Chapter

Biochar Potential in Improving Agricultural Production in East Africa

Godfrey Omulo

Abstract

Biochar is among the environmentally friendly bio-products possible of enhancing agricultural productivity due to inherent properties. Despite the increased biochar research output, the sustainability of biochar production and its applicability in developing countries is mostly uncertain. This chapter underscores the biochar production process, its environmental usefulness, and the prediction of its potential impact on agricultural productivity in East African countries. Currently, pyrolysis technology is the most effective means of biochar production. Predominantly, biochar is useful in carbon sequestration, soil amendment, and as a solid fuel source. In-depth analysis of crop residues production in East African countries vis-à-vis the potential for biochar production and the total planted areas strongly indicate that biochar could be sustainably produced and applied in agriculture without compromising the forests and the environment. This knowledge is vital in guarantying the feasibility of biochar technology among policymakers as a sustainable alternative to the exorbitant mineral fertilizers.

Keywords: biochar, agricultural productivity, East Africa, carbon sequestration, fertilizer, sustainable, climate-friendly

1. Introduction

One of the most significant bottlenecks to increased agricultural productivity in developing economies is continuous soil degradation due to land use change and erosion [1, 2]. Human activities have primarily destabilized the distribution of carbon in the universe that has released too much carbon to the atmosphere than what plants can utilize via the photosynthesis process (**Figure 1**). As a consequence, climate-change-related risks such as erratic rainfalls, floods, and fluctuating temperatures have ensued, causing soils to lose their nutrients through erosion and leaching. This has further led to the depletion of soil productivity, increased soil acidity, and a heightened need for mineral fertilizer application [4]. Acidity in soils is caused by factors ranging from nature of the soil, agroecological condition, and fertilization systems. For instance, the non-calcareous parent materials that are intrinsically acidic naturally undergo bleaching, especially in humid climates like East Africa and in high rainfall conditions. Further, reclaimed swampy soils (peats) and soils that have been highly treated with nitrogenous fertilizers tend to be acidic over time [5, 6].

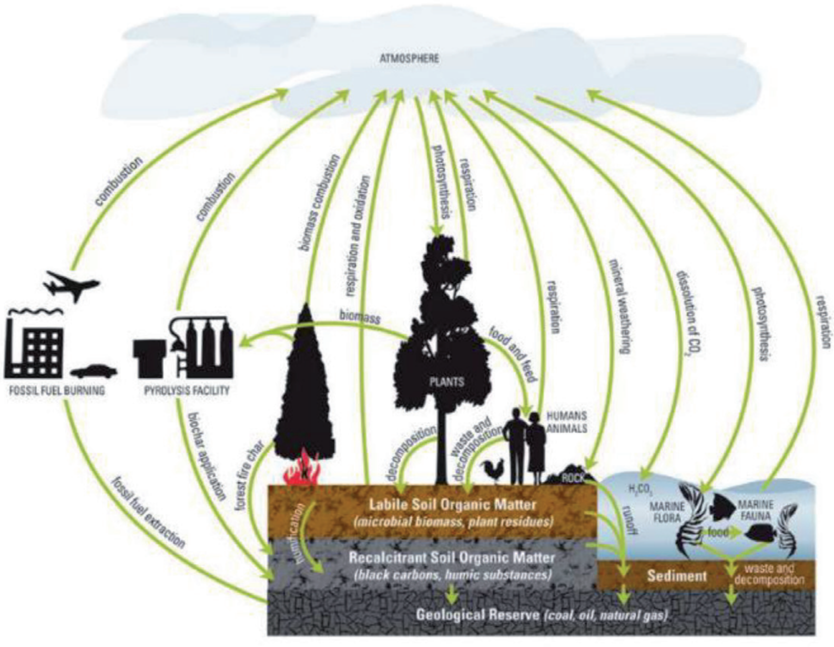

Figure 1.
Carbon cycle representing the global natural and anthropogenic contributions. Source: Brewer [3].

As a consequence, the production of biochar from various biomass sources has attracted immense attention among scientists and agricultural practitioners. This is because of its potential in revitalizing the fertility of degraded soils by sequestering carbon and reducing greenhouse gas emissions, thereby mitigating climate change [7].

Biochar is a black carbonaceous solid product that results from thermochemical decompositions of various biomass feedstocks at elevated temperatures under oxygen-deficient conditions [3, 8, 9]. Pyrolysis is the most common thermochemical process that yields biochar depending on the type of feedstock used and the variations in temperature regimes and the rate of heat application. Biochar from various types of biomass has been used predominantly as a soil amendment, carbon sequestrating tool, an agent for nutrient recycling, waste management tool [10–12], and as a solid fuel source [13]. Charcoal, one of the ancient products used for cooking, has also been investigated on its influence on agricultural productivity. In general, unlike biochar, charcoal has not been effective in fixing carbon into the soil except when it is mixed with mineral fertilizers or other organic manures. This is because mixing charcoal with organic fertilizers has the potential of enhancing nutrient accumulations at the crops root zone. Further, this mixture can minimize nutrient leaching in the vastly weathered tropical soils besides boosting crop productivity in acidic soils [14, 15].

According to Obi [16], more than 998 million tons of agricultural wastes result from crops, livestock, and aquaculture productions annually across entire Africa. Most of these wastes are reused as fuel sources, and others are left to decompose on the farms as organic manures or as feedstock for anaerobic digestions like biogas generation. From crop production alone, enormous amounts of plant-based biomasses are generated annually across East African countries. However, a clear focus toward their use as precursors of value-added products as biochar is mostly missing. The primary reason is the lack of appropriate technology to employ and limited informed strategies to spur biochar production in the region. Prudent implementation of sustainable biochar production is a potent stimulant to spanning agricultural productivity, better economic growth while minimizing negative environmental impacts in the area. Notably, the steady population increase in the region is exerting much pressure on the exponentially shrinking arable land besides other implications as climate change and land use change. Thus, ardent efforts to restore the degraded soils through the use of biochar are a potential remedy. This must be done while ensuring that the present and future regional agricultural production standards, food security, and renewable energy sources are uncompromised. This is a fundamental element in the biochar bio-economy discourse, which is aimed at revolutionizing agronomic operations in East Africa while underscoring the spectrum of its usefulness and viability [11].

2. Biochar production process

In this chapter, we highlight the overview of the biochar production process, its usefulness, and potentials in improving agricultural productivity in East Africa.

2.1 Biochar sources

In principle, biochar can be produced from a range of carbonaceous feedstocks subjected to various thermochemical processes. The feedstocks can include agricultural wastes, municipal solid wastes, residues from forests, used building materials, and hydrocarbon substances like used tires, among others. Important to note is that the suitability of various feedstocks principally depends on their availability, biosafety regulations, and the targeted market conditions. Depending on the desired end use, biochar production for agricultural production should take into considerations the environmental aspects and an understanding of soil condition as well as its properties. Discrete processes employed in biochar production are outlined in **Table 1**. The methods span from slow pyrolysis, fast pyrolysis, flash pyrolysis, intermediate pyrolysis, vacuum pyrolysis, hydropyrolysis, torrefaction, and gasification, receiving varied treatments according to the quality and quantity of the desired final product [17]. Generally, temperature, pressure, heating rate, residence time, reactive or inactive environment, type of the purifying gas, and its flow rate are engineered to yield the targeted products. In all the pyrolysis processes, three main products are generated: solid biochar or ash, bio-oil or tar liquid, and non-condensable gases or syngas [1, 3].

The principle behind pyrolysis and volatilization is combustion reaction of biomass in an inert atmosphere. The inert atmosphere is ensured by flushing through the reactors with argon or nitrogen gases [9]. The application of heat to biomass feedstock causes disintegration of chemical bonds leading to smaller molecules vaporizing into gas oxidation state [18]. Due to the oxygen-deficient condition, the products formed are water, methane, carbon monoxide, and carbon dioxide, otherwise, in the presence of excess oxygen, heat and light results. Thus, the lack of oxygen causes the volatiles to form into dense gases or liquid tar and soot. Consequently, once all the volatile components are eliminated or oxidized, the remaining slow-burning residue undergoes the final stage of combustion called solid-phase oxidation to yield radiant coal. Therefore, each thermochemical decomposition process is dependent on the heat energy applied, pressure, the quantity of oxygen supplied, type of precursor, and the residence time [9].

2.2 Slow pyrolysis

Slow pyrolysis takes place at low heating temperatures of 400°C and a long solids residence time, causing secondary cracking of the primary products. In a slow pyrolysis process, biochar yields are higher (up to 45%) compared to bio-oil (30%).

Thermochemical process	Temperature range (°C)	Heating rate	Pressure	Residence time	Primary product
Slow pyrolysis	350–800	Slow (<10°C/min)	Atmospheric	Hours–days	Biochar
Fast pyrolysis	500–1250	Very fast (10–200°C/sec)	Vacuum–atmospheric	10–20 s	Bio-oil
Flash pyrolysis	900–1200	Fast	Elevated	0.1–1 s	Biocarbon/char
Intermediate pyrolysis	500–650	0.1–10°C/sec	Low (0.1 MPa)	5–35 min	Bio-oil/biochar
Vacuum pyrolysis	450–600	Slow	Low (0.05–0.20 MPa)	Hours	Biochar
Hydropyrolysis	500–1000	Very fast in hydrogen	High (5–20 MPa)	10–20 s	Bio-oil
Torrefaction	200–300	Slow (<10°C/min)	Atmospheric	Minutes–hours	Stabilized, friable biomass
Gasification	700–1500	Moderate–very fast	Atmospheric-elevated	Seconds–minutes	Syngas/producer gas

Source: Omulo [17].

Table 1.
Thermochemical processes, their representative reaction conditions, particle residence times, and primary products.

The lower heating rates and longer retention time enable vapor formed from complete secondary reactions to be eliminated, thus forming the solid carbonaceous biochar [10, 11, 19–21].

2.3 Slow pyrolysis versus traditional charcoal making

Charcoal has been used as a perennial fuel for domestic heating. In practice, charcoal is made by slow burning of wood in the absence of oxygen at mild to high temperatures [22]. Even though the charcoal making process can be referred as slow pyrolysis, the initial heat required to ignite the reaction is generated by burning part of the wood or the feedstock making it hard to achieve inert environment. For a typical slow pyrolysis process, the heat needed to decompose the feedstock thermally is supplied externally via an indirect heating medium. In contrast to the charcoal making process, the feedstock remains in airtight vessels or reactors [8]. Thus, the goal of slow pyrolysis is to yield a biochar product with high energy and carbon content. This is besides other by-products like pyroligneous acid or wood tar and non-combustible or syngas.

3. Environmental usefulness of biochar

3.1 Biochar from biomass as a fertilizer and a soil conditioner

The use of biochar from plant biomass as a soil fertilizer or conditioner has received significant attention in the recent past [12]. Formerly, extractions from the fermentation of bioethanol and flavonoids as well as recoveries from chemicals have also been applied as organic soil fertilizers [22]. However, the residues from fermentation processes have short lifespans. They are uneconomical to use as fertilizer because of their high moisture content. Thus, the need to develop alternative products from sustainable thermal conversion ways has put the use of biochar into perspective [23]. This is key since the conventional method of leaving raw biomass wastes on the soil to degrade naturally has remarkable risks primarily due to high bulk density, high moisture content, and the hygroscopic nature. Further, the biomasses contribute to air and water pollution and greenhouse effects via smoke resulting from burning. On the other hand, the use of biochar has been cited as a viable way of stabilizing soil organic carbon while minimizing greenhouse gas (GHG) emissions [2].

Biochar has been identified as a carbon-neutral bioenergy resource capable of enhancing soil conditions for better agriculture. It can also aid in curbing greenhouse emission effects and global warming [24]. Biochar as a carbon sequester can significantly contribute to agricultural productivity through the improvement of soil fertility and controlled pollution of rivers and groundwater, which are threatened by continued unsustainable agrarian practices [25]. Besides influencing carbon content in the soil, fresh biochar is instrumental in immobilization of nitrogen, improvement of soil pH and soil structure [1]. Further, soils affected by continuous leaching due to herbicides application, research has shown that biochar can curb the leaching process and assist in reigniting microbial activity in the soil [24, 26]. The following biomass feedstocks have been used for biochar production to utilize it as a fertilizer: microalgae [24], eucalyptus crop residues, castor meal, coconut pericarp, sugarcane bagasse [27], water hyacinth [28], and banana wastes [29]. **Table 2** illustrates the biochar nutrient contents of various biomass feedstocks.

3.2 The potential of biochar in carbon sequestration

The potential of biochar as a viable tool to carbon sequestration has recently been centered on the common discourse of climate change. Biochar has been pointed out to enhance carbon sinks, especially in dry regions [32]. However, the degree with which biochar achieves carbon sequestration depends on various factors. Most importantly, it depends on the desired soil carbon content and the rate of carbon dioxide removal from the atmosphere [3]. There are considerable large sizes of arable lands (estimated at 6% of the earth's surface); thus, they require relatively high amounts of biochar to be incorporated therein. Ideally, up to 90 tons of biochar per hectare should be incorporated into the farms compared to the current recommendations of 50 tons of biochar in a hectare [1] to help in reducing the level of carbon dioxide in the atmosphere. Since it takes long to sequester carbon dioxide

Residue	N	P	K	C	Ca	Mg
Wheat straw		0.21	2.90	18.29	7.70	4.30
Maize cob	10.8	0.45	9.40	429	0.18	1.70
Maize stalk	8.1	2.10	0.03	427	4.70	5.90
Forest residue	1.6	0.29	0.11	39	130	19.0
Peanut	15.0	2.4	—	429	—	—
Soybean	23.8	0.9	—	441	—	—
Rice husk	0.3	0.16	0.48	36	1.63	—

Table 2.
Biochar nutrients proportion from various biomass feedstocks (in g kg^{-1}) [27, 30, 31].

from the atmosphere, the predisposition asserted by industrial activities makes the process even longer. This means that even though biochar has the potential to sequester carbon, sustainable land use change and pollution control are indispensable. With improved and cheaper innovations like pyrolysis techniques, biochar productions potentially depend on biomass availability [3, 17, 27]. **Table 3** highlights the average agricultural wastes across East African countries generated from the major food crops [33].

3.3 The extent of biochar use in agriculture

The continued awareness of the benefits of biochar as a carbon sequester and soil conditioner has propelled its demand and use in the agricultural sector worldwide [34]. Research institutions and organizations have championed evidence-based research as incentives to upscale biochar acceptability and salability to farmers. One such organization is the International Biochar Initiative (IBI), which is a non-profit organization founded in 2006. Even though it is the biggest biochar promoter, several other establishments exist in different countries and regions of the world [25, 35, 36]. These biochar promoter organizations have been at the forefront in organizing scientific conferences to share insights on the latest research on biochar. Most importantly, they have been instrumental in proposing policies regarding biochar legislation. One such milestone is the Post-Kyoto Climate Agreements under the UN Framework Convention on Climate Change (UNFCCC), where biochar was unilaterally accepted a viable mitigation strategy [30, 32]. The Kyoto protocol was further intended to aid small economy countries to achieve sustainable development goals and to secure compliance with GHG emission minimization targets [37].

3.4 How does biochar improve soil properties?

The historical background about the use of biochar as soil amendment tool can be traced back to as earlier as 1929 when John Morley working with the US National

Crop	Burundi (×1000MT)	Kenya (×1000MT)	Rwanda (×1000MT)	S. Sudan (×1000MT)	Tanzania (×1000MT)	Uganda (×1000MT)
Beans, dry	3.83	13.12	6.42	0.011	14.41	9.96
Maize	2.55	32.59	3.93	1.06	61.57	27.47
Millet	0.12	0.69	0.069	0.059	3.83	2.50
Potatoes	0.60	5.62	2.85	—	6.27	1.00
Rice, paddy	1.59	1.20	1.45	—	44.59	3.89
Sorghum	0.37	3.02	2.53	9.27	13.60	6.51
Soybeans	0.072	0.044	0.84	—	0.116	0.80
Wheat	0.12	2.27	0.17	—	1.59	0.34
Barley	—	0.93	—	—	0.18	—
Oats	—	0.059	—	—	—	—
Total	**9.26**	**59.54**	**18.26**	**10.40**	**146.15**	**52.48**

Source: FAOSTAT [33].

Table 3.
Comparison of crop residues among East African countries (×1000MT) nitrogen content.

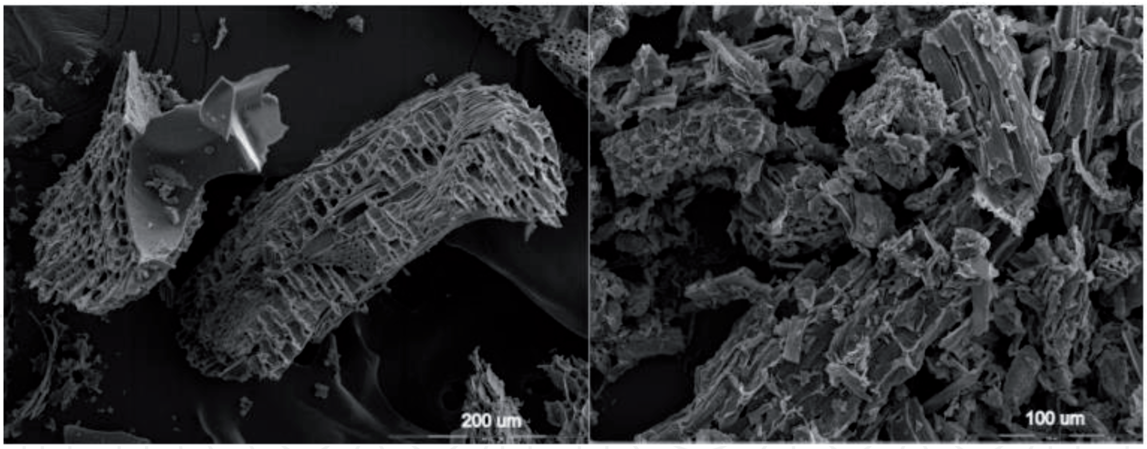

Figure 2.
Scanning electron micrographs of biochar particles showing porosity. Source: Brewer [3].

Greenkeeper realized that addition of traces of charcoal enhanced soil porosity [3]. Different kinds of biochar porosity exist depending on pore size. Pores can be categorized into micropores (diameter < 2 nm), mesopores (diameter 2–50 nm), and macropores (diameter > 200 nm) [3]. Mostly, macropores are susceptible to water, plant roots, and fungal hyphae penetration. Thus, the large pores influence the soil's hydrology and microbial ecosystem. It is easy to see the biochar pore size distributions using the scanning electron micrographs depending on the parent plant structure, see **Figure 2**. Therefore, it is the high porosity property of biochar that makes it contributes to the susceptibility of soil to water infiltration and increased micropore network in the soil [1, 30]. Thus, water retention in both sandy and silty soils can be significantly improved with the incorporation of biochar [1, 30].

Biochar's larger surface area to volume ratio also plays a significant role in cation exchange capacity (CEC) and the extent to which biochar can be integrated into the soil. The bigger the biochars' surface area, the greater the chemical exchanges; it can accommodate per unit gram [38]. Thus, it potentially curbs any form of nutrient leaching while boosting nutrients uptake [7, 31]. Biochar's bulk density is relatively low compared to soil bulk density; this encourages ease of nutrient release to plants and also lowering the effects of soil compatibility [3, 4].

Biochar is alkaline; this may influence the type of soil upon which it can be applied [39]. Depending on the type of feedstock pyrolyzed, biochar contains both primary and trace mineral elements useful for plants development [4]. Nonetheless, it has been noted that the presence of various functional hydrocarbon groups in biochar limits its release of water to plant roots especially in water stress conditions [36].

4. Potential of biochar use to boost East African agricultural productivity

East Africa is among the countries with the highest nutrient loss across sub-Saharan Africa with annual nutrient depletion rate of 41 kg N, 4 kg P and 31 kg K per hectare [40]. Even though soil fertility is quite dynamic, its inherent chemical, biological, physical, and anthropogenic characteristics play a significant role too [40]. Most soils in East Africa are acidic without enough nutrients to support sustainable crop production. This is because a bigger portion of the soils are extremely weathered, making them nutrient-deficient, especially with a limited stock of phosphorus, potassium, calcium, magnesium, and sulfur [41]. Similarly, soil acidity is influenced by the robust soluble aluminum, which is poisonous to most crops. Therefore, to ensure sustained crop productivity, improved soil fertility management is inevitable. This calls for sustainable and cheaper soil fertilization ventures like the use of biochar in these resource-constrained countries [40].

However, despite the known benefits of biochar to the scientific world, other stakeholders have concerns that are yet to be addressed. One of the significant issues is the uncertainty regarding the sustainable supply of feedstock for biochar production. Policymakers argue that mass production of biochar would need vast land for the feedstock required [1]. On the other hand, farmers still seem not to acknowledge that the crop residues within their farms can serve as biochar feedstock. The lack of reliable evidence in the literature regarding the sufficiency of crop residues as feedstock for biochar production in the context of East Africa is a gap. This section reiterates the fact that every field, farm, or region has the potential of generating enough biomass feedstock for biochar production. The analyses were carried out with a focus on the East African region. A few recent field and pot trials on the effectiveness of biochar on soil fertility enhancement have yielded very positive results [41]. Thus, the empirical evidence illustrated in this chapter reinforces the feasibility and sufficiency of biochar technology to impact the agricultural performance of smallholder farmers in East Africa amidst the effects of climate change.

According to the United Nations (UN) regional boundary delineation, East African region spans from the Red Sea coast in Eritrea, through to the Horn of Africa (Somalia) transcending the Indian Ocean coast line up to Mozambique. It further stretches inwards to Zimbabwe on the south, Zambia on the southwest and along the western rift valley encompassing Burundi, Rwanda, Uganda, South Sudan, and Sudan [4]. It also includes Indo-Oceanian Islands like Madagascar, Seychelles, Mauritius, and Comoros [42]. However, based on this chapter, a close focus will be given to the six countries forming the East African Community block. These countries include Kenya, Tanzania, Uganda, Rwanda, Burundi, and South-Sudan (although scarce information is available) (**Figure 3**). Agriculture still contributes substantially to the economic growth of East African, and it offers job opportunities to more than 70% of the region's population [44]. **Figure 4** illustrates the percentage of contributions of agriculture to the GDP of the countries in comparison with other sectors.

Despite this immense reliance on agriculture, agricultural production in East African countries is predominantly under subsistence basis. The bulging population, perennial low productivity recorded, alarming food insecurity and high demand for rich nutrient grains compound the desperate state of the agricultural sector in the region. Notwithstanding, the region is still estimated to harbor excellent agricultural potential. However, to harness this potential, sustainable and increased agricultural extensification via appropriate mechanization, improved land use management, and climate-adapted farming methods are inevitable [45].

The soils in East Africa have been affected by unsustainable continuous land use, non-conservation tillage methods employed, and native volcanic soils that are prone to degradation [4]. Consequently, the antidote to this menace is embracing sustainable and climate-friendly farming methods capable of increasing and preserving soil fertility. Biochar technology is one such viable means to achieve this noble vision [3].

4.1 How abundant are agricultural residues in East Africa?

The scalability of pyrolysis technologies in East African countries is yet at a very dismal stage. The primary reason is the low level of industrialization and little

Figure 3.
Map of East African countries. Source: United Nations [43].

appreciation of such technologies. This, however, does not disannul pyrolysis' potential to foster sustainable agricultural production through biochar production and use [7]. To underscore this hypothetical biochar usefulness in the region, critical scenario-based analysis seeking to disentangle the uncertainty on the availability and sustainability of biomass feedstock is paramount. The revelation will further contribute to changing the perception of both policymakers and farmers about biochar potential in the region [1]. As earlier stated, the feedstock can be generated from a range of biomass residues; the author, however, explore the potential in crops specifically on maize [46].

Maize is the most popular crop grown in East Africa because it is the staple food. Despite this, its productivity per hectare is below the estimated regional average (2.5 tons per hectare). Maize is a very high nutrient feeder crop; thus, its production requires extensive fertilizer use [47]. Other crops grown in the region include cash

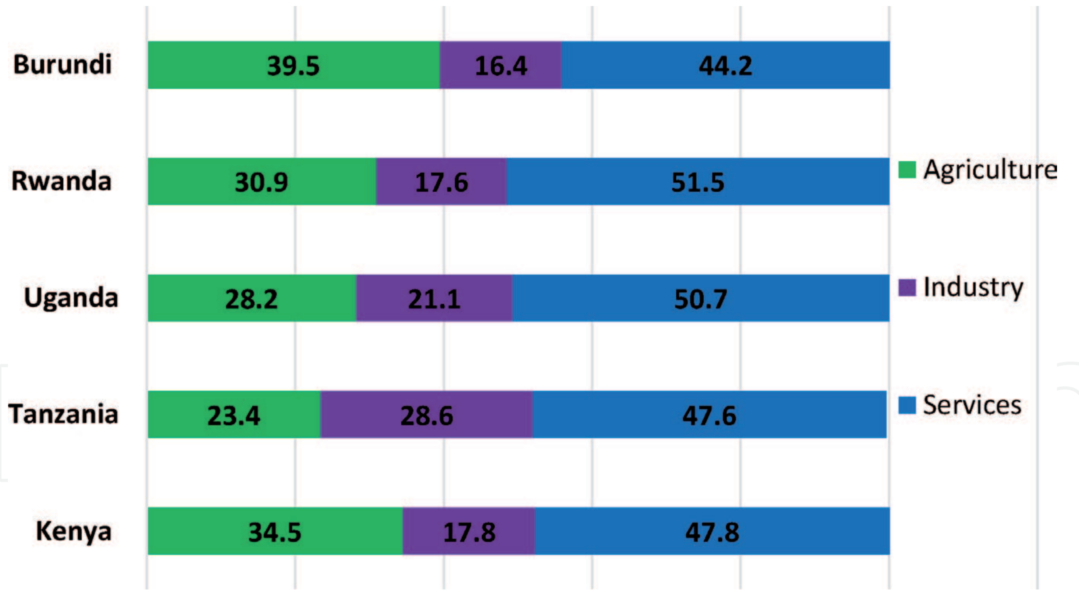

Figure 4.
Percentage contribution of agriculture to countries GDP compared to other sectors based on 2017 estimates. Source: The Centre of Intelligence, CIA [44].

crops such as tea, coffee, sugarcane, pyrethrum, and cotton; and food crops such as rice, wheat, beans, groundnuts, millet, sorghum, bananas, and potatoes, among others [48]. Taking maize as the most common crop, an illustration of its residues adequacy for biochar production is highlighted. **Table 4** outlines the estimates of maize production in the year 2019 versus the area planted across the selected East African countries.

The greatest challenge has been the inability to estimate the quantity of residues resulting from maize farming accurately. Even though proper records and monitoring of maize grains and other crops exists, very little has been done to quantify crop residues [49]. Nevertheless, in this section, the residues-to-product ratios (RPRs) estimation method is used. It is one of the most reliable ways to compute residue mass of any crop [49, 50]. Generally, maize crop generates 12% husks, 27% leaves, 49% stem, and 12% cob residues of the total plant mass [50]. Thus, the RPRs for maize residue are as follows: 2 for the stalk, 0.273 for cob, and 0.2 for husks. These factors are systematically used to quantify the possible maize residue that can be generated based on the current maize production rates in the East African countries

Country	Production (×1000 MT)	Planted area (×1000 Ha)	Yield (MT/Ha)
Kenya	3400	2000	1.7
Tanzania	6200	4200	1.5
Uganda	2800	1150	2.4
Rwanda	411	250	1.6
Burundi	260	180	1.4
South Sudan*	400	330	1.2
Total	**13,471**	**8110**	**1.7**

Source: The US Department of Agriculture, USDA [27].
**South Sudan data are based on 2016 statistics.*
Source: McKee [26].

Table 4.
Maize production, area planted and yield estimates in East Africa as of 2019.

(**Table 4**). Since the recorded crop masses are weighed in N kg, the respective residue masses are as follows: 76% representing stalk residue (leaves 27% and stem 49%) is 2.0 N kg at 15% moisture content, 12% representing cob residue is 0.273 N kg at 7.53% moisture content, and 12% representing husk residue is 0.2 N kg at 11.11% moisture content. When summed up, the expected total residue mass from the maize crop is approximately 2.47 N kg. Thus, expected total residue mass is 2.47 N kg [4, 50].

Consequently, a total of 13.5 million tons of maize is produced in East Africa under the total planted area of 8.1 million hectares. This implies that 33.3 million tons (13,471,000 × 2.47) of residues are generated annually. These residues are potential feedstock for pyrolysis for biochar production. To further estimate the possible amount of biochar that can be generated from these residues, pyrolysis parameters like residence time and heating temperature are paramount. Omulo et al. [29], Cantrell et al. [39] and Djurić et al. [51] noted that subjecting residues to temperature regimes of 300–650°C can lead to a biochar yield of between 40 and 28%. Thus, supposing that maize residues are pyrolyzed at a low temperature of 300°C, it is possible to generate up to 40% biochar as by-products. Thus, the rate of conversion of residues to biochar is taken as 0.4. This means that from the total mass of residues generated, about 13.3 million tons of biochar can be produced.

However, what percentage of the planted area in the region can be sustained by the produced biochar? In principle, biochar application can be made in two ways: a one-time application where biochar is applied at the required rate or an intermittent application where biochar is progressively applied until the acceptable threshold is achieved. Assuming that one-time biochar application is employed, Major [35] recommends the rate of 5 tons of biochar per hectare. Thus, based on the probable biochar yield in East Africa, a total of 2.7 million hectares (approximately 30% of the total planted area) can be adequately fertilized by biochar every season. Moreover, noting that biochar has a long decay life, even a one-time application is estimated to have long time effects on the soil [3].

4.2 Economic savings and biochar adoption potential for agricultural use

A plethora of evidence has shown that biochar use has the potential to improve agricultural productivity, especially among the acidic weathered soils [46]. Further proofs indicate that biochar application can double maize yield by application of only 4 tons per hectare [52]. Because soil degradation in East Africa has not escalated to irredeemable limits, proper biochar application is projected to have more profound impacts on crops productivity. Consequently, utilizing biochar to fertilize the staple maize farms can minimize the cost of fertilizers in the region while the saved revenue is used to extensify farming operations. Based on the estimations by Berazneva [41, 53], the mean shadow value of maize residues for farm soil fertility amendment is 0.07 USD/kg.

In comparison, an estimated cost of 0.04 USD/kg of fertilizer is conserved when the same residues are left on the field as mulch [53]. These values may differ slightly when pyrolysis costs are factored. Nevertheless, biochar production and utilization will potentially maximize the residue used to improve soil quality.

Hypothetically, considering the current low maize yield potential of the East African region, 1.7 tons per hectare, every hectare of maize would generate a total of 4199 kg of residues (**Table 5**). If these residues were to be utilized in biochar generation via pyrolysis process, then approximately $67.18 cost of fertilizer can be saved in 1 hectare of land. This implies that with the current price of $29.75 per 50 kg bag of diammonium phosphate (DAP), $24.05 per 50 kg bag of urea, and $29.15

Country	Production (×1000 MT)	Planted area (×1000 Ha)	Residue (×1000T)	Biochar (×1000T)	Area applied (×1000Ha)	Covered area as percentage of planted area
Kenya	3400	2000	8398	3359.2	671.84	33.59
Tanzania	6200	4200	15,314	6125.6	1225.12	29.17
Uganda	2800	1150	6916	2766.4	553.28	48.11
Rwanda	411	250	1015.17	406.068	81.2136	32.49
Burundi	260	180	642.2	256.88	51.376	28.54
South Sudan*	400	330	988	395.2	79.04	23.95
Total	**13,471**	**8110**	**33273.37**	**13309.348**	**2661.8696**	32.82

Source: USDA [48].
**Estimates are based on 2017 statistics except for South Sudan it is 2016.*

Table 5.
Possible area under biochar application as a percentage of the planted area at country level.

per 50 kg bag of NPK fertilizers [54], the saved cost can enable farmers to buy two more bags of fertilizers respectively. Ideally, this will reduce the amount of chemical fertilizers applied to the farm by two bags but with the same prospect of crop yield.

The basis of biochar production and use adoption in East Africa hangs on the current practices and use of crop residues in the region, especially the principal food crop, maize. According to Berazneva [41], most of the residues are burnt in situ on the farms to clean the land for the subsequent season and also to sterilize traces of pests and diseases. On the other hand, most farmers leave the residues on the farms for soil amendment even though their farms are susceptible to open grazing. Still, other farmers use the residues as a fuel source besides feeding their animals. Therefore, adoption of biochar technology to sustainably manage the generation of residues for fertilization can empower an Integrated Soil Fertility Management (ISFM) system.

This model of quantifying maize residues for biochar production underscores the potential of every country to achieve biochar application rate of 5 tons per hectare. The percentage areas that can be sustained by biochar in comparison to the planted areas depict that potential crop yield increment of the region (**Table 5**). Even the smallholder farmers have the opportunity to boost their productivity due to biochar application [55].

5. Possible barriers to biochar production in East Africa

Promotion and adoption of biochar technology in East Africa and across entire sub-Saharan Africa (SSA) is hampered by several obstacles ranging from policy and legal frameworks, institutional, socio-economic, fiscal, ecological, health, and technical issues [1]. This is majorly due to the lack of workable local policies and legal frameworks highlighting the rationale, the terms and conditions of biochar production as well as the associated technological aspects [41]. As a consequence, necessary measures to fast-track these impediments are deemed paramount and thus demands urgent actions as illustrated in **Figure 5**.

Borrowing a leaf from promotion and adoption of other renewable energy technologies, it is paramount that biochar technology is adapted to the local

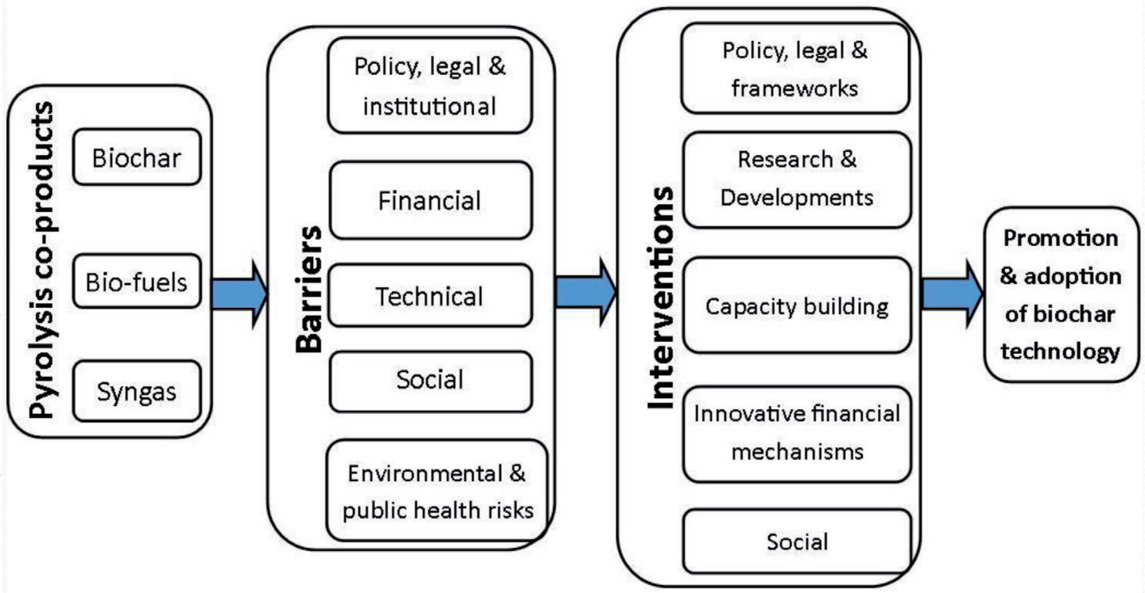

Figure 5.
Barriers to biochar and co-products production and use in SSA and viable interventions actions. Source: Gwenzi [1].

conditions and realities and should be affordable as possible. Deliberate capacity building on biochar technology through research and innovations channeled through various social strata can also break these constraints. Thus, for biochar technology to be feasible in East Africa, smallholder farmers should be able to understand the technology and afford the production and investment costs involved [1].

Another bottleneck to upscaling of biochar technology is the negative attitudes and perception surrounding it, especially by the majority risk-averse smallholder farmers. Discourses compound these cynicisms on nature conservation, competing interests, and deprivation of the scarce animal feeds [53]. The general belief that biochar production leads to deforestation besides being a complicated technology is quite difficult to disentangle. Nevertheless, proper knowledge sharing, supported by evidenced-based research, can serve as the most persuasive argument against such antagonistic ideologies. Further, the real potential and benefits of sustainable production and use of biochar for crop production can be underscored based on the perceived usefulness. Improved crop production implies better food security, poverty reduction, and reduced mortality rates. These challenges are faced by a majority of resource-constrained smallholder families across entire sub-Saharan Africa.

6. Future of biochar production and use

Biochar technology continues to offer numerous opportunities for developing economies. Apart from its suitability in agricultural production, biochar is highly an efficient and safe source of heat energy for small households compared to the current conventional use of charcoal [3]. Charcoal fires are usually operated openly, exposing then to inefficient heat transfer and air pollution, which can cause health complications too. Therefore, harnessing biochar production from crop residues offers excellent prospects for both energy and income generation even among smallholder families across the region. Government-led compensation schemes based on carbon credits on the amount of carbon sequestered and participation in climate change mitigation would highly incentivize biochar use.

With proper organization, biochar producers can significantly benefit from the improved market where they can sell their products and even via cooperatives to get better bargaining power. Access to the improved energy source for domestic use like biochar can create time for women to be involved in other more income-generating activities. Consequently, increased income will lead to improved quality of life among their households [3]. Biochar use can be diversified without interfering with the necessary amounts needed for soil amendments and increased crop productivity [4].

Critics have pointed out that sufficient biochar production may potentially lead to deforestation and that the use of inappropriate production methods may also result in air pollution [1]. Nevertheless, as earlier stated, sustainable biochar generation might not be dependent on a single biomass source. Instead, sourcing biomass residues from a wide range as forest products, crop wastes, animal wastes, biodegradable landfills, urban, and construction bio-wastes are more viable [17, 29]. This means that in future, pyrolysis techniques employing efficient bio-reactors for biochar production will potentially minimize any heat loss and pollution [3] while maximizing the yields. A more informed decision among users and action-oriented policy frameworks, as well as research development, can reinforce the desired production and use of biochar in the region.

7. Conclusion

The problems of land degradation and climate change effects are spread uniformly across East African countries. Farmers desire amicable solutions to these challenges. Biochar technology has proven to be such a feasible solution that doubles as a soil conditioner and a climate-friendly product. Based on the current maize production trends in the region, it is possible to generate enough biomass residues for biochar production. This has the potential of reducing fertilizer use by farmers in the region by up to 30% cushioning them from the exorbitant mineral fertilizers while still getting the desired yield. Thus, with proper uptake and implementation, driven by sound policies and good governance, biochar production has a great potential to boost farmers production and improve their quality of life. Nevertheless, it is paramount that the technology is adapted to the local conditions, be backed up with current research evidence, proper capacity building, and concerted efforts among the stakeholders.

Acknowledgements

The author would like to appreciate the auditors for their time and input throughout the review process of this chapter.

Conflict of interest

No conflict of interest to declare.

Author details

Godfrey Omulo
Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute), Universität Hohenheim (490), Stuttgart, Germany

*Address all correspondence to: omuloh@gmail.com

References

[1] Gwenzi W, Chaukura N, Mukome FND, Machado S, Nyamasoka B. Biochar production and applications in sub-Saharan Africa: Opportunities, constraints, risks and uncertainties. Journal of Environmental Management. 2015;**150**:250-261

[2] Duku MH, Gu S, Ben Hagan E. Biochar production potential in Ghana—A review. Renewable and Sustainable Energy Reviews. 2011;**15**(8):3539-3551

[3] Brewer CE. Biochar Characterization and Engineering. United States: Iowa State University; 2012

[4] Ndhlovu M, Banadda N. Determination of sufficiency of crop residue for biochar application. African Journal of Agricultural Research. 2017;**4**(1):254-262

[5] Kanyanjua SM, Ireri L, Wambua S, Nandwa SM. Acidic Soils in Kenya: Constraints and Remedial Options. Nairobi, Kenya: Kenya Agricultural Research Institute; 2002. p. 11

[6] Abate E, Hussein S, Laing M, Mengistu F. Soil acidity under multiple land-uses: Assessment of perceived causes and indicators, and nutrient dynamics in smallholders' mixed-farming system of Northwest Ethiopia. Acta Agriculturae Scandinavica Section B Soil and Plant Science. 2017;**67**(2):134-147

[7] Kong SH, Loh SK, Bachmann RT, Rahim SA, Salimon J. Biochar from oil palm biomass: A review of its potential and challenges. Renewable and Sustainable Energy Reviews. 2014;**39**:729-739

[8] Nartey OD, Zhao B. Biochar preparation, characterization, and adsorptive capacity and its effect on bioavailability of contaminants: An overview. Advances in Materials Science and Engineering. 2014;**2014**:1-12

[9] Zaman CZ et al. Pyrolysis: A sustainable way to generate energy from waste. In: Pyrolysis. London: Intech Open Science; 2017. p. 35

[10] Brewer CE, Schmidt-Rohr K, Satrio JA, Brown RC. Characterization of biochar from fast pyrolysis and gasification systems. Environmental Progress & Sustainable Energy. 2009;**28**(3):386-396

[11] Spokas KA et al. Biochar: A synthesis of its agronomic impact beyond carbon sequestration. Journal of Environmental Quality. 2012;**41**(4):973-989

[12] Klinar D. Universal model of slow pyrolysis technology producing biochar and heat from standard biomass needed for the techno-economic assessment. Bioresource Technology. 2016;**206**:112-120

[13] Sadaka S, Sharara M, Ashworth A, Keyser P, Allen F, Wright A. Characterization of biochar from Switchgrass carbonization. Energies. 2014;**7**(2):548-567

[14] Steiner C et al. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered central Amazonian upland soil. Plant and Soil. 2007;**291**(1-2):275-290

[15] Steinera C, Das KC, Garciac M, Försterd B, Zech W. Charcoal and smoke extract stimulate the soil microbial community in a highly weathered xanthic Ferralsol. Pedobiologica. 2008;**51**:359-366

[16] Obi F, Ugwuishiwu B, Nwakaire J. Agricultural Waste

Concept, Generation, Utilization and Management. Nigerian Journal of Technology. 2016;**35**(4):957

[17] Omulo G. Optimizing Slow Pyrolysis of Banana Wastes Using Response Surface Methodology to Enhance Bio-Infrastructure Products Yield. Kampala, Uganda: Makerere University; 2017

[18] Bridgwater V. Principles and practice of biomass fast pyrolysis processes for liquids. Journal of Analytical and Applied Pyrolysis. 1999;**51**(1):3-22

[19] Brennan L, Owende P. Biofuels from microalgae — A review of technologies for production, processing, and extractions of biofuels and co-products. Renewable and Sustainable Energy Reviews. 2010;**14**:557-577

[20] Demirbas A. Biofuels sources, biofuel policy, biofuel economy and global biofuel projections. Energy Conversion and Management. 2008;**49**:2106-2116

[21] Tripathi M, Sahu JN, Ganesan P. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. Renewable and Sustainable Energy Reviews. 2016;**55**:467-481

[22] Chew KW, Chia SR, Yen HW, Nomanbhay S, Ho YC, Show PL. Transformation of biomass waste into sustainable organic fertilizers. Sustainability. 2019;**11**:1-19

[23] Volpe M, Panno D, Volpe R, Messineo A. Upgrade of citrus waste as a biofuel via slow pyrolysis. Journal of Analytical and Applied Pyrolysis. 2015;**115**:66-76

[24] Chang YM, Tsai WT, Li MH. Chemical characterization of char derived from slow pyrolysis of microalgal residue. Journal of Analytical and Applied Pyrolysis. 2015;**111**:88-93

[25] Barrow CJ. Biochar: Potential for countering land degradation and for improving agriculture. Applied Geography. 2012;**34**:21-28

[26] Hagner M, Penttinen O, Tiilikkala K, Setälä H. The effects of biochar, wood vinegar and plants on glyphosate leaching and degradation. European Journal of Soil Biology. 2013;**58**:1-7

[27] Abdelhafez AA, Abbas MHH, Li J. Biochar: The black diamond for soil sustainability, contamination control and agricultural production. In: Engineering Applications of Biochar. London: Intech Open Science; 2017. p. 23

[28] Doumer ME et al. Slow pyrolysis of different Brazilian waste biomasses as sources of soil conditioners and energy, and for environmental protection. Journal of Analytical and Applied Pyrolysis. 2015;**113**:434-443

[29] Omulo G, Banadda N, Kabenge I, Seay J. Optimizing slow pyrolysis of banana peels wastes using response surface methodology. Environmental Engineering Research. 2019;**24**(2):354-361

[30] Verheijen F, Jeffery S, Bastos AC, Van Der Velde M, Diafas I. Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions. Vol. 8. No. 4. Luxembourg: Functions. EUR 24099 EN, Office for the Official Publications of the European Communities; 2009

[31] Yuan JH, Xu RK, Zhang H. The forms of alkalis in the biochar produced from crop residues at different temperatures. Bioresource Technology. 2011;**102**(3):3488-3497

[32] Matovic D. Biochar as a viable carbon sequestration option: Global and Canadian perspective. Energy. 2011;**36**(4):2011-2016

[33] FAOSTAT. FAOSTAT Crop Residues. Food and Agriculture Organization of the United Nations [Online]. 2017. Available from: http://www.fao.org/faostat/en/#data/GA [Accessed: 19 March 2020]

[34] Obia A, Mulder J, Martinsen V, Cornelissen G, Børresen T. In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. Soil and Tillage Research. 2016;**155**:35-44

[35] Major J. Guidelines on Practical Aspects of Biochar Application to Field Soil in Various Soil Management Systems. New York, United States: International Biochar Initiative; 2010

[36] Fryda L, Visser R. Biochar for soil improvement: Evaluation of biochar from gasification and slow pyrolysis. Agriculture. 2015;**5**(4):1076-1115

[37] Beeharry RP. Carbon balance of sugarcane bioenergy systems. Biomass and Bioenergy. 2001;**20**(12):361-370

[38] Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. Biochar effects on soil biota—A review. Soil Biology and Biochemistry. 2011;**43**(9):1812-1836

[39] Cantrell KB, Hunt PG, Uchimiya M, Novak JM, Ro KS. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresource Technology. 2012;**107**:419-428

[40] Bekunda M, Ebanyat P, Nkonya E, Mugendi D, Msaky J. Soil fertility status, management, and research in East Africa. Eastern Africa Journal of Rural Development. 2005;**20**(1):1-23

[41] Berazneva J. Economic value of crop residues in African smallholder agriculture. In: AAEA and CAES Annual Meeting, August 4-6, 2013.; 2013, No. July. pp. 1-25

[42] Blein R et al. Agriculture in Africa, Transformation and Outlook. Johannesburg: NEPAD Transforming Africa; 2013. p. 72

[43] United Nations. Map of East African Community. United Nations Department of Field Support. p. 1

[44] CIA. The World Fact Book. The Centre of Intelligence Agency, Washington, DC, United States [Online]. 2020. Available from: https://www.cia.gov/library/publications/the-world-factbook/fields/214.html [Accessed: 03 March 2020]

[45] Mrema GC, Kienzle J, Mpagalile J. Current status and future prospects of agricultural mechanization in sub-Saharan Africa [SSA]. AMA, Agricultural Mechanization in Asia, Africa & Latin America. 2018;**49**(2):13-30

[46] Cornelissen G et al. Biochar effect on maize yield and soil characteristics in five conservation farming sites in Zambia. Agronomy. 2013;**3**:256-274

[47] McKee D. Maize Production Soaring in Eastern Africa. World Grain.com [Online]. 2016. Available from: https://www.world-grain.com/articles/7172-maize-production-soaring-in-eastern-africa [Accessed: 03 March 2020]

[48] USDA. Countries Agricultural Production Statistics, Index Mundi [Online]. 2020. Available from: https://www.indexmundi.com [Accessed: 03 March 2020]

[49] Bentsen NS, Felby C, Thorsen BJ. Agricultural residue production and potentials for energy and materials services. Progress in Energy and Combustion Science. 2014;**40**(1):59-73

[50] Koopmans A, Koppejan J. Agricultural and forest residues—Generation, utilization and availability. In: Regional Consultation on Modern

Applications of Biomass Energy; 1997, No. January, pp. 6-10

[51] Djurić SN, Brankov SD, Kosanić TR, Ćeranić MB, Nakomčić Smaragdakis BB. The composition of gaseous products from corn stalk pyrolysis process. Thermal Science. 2014;**18**(2):533-542

[52] Cornelissen G, Martinsen V, Obia A, Abiven S. Improving Crop Yield and Storing Carbon: Biochar in Conservation Farming in Zambia. Lusaka, Zambia: Norwegian Geotechnical Institute; 2014

[53] Berazneva J, Lee DR, Place F, Jakubson G. Allocation and valuation of smallholder maize residues in Western Kenya. Ecological Economics. 2018;**152**:172-182

[54] AF. Fertilizer Statistics. AfricaFertilizer.org [Online]. 2019. Available from: https://africafertilizer.org/statistics/ [Accessed: 05 March 2020]

[55] Ndhlovu M, Kiggundu N, Wanyama J, Banadda N. Effects of incorporating biochar into the soil using power tiller and. Sustainable Agricultural Resarch. 2017;**6**(4):93-103