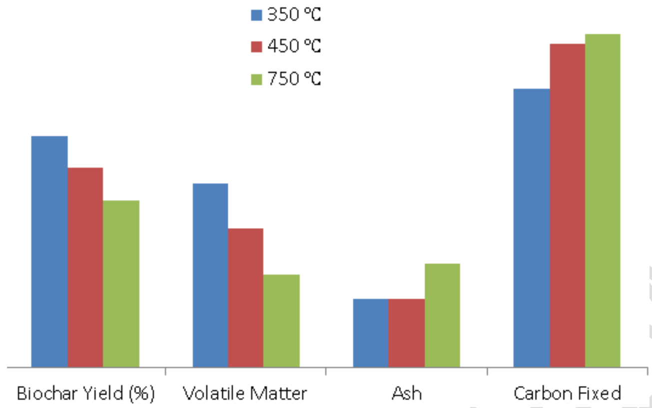

Figure 4. Biochar yield, volatile matter, ash and fixed carbon contents at different pyrolysis temperatures.

The pH values of coffee husk biochar (CHB) were found to be strongly alkaline, ranging from 9.33 to 11.30 (Table 1), indicating a high potential for neutralising soil acidity. This alkalinity is primarily attributed to the presence of substantial amounts of carbonates, oxides, and hydroxides formed during pyrolysis (Figure 2). The high pH and alkalinity of CHB therefore make it an effective amendment for ameliorating acidic soils. Previous studies have demonstrated that increasing pyrolysis temperature enhances the formation of basic cations and alkaline compounds, such as carbonates, oxides, and hydroxides (Yuan et al., 2011; Houben et al., 2013), while simultaneously reducing acidic surface functional groups in biochar (Singh et al., 2010), leading to an overall increase in pH (Meena et al., 2019).

In addition, appreciable concentrations of Ca, Mg, and K were detected in CHB (Table 1). X-ray diffractometry further confirmed the presence of mineral phases such as $CaCO_3$, $KHCO_3$, KCl, and SiO_2 in CHB (Figure 2). The high contents of carbonates and bicarbonates significantly enhance the liming potential of CHB (Bayu et al., 2017). Moreover, the relatively high availability of P and K in CHB suggests that it can also serve as a supplementary source of phosphorus and potassium fertilisers.

Pyrolysis temperatures above 300 °C generally increase CHB pH, whereas biochars produced below 300 °C tend to contain higher concentrations of organic acids and phenolic compounds derived from the partial decomposition of cellulose and hemicellulose, which can lower the pH of the resulting biochar (Yu et al., 2014).

Table 1: Characteristics of coffee husk biochar

Pyrolysis temperature	pH	OC	TN	Avai. P	Ca	Mg	K	Reference
		%		mg kg^{-1}	cmol(+)kg^{-1}			
350	9.62	16.45	1.42	105.25	50.48	6.71	1.96	Bayu *et al.,* 2015
	9.33	67.10	-	866.02	-	-	1.96	Gilles *et al.,* 2023
500	11.04	26.91	2.32	149.12	61.48	8.21	2.77	Bayu *et al.,* 2015
	10.31	67.11	2.05	470.65	0.14	0.12	22.17	Lima *et al.,* 2018
	10.31	67.11	2.05	470.65	0.14	0.12	22.17	Argemiro *et al.,* 2021
	11.05	17.29	0.62	1109	16.23	7.63	243	Alemnesh *et al.,*2021
550	9.69	66.67	-	954.54	-	-	-	Gilles *et al.,* 2023
	10.61	31.26	2.03	16.8	58.3	7.77	3.10	Solomon *et al.,* 2024
	9.42	46.4	2.81	1.11%	0.97%	0.43%	4.37%	Alefsi *et al.,* 2023
	8.10	29.05	0.36	536.20	-	-	449.36	Situmeang *et al.,*2023

OC: Organic carbon, TN: Total nitrogen, Avai. P: available phosphorus, Ca: calcium, K: potassium, Mg: magnesium

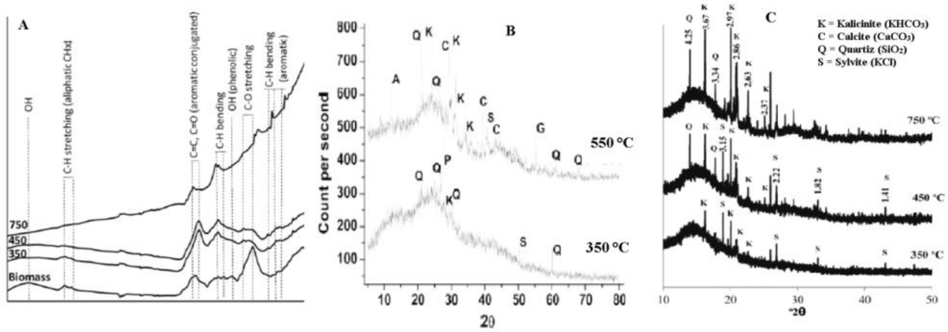

Figure 5. Coffee husk biochar pyrolized at different temperatures: (A) FTIR-ATR spectra, (B and C) X-ray diffraction spectra (Domingues *et al.,* 2017$^{A\&C}$; Gilles *et al.,* 2023^{B}).

Coffee husk biochar effects on soil chemical properties

Soil pH

Soil pH is one of the most important parameters influencing the surface charge of both adsorbents and adsorbates, thereby affecting nutrient availability and chemical reactions in soil systems. Application of coffee husk biochar (CHB) has been consistently shown to increase soil pH in acidic soils. For example, Alemnesh et al. (2021) reported an increase in soil pH from 4.89 to 6.68 following the application of CHB at a rate of 20 t ha^{-1}. Similarly, Bayu et al. (2016) observed increases in soil pH from 5.20 to 6.21 and from 5.20 to 6.66 with CHB produced at 350 °C and 500 °C, respectively, applied at 15 t ha^{-1}. Solomon et al. (2024) further confirmed that CHB application increased soil pH from 5.10 to 6.11 in Farm-1 and from 4.64 to 6.22 in Farm-2. Moreover, incubation studies demonstrated that after 60 days, soil pH increased by 0.46, 0.81, and 2.51 units at 350 °C and by 0.75, 1.41, and 2.71 units at 550 °C compared with the control at application rates of 20, 40, and 80 g kg^{-1}, respectively (Gilles et al., 2023).

The observed increase in soil pH is primarily attributed to the presence of silicates, carbonates, and bicarbonates, the high alkalinity (expressed as % $CaCO_3$ equivalent), and the abundance of negatively charged surface functional groups, such as phenolic, carboxyl, and hydroxyl groups, on biochar surfaces (Dai et al., 2017; Gilles et al., 2023). Consequently, the alkaline components of biochar react with H^+ and Al^{3+} ions in the soil solution, reducing their activity and concentration and thereby increasing soil pH (Chintala et al., 2014; Zhang et al., 2019).

Soil organic carbon

Application of coffee husk biochar (CHB) produced at different pyrolysis temperatures and applied at various rates has been shown to increase soil organic carbon (SOC) (Table 2). For instance, Bayu et al. (2016) reported that CHB applied at 15 t ha^{-1} increased SOC from 3.64% to 6.18% at 350 °C and to 6.69% at 500 °C. Similarly, Solomon et al. (2024) observed an increase in organic carbon (OC) from 57.24% to 398.47% over the control following CHB application. Alemnesh et al. (2021) also reported that applying CHB at 20 t ha^{-1} increased OC from 2.76% to 5.04% in acidic soils. Incubation studies showed that SOC increased by 2.7, 2.6, and 3.2 times at 350 °C and by 1.99, 1.97, and 2.1 times at 550 °C compared with the control at application rates of 20, 40, and 50 g kg^{-1}, respectively (Gilles et al., 2023). Furthermore, CHB produced at 500 °C increased SOC by 38.84% relative to the control (3.7%) in acidic soils (Bayu et al., 2015). The observed increase in SOC is attributed to the presence of highly recalcitrant carbon in biochar (Nyambo et al., 2018), the sorption of labile organic matter onto biochar surfaces (Zhang et al., 2019; Singh and Cowie, 2014), and the reduced mineralisation of organic carbon in amended soils (Spokas et al., 2011). These mechanisms collectively enhance the stabilisation and accumulation of SOC in acidic soils following CHB application.

Total nitrogen

Application of coffee husk biochar (CHB) to acidic soils has been shown to significantly increase total nitrogen (TN) content, with reported gains ranging from 15.87% to 195.24% over control soils (Solomon et al., 2024). For example, Bayu et al. (2015) reported that applying 15 t ha^{-1} of CHB produced at 500 °C increased TN from 0.32% in the control soil to 0.45%, representing a 40.74% increase. Similarly, Bayu et al. (2016) found that 15 t ha^{-1} of CHB raised TN from 0.32% to 0.53% at 350 °C and to 0.58% at 500 °C, highlighting the positive effect of both application rate and pyrolysis temperature on nitrogen enrichment in acidic soils.

Commented [MY3]: Describe how the CHB mechanism influences total soil nitrogen.

Available phosphorous

Application of coffee husk biochar (CHB) to acidic soils significantly ($P < 0.05$) increased available phosphorus (P) at various pyrolysis temperatures and application rates (Table 2). Biochars produced at higher pyrolysis temperatures (300–500 °C) generally exhibited higher available P content. For example, applying 15 t ha^{-1} of CHB increased available P from 4.51 to 11.33 mg kg^{-1} at 350 °C and to 18.21 mg kg^{-1} at 500 °C (Bayu et al., 2016). At 20 t ha^{-1}, CHB raised available P from 7.48 to 13.56 mg kg^{-1} (Alemnesh et al., 2021). Similarly, Solomon et al. (2024) reported increases in available P ranging from 45.19% to 147.68% over control soils. Incubation studies further showed that CHB applied at rates of 20, 40, and 80 g kg^{-1} increased available P by 23.9%, 40.6%, and 147.5% at 350 °C, and by 24.0%, 36.0%, and 32.0% at 550 °C compared with the control (Gilles et al., 2023).

The increase in soil P availability is attributed to several mechanisms: the direct contribution of P from CHB, dissolution of inorganic P in acidic soils (Chathurika et al., 2016; Dume et al., 2017), reduced leaching through adsorption (Madiba et al., 2016), mineralisation of organic P (Biederman and Harpole, 2013), and the liming effect of CHB. Additionally, ligand exchange between functional groups on biochar and phosphate anions at Al–OH and Fe–OH sites decreases P sorption, further enhancing P availability. Consequently, CHB can serve as an effective source of phosphorus for plant growth in acidic soils.

Table 2. Effects of coffee husk biochar on soil properties

Rate (t ha^{-1})	Effects	From	To	Temperature (°C)	References
15	Increase soil pH	5.18	6.08	350	Bayu et al., 2015
		5.18	6.14	500	
	Increase organic carbon	3.70	5.41	350	
		3.70	6.24	500	
	Increase TN	0.32	0.47	350	
		0.32	0.54	500	
	Increase available phosphorus	4.51	11.33	350	
		4.51	18.21	500	
	Increase CEC	14.37	18.27	350	
		14.37	20.99	500	
	Increase exchangeable Ca^{2+}	5.57	9.50	350	
		5.57	10.84	500	
	Increase exchangeable Mg^{2+}	1.53	3.66	350	
		1.53	3.98	500	
	Increase exchangeable K^{+}	2.85	3.99	350	
		2.85	5.96	500	
20	Increased soil pH	4.89	6.68		Alemnesh et al., 2021
	Reduce exchangeable acidity	2.82	1.19		
	Exchangeable Al^{3+}	1.63	0.76		
	Exchangeable H^{+}	1.19	0.43		
	Increase organic carbon	2.76	5.04		
	Increase available phosphorus	7.48	13.57		
	Increase CEC	19.56	41.56		
10	Increased soil pH	5.1	6.11		Solomon et al., 2024
		4.64	6.22		
	Increase organic carbon	1.52	6.37		

	1.02	5.59
Increase total nitrogen	0.63	1.40
	0.27	0.97
Rise in available phosphorus	2.19	2.81
	2.81	4.08
Reduce exchangeable Acidity	4.64	3.19
	5.00	2.79
Reduce exchangeable Al^{3+}	3.92	2.66
	3.95	2.23

Cation exchange capacity and Exchangeable cations

The high surface area, presence of hydroxyl and carboxylic functional groups, and variable surface charges of coffee husk biochar (CHB) contribute to improvements in the cation exchange capacity (CEC) of soils (Van Zwieten et al., 2010). For example, application of CHB at 20 t ha⁻¹ increased soil CEC from 19.65 to 41.56 cmol(+) kg⁻¹ (Alemnesh et al., 2021). Similarly, Bayu et al. (2015) reported that CHB increased CEC from 14.37 to 18.27 cmol(+) kg⁻¹ at 350 °C and to 20.99 cmol(+) kg⁻¹ at 500 °C. In addition, the CHB application enhanced the levels of exchangeable K^+, Ca^{2+}, and Mg^{2+} in acidic soils. At a rate of 15 t ha⁻¹, CHB increased exchangeable K^+, Ca^{2+}, and Mg^{2+} by 52.52%, 48.61%, and 61.55%, respectively (Bayu et al., 2015). These effects are primarily due to the high ash content of CHB, which facilitates the immediate release of K^+, Ca^{2+}, and Mg^{2+} (Scheuner et al., 2004; Niemeyer et al., 2005) and can also partially supplement inorganic potassium fertilisers (Singh et al., 2019).

Commented [MY4]: To confirm this statement, include data on the surface charge variability of CHB.

Exchangeable acidity, Al^{3+} and H^+

Commented [MY5]: Describe how CHB application reduces soil exchangeable acidity, including Al^{3+} and H^+.

Application of coffee husk biochar (CHB) significantly ($P < 0.05$) reduces exchangeable acidity, Al^{3+}, and H^+ in acidic soils across different rates and pyrolysis temperatures (Table 2). For instance, applying 10 t ha⁻¹ of CHB decreased exchangeable acidity from 4.64 to 3.19 cmol(+) kg⁻¹ in Farm-1 and from 5.00 to 2.79 cmol(+) kg⁻¹ in Farm-2 (Solomon et al., 2024). Similarly, Alefsi et al. (2023) reported a 60% reduction in exchangeable acidity at 16 t ha⁻¹ of CHB, while Alemnesh et al. (2021) observed a decrease from 2.82 to 1.19 cmol(+) kg⁻¹ at 20 t ha⁻¹. Incubation studies further demonstrated reductions in exchangeable acidity of 60.8%, 87.2%, and

95% at 350 °C and 75.6%, 90%, and 97.3% at 550 °C compared with controls at application rates of 20, 40, and 80 g kg^{-1}, respectively (Gilles et al., 2023).

Exchangeable Al^{3+} and H^{+} also decreased substantially; for example, at 20 t ha^{-1} of CHB, Al^{3+} decreased from 1.63 to 0.76 cmol(+) kg^{-1} and H^{+} from 1.19 to 0.43 cmol(+) kg^{-1} (Alemnesh et al., 2021). Solomon et al. (2024) further confirmed reductions in exchangeable Al^{3+} from 3.92 to 2.66 cmol(+) kg^{-1} in Farm-1 and from 3.95 to 2.23 cmol(+) kg^{-1} in Farm-2 at 10 t ha^{-1} of CHB. These effects are attributed to the presence of oxides, carbonates, silicates, and organic functional groups (–O, –OH, –COOH) in CHB, which complex with Al^{3+} and H^{+} ions in the soil solution, thereby reducing their concentrations in acidic soils (Qian et al., 2013). The high liming potential and acid-neutralising capacity of CHB make it an effective amendment for reclaiming acidic soils and reducing exchangeable acidity and toxic Al^{3+} levels.

Liming potential of coffee husk biochar

Commented [MY6]: Compared with dolomite, which is commonly used to amend acidic soils, CHB contains relatively low CaCO$_3$. How does CHB exhibit liming potential?

The liming potential of coffee husk biochar (CHB) is relatively high compared with other locally available feedstocks, averaging approximately 12% CaCO$_3$ equivalent (Table 3). CHB produced from the Dale and Aleta Wondo districts in the Sidama region exhibited the highest CaCO$_3$ content at 17.14% (Hibret et al., 2023). Liming potential generally increases with pyrolysis temperature due to elevated levels of carbonates (CaCO$_3$) and bicarbonates (KHCO$_3$) in the biochar (Domingue et al., 2017; Gilles et al., 2023). Notably, the acid-neutralising capacity of CHB remains high regardless of pyrolysis temperature, which is attributed to the presence of alkaline mineral components such as calcite and kalicinite (confirmed by XRD; Figure 2) and functional groups (–O^{-} and –COO^{-}) capable of binding H^{+} ions (Gilles et al., 2023).

Overall, CHB demonstrates superior liming potential due to its greater alkalinity, higher CaCO$_3$ equivalent, and enhanced acid-neutralising capacity. This makes it a practical and cost-effective alternative for smallholder farmers who face challenges in remediating acidic soils due to the high cost of agricultural lime. Specifically, CHB produced at a pyrolysis temperature of 450 °C represents an economically viable solution for reclaiming soil acidity and improving soil fertility on small-scale farms.

Table 3. Biochar liming equivalence of $CaCO_3$ (%).

Feedstock	Temperature (°C)	$CaCO_3$ (%)	References
Coffee husk	350	1.39	Domingues *et al.,*2017
	450	1.6	Domingues *et al.,*2017
	450	17.14	Hibret *et al.,* 2023
	750	2.1	Domingues *et al.,*2017
Bamboo	450	5.47	Hibret *et al.,* 2023
	550	5.22	Hibret *et al.,* 2023
Avocado seed	450	3.19	Hibret *et al.,* 2023
	550	7.47	Hibret *et al.,* 2023
Corncob	450	6.43	Hibret *et al.,* 2023
Switchgrass	400	1.9	Singh *et al.,*2017
	550	3	Singh *et al.,*2017
Pine chips	400	3.9	Singh *et al.,*2017
	550	5	Singh *et al.,*2017
Eucalyptus wood	450	2.6	Singh *et al.,*2017
	550	6.3	Singh *et al.,*2017
Poultry litter	550	11.8	Singh *et al.,*2017

Environmental benefits of coffee husk biochar

Coffee husk biochar (CHB) exhibits a highly aromatic character due to its low H: C ratio, which contributes to a long carbon residence time in CHB-amended soils (Domingue et al., 2017). This prolonged carbon stability enhances soil carbon sequestration and helps mitigate greenhouse gas emissions (Zimmerman, 2010). A significant proportion of N_2O emissions originates from agricultural fields fertilised with nitrogen and from manure deposition in both low- and high-intensity livestock production systems. Biochars with an H: C ratio below 0.3, indicating a high degree of polymerisation and aromaticity, have been shown to reduce N_2O emissions by up to 73%, whereas biochars with H: C ratios above 0.5 decrease N_2O emissions by only 40% (Cayuela et al., 2015).

In contrast, biochars produced at lower pyrolysis temperatures (350–450 °C) retain a higher aliphatic character and O: C ratio, making them more susceptible to microbial degradation. This can result in short-term immobilisation of inorganic nitrogen in the soil (Deenik et al., 2011), which may temporarily limit nitrogen availability to plants (Deenik et al., 2011; Rondon et al., 2007) while simultaneously mitigating N_2O emissions and reducing inorganic nitrogen leaching (Novak et al., 2010).

Agronomic benefits of coffee husk biochar

The high ash content of coffee husk biochar (CHB) ensures it is rich in nutrients and possesses strong alkalizing capacity (Deenik et al., 2011; Sigua et al., 2016). This ash is largely composed of alkaline chemical species such as $KHCO_3$ and $CaCO_3$, as confirmed by XRD analysis (Figure 2) (Domingue et al., 2017; Gilles et al., 2023). These characteristics make CHB a promising amendment for increasing soil buffering capacity and neutralising soil acidity, potentially reducing the need for large applications of agricultural lime in crop fields. The solubilization of these alkaline compounds can increase soil pH, decrease exchangeable acidity, Al^{3+}, and H^+ concentrations, reduce the availability of Fe and Mn, and enhance soil cation exchange capacity (CEC) (Fellet et al., 2011; Qian and Chen, 2014). These changes may also decrease phosphorus fixation while increasing the availability of Ca and K for plants, enhancing the agronomic value of CHB (Figure 4) (Xu et al., 2014).

However, the nutrient availability and functional properties of CHB are strongly influenced by pyrolysis temperature. Low-temperature CHB (350–450 °C) exhibits high CEC, enabling it to adsorb up to 2.3 mg g^{-1} of NH_4^+ and reduce nitrogen leaching (Gai et al., 2014). In contrast, high-temperature CHB (>600 °C) has a high surface area but low CEC and markedly lower levels of N, P, and S, which may limit its nutrient contribution in soils (Zhang et al., 2019). Overall, CHB has strong potential to ameliorate soil acidity and partially replace limestone for soil reclamation in crop production systems in Ethiopia.

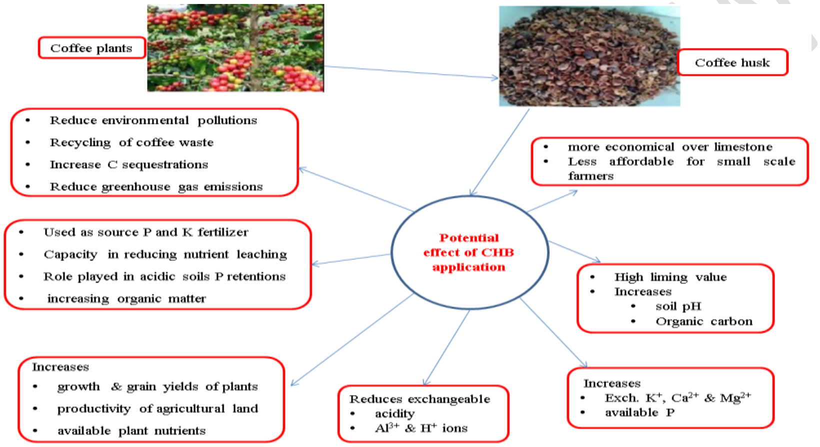

Figure 6: Coffee husk biochar integration into a coffee production system, and potential impacts

Carbon Sequestration Potential

Biochar is an effective strategy for long-term carbon storage in soils because its aromatic carbon compounds are highly resistant to microbial decomposition (Basanta and Rajasekhar, 2025). Application of biochar has also been shown to reduce soil CO_2 fluxes in agricultural systems (He et al., 2017). Several key factors contribute to the enhanced carbon sequestration potential of biochar-amended soils (Figures 7and 8), including: (i) increased soil organic carbon (SOC) content, (ii) protection of organic matter against microbial degradation, (iii) improved soil aggregation, (iv) enhanced nutrient and water retention, (v) stabilization of labile carbon fractions, and (vi) promotion of soil microbial abundance, diversity, and functional enzyme activity (Li and Tasnady, 2023).

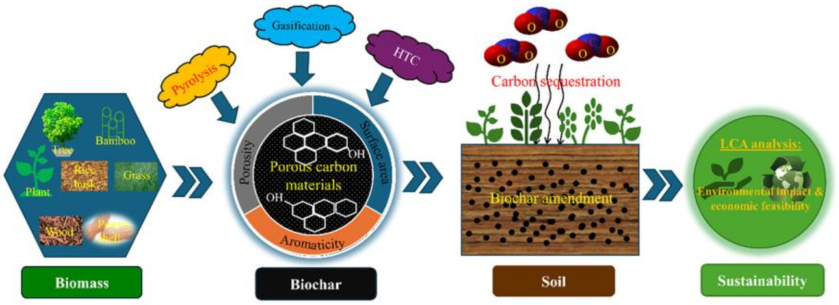

Figure 7. Schematic presentation on the overall scope and objectives of this comprehensive review (Basanta and Rajasekhar, 2025).

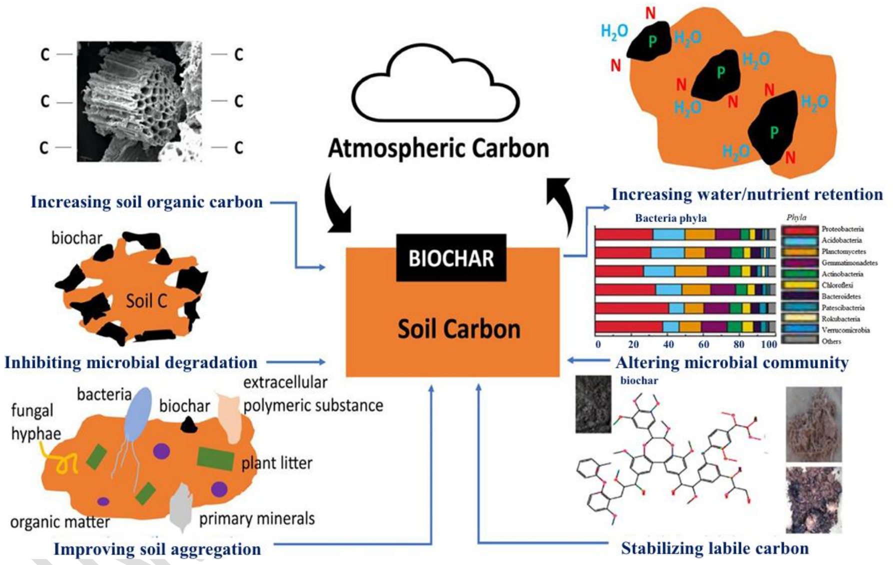

Figure 8. Key mechanisms of biochar on enhancing soil carbon sequestration (Zhou et al., 2017)

Conclusions and Future Perspective

Coffee husk biochar (CHB), a sustainable solid material produced through biomass pyrolysis, has received increasing attention for its potential to sequester atmospheric CO_2 in soils and contribute to carbon neutrality. This review comprehensively examines recent developments on the use of biomass-derived CHB as a sustainable material for soil carbon sequestration. Coffee husk residues are rich in lignocellulose, making them ideal feedstocks for biochar production with a high carbon content, which enhances long-term carbon storage in soils. Biochar produced at high pyrolysis temperatures (e.g., >500 °C) contains a high proportion of aromatic carbon compounds, rendering it stable and recalcitrant. This carbon-rich biochar exhibits strong sorption capacity for CO_2 and is highly resistant to microbial and physicochemical degradation. Most studies report that CHB amendment enhances soil carbon sequestration by reducing organic carbon mineralisation and decreasing CO_2 release, thereby enabling soils to act as long-term carbon sinks. Incorporation of CHB also alters soil microbial communities, shifting bacterial and fungal populations and influencing enzymatic activities, particularly those involved in C, N, and P cycling. Key mechanisms facilitating enhanced carbon sequestration include the adsorption of labile soil organic carbon (SOC) onto biochar surfaces and the regulation of carbon-metabolising microbial communities. However, most experiments on biochar-mediated carbon sequestration have been conducted under controlled pot conditions, with limited field-scale studies in real environmental settings. Therefore, well-designed field experiments are urgently needed to fully evaluate the potential of CHB for enhancing carbon sequestration in complex soil systems.

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