

REVIEW PAPER

Review of Scientific Advances and Importance of Biochar for Agricultural and Industrial Uses

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Received: 10-09-2024

Revised: 30-11-2024

Accepted: 07-12-2024

ABSTRACT

Biochar has been known as an effective soil amendment with capabilities of boosting soil moisture storage, increasing soil fertility, and enhancing crop productivity. Biochar also has the potential for industrial use for wastewater treatment, water purification, steel making, building insulation, and air pollution control. The current metadata analysis evaluated the importance of biochar for agricultural and industrial uses and its relevance for use in Kenya. A total of 120 reference materials comprising journal papers, conference proceedings, and book chapters were used. Numerous studies conducted across the globe have documented the positive effects of biochar in increasing available soil nutrients (increased by 28.6% and phosphorus by 2 folds), lowering bulk density by 3-31%, enhancing soil moisture storage by 18-108%, and boosting microbial activities in the soil thus enhancing nutrient cycling. The metadata analysis also showed that biochar can reduce CO₂ emissions by up to 33% thereby mitigating climate change. Biochar equally increased maize yield by 32-135% and rice yield by 8.5-10.7%. The review also showed that biochar can play a crucial role in different industrial uses such as wastewater treatment, steel making, and water purification. Some of the main impediments to the adoption of biochar were; the lack of a regulatory framework to govern the sector and the lack of a decision support system for use by end users.

HIGHLIGHTS

- Biochar has the capacity to increase available soil nutrients, lower bulk density, enhance soil moisture storage and boost microbial activities hence enhance nutrient cycling.
- It can reduce CO₂ emissions by up to 33% thus mitigating climate change.
- Biochar is equally vital in wastewater treatment, steel making, and water purification.
- To boost the adoption of biochar, there is need to enact a regulatory framework to govern the sector.

Keywords: Biochar, agriculture, industry, Feedstock, Pyrolysis, climate change

Agriculture plays a crucial role in Africa's socio-economic development (Diao *et al.* 2010). It employs about two-thirds of the continent's working population and for each country, it contributes an average of 30 to 60 percent of gross domestic product (GDP). In Kenya, agriculture contributes

22% of GDP and a further 27% through linkages

How to cite this article: Mwadalu, R., Ndufa, J., Maitra, S., Gweyi-Onyango, J. and Gitari, H. (2024). Review of Scientific Advances and Importance of Biochar for Agricultural and Industrial Uses. *Int. J. Bioresource Sci.*, 11(02): 259-273.

Source of Support: IUCEA; **Conflict of Interest:** None 

with agro-based industries (CBK, 2022). However, declining soil fertility coupled with frequent droughts in Sub-Saharan Africa (SSA) leads to perennial food shortages thereby increasing the problem of food insecurity (Mwadalu *et al.* 2022; Ochieng' *et al.* 2023; Nungula *et al.* 2023). Frequent and prolonged dry spells have become a characteristic of Arid and Semi-Arid Lands (ASALs), which account for 80% of Kenya's land mass (Mwadalu and Mwangi, 2013; Alhammad *et al.* 2023). As climate change unfolds, climate predictability is expected to deteriorate (Ochieng *et al.* 2016) thus leading to higher temperatures and erratic rainfall. To address these challenges, studies have been conducted to come up with soil amendments that enhance soil fertility while boosting soil moisture retention (Kisaka *et al.* 2022; Shanthi Priya *et al.* 2023; Shao *et al.* 2024; Sahoo *et al.* 2024). Among many technologies, the use of biochar has been reported to offer a cost-effective means of improving soil fertility and water-holding capacity (Imoro *et al.* 2012; Nair *et al.* 2017; Allohverdi *et al.* 2021). Biochar has been proven to provide nutrients for crop growth and development (Baidoo *et al.* 2016) while enhancing soil moisture retention (Al-Wasfy and El-Khawanga, 2008; Pühringer, 2016; Adeyemi and Idowu, 2017; Mwadalu *et al.* 2021).

Equally, studies have shown that biochar has the potential for industrial use in housing insulation, wastewater treatment, and removal of heavy metals from water treatment plants (Schmidt, 2013; Garcia *et al.* 2020). Studies have also shown that biochar has the potential for climate change mitigation through carbon storage in recalcitrant form and suppression of nitrous oxide and methane emissions from agricultural landscapes (Omulo, 2020; Kalu *et al.* 2022; Alkharabsheh *et al.* 2023). However, conclusive results on the potential of biochar for agriculture and industrial use are limited. Research undertaken in different parts of the globe has yielded conflicting results, especially about agricultural productivity. While studies by Drabkin and Weinfurther (2014), Imoro *et al.* (2012), and El-Dayem (2003) showed improved plant growth with biochar application, those of McElligot (2011), and Velez (2012) noted that biochar had no significant effect on plant growth even with improved soil properties. The conflicting results have been attributed to the use of different feedstock, pyrolysis conditions, and varying soil

types (Singh *et al.* 2014). Additionally, there is a lack of standardization in the biochar industry due to the inexistence of a proper regulatory framework for the sector (Laer *et al.* 2013; Singh *et al.* 2014). This metadata analysis reviews the potential of biochar for agricultural and industrial use in Kenya.

MATERIALS AND METHODS

This literature review was undertaken through a purposeful sampling of relevant journal papers, book chapters, and conference proceedings through different search engines such as Google Scholar, Scopus, and Web of Science. The literature review involved an in-depth analysis of 125 literature materials all addressing issues of biochar's potential for use in agriculture and industries. The keywords used for obtaining literature materials were biochar, feedstock, pyrolysis, industrial use, and carbon sequestration among others. The literature materials comprised 57.5% of research conducted between the years 2017 and 2024 and 42.5% of research undertaken prior to the year 2017; this was to ensure recent data is available for the metadata analysis.

RESULTS AND DISCUSSION

Definition of Biochar

Biochar is been defined as fine-grained biomass residue with high carbon content which is produced through pyrolysis processes (Kazmi *et al.* 2010; Joseph *et al.* 2016; Oshunsanya & Aliku, 2016). On the other hand, pyrolysis is defined as the direct thermal decomposition of biomass in the absence of oxygen to obtain a range of products namely; solid (biochar), liquid (bio-oil), and gas (syngas) (Gwenzi *et al.* 2021). The specific product from the pyrolysis process is mainly dependent on the feedstock and pyrolysis conditions, which can be optimized to produce either energy or biochar (Kazmi *et al.* 2010). Biomass for biochar production may include woody materials, animal manure, and crop residues, among other farm wastes (Omulo, 2020).

Properties of Biochar

Biochar's efficiency in the agriculture and industrial sector are dependent on biochar properties. Table 1 gives a summary of biochar properties, which determine its efficiency for agriculture and industrial use. All studies concur that biochar's large

surface area and high adsorption capacities play crucial roles in nutrient and water retention (Fayong *et al.* 2019; Gwenzi *et al.* 2021). The main properties of biochar are low bulk density, high surface area and porosity (Figure 1), moderate to high nutrient content, high stability, high cation exchange capacity (CEC) (Mohan *et al.* 2018), neutral to high pH and high carbon content (Berek, 2014). These properties make biochar a suitable amendment for tropical soils in sub-Saharan Africa (Gwenzi *et al.* 2015; Mensah & Frimpong, 2018).

Factors influencing biochar properties

The physico-chemical properties and quality of biochar are highly dependent on the chemical composition of the biomass used, the pyrolysis system, and production conditions such as temperature and residence time (Poitras & Straubing, 2009; Mekuria & Noble 2013; Pühringer, 2016). Studies have also shown that biochar generated

under different pyrolysis temperatures has varying nutrient retention capacities. This can be attributed to the alteration of biochar surface properties at different pyrolysis temperatures (Adeyemi & Idowu, 2017). Previous studies have reported that heat treatment of biomass used for biochar production contributes to its large surface area and its aromatic structure which resists decomposition (Poitras and Straubing, 2009; Xie *et al.* 2015). Table 2 summarizes the factors influencing biochar properties.

Biochar production technologies and potential feedstock

The agriculture and forestry sectors produce substantial amounts of waste such as crop residues, forest residues (lumber, pulp, veneers), and animal manure (Gwenzi *et al.* 2015). These waste materials can be used for the production of biochar that can be used for both agriculture and industrial use. The most suitable feedstock for biochar production

Table 1: Selected biochar properties

No.	Biochar Property	References
1	Large surface area	Oshunsanya and Aliku (2010)
2	High water holding capacity	Oshunsanya and Aliku (2010), Mwadalu <i>et al.</i> (2021)
3	High porosity resulting from biochar's micropores	Fayong <i>et al.</i> (2019)
4	Low bulk density	Mekuria and Noble. (2013), Mwadalu <i>et al.</i> (2021)
5	High adoption capacity for nutrients	Kelly <i>et al.</i> (2015)
6	Low susceptibility to microbial processes	Brantley <i>et al.</i> (2015), Tel (2018)
7	Moderate nutrient concentrations such as N, P, K, Mg, Ca	Poitras and Straubing (2009), Clough <i>et al.</i> (2013)
8	High carbon content and strong resilience to biochemical composition	Weber and Quicker (2018), Fayong <i>et al.</i> (2019)

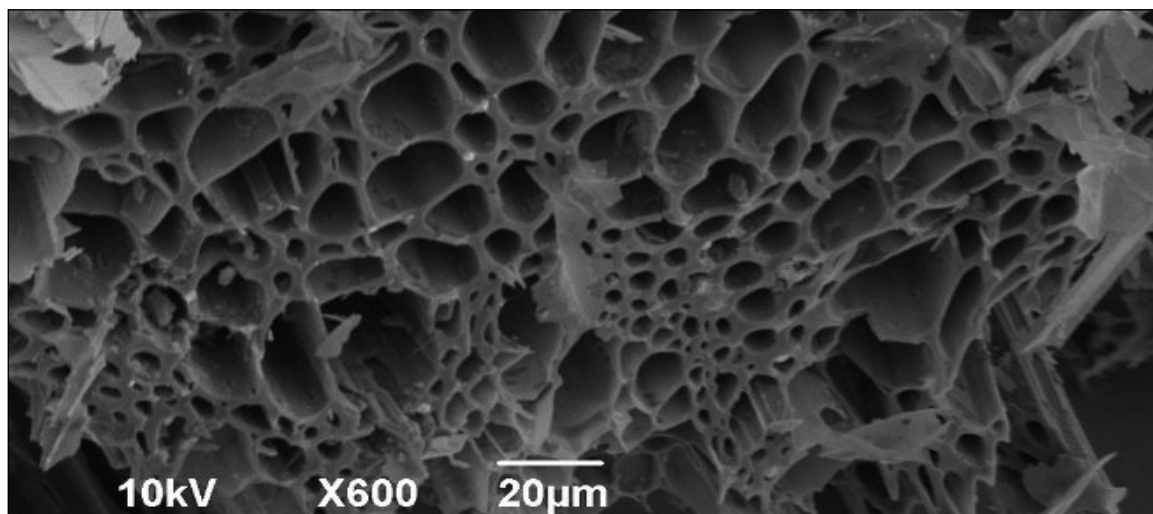


Fig. 1: Biochar has a huge surface area and a highly porous structure

Image source: www.carbolea.ul.ie via Biochar Ireland

Table 2: Production factors influencing biochar properties

Factor	Parameter influenced	References
Type of feedstock used for biochar production	Carbon content and nutrients such as N, Mg, Ca, K	Adeyemi and Idowu (2017), Poitras and Straubing (2009), Joseph and Tailor (2014)
Pyrolysis conditions such as temperature and residence time	Adsorption capacity; nutrient content; porosity; bulk density;	Adeyemi and Idowu (2017), Fayong <i>et al.</i> (2019), Joseph and Tailor (2014)
Chemical composition of biomass	Chemical properties of biochar such as nutrient composition	Fayong <i>et al.</i> (2019), Pühringer (2016)

should contain high lignin content which results in high biochar yields (Lane, 2016; Adeyemi & Idowu, 2017). Potential feedstock for realizing higher biochar yields includes wastes from sawmills, forest residues, and nut shells. The suitability of particular biomass as a potential feedstock for biochar production depends on various characteristics such as moisture content, calorific value, fixed carbon, oxygen, hydrogen, nitrogen, volatiles, ash content, and cellulose/lignin ratio (McHenry, 2009; Sánchez, 2009; Mohan and Steele 2006).

There are several thermochemical technologies used for the production of biochar such as pyrolysis, gasification, torrefaction, and hydrothermal conversion (Garcia *et al.* 2020). However, pyrolysis is the most common method used for biochar production (Mekuria & Noble, 2013). Pyrolysis is a process that involves the heating of biomass in the absence of oxygen to yield a series of bioproducts: biochar, bio-oil, and syngas (Adeyemi & Idowu, 2017). Gasification on the other hand is a thermochemical process where biomass is heated with a small amount of air to produce syngas as the main product and biochar as a by-product. Gasification produces approximately 10% of biochar (Adeyemi & Idowu, 2017). Another technique used for biochar production is Hydro-thermal carbonization (HTC); this process involves steaming biomass together with different types of acid which act as a catalyst. The main by-products of this process are bio-oil and limited amounts of biochar (Mekuria & Noble, 2013). Torrefaction on the other hand is the slow heating of biomass in an inert or oxygen-deficit environment in the temperature range of 200–300°C. During torrefaction, moisture and some volatile organic compounds volatilize from the biomass (Tumurulu *et al.* 2021). Table 3 highlights the biochar production methods and biochar yield resulting from each method. The studies reviewed show that slow pyrolysis is the

most efficient biochar production method (Mekuria & Noble, 2013; Zhang *et al.* 2022).

Biochar's effect on soil properties

Biochar's properties such as large surface area, high porosity, low bulk density, and high soil moisture storage have the potential to improve soil physical properties (Omondi *et al.* 2016). Soil physical conditions have a direct effect on soil productivity for crop production (Aslam *et al.* 2014). The effect of biochar on soil fertility has been widely explored by different researchers in the recent past since the discovery of Terra Preta soils (Oshunsanya & Aliku, 2016). Numerous studies have dealt with the impact of biochar on different soil chemical properties. Soil nutrient transformations are mainly dependent on the type and quality of biochar applied (Page-Dumroese, 2015). While some studies have reported increased nutrient availability with biochar application (Carvalho *et al.* 2013; Abdullaeva, 2014; Mohan *et al.* 2018), other studies have observed an insignificant effect of biochar on soil properties (Bonanomi *et al.* 2017). In some instances, studies have reported the negative impact of biochar on soils. Velez (2012) reported that the addition of biochar at 5% significantly reduced available soil nutrients.

The capacity of biochar to enhance soil moisture retention has been attributed to numerous factors. According to Carvalho *et al.* (2013), biochar's high total porosity is an attribute that enables it to retain water in small pores and thus increase water holding capacity and assist water to rise from lower soil horizons to the topsoil through capillary rise. The influence of biochar on soil moisture content has also been reported to be determined by the age of biochar where the use of fresh biochar increased soil moisture retention while aged biochar reduced soil moisture retention (Aller, 2017). The mechanism

**Table 3:** Biochar production methods

Production method	Temperature (° C)	Production conditions	Biochar yield (%)	References
Slow pyrolysis	300-800	Suitable for biomass with high lignin; absence of oxygen	30-55	Mekuria & Noble (2013), Garcia <i>et al.</i> (2020), Zhang <i>et al.</i> (2022)
Fast pyrolysis	450-600	Suitable for biomass with high lignin; absence of oxygen	10-25	Mekuria & Noble (2013), Garcia <i>et al.</i> (2020)
Gasification	750-1000	Presence of an oxidizing agent	14-25	Adeyemi and Idowu (2017), Garcia <i>et al.</i> (2020), Zhang <i>et al.</i> (2022)
Torrefaction	200-300	Moisture, CO ₂ and O ₂ contained in biomass are removed in inert conditions	70-80	Mekuria and Noble, (2013), Garcia <i>et al.</i> (2020)
Hydrothermal Carbonization (HTC)	180-300	Involves steaming biomass with different types of acids which act as catalysts	50-80	Garcia <i>et al.</i> (2020), Zhang <i>et al.</i> (2022)

under which biochar's age influences soil moisture retention is a subject requiring further studies. Pühringer (2016) in a study undertaken in Siaya, Kenya reported an increase in water retention by 18% with biochar application. Mwadalu *et al.* (2022) reported moisture enhancement with biochar application of up to 108% in sandy soil. On the other hand, some studies have reported no significant changes in soil moisture as a result of biochar application (Abdullaeva, 2014; Brantley *et al.* (2015). Vitoka *et al.* (2017) contrary reported that plots treated with biochar recorded lower soil moisture content than the control across the growing season.

Most studies have reported a decrease in bulk density following biochar application (Aslam *et al.* 2014; Lane, 2016; Oshunsanya & Aliku, 2016; Harder *et al.* 2017; Humberto, 2017). Humberto (2017) reported a decrease of bulk density by 3 to 31% with biochar addition. Omondi *et al.* (2016) also reported a decrease in bulk density by 7.6% after biochar utilization. A study by Omondi *et al.* (2016) revealed that biochar reduces bulk density in coarse-textured soils more than fine-textured soils. This is estimated at 14.2% in coarse-textured soils and 9.2% in fine-textured soils (Omondi *et al.* 2016). The decrease in bulk density following biochar application may be a result of biochar's lower bulk density (0.63g cm⁻³) than soil (1.25g cm⁻³) through mixing or dilution (Humberto, 2017). The reduction in bulk density with biochar application could also be a result of increased soil porosity thus enhancing aeration and root development. Biochar has a

porosity of 70 to 90% (Aslam *et al.* 2014; Are, 2020). Higher bulk density restricts root development due to soil compaction (Kormanek *et al.* 2015).

According to Xie *et al.* (2015), the use of biochar is an appropriate strategy for carbon neutralization resulting from carbon storage by itself and the decrease of total greenhouse gas emissions. Gao *et al.* (2017) and Truong & Marschner (2018) reported an increase in Total Carbon following biochar application of up to 38.19%. Mensah & Frimpong (2018) equally reported enhanced Total C following biochar application due to biochar's recalcitrant carbon.

Biochar application was reported to increase soil pH (Mensah & Frimpong, 2018; Mohan *et al.* 2018 and Mwadalu *et al.* 2020). Zang *et al.* (2019) reported a significant increase in soil pH by 0.5 to 1 unit with biochar application. Dai *et al.* (2014) also reported an increase in soil pH with biochar application; at a 3% biochar application rate, pH increased by up to 2.52 units with application of swine manure biochar. The increase in pH following biochar application can be attributed to high cation exchange capacity (CEC) due to the biochar's large surface areas and porosity (Mohan *et al.* 2018); carbonates and organic anions (-O⁻ and COO⁻) (Dai *et al.* 2014; Trupiano *et al.* 2017). Liming effect of biochar depends on the feedstock used for its production (Leghari *et al.* 2016; Yunilasari *et al.* 2020).

Nitrogen is the most critical nutrient limiting plant growth in most soils (Nyamangara *et al.* 2005). Studies have shown that nitrogen availability

resulting from biochar application is highly dependent on the feedstock used. Truong & Marschner (2018) observed enhanced nitrogen with biochar application; this was attributed to the large surface area of biochar which enhanced retention of NH_4^+ thus leading to improved N nutrition. Contrary, Gao *et al.* (2017) recorded a decrease in soil N with increased biochar rates applied.

Biochar has been reported to be a feasible short, mid, and long-term phosphorus (P) fertilizer with its effects depending on the feedstock, pyrolysis temperature, and application amount (Trupiano *et al.* 2017; Truong and Marschner, 2018; Glasser & Lehr, 2019). Studies have shown that biochar application in acid soils led to increased P availability than alkaline soils (Shen *et al.* 2016; Fayong *et al.* 2019). Enhanced P can also be attributed to reduced iron (Fe) and Aluminium (Al) activity as a result of increased pH; and biochar's capacity to retain and exchange phosphate ions due to its positively charged surface (Mensah & Frimpong, 2018). Studies have shown that biochar from woody sources has a higher P content than biochar from manure. It has also been noted that biochar produced from high-temperature pyrolysis $>550^\circ\text{C}$ has a higher surface area and P content (Fayong *et al.* 2019). Previous studies observed a gradual increase in P concentration as pyrolysis temperatures increased (Glasser & Lehr, 2019; Fayong *et al.* 2019). Phosphorus content in biochar can increase by two to threefold during the pyrolysis process (Mensah & Frimpong, 2018). The P increase with biochar application contributes to greater root growth thus enhancing nutrient and water uptake by plants. Application of biochar with liming properties on P-deficient soil increased plant growth by 59% and P uptake by 73% (Shen *et al.* 2016).

Studies have also reported enhanced soil CEC following biochar application (Gao *et al.* 2017; Mensah & Frimpong, 2018; Truong & Marschner, 2018; Tomczyk *et al.* 2020). Mohan *et al.* (2018) reported that amending soil with biochar increases Na^+ , K^+ , Ca^{2+} , and Mg^{2+} availability. The study further reported increased CEC of up to 362% with increasing biochar application rates as compared to the control. The increase in CEC can be attributed to slow biochar oxidation in the soil which is reported to increase the number of the char's carboxyl groups (Carvalho *et al.* 2013; Sahoo *et al.* 2024;

Pühringer, 2016; Mohan *et al.* 2018). The relatively high CEC values accrued to biochar application is an indication of the ability of biochar to retain soil nutrients (Mohan *et al.* 2018).

The porous and adsorption properties of biochar provide a favorable environment for the growth and reproduction of microorganisms (Gao *et al.* 2017). The increase in pH with biochar application increases bacteria abundance in the soil (Truong & Marschner, 2018). Bacteria and fungi populations in the soil are influenced by various factors such as organic matter, porosity, oxygen and carbon dioxide concentration, and soil pH (Bhattarai *et al.* 2015). Table 4 summarizes biochar's effect on soil properties.

Effect of Biochar on plant growth and crop yield

The growth of crops as influenced by biochar has received significant focus in the recent past with studies being conducted to evaluate the effect of biochar on yields (Poitras & Straubing, 2009, Pühringer, 2016; Harder *et al.* 2017). Biochar has been tested on different crops to evaluate its potential as a soil amendment. For instance, Mohan *et al.* (2018) reported increased eggplant growth due to biochar application as compared to the control. The study further revealed that biochar-amended soils (3%) had the highest increase in both plant height and number of leaves. The average plant height improved from 8.3 cm in the first week to 20 cm (7th week) versus 6 cm (1st week) to 9.5 cm (7th week) in control. Similar results on the increase of plant growth resulting from biochar application were reported by Carter *et al.* (2013) and Mwadalu *et al.* (2021). Biochar promotes plant productivity through several mechanisms (Khaitov *et al.* 2019) such as enhancement of physical conditions such as water holding capacity thereby providing water for plant growth.

According to Hafeez *et al.* (2017), there was a significant increase in height of *Glycine max* (L.) with biochar application. The study attributed this to alleviating the physiochemical stresses particularly water and nutrient scarcity as a result of biochar application. These findings concur with those of Berek (2014) that biochar application increased plant biomass by 2 to 4 folds. Studies have also reported increased yield of various crops such as maize,

**Table 4:** Biochar's effect on soil properties

Biochar effect	References
Enhanced soil moisture by 18-108%	Wilson and Major (2010), Novak <i>et al.</i> (2012), Pührringer (2016), Glaser <i>et al.</i> (2002), Pührringer (2016), Mwalulu <i>et al.</i> (2021)
Decreased soil bulk density by 3-31%	Omondi <i>et al.</i> (2016), Humberto (2017), Aslam <i>et al.</i> (2014), Lane (2016), Oshunsanya and Aliku (2016), Harder <i>et al.</i> (2017), Humberto (2017)
Increased soil porosity by 70-90%	Aslam <i>et al.</i> (2014), Are (2020), Hseu <i>et al.</i> (2014), Kormanek <i>et al.</i> (2015), Humberto (2017)
Increased soil carbon by 38.19-328%	Mohan <i>et al.</i> (2018) Truong and Marschner (2018)
Increased soil pH by 2.52 units	Dai <i>et al.</i> (2014)
Enhanced available soil P by 2-3 folds	Fayong <i>et al.</i> (2019), Glasser and Lehr (2019)
Enhanced soil CEC by 362%	Mohan <i>et al.</i> (2018)
Total N increased by 28.6%	Frimpong <i>et al.</i> (2021)

Table 5: Effect of biochar on crop yield

Effect on crop yield	Biochar source& application rate	References
Maize yield increased by 32-135.3% in Western Kenya and Embu respectively	1 to 10 t ha ⁻¹ of agricultural waste biochar	Katterer <i>et al.</i> (2022)
Increased paddy rice yield by 8.5-10.7% in Zhejiang, China	20 t ha ⁻¹ of bamboo biochar	Liu <i>et al.</i> (2021)
Biochar had no significant effect on sorghum yield in Sudan	10 t ha ⁻¹ of biochar	Deng <i>et al.</i> (2017)
Increased sorghum yield by 14.8-27% in Sudan	24 t ha ⁻¹ of maize straw biochar and woody biochar	Fouda and Al-Agazy (2020)
Increased wheat grain yield by 58.5% in China	2% milk tea waste in a potting experiment	Sial <i>et al.</i> (2019)
Increased wheat grain yield by up to 16.5% in Tigray, Ethiopia	4 t ha ⁻¹ of <i>Prosopis juliflora</i> biochar	Gebremodhin <i>et al.</i> (2015)
Increased bean yield by 4 folds	10% biochar from agricultural waste	Silva <i>et al.</i> (2017)

rice, and sorghum following biochar application (Liu *et al.* 2016; Fouda and Al-Agazy, 2020; Liu *et al.* 2022; Katterer *et al.* 2022). However, Blair (2014) reported that biochar did not significantly influence maize growth while Deng *et al.* (2017) reported an insignificant effect of biochar on sorghum yields. The contradicting results can be attributed to feedstock and pyrolysis conditions used for biochar production and differences in soil types (Mekuria and Noble, 2013). Table 5 summarizes the effect of biochar on yield of selected crops.

Biochar for environmental sustainability

Biochar has the potential to enhance environmental protection through the remediation of polluted soils, climate change mitigation and adaptation, and waste management. Studies have shown that biochar enables long-term sequestration of carbon (Saletink *et al.* 2019; Karan *et al.* 2023). Amending one hectare with biochar sequesters approximately 13 tons of

CO₂eq in the soil (Lawewiec *et al.* 2019). During pyrolysis, 0.04 tCO₂eq is emitted to the atmosphere for each ton of biomass pyrolyzed, however, 1.67 t CO₂eq per ton of feedstock is stored in the soil. Biochar captures and stores atmospheric carbon in recalcitrant form thereby reducing carbon emission to the atmosphere (Tisserant and Cherubini, 2019). Biochar also reduces soil emissions of N₂O by 32–38% on average after biochar application to soils. Hence, biochar use in agricultural systems is a viable option for enhancing natural rates of carbon sequestration in soil, reducing farm wastes, and improving soil quality (Srinivasarao *et al.* 2013). Post-Kyoto agreements under the UNFCCC unilaterally accepted biochar as a viable climate change mitigation strategy (Omulo, 2020). Globally, biochar technology can reduce greenhouse gas emissions by 3.4–6.4 PgCO₂-eq, of which 1.7–3.7 PgCO₂-eq (49–59%) is attributed to CO₂ withdrawal from the atmosphere (Zhang *et al.* 2022). Table 6

Table 6: Potential of biochar for climate change mitigation

Biochar effect on GHG emissions	Mechanisms for emission reduction	References
Reduced N ₂ O emission by up to 500%	Adsorption of nitrifier-inhibitory compounds; promotion of proliferation of nitrifiers	Gwenzi <i>et al.</i> (2015), Kalu <i>et al.</i> (2022)
Suppressed CO ₂ emissions by 33%	Biochar adsorption	Case <i>et al.</i> (2014), Kalu <i>et al.</i> (2022)
Suppressed CH ₄ emissions by 37%	Biochar adsorption	Case <i>et al.</i> (2014), Shakoor <i>et al.</i> (2021), Kalu <i>et al.</i> (2022)
Carbon sequestration by storing 1.67tCO ₂ eq per ton of feedstock used	Store carbon in recalcitrant form with low susceptibility to decomposition	Gwenzi <i>et al.</i> (2015) Tisserant and Cherubini, (2019), Shakoor <i>et al.</i> (2021), Kalu <i>et al.</i> (2022)

Table 7: Industrial uses of biochar

Sector	Industrial use	Responsible biochar property	Reference
Housing	Building insulation; humidity control (maintains humidity a 45-70% during winter and summer); production of building bricks with tensile strength of 20 N/mm ²	Large surface area; low thermal conductivity; high porosity	Schmidt (2013), Pandey (2022)
Wastewater treatment	Absorbent for removal of heavy metals, organic contaminants, nitrogen, and phosphorus; Biochar enhances flocculation, dewatering, adsorption, and oxidation processes during municipal wastewater treatment, which in turn aids sludge management, odor mitigation, and nutrient recovery	Large surface area; high porosity; stronger adsorption capacity; abundant surface functional groups; ion exchange capacity	Schmidt, (2013), Duwiejuah <i>et al.</i> (2020), Pokharel <i>et al.</i> (2020), Xiang <i>et al.</i> (2020), He <i>et al.</i> (2022), Wang <i>et al.</i> (2022)
Air purification	Ozone, volatile organics, and odors; Biochar air filters can be used in incinerators, kilns, cremation, and smelters; removal of heavy metals from industrial flue gas; reducing emissions of nitric oxide from soil	Carbon content; high ion exchange capacity	Gwenzi <i>et al.</i> (2021)
Water purification	Production of biochar water filters for removal of pesticides and other agrochemicals from water; removal of contaminants such as Heavy metals and pathogens	High adsorption capacity with many functional groups; large surface area; high porosity;	Gwenzi <i>et al.</i> (2015)
Metalwork	Reducing agent for blast furnace	High porosity; lower ash and sulfur contents; large surface area; high porosity, higher reactivity.	Suopajarvi <i>et al.</i> (2013), Schmidt, (2013), Adrados <i>et al.</i> (2015)
Mining	Rehabilitation of degraded soils in mining sites. Biochar enhances plant growth in contaminated soils	High adsorption capacity, soil moisture retention	Gwenzi <i>et al.</i> (2015)

summarizes the mechanisms under which biochar contributes to climate change mitigation.

Industrial uses of biochar

Studies have shown that biochar harbors great potential for industrial use in different sectors (Schmidt, 2013). Biochar can be used for the remediation of polluted soils through the binding of heavy metals in soil, which helps to keep them from reaching plants or entering water supplies (He *et al.* 2021). Biochar is also showing potential in cleaning up polluted water, as a much cheaper replacement for activated charcoal, which is used in the treatment of plants as well as in areas that are

heavily contaminated with toxic chemicals (Hassan *et al.* 2020; Wang *et al.* 2022). Biochar particles have a relatively large surface area, which expands even further in water, providing a vast number of sites for contaminants to bind to (Cernansky, 2015). Biochar effectively removes metal vapors, particularly elemental mercury (Hg⁰), acidic gases (H₂S, SO₂, CO₂), ozone, nitrogen oxides (NO_x), and organic contaminants including aromatic compounds, volatile organic compounds, and odorous substances (Gwenzi *et al.* 2021). Biochar has also shown potential in the housing sector, air pollution control, water purification, metal work, and mining as summarized in Table 7.

**Table 8:** Constraints to the use of biochar for agriculture and industrial use

Constraint	References
(a) Industrial use	
Lack of policies and regulations to govern the sector	Singh <i>et al.</i> (2014); Pokharel <i>et al.</i> (2020)
Feasibility for large-scale production not known	Pokharel <i>et al.</i> (2020)
Competition from other industrial alternatives	Pokharel <i>et al.</i> (2020)
Lack of prototypes	Pokharel <i>et al.</i> (2020)
Lack of design data for reactors	Pokharel <i>et al.</i> (2020)
(b) Agriculture	
Lack of regulatory frameworks on biochar use for agriculture	Laer <i>et al.</i> (2013; Singh <i>et al.</i> (2014)
Lack of standardized analytical procedures for biochar analysis	Singh <i>et al.</i> (2014)
Inadequate long-term data for informed decision-making by research organizations and governments	Singh <i>et al.</i> (2014)
Lack of systems for classification and governance of biochar as a soil conditioner	Singh <i>et al.</i> (2014)
Lack of decision-support system to help end users with choosing appropriate biochar type and application rate	Singh <i>et al.</i> (2014)
Research outcomes are unavailable to the intended end users thus hindering the adoption of the technology	Singh <i>et al.</i> (2014)

Table 9: Biochar projects/ studies undertaken in Kenya

Biochar study/ project	Project location	Study focus	References
Persistence of biochar, its effects on carbon dioxide, methane, and nitrous oxide emissions and soil fertility by ICRAF	Western Kenya, 2004	Climate change mitigation, food production	B4SS, 2022
Quantification of life-cycle GHG emissions e.g., energy and mass balances of biochar production, biomass procurement, and biochar use by ICRAF and UoN	Western Kenya, 2007	Climate change mitigation, food production	B4SS, 2022
Production of biochar seed balls for restoration activities	Countrywide, 2022	Climate change mitigation through restoration initiatives	Glaser and Lehr (2019)
Biochar in Kenya – quality, soil fertility, and crop production	Western Kenya, Central Kenya, Coast	Food production	Mahmoud <i>et al.</i> 2021
Soils, sinks, and smallholder farmers: Examining the benefits of biochar energy transitions in Kenya	Embu, Siaya and Kwale, 2018	Clean energy, soil fertility enhancement, carbon sequestration	Mahmoud <i>et al.</i> 2021
Maize grain yield responses to realistic biochar application rates on smallholder farms in Kenya	Kwale, Siaya and Embu, 2015	Food production; soil fertility improvement	Kätterer <i>et al.</i> 2022
Effects of applying biochar to soils from Embu, Kenya	Embu, 2012	Soil fertility improvement	Åslund, 2012

Constraints to the utilization of biochar for industrial and agricultural use

The biochar sector is relatively new and uncoordinated in most countries despite its great potential in agriculture and industrial use (Singh *et al.* 2014; Jatav *et al.* 2020; Pokharel *et al.* 2020). There are also several constraints, which could hinder the adoption of biochar as a soil conditioner and for

use in industries as summarized in Table 8. Most of these constraints can however be addressed through proper regulation, more research, and dissemination of relevant research findings.

Potential of biochar for agriculture and industrial use in Kenya

The potential of biochar for industrial and

Table 10: Emerging opportunities for biochar use

Opportunity	References
Growth media for the horticultural industry; biochar can replace peat as a growth media	Singh <i>et al.</i> (2014)
Waste management; industrial and municipal waste can be pyrolyzed into biochar for brick-making and other industrial uses	Singh <i>et al.</i> (2014)
Mine site rehabilitation, biochar enhances the growth of trees in disturbed sites through nutrient provision, soil moisture retention, and adsorption of contaminants such as heavy metals	Singh <i>et al.</i> (2014); Puhlinger (2016); Mwadalu <i>et al.</i> (2021)
Construction industry; biochar is being explored for brick-making and insulation of buildings due to its low thermal conductivity	Schmidt (2013)

agricultural use has been explored in the current metadata analysis. Many studies have reported positive effects of biochar on plant growth, crop yield, and soil properties (Gwenzi *et al.* 2015; Mwadalu *et al.* 2025; Katterer *et al.* 2022). Studies have also shown the potential of biochar for industrial use (Schmidt, 2013; Duwiejuah *et al.* 2020; Suopajarvi *et al.* 2013; Schmidt, 2013; Adrados *et al.* 2015). From the metadata analysis, biochar could immensely contribute to the growth of the Kenyan agricultural sector and industrial development. For wastewater treatment, the most common method used in Kenya is the Membrane Bioreactor (MBR) which integrates biological units and membrane separation units. The technology utilizes high-efficiency fluidized media that has a large surface area to provide optimal environmental contact for bacteria, air, waste, and water. Bacteria grow and thrive in open pores (Wainoga, 2020); biochar could act as a substitute for the fluidized media due to its large surface area and high adsorption capacity (Gwenzi *et al.* 2021). Table 9 gives a summary of selected past and present biochar projects and studies conducted in Kenya.

Emerging opportunities for biochar use in agriculture and industrial use

The current metadata analysis shows that biochar could be used in a myriad of ways, which could contribute to the growth of the agriculture and industrial sectors. Emerging opportunities show potential in the horticulture industry; waste management and mines rehabilitation (Singh *et al.* 2014) as shown in Table 10.

CONCLUSION

The metadata analysis shows that biochar harbors great potential for use in agriculture and industrial

development. The study shows that biochar can significantly increase crop yield and act as a reducing agent in blast furnace technology for steel making. It can also be used in wastewater treatment and water purification due to its large surface area and high adsorption capacity. The key impediment to the adoption of biochar for agriculture and industry is the lack of proper regulation to govern the biochar industry thus leading to the production of biochar of different qualities, which in turn influences crop production differently. The lack of a decision support system to help end users select appropriate biochar types and application rates has also hindered the adoption of biochar technology. Hence, more studies are needed to pilot the use of biochar for industrial use.

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