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Biochar amended soils and crop productivity: A critical and meta-analysis of literature

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Abstract

Biochar is a kind of charcoal used for soil improvement and it is produced by pyrolysis of biomass under low or anaerobic conditions. It has the potential to mitigate climate change, via carbon sequestration, decrease soil acidity and increase agricultural productivity. Historically it is known that the Amazonians used biochar to enhance soil productivity by smoldering agricultural wastes. Desk reviewed of articles of soil amended biochar and some attributes which enhance crop development and the economic benefits derived from its use in agriculture were critically analysed. A meta-analysis using twenty-seven (27) articles reveal that the temperature at which pyrolysis is done is a major contributing factor towards the intended use of the biochar. For the purpose of crop yield, a temperature of 550^{0}C is recommended based on the regression results. It is recommended that an in-depth study should be done for particular crops taking into consideration the soil and the geographical location of such crops for yield enhancement.

Keywords: Biochar, Pyrolysis, Soil Amendment, Agriculture

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1. Introduction

The term 'biochar' was coined by Read to describe charcoal used for soil improvement (Read et al., 2004). Like most charcoal, biochar is produced by pyrolysis of biomass in low or anaerobic conditions and has the potential to mitigate climate change, via carbon sequestration (Woolf et al., 2010). It increases pH of acidic soils, agricultural productivity, and provides protection against some foliar and soil-borne diseases and reduces pressure on forests (Ndameu, 2011). It is a stable solid, rich in carbon, and can endure in soil for thousands of years (Lean and Rind, 2008). Historically, Pre-Columbian Amazonians were believed to have used biochar to enhance soil productivity. They produced it by smoldering of agricultural wastes. Biochar production and application has been proposed as one of the options that mitigates climate change (Lehmann 2007) and improving soil fertility and crop productivity (Major et al., 2010). Its porosity is very beneficial for improving soil structure and water holding capacity (Karhu et al., 2011; Vaccari et al., 2011) hence mitigating the increasing drought stress in dryland agriculture due to climate change. The objective of this study is to review literature on the effects of biochar amended soils on crop production, its mode of production, and attributes that indirectly affect crop productivity.

2. Methodology

Literatures were reviewed across board including greenhouse/glasshouse and field experiment using biochar amended soils with the main target of finding the effect of biochar on plant growth and productivity. After general review, they were critically analyzed as to why certain type of biochar were used, why the choice of the biochar, the application method, the experimental approach among other factors were considered and critiqued on them. It was then followed by data generated from the various articles for meta-analysis. In all 27 articles were considered for a meta-analysis. Data on the authors of the articles, experimental procedures applied in their researches, the effect of biochar on plant growth, the pyrolysis temperature, the pyrolysis time, type of biochar, amount of biochar applied, the effect of biochar on soil PH, the effect on water holding capacity and greenhouse gas mitigating effects were derived from the reviewed articles. The data was collated on excel spreadsheet and copied to statistical package for social science (SPSS) version 16 and Stata (version 12) software and analysed using descriptive statistics such as, frequencies, means and standard deviation, tables, figures and graphs and logistic regression model was run from data to ascertain the factors influencing crop productivity using biochar.

2.1. Effects of biochar on plant growth and development: Some critical review

Biochar is a technology that normally provides conditions suitable for crop improvement by providing the necessary nutrients for growth, development as well as the yield. For instance (Zhang et al., 2012; Rajkovich et al., 2012; Asai et al., 2009; Schulz and Glaser, 2012; Khan et al., 2013; Alburquerque et al., 2013; Vaccari et al., 2011; Revell et al., 2012; Dong et al., 2013; Van Zwieten et al., 2010; Saarnio et al., 2013) found from their studies using different methods in biochar study such as greenhouse/glasshouse, field laboratory and microcosm on the effect of biochar on plant and recorded a significant positive change in plant growth and development. But the nature of the plant growth and development is subjected to many factors. In the case of (Rajkovich et al., 2012) different types of biochars were applied including corn stover, dairy manure paper sludge, and food. Food for instance included in the Rajkovich et al. (2012) study was not specifically stated as to whether it is corn, millet, sorghum (cereal) or root and tubers based food but only stated its source implying it cannot be pinpointed which food biochar is for a specific crop. Zhang et al. (2012) used wheat straw biochar in their two year consecutive field experiment on maize production by hand broadcast of biochar may lead to a non-uniform distribution and spread on the field due to human error and may affect production of the targeted crop. Why the choice of wheat straw for maize production? Because others such as corncob, or the corn stover and any other biomass could have been used and given the same or better results. These are some of the questions that raise eye brows in the use of biochar for crop production for example that done by (Zhang et al., 2012). Schulz and Glaser (2012) and Asai et al. (2009) also recorded an increase in the yield of oat crop by the use of babecue charcoal. Also it is interesting to know that most of the application of biochar do well in tandem with organic or inorganic fertilizer. For instance Schulz and Glaser (2012) recorded a significant growth and biomass increase in the oat crop when biochar was added to compost though compost without biochar also perform well. Meaning for this study compost would have been used without a major difference, so then why the use of biochar? Considering the cost involved in the pyrolysis. Different biomass could have been used to bring out different results in order to make meaningful comparism. Creating an artificial tropical environment as well as degraded/highly weathered soil especially for this case by washing the soils also raise question. How sure is the soil degraded by washing? Washing under what pressure and what for how long was this done for the attainability of the so called 'degraded' soil was not stated. Alburquerque et al. (2013) choice of wheat straw and olive tree pruning biochars for their study in the drum wheat seem too contrasting though it enhanced the growth and yield of wheat drum significantly after the addition of fertilizer. They should have added other wood-based biochar in order to make a meaningful judgment and conclusion about the wheat development using biochar.

The use of sewage sludge biochar from waste water treatment from Xianam from the study done by Khan et al. (2013) makes a big headway for the area because of its abundance. But the metal and metalloids that contaminate it makes its use as a tool for agricultural development endangered. What constitutes sludge in the USA may differ from that in countries in Africa, Asia Europe among others. Will it do well for other countries? What is the threshold of metalloids concentration that should be accepted and used as biochar. The authors should have given a brief description of the sewage sludge produced from Xianam Waste water emphasizing its main components.

Vaccari et al. (2011) use special rotary tillage for biochar made from coppiced wood (beech, hazel oak and burch) application and saw a significant growth and yield. But the mode of application of the char though not tiring compared to hand broadcast may increase cost of biochar use which may deter most peasant farmers especially from developing countries from its use if that is it to serve as baseline for enhancing agriculture through the use of biochar. Another issue is the addition of fertilizer to biochar most of the time as found in many researches such as (Van Zwieten et al., 2010) who use slow pyrolysis method to enhance growth and development of radish. Will the result be same for fast pyrolysis? Broiler chicken feed used by (Revell et al.,

2012) also has its own problem as far as the constitution of the litter is concerned. Most litter contains a lot more than the faecal matters that is known. This comprises of the saw dust (for example in the deep litter system), the remnants of feed, feathers aside the known normal faecal matters. Therefore broiler litter may differ from unit to unit of a typical poultry farm. There is therefore probability attached to the use of broiler litter as biochar for crop production. It may be different across board. Dong et al. (2013) significant improvement in the use bamboo and rice straw biochar calls for further investigation especially using bamboo, does not hold plant nutrients or it provides itself. Studies done have demonstrated that biochar can be produced from anything 'organic' such as paper sludge, bamboo, rice straw, poultry litter, sewage sludge, rice husk, cassia stem, palm leaves sawdust, spruce chips corn stover, wood chip, corn and corn stalk, wheat and other agriculture wastes have been used for crop growth and development. The identification of the type of biochar that can be used for specific purpose is imperative for proper identification and documentation.

Despite that biochar contributes to plant growth, some studies have shown that biochar application and incoperation to soils sometimes does and some does not enhance or delay crop improvement and production. Some research findings such as (Devereux et al., 2012; Unger and Killorn, 2011a; Unger and Killorn, 2011b; Major et al., 2010; Güereña et al., 2013; Xie et al., 2013; Lai et al., 2013; Karhu et al., 2011) on biochar show that its application had little or no effect on plant growth and development this is what Spokas et al. (2012) asserted that fifty percent of reviewed articles reported yield increases after black carbon or biochar additions, with the remainder of the studies reporting alarming decreases to no significant differences

2.2. Biochar as a heavy metal sequester and liming of acidic soils

Jiang and Xu (2013) observed a reduction in the concentration of Cu(II) and Pb(II) when soils were treated with biochar in their experiments. It was found that biochar could retain Cu(II) for some days, indicating the long-term immobilization which was complemented by Uchimiya et al. (2011) that broiler litter biochar led to a greater enhancement of copper sorption in Norfolk soil than in San Joaquin soil. Yang et al. (2010) and Lü et al. (2012) found high retention of pesticides and herbicides in the biochar-amended soils increasing its efficacy. Yuan et al. (2011) found biochar as nuetraliser for acidic soils especially if biomass is a leguminous species. Biochar has been used as a heavy metal sequester and other chemicals such as herbicides, weedicide and insecticides as shown by Yang et al. (2010), Lü et al. (2012), Jiang and Xu (2013) and Uchimiya et al. (2011). Heavy metals such as Cu (II) Pb (II) Cd(II) and high acidic soil are held on and reduced respectively by biochar. This depends on the type of biochar, for instance straw and poultry litter biochar show remarkable results in sequestering heavy metals which is not only interesting but a breakthrough since most acidic soils and heavy metallic compounds that contaminate soils lie fallow and cost a lot of financial resources to rejuvenate them to cultivable fields. Binding of herbicides and insecticides by biochar makes their efficacy high in protecting crops against weeds and insect prone which ultimately increase food production and security.

2.3. Biochar production and other properties

Production process of biochar is very important since the method used defines its attributes and how efficient it can deliver its purpose. Therefore some of the methods of production in terms of the temperature, the pyrolysis procedure, the biomass used, the type of pyrolysis equipment used among others contribute immensely in the functional properties of the product. Yu et al. (2011) used wood-based biochars and straw and found that straw biochar is more effective and desirable for improving soil fertility. Tsai et al. (2012) produce a series of biochars from dried swine manure waste by slow pyrolysis at temperatures between 400 to 800 °C and found that the mesoporous manure-derived biochar could be used as an excellent medium to soil environment. Schimmelpfennig and Glaser (2012) used traditional charcoal stack, rotary kiln, Pyreg reactor, wood gasifier, and hydrothermal carbonization) and analyzed the physical and chemical properties found a significant influence of production processes on biochar properties. Wu et al. (2012) found that pyrolysis temperature had a greater influence than residence time on the chemical composition and structure of rice straw-derived biochar produced at low heating rate. Herath et al. (2013) did a study to investigate to what extent the addition of corn stover (CS) and biochars produced from the pyrolysis of corn stover feedstock (CS) at 350 and 550 °C temperatures (CS-350, CS-550) and found that these biochars may facilitate drainage in the poorly drained soil. Ghani et al. (2013) produce biochar from waste rubber-wood-sawdust and concluded that higher temperatures (>650 °C), biochar samples were thermally stable and became hydrophobic due to the presence of aromatic compounds.

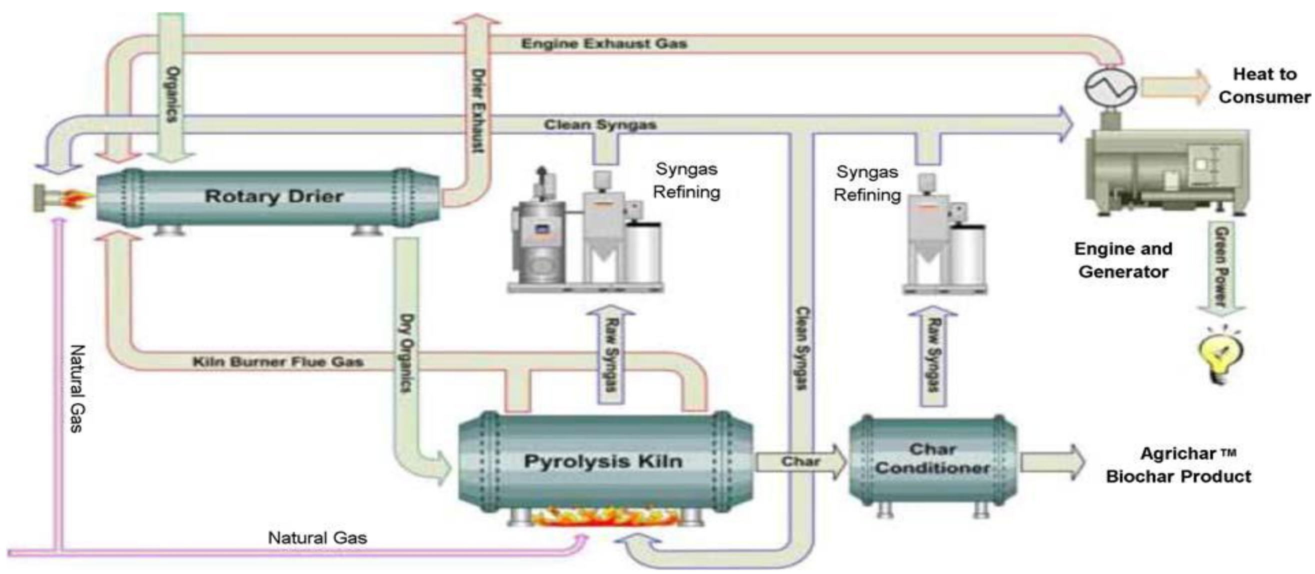

Figure 1. Schematic diagram showing slow pyrolysis process (Sohi et al., 2009; and www.bestenergies.com)

2.4. Anti-leaching and other properties of biochar

Biochar can be labelled as a universal sequester since it can bind itself to almost every substance especially in an aqueous solution and by so doing delaying the movements of such substances from the top soils making its efficacy rate comparatively higher. This is shown in researches conducted by (Borchard et al., 2012; Major et al., 2012; Kameyama et al., 2012; Major et al., 2012; Jien and Wang, 2013; Abel et al., 2013; Morales et al., 2013) and found that leaching of soil nutrients and soil loss significantly reduced and that biochar increases the resident time of some soil nutrients to make it more available for plant use. Castaldi et al. (2011) found char treatments showed a minimal impact on microbial parameters and GHG fluxes. Kolton et al. (2011) found biochar-augmented genera may be at least partially responsible for the beneficial effect of biochar amendment on plant growth and viability. Unger and Killorn (2011a; 2011b) found that conditions during pyrolysis influenced how the biochar/fertilizer reacted with the soil. Omil et al. (2013) ascertain that soil response to the application of mixed wood ash is greatly influenced by the soil properties, nutrient and soil organic matter dynamics are directly affected by interactions between the ash and soil components and indirectly by soil biological activity and plant growth.

2.5. Some economic benefits of biochar application in crop production

As illustrated above, soil amended biochar improves crop production by increasing growth rate as well as yield. Evidently, for example, Galinato et al. (2011) found that it may be profitable to apply biochar as a soil amendment under some conditions if the biochar market price is low enough and that carbon offset market exists. Yoder et al. (2011) estimated a quadratic production functions for biochar and bio-oil. The results are used to calculate a product transformation curve that characterizes the yields of bio-oil and biochar that can be produced for a given amount of feedstock, movement along the curve corresponds to changes in temperatures, and it can be used to infer optimal pyrolysis temperature settings for a given ratio of biochar and bio-oil prices. Ninson (2015) in his thesis (unpublished) found that biochar adoption was more profitable in the Kwahu East District of Ghana in the two seasons. Duku et al. (2011) did an assessment of biomass resources and concluded that a large availability of biomass in Ghana gives a great potential for biofuels production from these biomass resources.

3. Meta-analysis of biochar application for crop improvement

This section of review was done by generating data from various researches done with the focus of increasing crop productivity. In doing so diverse researches were considered from simple laboratory to greenhouse experiments to large area of land for field work were used for the analysis

3.1. Experimental procedures

To get a deeper understanding of biochar application and crop productivity, 27 articles were selected for a meta-analysis in order to ascertain whether biochar and its associated attributes indeed improve crop production. In all, 12(44.4%) of the articles reviewed did their research in the field, 7(25.7%) did it in the greenhouse or glasshouse another 7(25.7%) in the laboratory with 1(3.7%) done in the microcosm. The authors though aimed at getting the positive effect that biochar has on crop production the articles were selected at random but focusing on the productivity of biochar amended soils. Therefore getting more than

40% of the experiment done at the field level is worth noting. This may be due to the authors' choice of doing a clearer and also having enough space for flexibility of experiment unlike other experiments. Laboratory was the second choice of the experiment probably for the avoidance of interferences associated with especially field experiment. It also known that laboratory experiments are mostly done as an eye opener for further work for instance for choice of necessary materials for field and other experiments.

3.2. Pyrolysis temperature

Temperature that biomass is pyrolysed contributes immensely to the type of biochar produced. As to whether it is used as nutrient supplement for plant growth or carbon dioxide/greenhouse gases chelating agent or heavy metals and compounds sequestration such as weedicides and herbicide-based compounds are some of the issues considered before the charring process begins. For this review the focus was on that temperature that would produce biochar conducive for plant growth. It was observed from data gathered from literature that temperature of 550^{0}C was mostly used for producing biochar as nutrient supplement. This recorded 10(38.8%) of the articles reviewed, followed by 500^{0}C which recorded 4(15.45%). The highest temperature observed from the 27 articles reviewed is 850^{0}C and the lowest is 200^{0}C. The mean temperature was 530 with standard deviation of 106.8^{0}C. The temperatures were categorized into three different types according to the above literature (Figure 2).

3.3. Pyrolysis time

Apart from the temperature that contributes significantly in the production of biochar, the rate of pyrolysis is also very important since taking too much time in the process destroys a lot of the functional properties that exhibit as nutrients for plant growth. It is known that charring for too long a time produces more carbon and destroys nutrients from the biomass which may not be economically beneficial for crop production. Therefore charring and charring temperature work in tandem with each other. For this review, 2(7.4%) of the work done charred the biomass at faster rate while 6(22.2%) charred it at slow rate, the others did not specify the rate of pyrolysis. The fact that more than 20% of the article considered use biochar charred at slow rate for crop improvement is worth mentioning and may be considered as one of the ways through which biochar can be used as source of fertilizer

3.4. Types of biochar used

Biomass used for biochar ranges from plants and animal sources but dominated by plant residues. For the reviewed paper some of the plant source biochar used include, wood charcoal, birch charcoal, oak wood, pine wood, commercial charcoal, bamboo, teak, rosewood, barbeque charcoal, wood biochar, beech, hazel, birch eucalyptus, wheat straw, corn stover, hazelnut shells, rice straw, rice straw, mixed sawdust, wheat straw, olive tree pruning, maize stover, cotton straw chips. Animal based biochar are, poultry with sawdust bedding, digested dairy manure, poultry litter, broiler litter, sewage sludge. Others are paper mill wastes and food wastes.

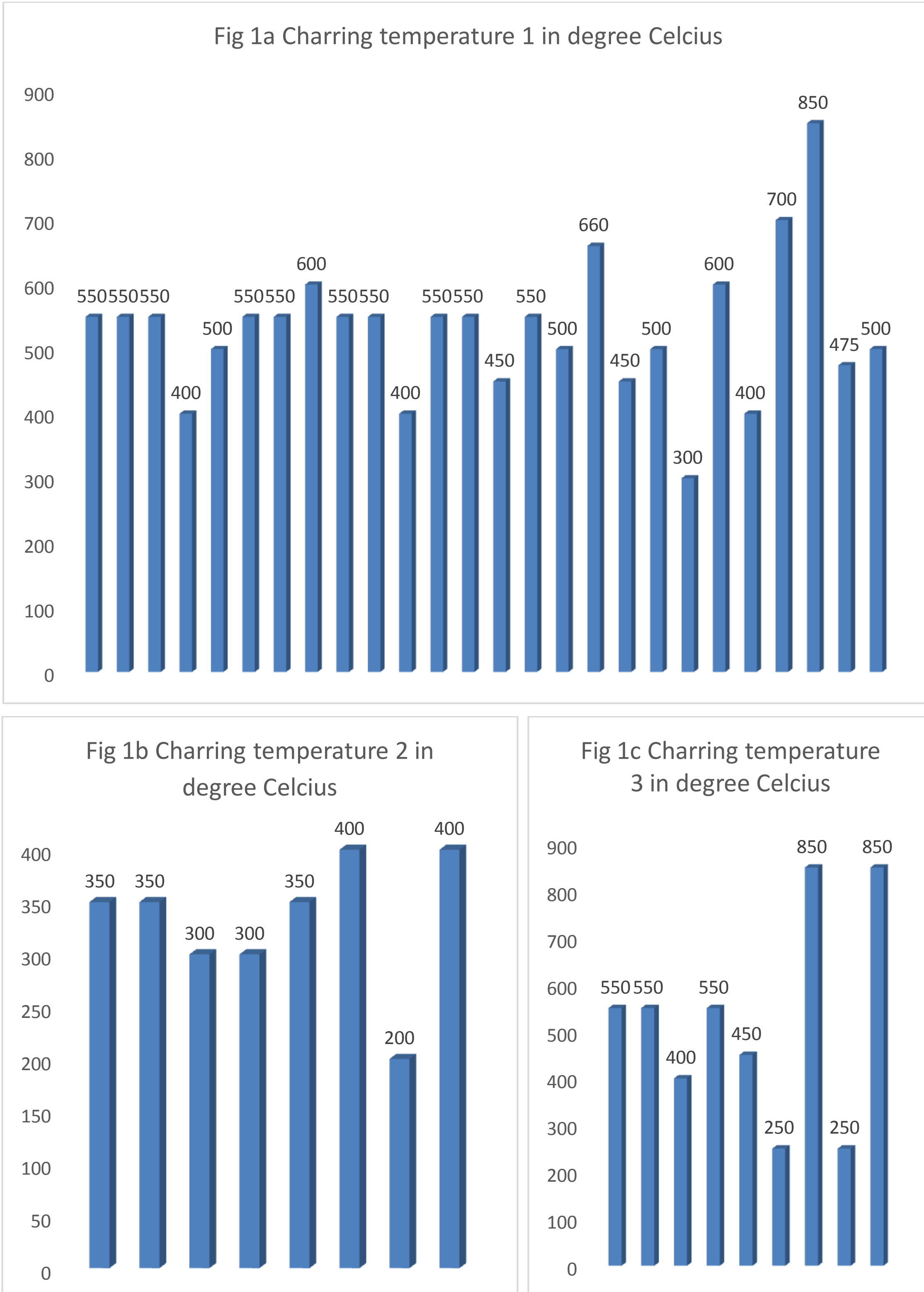

Figure 2. The charring temperatures categorized into three different types

Most of the biochar used in the various researches from plant sources are wood and straw based. This presupposes that detailed work has to be done in these areas especially with regards to location specific so that resources committed for plant growth and development supplements would be at it optimum level so that it would be more profitable in both food crop and cash crop production

3.5. Amount of biochar used

Biochar amount applied in the various study done ranges from 0t/ha to as high as 90t/ha rate. From the article reviewed 6(22.2%) used 0t/ha as negative control while 5 (18.5%) used 10t/ha application rate, 3 (11.1%) used 15t/ha application rate. Since not only the biochar but the application rate contributes to the upkeep of plant and it development it is worth investigating into which biochar is optimum for growth and development for a given type of crop. Most literature cited between 10t/ha and 80t/ha as appropriate quantity for growth. The lowest amount of biochar used from the articles is 1t/ha and the highest is 91t/ha. The mean amount of biochar used is 16t/ha with standard deviation of 29.2t/ha (Figure 3).

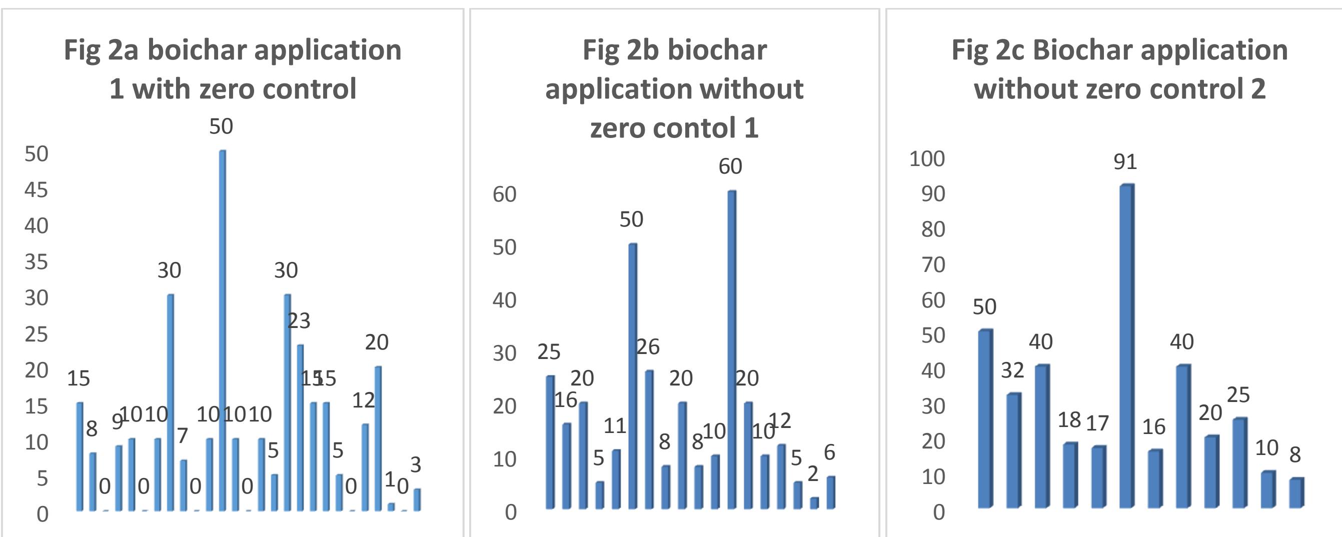

Figure 3. Various biochar application rate used

3.6. PH of soil after application

The neutralizing property of biochar was also considered by the reviewers of the various articles. This is so because of the indirect effect of PH of soils on crop production and hence profitability. Acidic soils mostly do not support plant growth, but soils of approximately neutral PH is highly likely to support the growth and development of crop. The articles reviewed reveals that 3(11.1%) of biochar application led to a reduction in the acidity of the soil and the other 24(88.9%) did not specify anything about the PH of the soil after the application of biochar. It is known by literature that leguminous plants converted to biochar have high alkaline property which aid in neutralizing soils that are acidic (Yuan et al., 2011).

3.7. Growth of plant

The main aim of the authors of this reviewed article is to ascertain whether plant growth and development are supported by soils amended with biochar. Out of the 27 main articles considered for this meta-analysis, 16(59.3%) reveal that biochar helped improve plant growth while 11(40.7%) recorded no improvement in the growth of plant which complements the work done by (Spokas et al. 2012) that 50% of the reviewed article reported yield increases after biochar additions, with the remainder of the studies reporting decreases to no significant differences in yield. In some cases biochar support is found late after its application. For this articles it was found that some biochar show no significant effects on the growth of plant especially in the first year of application but later showed a positive response to plant development. This presupposes that biochar should be labelled as a generational technology that reveals itself as a 'helper and a saviour' in crop industry in the future. That is to say biochar is a futuristic technology. It is therefore imperative that it is studied for a long time so as to reveal its true nature and contributions to soil fertility. Study should be done for a specific biochar and a specific crop and then trickled down to others.

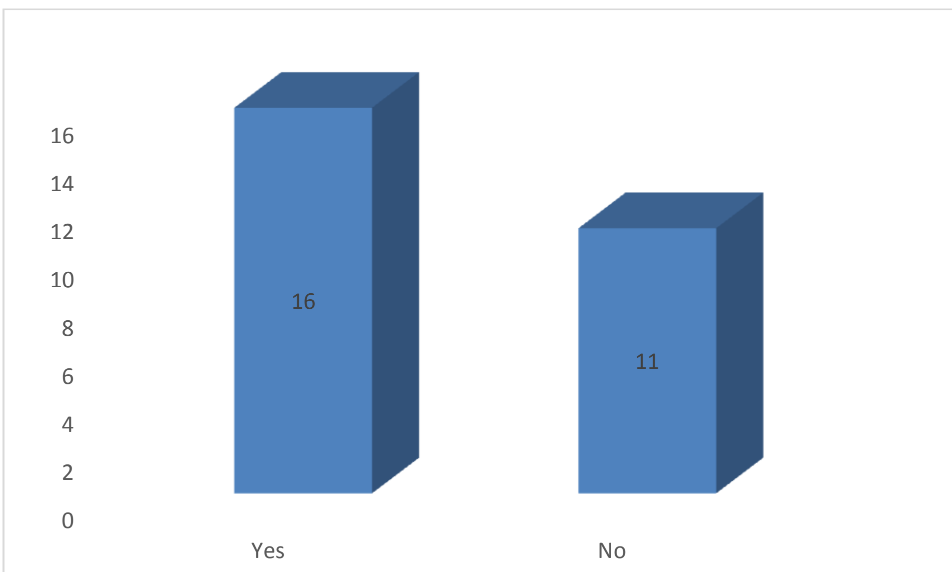

Figure 4. Biochar and plant growth

3.8. Water holding capacity

Water is a key ingredient in plant development as it is used for photosynthesis ($_nCO_2$ $+_{2n}H_2O$+photons → $(CH_2O)_n$$+_nO_2$ $+_n$ H_2O). Therefore with the property of holding water and then making it accessible for plant use indirectly contributes to plant growth. The extent to which it holds water depends on a lot of factors notable among them are the biochar type, the charring temperatures among others. Studies have shown that biochar helps in plant development in highly weathered soils by holding on to water for plant use apart from contributing to the soil the integrity

3.9. Greenhouse gas mitigating effect

The use of specific biochar reduces the atmospheric greenhouse gases which cause global warming with its associated drought due to high temperatures and flooding as result of release of water vapour that has condensed beyond certain threshold in the atmosphere. Biochar contributes to reducing global warming by sequestering atmospheric carbon dioxide, methane and nitrous oxide. The article reviewed show that 6 (22.2%) reported biochar as global warming mitigating agent. This also indirectly leads to enhanced food crop production since crop which has gone through the stages of development and grown to maturity would be destroyed by floods and excessive drought.

3.10. Factors affecting the growth of plants

To ascertain the factors affecting the growth of crop as far as biochar is concerned a logistic regression model with growth of plant as dependent variable (support growth=1, Otherwise=0) and temperature of pyrolysis (natural log), type of experiment, amount of biochar and the product of the amount of biochar and temperature of pyrolysis used (interactive term) as independent variables were run with Stata version 12 software. The outcome of the results shows that the natural logarithm of temperature at which biomass was charred significantly affect the growth of plant (marginal effect =7.69) (See appendix 1). This means that pyrolysis temperature is very important when it comes to biochar use for plant growth. Also temperature and the rate of pyrolysis work in tandem with each other (See appendices 1 and 2 for detailed results).

Table 1. Logistic Regression Results

Variables	Coefficients	Z
biat	0.8228	0.87
ltp	7.699	1.70
tyep	1.997	1.48
ltb	-2.3076	-1.08
Constant	-29.149	-1.48

biat= biochar amount, Ltp= Natural log of temperature of pyrolysis, tyep = Type of experiment, ltb= Natural, log of temperature of pyrolysis and amount of biochar used cons= constant term and the dependent term gwtd is growth of plant (1= yes and 0 otherwise)

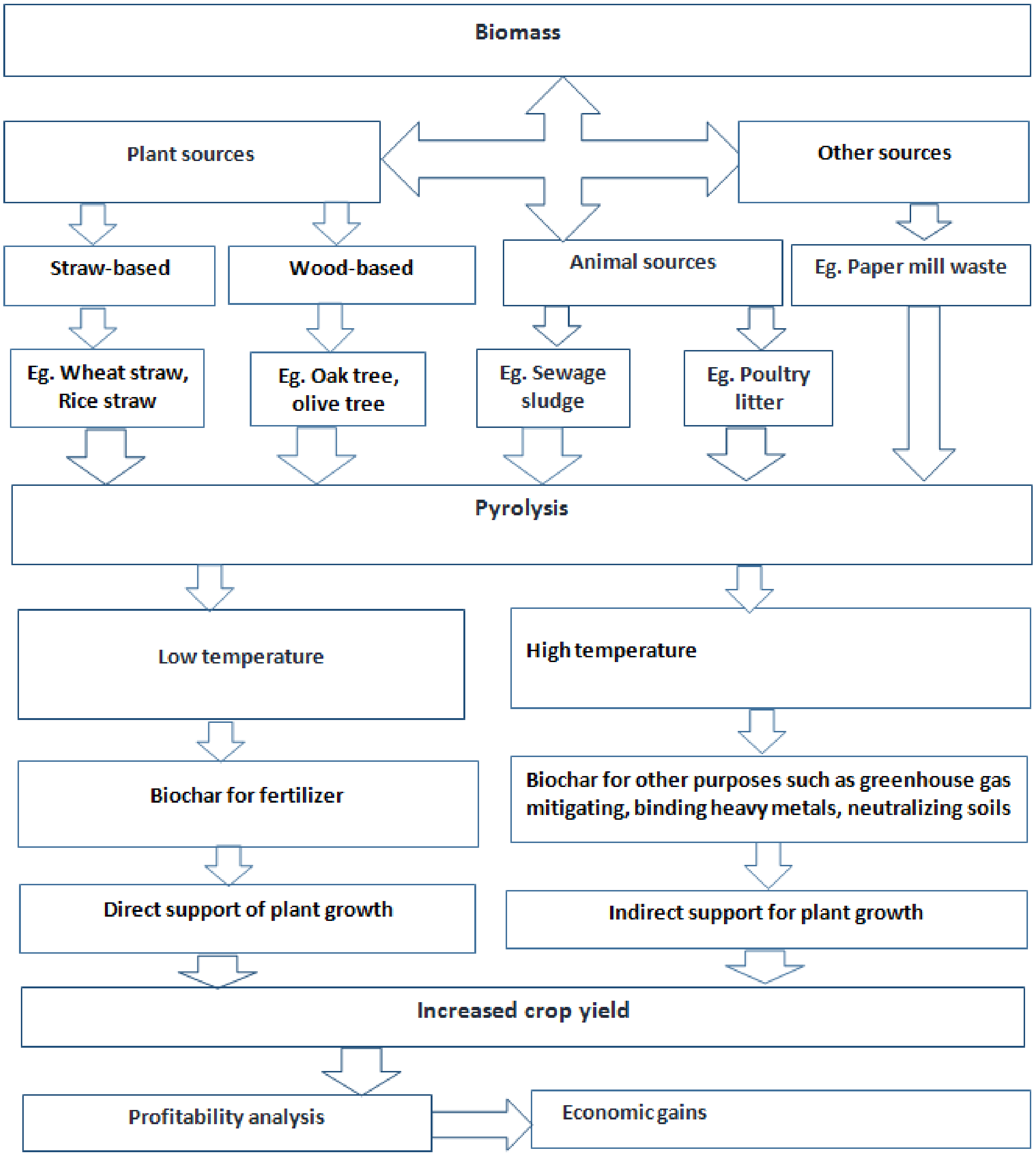

Figure 5. A flow diagram showing biochar sources and contribution for crop production

4. Summary and conclusions

Critical review of the literature shows that biochar has a positive effect on some growth parameters but pronounced when mineral fertilizer is added. In addition, there was a significant biochar and mineral fertilization interaction since the highest production level was obtained when biochar was combined with mineral fertilization, demonstrating the beneficial effect of biochar on yield. Biochar had much influence on soil properties, which can explain its effects on plant growth and increase crop production. A meta-analysis using a good number of articles and running regression shows that temperature of pyrolysis is a major contributing factor for plant productivity Summing it up, biochar addition enhances crop yield with the environmental benefits of global warming mitigation, contributing to a more sustainable agriculture. The knowledge gathered from this study is a key tool to implement pyrolysis as a management option for waste materials for both agricultural and environmental benefits.

In conclusion, application of biochar materials promise as an ecologically sound technology for improvement of soil properties and crop productivity. Its strong resistance to microbial decomposition and hence continued persistence in the soil ensures its long term application. However, sometimes there is delay in gains in crop productivity. Also the significant alternative uses of biochar as an energy source constitutes a major economic constraint to the practical application of this technology.

5. Recommendations

From the results above it is recommended that apart from the biomass which is to be taken seriously for a particular purpose for instant if it for solving highly acidic as well as weathered soil and also for nutrient for plant growth, the temperature at which the pyrolysis is done must be the first point of consideration so as not to defeat the purpose for which it is intended for. Also biochar is specific for a specific soils and geographical location, therefore it recommended that detailed studies are done with special reference to geographical location taking also into consideration the type of crop to be grown.

From literature, it is shown that some of the application and incorporation for soils with the intention of yielding crop spontaneously does not necessary hold but delayed and therefore one may be disappointed especially farmers who have invested and are ready to harvest would be found wanting and may label the technology as ‘impotent’ and will never be willing to use it any further. Therefore in-depth study should be done emphasizing on the type of biochar that should yield quick results for the farmers who are mostly rural and peasant are in need of financial gains. Also farmers should be educated on the use of what we call ‘generational’ nature of biochar so that if they don’t benefit from its use from the word go, their progenitors may benefit in the rest of the years ahead

Detailed study should be done with special attention on biochar responses quickly to the need of farmers as fertilizer so that they can be used as an alternative nutrients/fertilizer for plant growth. Trials to develop more productive management techniques that include biochar application to soils by finding cheaper sources of biochar and combining it with other organic materials need to be undertaken. Additionally, long-term evaluation of the influences on soil and plant growth would be necessary.

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Appendix A. Logistic Regression results

```
Logistic regression                                Number of obs   =         20
                                                   LR chi2(4)      =       8.33
                                                   Prob > chi2     =     0.0803
Log likelihood = -8.7854072                        Pseudo R2       =     0.3215
```

gwtd	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
biat	.0822768	.0942447	0.87	0.383	-.1024394	.266993
ltp	7.689745	4.517434	1.70	0.089	-1.164264	16.54375
tyep	1.997046	1.351034	1.48	0.139	-.6509309	4.645024
ltb	-2.307632	2.14454	-1.08	0.282	-6.510853	1.895588
_cons	-29.1492	19.71398	-1.48	0.139	-67.78789	9.489481

```
Marginal effects after logit
      y  = Pr(gwtd) (predict)
         =  .76895424
```

variable	dy/dx	Std. Err.	z	P>|z|	[95%	C.I.]	X
biat	.0146176	.01239	1.18	0.238	-.009658	.038894	20.1
ltp	1.366188	.70368	1.94	0.052	-.013004	2.74538	6.24001
ltb	-.4099823	.279	-1.47	0.142	-.95681	.136845	8.66046
tyep*	.300907	.20326	1.48	0.139	-.09747	.699284	.35

(*) dy/dx is for discrete change of dummy variable from 0 to 1

tyep = Type of experiment, ltp= Natural log of temperature of pyrolysis, biat= biochar amount, ltb= Natural log of temperature of pyrolysis and amount of biochar used cons= constant term, and the dependent term gwtd is growth of plant (1= yes and 0 otherwise)

Appendix B. Data generated for analysis

Authors	Type of experiment	Pyrolysis temp in degree celcius	temp	temp 1	temp2	temp3	pyrolysis time in hours	Type of biochar	Amount 1	Amount 2	Amount 3	Ph	Growth	WHC	GHG
Devereaurex etal (2012)	Glasshouse	550	550				Not specified	wood charcoal	15Mg/Ha	25Mg/Ha	50Mg/Ha	Not specified	1	1	Not specified
Petter etal (2012)*	Field experiment	550	550				Not specified	Eucalyptus	8Mg/Ha	16Mg/Ha	32Mg/Ha	Not specified	1	Not specified	Not specified
Zhang etal (2012)	Field experiment	350-550	550	350	550		Not specified	wheat straw	0 t/Ha	20t/Ha	40t/Ha	Not specified	1	1	1
Karhua etal (2011)	Field experiment	400	400				Not specified	birch charcoal	9t/Ha			Not specified	1	1	1
Ventura (2012)*	Field experiment	550	500				Not specified	Agric waste	10t/ha	20t/Ha		Not specified	0	0	Not specified
Unger & Killorn (2011)	Field experiment	550	550				Not specified	Corn stover	0Mg/Ha	4.5Mg/Ha	18Mg/Ha	Not specified	1	Not specified	1
Herath etal (2013)	Lab experiment	350 and 550	550	350	550		Not specified	corn stover	10.0 t/Ha	11.3 t/Ha	17.3 t/Ha	Not specified	1	1	Not specified
Jiang &Xu (2013)	Lab experiment	300, 400, 500		300			Not specified	straw	30g/Kg	50g/kg		increased		Not specified	Not specified
Rajkovich etal (2012)	Greenhouse	300°C, 400°C, 500°C, or 600°C	600	300	400	500	Not specified	corn stover, hazelnut shells,oak wood, pine wood, digested dairy manure, food waste, paper mill waste (sludge), or poultry withsawdust bedding	2.6 t/Ha	6.5	26, and 91 t/Ha	Not specified	1	1	Not specified
Asai (2009)*	Field experiment	550	550					teak and rosewood	0, t/ha	8t/ha	16t/ha	Not specified	0		Not specified
Van Zwieten etal (2010)	glasshouse	550	550				slow	paper mill wastes	10t/ha			Not specified	0	Not specified	Not specified
Schulz1 and Glaser (2012)	Greenhouse	400	400				Not specified	Barbeque charcoal	50Mg/Ha			Not specified	0	Not specified	Not specified
Zhang etal (2012)	Field experiment	350-550	550	350	550		Not specified	rice straw	0t/ha	10t/ha	20t/ha 40t/Ha	increased	1	Not specified	Not specified
Major etal (2010)*	Field experiment	550	550				Not specified	Not specified	0t/ha	8t/ha	20t/ha	increased	1	Not specified	Not specified
Saarnio (2013)	Lab experiment	400 and 450	450	400	450		Not specified	Wood biochar	10 Mg /ha			Not specified	0	Not specified	Not specified
Khan etal (2013)	Greenhouse	550	550				Not specified	sewage sludge	50Mg/Ha	10Mg/Ha		Not specified	1	Not specified	reduced
Vaccaria etal (2011)	Field experiment	500	500				Not specified	Commercial charcoal	30-60t/ha			Not specified	1	Not specified	Not specified
Da Dong etal (2013)	Field experiment	600	660				slow	bamboo and rice straw	22.5t/ha			Not specified	1	Not specified	Not specified
Revell etal (2012)	Glasshouse	450	450				fast	Polutry litter	150Mg/ha			Not specified	1	increased	Not specified
Spokas etal (2012)	Lab experiment	500	500				fast	mixed sawdust	150Mg/ha	200Mg/Ha		Not specified	1	Not specified	reduced
Albuquerque etal (2013)	Lab experiment	300	300				1.5	Wheat straw and olive tree pruning	5Mg/ha	10Mg/ha	25Mg/ha	Not specified	0	Not specified	Not specified
Güereña etal (2013)	Field experiment	600	600				slow	Maize stover	0t/ha	12t/ha		Not specified	0	Not specified	Not specified
Xie etal (2013)	microcosm	200, 250, 300, 400	400	200	250	300	slow at 1.5 hr for 10hrs	Wheat straw	12Mg/ha			Not specified	0	Not specified	Not specified
Uchimiya (2011)	Lab experiment	700	700				Not specified	broiler litter	200Mg/ha			Not specified	0	Not specified	Not specified
Yang etal (2010)	Lab experiment	450 and 850	850	450	850		1 and 2	cotton (Gossypium spp.) straw chips	1Mg/ha	5Mg/ha	10Mg/ha	Not specified	1	Not specified	Not specified
Borchard (2012)	pot experiment	475	475				Not specified	beech and oak wood	0t/ha	2t/ha	7.5t/ha	Not specified	0	0	Not specified
Castaldi (2011)	Field experiment	500	500				Not specified	beech, hazel, oak and birch	3kg/m2	6kg/m2		Not specified	1	Not specified	reduced

Appendix C. The benefit of biochar to the soil and the atmosphere and plant