African Phytosanitary Journal
ISSN 2617-1856 (Paper) DOI: 10.52855/ HKZC5394
Volume 4, Issue 2, 2024
https://www.africanphytosanitaryjournal.go.ke

# Rice husk biochar for carbon sequestration, soil fertility and plant health improvement: A review

Wachira Ephraim[1*], Nthakanio Njiru Paul[2], Yegon Rebbeca[2]
[1]Kenya Plant Health Inspectorate Service, P. O. Box 49592-00100, Nairobi Kenya
[2]University of Embu P. O. Box 6-60100, Embu, Kenya
*Corresponding author's email: ewachira@kephis.org

## Abstract

Carbon dioxide ($CO_2$) is considered one of the ozone layer gases that contribute to climate change. As the area under agricultural use expands, the level of $CO_2$ from soil as an agricultural by-product increases in the atmosphere. Burning rice husks in open air, decomposing plant materials among other activities release $CO_2$ directly to the atmosphere. Rice husks as a by-product of rice production in Kenya has both the potential to be a source of greenhouse gas (GHG) and production of biochar. Production and deposition of rice husk biochar (RHB) into soil is thought to be one of the viable options for permanent carbon storage with related benefits to soil fertility. This review seeks to consolidate information from various studies that highlight the innovative way of using RHB in combating climate change, improving soil fertility, plant health and crop yields. Studies that have demonstrated beneficial use of RHB were evaluated to prepare this review. When RHB is used as a soil amendment, it has the ability to increase soil carbon storage, mitigate 10% of the current anthropogenic carbon emissions, improve pH and raise Cation Exchange Capacity (CEC), increase available plant nutrients, enhance inherent plant immunity, increase crop yields and improve water quality by increasing retention of nutrients and agrochemicals for plant utilization. A review of the benefits of RHB use in agriculture and climate change mitigation will enhance its adoption. The review further emphasizes the usefulness of pyrolysis in turning organic waste into bioenergy, compost and other beneficial products while protecting the environment.

**Key Words:** Carbon dioxide, climate change, global warming, innovation, ozone layer, temperature.

ISSN 2617-1856 (Paper) DOI:10.52855/HKZC5394
Volume 4, Issue 2, 2024


## Introduction

Biochar use is considered a viable strategy in reducing farm waste, improving soil quality and sequestering carbon to reduce greenhouse gas emissions and mitigate climate change (Mandal & Jeyaraman, 2013). Globally biochar is viewed as a soil management strategy that can increase soil carbon, provide energy and increase crop yield, while mitigating the effects of climate change through carbon sequestration (Griscom *et al.*, 2017; Smith *et al.*, 2020). Recent research has shown that biochar is effective in suppressing plant pathogens such as *Ralstonia solanacearum* in tomatoes, nematodes and insect pests (Lehmann, 2009; Lehmann *et al.*, 2011; Poveda *et al.*, 2021). In a potted plants experiment, Huang *et al.* (2015), found that soil amended with biochar at a concentration of 1.2% increased rice plants resistance against root gall nematodes (*Meloidogyne graminicola*). Rice husk biochar has potential to boost the resistance of rice seedlings against nematodes and improve rice growth parameters and increase rice yields among other crops to boost food security (Liu *et al.*, 2020).

In China, Qian *et al.* (2014), found that biochar as a soil amendment improved nitrogen use efficiency and increased crop productivity leading to reduced nitrogen fertilizer use. In Ghana, biochar was used to improve soil moisture and nutrient retention for vegetable production (Yakubu *et al.*, 2020) while in Nigeria, it was used as a soil amendment to enhance cocoyam productivity and soil sustainability in sandy loam soils (Adekiya *et al.*, 2020). Studies in Kenya have shown the positive effect of biochar application in soil in increased maize and soybean yields (Kimetu *et al.* 2008 ;Kätterer *et al.* 2019).

Kenya's communication to United Nations Framework Convention on Climate Change in 2015 identified charcoal production as a major contributor to Green House Gas emissions and identified a dual approach of promoting improved biochar kilns and supporting alternative fuel sources (Government of Kenya, 2018; Johnson & Johnson, 2018). The same report proposed that more efficient charcoal production methods be sought while pursuing alternative fuels. Pyrolysis of biomass at high temperatures and low oxygen conditions produce biochar, syngas and bio-oils in a process with low GHG production (Verheijen *et al.,* 2010; Woolf *et al*., 2010; Wuebbles *et al*., 2017). Biochar is considered an affordable negative emission technology for large scale deployment in carbon dioxide removal and sequestration (Tisserant & Cherubini, 2019).

In Kenya, climate change induced droughts, floods and heat have negatively impacted on human health, food security and economic development. Agriculture is among the identified sources of GHG emissions in Kenya (Nin-pratt, 2023) . Rice husk as an agricultural waste, has continued to increase GHGs in the atmosphere in its common disposal methods. It is estimated that 20% of total rice yields is rice husks. When disposed in canals, the husk increases water turbidity and lowers its quality while affecting the health of its users. When used as mulch in the paddy fields, rice husks decompose and release methane and nitrous oxide which are greenhouse gases.

While biochar-derived media has been internationally identified as a viable carbon sequestration medium, growth stimulant and plant health booster when used as a soil amendment or growth medium (Huang *et al*., 2015), its use in Kenya is limited and not popular with farmers in agricultural production.

This review is focused on the potential for inclusion of biochar soil amendment in integrated pest management systems for plants. Its potential use as a sterilized plant media is also significant in production of pest free seedlings.

## Biochar production and properties

Biochar is an organic material produced from biomass which has been pyrolyzed at zero or low oxygen conditions (Verheijen *et al*., 2010). It is a solid carbonaceous residue that can be used as fuel, fertilizer or for activated carbon production. Other uses include; smelting of iron as a reductant, water and gas purification, waste water treatment, poisons adsorbent in the chemical industry and a scrubber in skincare industry (Manya, 2019).Thermochemical conversion of biomass through pyrolysis produce biochar, syngas ($H_2$, CO, $CO_2$ and $CH_4$), heat and liquid (bio-oil) and water (Stewart *et al*., 2013; (Nanda *et al*., 2016; Wuebbles *et al*., 2017). The temperatures, heating rate and time used during pyrolysis determine the quality of biochar produced as well as the by-products. Nanda *et al*. (2016) found that biochar produced at lower temperatures have higher yield, higher CEC and conductivity while production at higher temperature yields less biochar and more volatile liquids and syngas. The biochar produced at higher temperatures is highly adsorptive, high in fixed carbon, pH and porosity. Slow pyrolysis converts at least 50% of biomass into biochar with bio-oils and syngas as the byproducts (IBI, 2018). The bio-oils and syngas can be used as clean energy source. Agricultural by-products have gained attention in recent years as sources of energy due to their advantages of low cost, limited availability of wood and potential to reduce greenhouse gas emission (Dahou *et al*., 2018).

Rice Husk is one such agricultural by-product that could potentially be utilized in Kenya due to its abundance and lignocellulosic composition. However, rice stalks and husks take a long time to decompose and they pose a disposal challenge for rice millers in Mwea (CGA, 2018). In Kenya there is inefficient biochar production technologies with low conversion ratios such as the traditional earth mound kilns (Ministry of environment, water and natural resources, 2013).

The recently elevated interest on biochar as a soil amendment rose from the discovery that it is source of high amounts of organic carbon and sustained fertility of the Amazonian soils better known as the *terra preta de Indio* (Lehmann & Joseph, 2012).

**Biochar classification**

Biochar can be classified based on its physiochemical properties such as carbon storage value, fertilizer value, liming value and particle size distribution (Joseph, 2015; IBI, 2018). Classification of biochar based on its properties enables stakeholders to identify the most suitable biochar type for a particular use (Joseph, 2015). Jindo *et al*. (2014) found that biochar feedstock source and the pyrolysis temperature both affected the physiochemical properties of biochar, with high heat (over 600°C). The high heat pyrolysis degrades functional groups and yield high carbon content while lower temperature pyrolysis yields more biochar. Agricultural waste feed stocks produced more biochar which had unique chemical properties due to higher silica content while biochar from woody materials had higher carbon content and high absorption character. In his study of effect of biochar sources, application rate and placement in soil on soil health and crop growth, Guo, (2020) concluded that biochar from wood debris and crop residues contain low plant nutrients when compared with biochar derived from compost or manure. He also found that biochar types vary considerably in chemical and physical characteristics based on the feedstock used and biochar production conditions. Even when similar feedstock was used, variation in the pyrolysis temperature and duration changed the biochar characteristics significantly with poultry manure yield reducing from 60.1% to 45.7% when the pyrolysis temperature was doubled from 300°C to 600°C. Similarly corn cobs yield reduced from 26.4% to 18.5% when production temperatures were increased from 450°C to 500°C while the pH declined from 10.3 to 7.8. Ash also increased when pyrolysis temperatures were raised for hardwood from 32 to 42 $gkg^{-1}$ while the yield fell from 32.7% to 25.8%. The total nitrogen content for poultry litter reduced from 12.1 to 1.2 $gkg^{-1}$while total phosphorus and potassium increased from 27.9 and 87.9 $gkg^{-1}$ to 30.5 and 91.5 $gkg^{-1}$ respectively when pyrolysis temperature was raised from 300°C to 600°C. It followed the same trend even when the temperature was raised less drastically from 300°C to 400°C, where total nitrogen reduced from 41.7 to 26.3 gkg−1 and total phosphorus and potassium increased from 22.7 to 69.3 $gkg^{-1}$ to 26.3 and 81.2 $gkg^{-1}$ respectively (Guo, 2020).

In a study conducted in Taiwan, Varela Milla *et al*. (2013), found that RHB had higher EC and higher amount of dissolvable ions than wood biochar

(WB), both had low heavy metals, WB had a higher carbon content and micro porosity, both had high concentration of potassium and Silicon though fresh rice husks was much higher than RHB and WB. In the same analysis, Varela Milla *et al.* (2013) found that when compared to rice husk, RHB had a higher pH. Silica similarly increased from 107 to 171mg/Kg, calcium and magnesium also increased from 108 and 175nmg/Kg to 220 and 182 mg/Kg respectively. This explained the rise in pH after pyrolysis.

## Global use of biochar

Globally, biochar is viewed as a better soil management strategy that can increase soil carbon while mitigating effects of climate change through carbon sequestration, providing energy and increasing crop yields (Griscom *et al.*, 2017; Smith *et al.*, 2020). Biochar is considered an affordable negative emission technology for large scale deployment in carbon dioxide removal and sequestration (Tisserant & Cherubini, 2019).

Maikol *et al.* (2021) proposed the use of chicken litter-derived biochar as a soil amendment to increase soil nutrients, reduce soil acidity and exchangeable aluminium in Malaysia in order to increase rice yields. India has a huge problem in disposal of agricultural by products due to the age-old practice of burning crop residues (Sandip *et al.*, 2013). Biochar use is considered a viable strategy in reducing farm waste, improving soil quality and sequestering carbon to reduce greenhouse gas emissions and mitigate climate change (Sandip *et al.*, 2013). Biochar is used in south east Asian countries as renewable energy source, to improve soil fertility, control greenhouse gas emission and water filter in waste water treatment (Khawkomol *et al.*, 2021).

In Ghana, biochar was used to improve soil moisture and nutrient retention for vegetables production (Yakubu *et al.*, 2020). In Nigeria, it was used as a soil amendment to enhance cocoyam productivity and soil sustainability in sandy loam soils (Adekiya *et al.*, 2020).

## Biochar production and use in Kenya

African Phytosanitary Journal
ISSN 2617-1856 (Paper) DOI:10.52855/HKZC5394
Volume 4, Issue 2, 2024


According to the Kenya National Bureau of Statistics (KNBS), (2019), 11.7% of Kenyans use charcoal as their primary source of fuel with 55.1 using firewood. In urban areas, charcoal use has increased to 17.7%. An estimated 22 million cubic meters of wood are used annually to meet Kenya's charcoal demand (MEWNR, 2013). In Kenya over 90% biochar production is through traditional earth mound kilns which use wood as the primary feedstock and has an approximate conversion efficiency of 14% MEWNR, 2013; Njenga *et al.*, 2017). Second generation earth mound kilns have improved the conversion efficiency to 30% but its adoption is still low in Kenya. Other kilns used in Kenya include the drum kilns with a conversion rate of 20-30%, Mekko biochar kiln with a conversion rate of 50-75% and the large scale use retort kiln with a conversion rate 0f 70-80% MEWNR, 2013). Gasification jikos have also been used as an energy source while at the same time gasifying rice husks to biochar (Ismail *et al.*, 2016). Gitau *et al.* (2019), found that use of gasifier jiko converts 16.6% wood biomass into biochar while reducing household firewood use by 40% and carbon monoxide, carbon dioxide and particulate matter by 57%, 41%, and 79% respectively.

A study in Vihiga, Western Kenya demonstrated that pyrolytic stoves can be used to utilize farm waste to cook and produce biochar which can be used as a soil conditioner to improve crop production (Torres, 2011). Studies in Central, Eastern and Western regions of Kenya showed that small amounts of biochar from farm feedstock when used along with inorganic fertilizers increased maize yields (Kätterer *et al.*, 2022). Increasing soil organic carbon using biochar and sawdust was able to restore soil quality and crop productivity of degraded soils in Western Kenya (Kimetu *et al.*, 2008). Use of biochar in Njoro and Mau Narok as a soil amendment can increase soil fertility and increase potato yields (Mbabazize *et al.,* 2023).

**Effects of biochar-derived media on plant immunity**

Plant immunity is defined as the inherent or induced capacity of plants to resist biological attack by pathogens. Molecules released by pathogens are recognized by the plant's surface receptors which triggers the plant's defense mechanism. The plants defense mechanism is two pronged, relying on Pathogen-Associated Molecular System (PAMP), which is the first line of defense and the effector triggered immunity which is the second layer of defense (Bürger & Chory, 2019). The PAMP system triggers the first defense which may be overcome by some pathogen using effector proteins that interferes with the immune signaling system, this in turn triggers the plant to deploy the second line of defense - the effector triggered immunity (Bürger & Chory, 2019). Plant cells have gene transcription programs that regulate their response to their environment including stress due to pathogens (Moore *et al*., 2011). Encounter with pathogens leads to gene reprogramming to prioritize response to the pathogen over normal growth (Moore *et al*., 2011). The programming and reprogramming regulators are ordered by a blend of signaling hormones including salicylic acid, jasmonic acid and ethylene (Van Der Ent *et al*., 2009, Nahar *et al*., 2011).

**Effect of biochar media on soil organisms**

In Jiangxi, China biochar was found to have positive effects on soil microbes such as rhizobacteria but detrimental effects on some soil fauna including nematodes (Liu *et al*., 2020). The effect of biochar on soil biota was direct and included effect on soil pH and increasing pore size (Liu *et al*., 2020). In Egypt, the application of biochar in combination with furfural inhibited root knot nematodes in tomatoes more than untreated controls or individual applications of furfural or biochar (Abdelnabby *et al*., 2018). In Ghana, RHB decreased nematode population but had an insignificant effect on flying insect pests Huang *et al.* (2015). Biochar did not have a direct nematicidal effect on *Meloidogyne graminicola* nematodes but acted to suppress the nematodes by enhancing hydrogen peroxide ($H_2O_2$) accumulation in plants and activation of the ethylene signaling pathway. Adding 1.2% concentration of biochar to the potting mix reduced nematode effect on rice roots due to enhanced ethylene signaling pathway. Huang *et al.* (2015)

described this phenomenon as priming of the plant defense mechanism for rapid activation against plant pathogen. Biochar was found to be a priming agent for induced plant resistance against the negative effects of parasitic nematodes (Huang *et al.*, 2015). In a related research, biochar was demonstrated to have a priming effect on genes associated with plant growth and defense such as jasmonic acid, brassionosteroids and cytokins (Jaiswal *et al.*, 2020).

In Netherlands, priming of innate plant defence in *Arabidopsis thaliana* (L.) Heynh. accession Col-0 against downy mildew using a rhizobacteria (*Pseudomonas fluorens*) and β-aminobutyric acid induced plant resistance to the disease (Van Der Ent *et al.*, 2009). Jaiswal *et al.* (2020), explored the ability of biochar to induce systemic resistance in tomatoes against crown rot disease caused by *Fusarium oxysporium* f.sp. *radicis lycopersici*. The study used transcriptomic analysis to demonstrate that biochar had a priming effect on gene expression and up-regulated the pathways of plant defense genes such as jasmonic acid to significantly suppress the disease and improve plant performance by 63%.

Biochar was found to induce plant resistance to pests and diseases such as *Fusarium oxysporum* on asparagus, *Ralstonia solanacearum*, *Botrytis cinerea* and *Clavibacter michiganensis* subsp. *michiganensis* on tomato by boosting plant defense mechanisms (Frenkel *et al.*, 2017). According to the study conducted by Frenkel *et al.* (2017) use of biochar as a growth medium for seedlings suppressed plant diseases at lower concentrations (≤1%) while higher concentrations (≥3%) were ineffective or induced some diseases such as vascular wilt disease in tomato caused by *Fusarium oxysporum* f.sp *radicis lycopersici*. The same study found that biochar had positive influence on plant growth when in concentrations higher than 25%. In a similar study, Jaiswal *et al.*, (2020), found that biochar induced resistance in tomato plants against crown rot caused by a soil borne pathogen - *Fusarium oxysporum* f.sp *radicis lycopersici* by up to 63%. Various studies on effect of biochar on plant diseases proved that low concentrations of 0.5 to 5% had positive effect on disease suppression against *Botrytis cinera*, *Phytophthora cinnanomi*, *Plasmodiophora brassica*, *Ralstocia solanacearum* and *Rhizoctonia solani* (Frenkel *et al*., 2017)

**Effect of biochar-derived media on nematodes**

Plant parasitic nematodes are a major constraint in crop production due to their intricate relationship with host plants, wide host range and high level of damage caused (Bernard *et al*., 2017). Root knot nematodes (*Meloidogyne spp*), cyst nematodes (*Heterodera* and *Globodera spp*), and lesion nematodes (*Pratylenchus spp*) are the most economically important species due to their wide host range and level of damage caused by infestation (Bernard *et al*., 2017), (Gnamkoulamba *et al*., 2018). Nematodes penetrate the root elongation zone and enter the vascular bundles where they induce a permanent feeding site by injecting secretions from their pharyngeal glands into the plant cell. Management of nematodes includes use of nematicides, treatment of seed with carbofuran, dipping seedling roots in systemic insecticides and use of resistant varieties (Bernard *et al*., 2017). Over 100 nematode species affect rice production globally. In Mwea, Namu *et al*. (2019), found 22 genera of nematodes causing huge losses in rice production. Namu *et al.* (2018) found 11 of these nematode species in irrigated paddy fields in Mwea including the root knot nematodes (*Meloidogyne graminincola*) which was found across all sampled sites.

Desmedt *et al*., (2020), studied the mechanism of plant defense against nematodes and found the plant immunity against nematodes relies on production of metabolites with anti-nematode activity which they called anti nematode phytochemicals. Resistance to root knot nematodes in rice plants was largely attributed to jasmonic acid and ethylene signaling with salicylic acid playing a minor role (Nahar *et al*., 2011).

In Ghana, increased concentrations of sea shell biochar of 1 part to 1 part soil reduced root galling due to root knot nematodes in tomato (Ibrahim *et al.*

2019). In Egypt a study on the effect of rice straw biochar on root knot nematodes (*M. incognita*) by Ahmed, (2021), found that an application of 21g/pot reduced egg masses and root galls due to *M. incognita* in eggplants by 80 and 93%. A study in Western Kenya by Munyua, *et al*. (2015), found that galling due to root knot nematodes infection in beans reduced while bean yields increased when biochar and vermicompost soil amendments were added. Frenkel, (2017) urged further research to determine whether biochar addition in potting mixes can reduce nematode damage to plants.

## Biochar as a soil amendment

Nanda *et al*. (2016) concluded that biochar improves the soil and enhances plant growth by increasing bioavailability of water and essential plant nutrients while providing good micro-environment for proliferation of essential micro-organisms. Li *et al*. (2018) found that application of 2% biochar in silty clay soil significantly reduced nitrate leaching and increased potassium availability to plants in China. Application of 6-9 tha$^{-1}$ rice husk biochar as lime increased maize yield more than 23% in acidic soils in East Java, Indonesia (Nurhidayati & Mariati, 2014). This was due to the effect of rice husk charcoal on increasing available plant nutrients. Martinsen *et al.* (2015) found that an application of 1% RHB equivalent to 30 tha$^{-1}$ raised the pH of acidic Indonesian soil by 0.04. Soils amended with biochar in Nigeria were found to have neutralized pH, increased total nitrogen and phosphorous, improved CEC and higher count of soil beneficial fungi and bacteria (Nanda *et al*., 2016; Adekiya *et al*., 2020).

A trial in Nandi, Kenya found that soils in former charcoal earth mound kiln locations was rich in carbon, phosphorous and potassium whereas soil micro fauna were found to decrease except for centipedes when compared to non-kiln areas (Kamau *et al*., 2017). This observation was explored in further research where it was confirmed that biochar application over 60tha$^{1}$ exerted negative effects on soil fauna (Liu *et al*., 2020).

African Phytosanitary Journal
ISSN 2617-1856 (Paper) DOI:10.52855/HKZC5394
Volume 4, Issue 2, 2024



**Biochar as a plant growth media**

Important plant growth media characteristics includes the pH, CEC, C:N ratio, electrical conductivity (EC) which is a measure of total soluble salts in a media, porosity-which should range between 50-70%, Bulk density, water holding capacity which typically ranges from 45-65% by volume and sterility which is especially important in green house media (Robbins & Evans, 2011).

A study to compare the agronomic properties of rice and wood biochar found that RHB improves biomass production in water spinach by increasing the stem and leaf size (Varela *et al.*, 2013). According to Carter *et al.*, 2013, RHB application on soil properties and plant growth of pot grown lettuce (*Lactuca sativa*) and cabbage (*Brassica chinensis*), at rates of 25, 50 and 150 $gkg^{-1}$ increased the pH of the media in comparison to control and contained elevated levels of some trace metals and exchangeable cations (K, Ca and Mg). The final biomass, root biomass, plant height and number of leaves in all the cropping cycles also increased in comparison to no biochar treatments (Carter *et al.*, 2013). A long term experiment in Sumatra, Indonesia found that cacao biochar applied at a rate of 15 $tha^{1}$ increased PH, CEC and potassium resulting to significantly higher maize yields for three consecutive seasons as seen in the figure below (Cornelissen *et al.*, 2018).

Peat based plant growth media are expensive in Kenya and coco peat production from peat bogs have been found to contribute to the increased release of GHG to the atmosphere (Steiner & Harttung, 2014). Rice husk biochar has been found to have good plant growth media characteristics including sterility, neutral to high pH and high water-holding capacity (Frenkel *et al.*, 2017). Matt (2015), in her studies on nursery media for tree seedlings propagation in Missouri, USA, found that biochar can replace 45% peat, perlite and vermiculite mix without any decrease in plant biomass growth. In a study on horticultural rooting media improvement in the Netherlands, Blok *et al.* (2017), found that wood based biochar could replace other potting soil constituents by up to

20-50% without negative growth effects. A study of alternative tree seedlings growth media in Ghana, identified RHB and groundnut husk biochar as suitable growth mediums for African mahogany (*Khaya senegalensis*) (Bernard *et al.*, 2020). Soils amended with biochar in Nigeria were found to have neutralized pH, increased total nitrogen and phosphorous, improved CEC and higher count of soil beneficial fungi and bacteria (Adekiya *et al.*, 2020). Soil amendment with biochar was found to enhance cocoyam productivity and soil sustainability in sandy loam soils (Adekiya *et al.*, 2020). In Kenya, Abubakari *et al.* (2018) conducted a trial of various soil less media and found that soil less plant growth media composed of RHB and composted sawdust in a 2:1 ratio gave the highest yields. These studies demonstrate the potential of biochar effect as a growth media in increasing crop yields.

## Biochar and carbon sequestration

The Paris agreement on climate change requires that greenhouse gas emissions and sinks be balanced by the second half of this century (Anderson & Peters, 2016). Technologies of carbon dioxide removal from the atmosphere are required in order to limit global warming to less than 2°C based on pre-industrial levels (Hoad, 2016; Rogelj *et al.*, 2016). Integrated assessment models which inform policy makers assume massive deployment of negative emissions technologies (NET) to divert society from the high-temperature pathway (Anderson & Peters, 2016). Available NET include direct air capture of $CO_2$, enhanced weathering, bioenergy production with carbon capture and storage, afforestation and soil carbon sequestration (Smith, 2016; Tisserant & Cherubini, 2019). Soil carbon sequestration through biochar is one of the more affordable negative emission technologies for carbon dioxide removal with a net reduction of 1.67 tCO2eq per tonne of feedstock (Tisserant & Cherubini, 2019).

## The Carbon cycle and carbon sequestration

Plants convert atmospheric $CO_2$ naturally through photosynthesis. Plant decomposition releases $CO_2$ back to the atmosphere. In contrast, transforming this biomass into biochar that decomposes much more slowly diverts carbon from the rapid biological cycle into a much slower biochar cycle (Lehmann, 2007b; Lehman & Joseph, 2015). As the area under agricultural use expands, $CO_2$ from soil as an agricultural by-product has been added to the atmosphere (Schlesinger & Amundson, 2019). Rice production is associated with release of two GHG; methane ($CH_4$) and nitrous oxide ($N_2O$) under anaerobic production system (Chirinda *et al.*, 2018). Global rice production accounts for 2.5 of all human induced GHG mainly due to methane gas release estimated at 36 million MT (Aller *et al.*, 2017). According to Lehman & Joseph (2015), diverting merely 1% of annual net plant uptake into biochar would mitigate almost 10% current anthropogenic carbon emissions. In 2013, Mwea rice mills alone produced 10,095 tons of rice husks from 50,476 tons of rice milled. The husks were used as cooking fuel or burnt in open air with the attendant release of over 1000 tons of $CO_2$ emission to the atmosphere using a greenhouse gas emission factor of 0.1Kg $CO_{2eq}$/Kg rice. Other disposal methods for the rice husks such as disposal in canals, livestock bedding and mulch also contribute to production of other GHG such as methane and nitrous oxide.

*Terra preta*- black earth in Portuguese, found in the Amazonian jungle has served as an inspiration to many scientists researching ways of using biochar carbon to improve agricultural production while at the same time storing carbon in the soil and avoiding its use as charcoal hence reducing addition of $CO_2$ to the atmosphere (Clarke, 2013). Amazonian Indians in the Amazon basin used to produce the *terra preta* soils 1000 years ago and they are still more fertile than other surrounding soils (Lehmann & Joseph, 2015). Biomass consists of roughly 50% carbon, however when converted to biochar, the amount of carbon is reduced by 50% and the release is slowed down by one or two orders of magnitude (Scholz *et al.*, 2014). The normal carbon cycle is carbon neutral while the biochar carbon cycle withdraws 20% carbon from the atmosphere by sequestration (IBI, 2018)(Figure 1). Production and deposition of biochar into soil is thought to be a viable option in permanent

carbon storage with related benefits to soil fertility (Matovic, 2011).

In their work to test ability of RHB in promoting carbon sequestration, Carter *et al*. (2013), found a positive linear correlation between carbon storage in the top 10cm of soil and RHB application rate. Similarly, Koyama *et al*. (2015), found a positive linear correlation between carbon storage in the soil and RHB application with a corresponding increase of 98-149% of the added carbon. However, Schlesinger & Amundson, (2019) urge more experimental research on the extent of carbon sequestration through better soil management while averring that it contributes very little to stabilization of $CO_2$ concentration in the atmosphere.

Biochar has also attracted the attention of climate change mitigation experts since as a stable carbon store, it can be used for carbon sequestration in the soil when used as a soil amendment (Nanda *et al*., 2016). Besides sequestering carbon in the soil, biochar contains reductive and oxidative

function groups which play a significant role in degrading wastewater pollutants. A trial by Amen *et al*., 2020, demonstrated that RHB has a lead adsorption capacity of 96.41% and a cadmium uptake capacity of 96.73%. Biochar adsorbent qualities have also been found to be effective in removal of microplastic pollutants from water (Abuwatfa *et al*., 2021).

## Conclusions

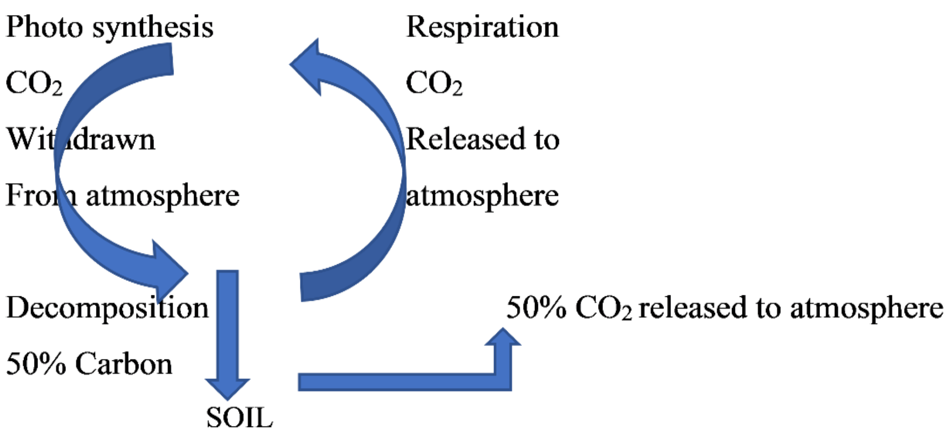
Biochar enhances plant growth and activates plants natural defenses. Its use has variously been demonstrated to suppress pathogens and improve soil conditions for the proliferation of beneficial microorganisms. Incorporation of biochar in the soil improves the soil's physical and bio-chemical properties. This tends to improve soil fertility and enhance plants productivity. This was found to be enhanced in sandy and acidic soils. Being a stable carbon store, biochar application to the soil diverts carbon found in biomass to a much slower carbon cycle and thus its use lowers carbon emissions to the atmosphere

African Phytosanitary Journal
ISSN 2617-1856 (Paper) DOI: 10.52855/HKZC5394
Volume 4, Issue 2, 2024


and sequesters carbon in the soil for long durations.

ISSN 2617-1856 (Paper) DOI:10.52855/HKZC5394
Volume 4, Issue 2, 2024

**Normal Carbon Cycle - 0% Net $CO_2$ withdrawal from atmosphere**




**Biochar Carbon Cycle - 20% Net Carbon withdrawal from the atmosphere.**

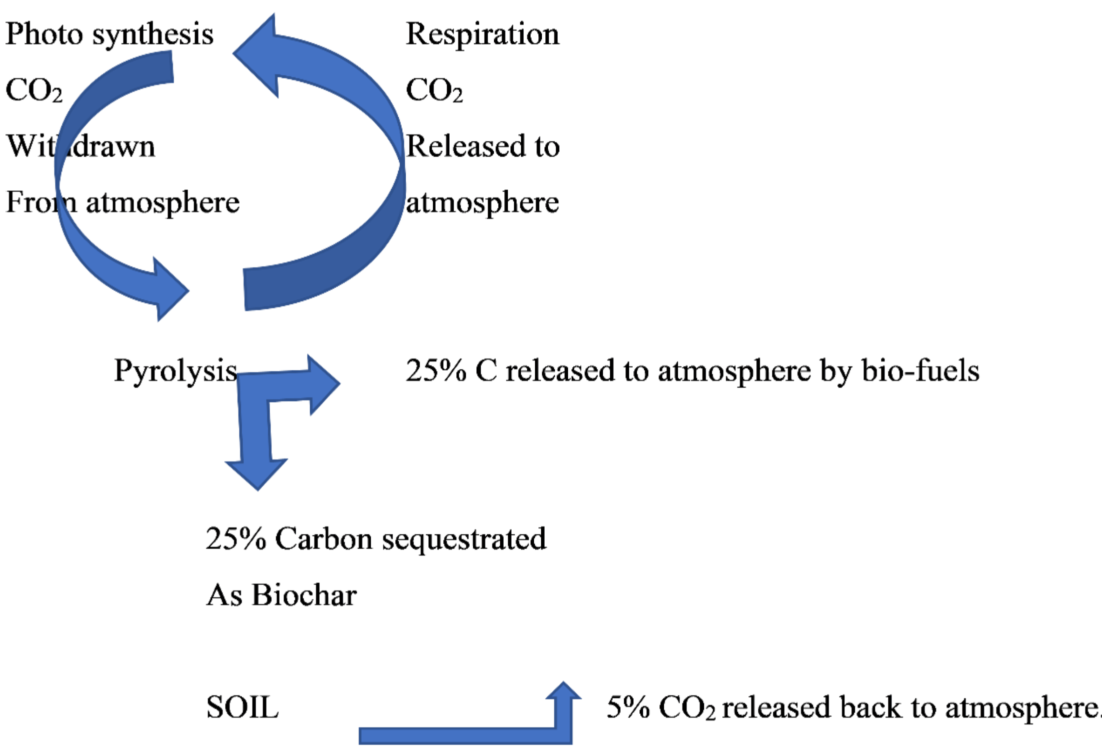



Figure 1: Normal Carbon cycle versus Biochar Carbon cycle.

## Recommendations

Biochar use should be adopted especially in dry or acidic soils in Kenya as a soil amendment to improve soil fertility and plant yield. It should also be considered as a cultural plant protection method in integrated plant protection systems. Biochar as a soil amendment should also be considered as a climate change mitigation strategy due to its carbon sequestration potential. Further research on use of biochar as a drought mitigation measure in ASALS due to its water retention characteristic and in its utility as potting media for plantlets and other potted seedlings that require sterile media should be conducted. Further research should be conducted on the applicability of biochar as a climate change mitigation measure in Kenya. It is also proposed to study further on use of energy produced from pyrolysis of biochar especially from sustainable feedstock such as agricultural, industrial and even urban waste. Applications for biochar as an affordable natural adsorbent of heavy metals and other soil and other contaminants should be further explored in purification of water and rehabilitation of soils.

## References

Abdelnabby, H., Hu, Z., Wang, H., & Zhang, X. (2018). Furfural–biochar-based formulations show synergistic and potentiating effects against *Meloidogyne incognita* in tomato. *Journal of Pest Science*, *91*(1), 203–218. https://doi.org/10.1007/s10340-017-0872-x.

Abubakari, A.H., Atuah, L., & Banful, B.K. (2018). Growth and yield response of lettuce to irrigation and growth media from composted sawdust and rice husk. *Journal of Plant Nutrition*, *41*(2), 221–232. https://doi.org/10.1080/01904167.2017.1384013.

Abuwatfa, W.H., Al-muqbel, D., Al-othman, A., Halalsheh, N., & Tawalbeh, M. (2021). Case Studies in Chemical and Environmental Engineering Insights into the removal of microplastics from water using biochar in the era of COVID-19: A mini review. *Case Studies in Chemical and Environmental Engineering*, *4*, 100151. https://doi.org/10.1016/j.cscee.2021.100151

Adekiya, A.O., Agbede, T.M., Olayanju, A., Ejue, W.S., Adekanye, T.A., Adenusi, T.T., & Ayeni, J.F. (2020). Effect of Biochar on Soil Properties, Soil Loss, and Cocoyam Yield on a Tropical Sandy Loam Alfisol. *Scientific World Journal*, *2020*. https://doi.org/10.1155/2020/9391630.

Ahmed, N. (2021). Rice Straw and Peanut Residues Biochars as Eco- Friendly Approaches for Controlling Root-Knot Nematode, *Meloidogyne incognita* Infecting Eggplant. *Egyptian Academic Journal of Biological Sciences, F. Toxicology & Pest Control*, *13*(2), 91–102. https://doi.org/10.21608/eajbsf.2021.189667.

Akoko, G., Kato, T., & Tu, L.H. (2020). Evaluation of irrigation water resources availability and climate change impacts-a case study of Mwea irrigation scheme, Kenya. *Water (Switzerland)*, *12*(9). https://doi.org/10.3390/W12092330.

Aller, D., Rathke, S., Laird, D., Cruse, R.,

& Hatfield, J. (2017). Impacts of fresh and aged biochars on plant available water and water use efficiency. *Geoderma*, *307*(August), 114–121. https://doi.org/10.1016/j.geoderma.2017.08.007.

Amen, R., Yaseen, M., Mukhtar, A., Ullah, S., Al-sehemi, A.G., Ra, S., Babar, M., Lai, C., Ibrahim, M., Asif, S., Shehzad, K., Majeed, M., & Bokhari, A. (2020). Lead and cadmium removal from waste water using eco-friendly biochar adsorbent derived from rice husk , wheat straw and corncob. *Cleaner Engineering and Technology*, *1*(May). https://doi.org/10.1016/j.clet.2020.100006.

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science*, *354*(6309), 182–183. https://doi.org/10.1126/science.aah4567.

Arouna, A., Fatognon, I.A., Saito, K., & Futakuchi, K. (2021). Moving toward rice self-sufficiency in sub-Saharan Africa by 2030: Lessons learned from 10 years of the Coalition for African Rice Development. *World Development Perspectives*, *21*(January). https://doi.org/10.1016/j.wdp.2021.100291.

Axelsson, L., Franzén, M., Ostwald, M., Berndes, G., Lakshmi, G., & Ravindranath, N.H. (2012). Perspective: Jatropha cultivation in southern India: Assessing farmers' experiences. *Biofuels, Bioproducts and Biorefining*, *6*(3), 246–256. https://doi.org/10.1002/bbb

Bernard, G.C., Egnin, M., & Bonsi, C. (2017). The Impact of Plant-Parasitic Nematodes on Agriculture and Methods of Control. In *Nematology - Concepts, Diagnosis and Control*. https://doi.org/10.5772/intechopen.

Bernard, N.B., Latif, I.N., & Edmond, G. T. (2020). Biochar as an alternative growth medium for tree seedlings in the Guinea Savanna Zone of Ghana. *African Journal of Plant Science*, *14*(7), 248–253. https://doi.org/10.5897/ajps2019.1796

Blok, C., Van Der Salm, C., Hofland-

Zijlstra, J., Streminska, M., Eveleens, B., Regelink, I., Fryda, L., & Visser, R. (2017). Biochar for horticultural rooting media improvement: Evaluation of Biochar from gasification and slow pyrolysis. *Agronomy*, *7*(1). https://doi.org/10.3390/agronomy7010006.

Bürger, M. & Chory, J. (2019). Stressed Out About Hormones: How Plants Orchestrate Immunity. *Cell Host and Microbe*, *26*(2), 163–172. https://doi.org/10.1016/j.chom.2019.07.006.

Carter, S., Shackley, S., Sohi, S., Suy, T., & Haefele, S. (2013). The Impact of Biochar Application on Soil Properties and Plant Growth of Pot Grown Lettuce (*Lactuca sativa*) and Cabbage (*Brassica chinensis*). *Agronomy*, *3*(2), 404–418. https://doi.org/10.3390/agronomy3020404.

Chirinda, N., Arenas, L., Katto, M., Loaiza, S., Correa, F., Isthitani, M., Loboguerrero, A.M., Martínez-Barón, D., Graterol, E., Jaramillo, S., Torres, C.F., Arango, M., Guzmán, M., Avila, I., Hube, S., Kurtz, D.B., Zorrilla, G., Terra, J., Irisarri, P., … Bayer, C. (2018). Sustainable and low greenhouse gas emitting rice production in Latin America and the Caribbean: A review on the transition from ideality to reality. *Sustainability (Switzerland)*, *10*(3). https://doi.org/10.3390/su10030671

Cho, M.S., Meng, L., Song, J.H., Han, S.H., Bae, K., & Park, B.B. (2017). The effects of biochars on the growth of Zelkova serrata seedlings in a containerized seedling production system. *Forest Science and Technology*, *13*(1), 25–30. https://doi.org/10.1080/21580103.2017.1287778.

Clarke, S. (2013). From the ground up. *The Canadian Nurse*, *109*(5), 20–24.

Cornelissen, G., Jubaedah, Nurida, N.L., Hale, S.E., Martinsen, V., Silvani, L., & Mulder, J. (2018). Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. *Science of the Total Environment*, *634*(0806), 561–568. https://doi.org/10.1016/j.scitotenv.

2018.03.380.

Dahou, T., Defoort, F., Thiéry, S., Grateau, M., Campargue, M., Bennici, S., Jeguirim, M., & Dupont, C. (2018). The influence of char preparation and biomass type on char steam gasification kinetics. *Energies*, *11*(8), 1–15. https://doi.org/10.3390/en11082126

Desmedt, W., Mangelinckx, S., Kyndt, T., & Vanholme, B. (2020). A Phytochemical Perspective on Plant Defense Against Nematodes. *Frontiers in Plant Science*, *11*(November). https://doi.org/10.3389/fpls.2020.602079

FAOSTAT. (2019). *FAOSTAT Data-Underrnourishment in Kenya*. http://www.fao.org/faostat/en/#data/FS

Frenkel, O., Jaiswal, A.K., Elad, Y., Lew, B., Kammann, C., & Graber, E.R. (2017). The effect of biochar on plant diseases: what should we learn while designing biochar substrates? *Journal of Environmental Engineering and Landscape Management*, *25*(2), 105–113. https://doi.org/10.3846/16486897.2017.1307202.

Gnamkoulamba, A., Tounou, A.K., Tchabi, A., Kolombia, Y.A., Agboka, K., Tchao, M., Adjevi, A.K.M., & Batawila, K. (2018). Occurrence, abundance and distribution of plant-parasitic nematodes associated with rice (*Oryza* spp.) in different rice agroecosystems in Togo. *International Journal of Biological and Chemical Sciences*, *12*(2), 618. https://doi.org/10.4314/ijbcs.v12i2.1

Government of Kenya. (2018). *National Climate Change Action Plan (Kenya): 2018-2022. Nairobi: Ministry of Environment and Forestry. I*. www.environment.go.ke

Government of Kenya. (2019). *Agricultural Sector Transformation and Growth Strategy*. 1–221. http://www.kilimo.go.ke/wp-content/uploads/2019/01/ASTGS-Full-Version.pdf

Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R.T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R.& Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114.

Guo, M. (2020). The 3R Principles for Applying Biochar to Improve Soil Health. *Soil Systems*, *4*(1), 9. https://doi.org/10.3390/soilsystems4010009.

Hoad, D. (2016). The 2015 Paris Climate Agreement: Outcomes and their impacts on small island states. *Island Studies Journal*, *11*(1), 315–320.

Huang, W. kun, Ji, H. li, Gheysen, G., Debode, J., & Kyndt, T. (2015). Biochar-amended potting medium reduces the susceptibility of rice to root-knot nematode infections. *BMC Plant Biology*, *15*(1), 1–15. https://doi.org/10.1186/s12870-015-0654-7.

Ibrahim, F., Quainoo, A.K., & Kankam, F. (2019). Effect of Shea Nut Shell Biochar on Root Knot Nematodes (*Meloidogyne spp*.) of Tomato (*Solanum lycopersicum L*.). *Annual Research & Review in Biology*, *30*(2), 1–7. https://doi.org/10.9734/arrb/2018/45187.

International Biochar Initiative. (2018). *Biochar - biochar-international*. https://www.biochar-international.org/biochar/

Jaetzold, R. & Schmidt, H. (1983). Farm management handbook of Kenya. *Natural Conditions and Farm Information*, *II*, 319.

Jaiswal, A.K., Alkan, N., Elad, Y., Sela, N., Philosoph, A.M., Graber, E.R., & Frenkel, O. (2020). Molecular insights into biochar-mediated plant growth promotion and systemic resistance in tomato against Fusarium crown and root rot disease. *Scientific Reports*, *10*(1), 1–16. https://doi.org/10.1038/s41598-020-70882-6.

Jindo, K., Mizumoto, H., Sawada, Y., Sanchez-Monedero, M.A., & Sonoki,

T. (2014). Physical and chemical characterization of biochars derived from different agricultural residues. *Biogeosciences*, *11*(23), 6613–6621. https://doi.org/10.5194/bg-11-6613-2014.

Johnson, O.W. & Johnson, F.X. (2018). *Overcoming barriers to sustainable charcoal in Kenya October 2018*. *October*, 1–6.

Joseph, J. L. and S. this is not complete(2015). Biochar for Environmental Management. In J. L. and S. Joseph (Ed.), *Biochar for Environmental Management*. https://doi.org/10.4324/9780203762264.

Joseph, S., Taylor, P., & Cowie, A. (2020). *Choosing a biochar reactor to meet your needs - Biochar for Sustainable Soils*. https://biochar.international/guides/biochar-reactor-to-meet-needs/

Kamau, S., Barrios, E., Karanja, N.K., Ayuke, F.O., & Lehmann, J. (2017). Spatial variation of soil macrofauna and nutrients in tropical agricultural systems influenced by historical charcoal production in South Nandi, Kenya. *Applied Soil Ecology*, *119*(June), 286–293. https://doi.org/10.1016/j.apsoil.2017.07.007.

Kätterer, T., Roobroeck, D., Andrén, O., Kimutai, G., Karltun, E., Kirchmann, H., Nyberg, G., Vanlauwe, B., & Röing de Nowina, K. (2019). Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. *Field Crops Research*, *235*(March), 18–26. https://doi.org/10.1016/j.fcr.2019.02.015.

Kätterer, T., Roobroeck, D., Kimutai, G., Karltun, E., Nyberg, G., Sundberg, C., & de Nowina, K. R. (2022). Maize grain yield responses to realistic biochar application rates on smallholder farms in Kenya. *Agronomy for Sustainable Development*, *42*(4). https://doi.org/10.1007/s13593-022-00793-5

Kenya National Bureau of Statistics (KNBS). (2019). *2019 Kenya Population and Housing Census Volume I: Population By County and*

*Sub-County: Vol. I* (Issue November). http://www.knbs.or.ke

Khan, Z., Zhang, K., Khan, M.N., Fahad, S., Xu, Z., & Hu, L. (2020). Coupling of biochar with nitrogen supplements improve soil fertility, nitrogen utilization efficiency and rapeseed growth. *Agronomy*, *10*(11). https://doi.org/10.3390/agronomy10111661

Khawkomol, S., Neamchan, R., Thongsamer, T., Vinitnantharat, S., Panpradit, B., Sohsalam, P., Werner, D., & Mrozik, W. (2021). Potential of biochar derived from agricultural residues for sustainable management. *Sustainability (Switzerland)*, *13*(15). https://doi.org/10.3390/su13158147

Kimetu, J.M., Lehmann, J., Ngoze, S.O., Mugendi, D.N., Kinyangi, J.M., Riha, S., Verchot, L., Recha, J.W., & Pell, A.N. (2008). Reversibility of soil productivity decline with organic matter of differing quality along a degradation gradient. *Ecosystems*, *11*(5), 726–739. https://doi.org/10.1007/s10021-008-9154-z.

Koyama, S., Inazaki, F., Minamikawa, K., Kato, M., & Hayashi, H. (2015). Increase in soil carbon sequestration using rice husk charcoal without stimulating $CH_4$ and $N_2O$ emissions in an Andosol paddy field in Japan. *Soil Science and Plant Nutrition*, *61*(5), 873–884. https://doi.org/10.1080/00380768.2015.1065511

Lehmann, J., Joseph, S. (2009). Biochar for Environmental Management: Science, Technology and Implementation - Google Books. In *Biochar for Environmental Management* (pp. 251–270.). https://books.google.com.pk/books?hl=en&lr=&id=gWDABgAAQBAJ&oi=fnd&pg=PA421&dq=Biochar+effects+on+soil+nutrient+transformations.+In:+Lehmann,+J.,+Joseph,+S.+(Eds.),+Biochar+for+Environmental+Management:+Science+and+Technology.+Earthscan,+London,+UK,+pp.+2.

Lehmann, J., & Joseph, S. (2012). Biochar for environmental management: An introduction.

*Biochar for Environmental Management: Science and Technology*, *1*, 1–12. https://doi.org/10.4324/9781849770552.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., & Crowley, D. (2011). Biochar effects on soil biota - A review. *Soil Biology and Biochemistry*, *43*(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022.

Li, S., Zhang, Y., Yan, W., & Shangguan, Z. (2018). Effect of biochar application method on nitrogen leaching and hydraulic conductivity in a silty clay soil. *Soil and Tillage Research*, *183*(June), 100–108. https://doi.org/10.1016/j.still.2018.06.006.

Liu, T., Yang, L., Hu, Z., Xue, J., Lu, Y., Chen, X., Griffiths, B. S., Whalen, J.K., & Liu, M. (2020). Biochar exerts negative effects on soil fauna across multiple trophic levels in a cultivated acidic soil. *Biology and Fertility of Soils*, *56*(5), 597–606. https://doi.org/10.1007/s00374-020-01436-1.

Maikol, N., Haruna, A.O., Maru, A., Asap, A., & Medin, S. (2021). Utilization of urea and chicken litter biochar to improve rice production. *Scientific Reports*, *11*(1), 1–20. https://doi.org/10.1038/s41598-021-89332-y.

Mandal, H.R., Katel, S., Subedi, S., & Shrestha, J. (2021). Plant Parasitic Nematodes and their management in crop production: a review. *Journal of Agriculture and Natural Resources*, *4*(2), 327–338. https://doi.org/10.3126/janr.v4i2.33950

Manya, J.J. (Universidad de Z. (Ed.). (2019). *Advanced Carbon Materials from Biomass:an overview* (Issue May). Green Carbon Project and Consortium.

Martinsen, V., Alling, V., Nurida, N.L., Mulder, J., Hale, S.E., Ritz, C., Rutherford, D. W., Heikens, A., Breedveld, G. D., & Cornelissen, G. (2015). pH effects of the addition of three biochars to acidic Indonesian mineral soils. *Soil Science and Plant Nutrition*, *61*(5), 821–834.

https://doi.org/10.1080/00380768.2015.1052985.

Matovic, D. (2011). Biochar as a viable carbon sequestration option: Global and Canadian perspective. *Energy*, *36*(4), 2011–2016. https://doi.org/10.1016/j.energy.2010.09.031..

Mbabazize, D., Mungai, N. W., & Ouma, J. P. (2023). Effect of Biochar and Inorganic Fertilizer on Soil Biochemical Properties in Njoro Sub-County, Nakuru County, Kenya. *Open Journal of Soil Science*, *13*(07), 275–294. https://doi.org/10.4236/ojss.2023.137012.

Ministry of Agriculture. (2008). Republic of Kenya Ministry of Agriculture National Rice Development Strategy ( 2008 – 2018 ). *Strategy*, 1–25. https://www.jica.go.jp/english/our_work/thematic_issues/agricultural/pdf/kenya_en.pdf

Ministry of Environment, Water and Natural Resources, Kenya. (2013). *Analysis of the Charcoal Value Chain in Kenya Final Report. August2013*. Kenya Forest Service.

Moore, J.W., Loake, G.J., & Spoel, S.H. (2011). Transcription dynamics in plant immunity. *Plant Cell*, *23*(8), 2809–2820. https://doi.org/10.1105/tpc.111.087346.

Mutiga, S.,& Rotich, F. (UoEm); Correll, J. C. (UARK) and Talbot, N. J. (TSL). (2019). *Factsheets for Rice Production , East Africa Rice Sheath Rot*. 2019.

Nahar, K., Kyndt, T., de Vleesschauwer, D., Höfte, M., & Gheysen, G. (2011). The jasmonate pathway is a key player in systemically induced defense against root knot nematodes in rice. *Plant Physiology*, *157*(1), 305–316. https://doi.org/10.1104/pp.111.177576.

Namu, J., Karuri, H., Alakonya, A., Nyaga, J., & Njeri, E. (2018). Distribution of parasitic nematodes in Kenyan rice fields and their relation to edaphic factors, rainfall and temperature. *Tropical Plant Pathology*, *43*(2), 128–137. https://doi.org/10.1007/s40858-017-0194-9.

Namu, J., Alakonya, A., Karuri, H., Nyaga, J., Masanga, J., & Njeri, E. (2019). Response of Selected Kenyan Rice Cultivars to Infection by Root Knot Nematode (*Meloidogyne incognita*). *Journal of Crop Science and Biotechnology*, *22*(1), 47–54. https://doi.org/10.1007/s12892-017-0101-0

Nanda, S., Dalai, A.K., Berruti, F., & Kozinski, J.A. (2016). Biochar as an Exceptional Bioresource for Energy, Agronomy, Carbon Sequestration, Activated Carbon and Specialty Materials. *Waste and Biomass Valorization*, *7*(2), 201–235. https://doi.org/10.1007/s12649-015-9459-z

Nin-pratt, A. (2023). Mitigating Greenhouse Gas Emissions in Kenya ' s Food System Economic Interdependencies and Policy Opportunities. August.

Nurhidayati, N. & Mariati, M. (2014). Utilization of maize cob biochar and rice husk charcoal as soil amendment for improving acid soil fertility and productivity. *Journal of Degraded and Mining Lands Management*, *2*(1), 223–230. https://doi.org/10.15243/jdmlm.2014.021.223

FAO, O. P. (2020). OECD-FAO Agricultural Outlook 2020-2029. In *OECD Publishing Paris, /Food and Agriculture Organization of the United Nations, Rome*. https://www.oecd-ilibrary.org/agriculture-and-food/oecd-fao-agricultural-outlook-2020-2029_1112c23b-en

Poveda, J., Martínez Gómez, Á., Fenoll, C., & Escobar, C. (2021). The use of biochar for plant-pathogen control. *Phytopathology*, 1–26. https://doi.org/10.1094/phyto-06-20-0248-rvw.

Qian, L., Chen, L., Joseph, S., Pan, G., Li, L., Zheng, J., Zhang, X., Zheng, J., Yu, X., & Wang, J. (2014). Biochar compound fertilizer as an option to reach high productivity but low carbon intensity in rice agriculture of China. *Carbon Management*, *5*(2), 145–154. https://doi.org/10.1080/17583004.2014.912866

Robbins, J.A., & Evans, M.R. (2011). *Growing Media for Container Production in a Greenhouse or Nursery: Part II – Physical and Chemical Properties*. 4. https://www.uaex.edu/publications/PDF/FSA-6098.pdf.

Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., & Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature*, *534*(7609), 631–639. https://doi.org/10.1038/nature18307.

Sandip Mandal, S. Jeyaraman, B.V. and A.K.S., Srinivasarao, K.A. Gopinath, G. Venkatesh, A.K. Dubey, H.W., & T.J. Purakayastha, H. Pathak, Pramod Jha, B.L. Lakaria, D.J.R. (2013). *Use of Biochar for soil Health enhancement and greenhouse gas mitigation in India*. *1*, 62.

Schlesinger, W.H., & Amundson, R. (2019). Managing for soil carbon sequestration: Let's get realistic. *Global Change Biology*, *25*(2), 386–389. https://doi.org/10.1111/gcb.14478.

Scholz, S.B., Sembres, T., Roberts, K., Whitman, T., Wilson, K., Lehmann, J., Ahmed, S., Hammond, J., Ibarrola, R., Shackley, S., & Haszeldine, S. (2014). Biochar Systems for Smallholders. In *The World Bank*. https://doi.org/10.1596/978-0-8213-9525-7.

Smith, P. (2016). Soil carbon sequestration and biochar as negative emission technologies. *Global Change Biology*, *22*(3), 1315–1324. https://doi.org/10.1111/gcb.13178

Smith, P., Soussana, J.F., Angers, D., Schipper, L., Chenu, C., Rasse, D.P., Batjes, N H., van Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J.E., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena,
A., & Klumpp, K. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. In *Global Change Biology* 26(1), 219–241.

https://doi.org/10.1111/gcb.14815

Steiner, C. & Harttung, T. (2014). Biochar as a growing media additive and peat substitute. *Solid Earth*, *5*(2), 995–999. https://doi.org/10.5194/se-5-995-2014.

Stewart, C.E., Zheng, J., Botte, J., & Cotrufo, M.F. (2013). Co-generated fast pyrolysis biochar mitigates green-house gas emissions and increases carbon sequestration in temperate soils. *GCB Bioenergy*, *5*(2), 153–164. https://doi.org/10.1111/gcbb.12001

Tisserant, A. & Cherubini, F. (2019). Potentials, limitations, co-benefits, and trade-offs of biochar applications to soils for climate change mitigation. *Land*, *8*(12). https://doi.org/10.3390/LAND8120179.

Torres, D. (2011). *Biochar Production With Cook Stoves and Use As a Soil*. *January*.

Van Der Ent, S., Van Hulten, M., Pozo, M.J., Czechowski, T., Udvardi, M.K., Pieterse, C. M.J., & Ton, J. (2009). Priming of plant innate immunity by rhizobacteria and β-aminobutyric acid: Differences and similarities in regulation. *New Phytologist*, *183*(2), 419–431. https://doi.org/10.1111/j.1469-8137.2009.02851.x.

Varela Milla, O., Rivera, E.B., Huang, W.J., Chien, C.C., & Wang, Y.M. (2013). Agronomic properties and characterization of rice husk and wood biochars and their effect on the growth of water spinach in a field test. *Journal of Soil Science and Plant Nutrition*, *13*(2), 251–266. https://doi.org/10.4067/S0718-95162013005000022

Verheijen, F., Jeffery, S., Bastos, A.C., Van Der Velde, M., & Diafas, I. (2010). Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions. In *Environment* 8(4). https://doi.org/10.2788/472.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*(5). https://doi.org/10.1038/ncomms1053

Wuebbles, D.J., Fahey, D.W., Hibbard,

K.A., Dokken, D.J., Stewart, B.C., & Maycock, T. K. (2017). Climate science special report: fourth National Climate Assessment. *U.S. Global Change Research Program*, *1*, 470. https://doi.org/10.7930/J0J964J6

Yakubu, A., Danso, E.O., Arthur, E., Kugblenu-Darrah, Y.O., Sabi, E.B., Abenney-Mickson, S., Ofori, K., & Andersen, M.N. (2020). Rice straw biochar and irrigation effect on yield and water productivity of okra. Agronomy Journal, 112(4), 3012–3023. https://doi.org/10.1002/agj2.20230.