Biochar - a Soil Conditioner to Protect the Climate

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The analysis, results, and recommendations presented in this paper represent the opinions of the author(s) and are not necessarily representative of the position taken by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

This paper accepts comments and will be updated regularly in order to take relevant comments and new scientific publications into account.

Key points:

- **Biochar application to soils is listed as a net negative emission technology on account of the fact that biochar stores carbon in soils for extended time periods, thereby improving soil properties. Negative emission is achieved once biomass is produced sustainably and the pyrolysis process used in producing biochar proves to be efficient.**
- **Biochar application results in crop yield increases in a wide variety of soils: nutrient-poor, acidic, sandy soils in the tropics and sub-tropics, particularly in semi-arid or arid climates.**
- **Biochar is primarily a soil conditioner that enables soils to better store and deliver nutrients and water to plants.**
- **The use of small amounts of biochar has already demonstrably yielded crop increases for small farm holders.**
- **The use of small amounts of biochar chiefly improves nutrient availability and soil pH, improving water retention needs larger amounts of biochar.**
- **The use of biochar on its own results in crop yield increases, but when combined with fertilizer – inorganic or organic – biochar unlocks the soil's full potential, thereby boosting crop yields.**
- **If farmers have nutrient-poor residues (such as wood or straw) available, even in small amounts, it is recommended to convert these residues into biochar and apply it to the soil. Such a course of action would represent a worthwhile investment in their land.**
- **Farmers can benefit from the pyrolysis process to create biochar by making use of thermal energy for cooking.**
- **Allocating land to produce feedstock for biochar production on a large-scale is not recommended.**
- **Biochar offers opportunities to recycle plant nutrients back into agriculture by processing waste materials as feedstock.**

1 Introduction

Worldwide, food demand is expected to rise over the coming decades due to an increasing global population and dietary changes over the course of economic growth in developing and emerging economies. Expanding food production is specifically a top priority in many developing countries given that undernourishment persists as a dominant problem. Furthermore, expanding food production is critical to generate higher incomes for rural populations in developing countries (Otsuka and Fan 2021).

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Worldwide, agriculture (including land used for pasture) covers 38% of the planet's land surface. Any future expansion of global agricultural land will be further limited due to competition with other land uses, such as forests and their associated purposes, as for example lands set aside for climate and biodiversity protection. As a response to this critical situation, sustainable intensification has been advocated in order to achieve the yield potential on those lands that currently produce yields below their full potential (Otsuka and Fan 2021).

Climate change is expected to impact agriculture on multiple fronts: through increased heat stress; a growing number of drought events, and a greater frequency in heavy rainfalls. While certain agricultural practices have contributed substantially to climate change, the agricultural sector also has the potential to help mitigate its detrimental impact. Agriculture, forestry, and other land uses contribute to approx. 23% of anthropogenic greenhouse gas emissions (Intergovernmental Panel on Climate Change (IPCC) 2019). The expansion of croplands and burgeoning deforestation have been major contributors to CO_2 emissions, considering that soil organic matter content generally decreases when forests are degraded or disappear. Soils under cropland generally have a lower soil organic carbon content than those soils under forest lands. Agriculture is the largest emitter of nitrous oxide (N_2O) and methane (CH_4), accounting for half of global nitrous oxide and 44% of global methane emissions. N_2O is mainly emitted as a result of the denitrification of fertilizer nitrogen, (both organic and inorganic), while CH_4 is primarily emitted by ruminants (chiefly cattle) and from rice paddies (IPCC 2019).

Carbon sequestration through good soil management is seen as one potential option to remove CO_2 from the atmosphere in order to help achieve the 1.5°C goal and to balance out future unavoidable greenhouse gas emissions (Amelung et al. 2020). Applying biochar to soils has been recognized both as one of those soil management practices that can sequester carbon (Amelung et al. 2020) and also as a net negative emission technology or carbon dioxide removal method (MCC 2016, Smith 2016, IPCC 2019, 2021, 2022, Njenga et al. 2021, Otsuka and Fan 2021), given that biochar stores carbon in soils for extended periods (cf. sources in Section 6), while also improving soil properties in a number of soil types (cf. sources in Section 3), particularly in nutrient-poor, acidic, and sandy soils in the tropics and sub-tropics. Biochar's beneficial impact on soils has been well-known for some time (Lefroy 1883).

Worldwide, the technical mitigation potential through biochar application is estimated at 2.6 (0.2-6.6) Gt CO_{2eq}/year (IPCC 2022), out of which 1.1 (0.3-1.8) Gt CO_{2eq}/year can be realized at costs of up to 100 USD/t CO_{2eq}, which is more than Germany's annual greenhouse gas emissions of 0.8 Gt CO_{2eq}/year (Umweltbundesamt 2021). Extensive land areas are needed in order to unlock a global mitigation potential of 6.6 Gt CO_{2eq}/year; this could represent up to 20% of the planet's entire croplands (IPCC 2019).

Finally, applying biochar to soils is a non-reversable process. Any decision regarding biochar's use thus needs careful consideration, in order to avoid any harmful ramifications with potentially detrimental long-term impact on soils, crops, and livelihoods.

Against this backdrop and counter arguments, this paper will compile knowledge on biochar application on soils, including its production, in order to deliver recommendations for those actors working in the field of development cooperation. This paper will also present conclusions about where and how to support biochar application, where to refrain from it, as well as identify those research questions that still need to be addressed.

The knowledge and expertise brought together and compiled for this synthesis paper devoted to biochar was primarily taken from internationally published and peer-reviewed meta-analyses and reviews. Literature from a limited number of field and case studies, also internationally published and peer-reviewed, has also been included in order to underpin other aspects not well covered by meta-analyses, such as the long-term ramifications of biochar usage and specific case studies.

Reviews and meta-analyses have presented findings from a great number of single experimental studies. The reviews compile those results in a more descriptive way, while the meta-analyses tend to calculate averages and subject single data to statistical analyses. Yet, there's still a notable lack of experimental studies that have observed how biochar impacts soils and crops for more than three successive years. The vast majority of studies cover less than one year following the initial application of biochar, as discussed by Gao et al (2020). Furthermore, there are somewhat significant differences between lab, pot, and field studies with regard to how applying biochar impacts soils and crops (Jeffery et al. 2011, He et al. 2016, Gao et al. 2020).

To date, the only long-term field trials to be found in internationally published and peer-reviewed papers are Güerena et al. (2016), which covered a period spanning seven years, and Kätterer et al. (2019), which reported on its application over sixteen years. Findings from the meta-analyses might thus stress short-term impact over long-term effects.

2 What is biochar?

Biochar and charcoal are both constituted from charred organic matter, which means the matter in question has been subjected to pyrolysis. Their intended uses differ, however: Biochar is charred for the purpose of applying it to soils in order to improve soil properties, whereas charcoal is produced in order to use it as an energy source. Technically, charcoal could be used as a soil supplement with similar outcomes as would be derived from using substances labelled biochar (Verheijen et al. 2009). Given that biochar is used on soils primarily to improve agricultural practices, it has to meet certain quality standards, which are stipulated in, for example, the European Biochar Certificate (EBC 2020).

The pyrolysis process is the thermal decomposition of organic matter in the absence of oxygen, or in an oxygen-poor environment (Verheijen et al. 2009). Pyrolysis can be executed in a wide range of settings; from small stoves in single households (Njenga et al. 2016) all the way to large communal or industrial devices. Over the course of biochar production, pyrolysis yields energy that can be combined with activities such as cooking on small stoves in households, or generating electricity by larger devices.

Combining certain feedstocks (plant-based organic matter), pyrolysis temperature, pyrolysis duration, and possibly physical and chemical activation will enable the production of a broad spectrum of biochar types, as well as oil and gas as by-products, as reviewed by Cha et al. (2016) and by Kwon et al. (2020), ranging from absorbents of environmental pollutants and soil amendments to catalysts. This paper will primarily focus on biochar as a viable soil amendment for agricultural purposes and for climate protection in the context of development cooperation.

The first condition for biochar production and its application to soils is that biomass must be available as feedstock. Biochar production might thus potentially compete with other uses of a given amount of biomass. In agricultural settings, the most common feedstocks are wood, crop residues, and animal manure. In order to avoid that the sourcing for biochar feedstocks might encourage unsustainable biomass removal, the European Biochar Certificate guidelines stipulate that forest wood and primary agricultural products come from sustainable production (such as FSC certified forestry) and preserve soil carbon (EBC 2020).

In many developing countries, the biochar production technologies are similar to those used in producing charcoal. Unsustainable biomass production and inefficient pyrolysis processes have been contributing to climate change.

Table 1: *Yield increases [% relative to control] and 95% confidence interval revealed by meta-studies. The yield increases are grand means, i.e., all the data from a given meta-analysis across crop, soil type, climate, biochar properties, and soil management pooled together.*

Yield increase [%]	95% confidence interval [%]	Number of single data points and/or studies included	Source
10	7 – 13	782 data points	Jeffery et al. 2011
18	6 – 30	30 studies	Biedermann and Harpole 2013
13	10 – 16	1125 data points from 109 studies	Jeffery et al. 2017
28.7	19 – 40.5	150 data points from 23 studies	Ye et al. 2019
16	14 – 18	1254 data points from 153 studies	Dai et al. 2020
21	16 – 26	93 data points	Zhang et al. 2020

3
Biochar's impact on soils and crops

Multiple meta-analyses have shown that plant productivity, water use efficiency, soil organic carbon, and nutrient availability have increased significantly after biochar application as shown in Figure 1. This figure is a summary of meta-analyses on different impacts of biochar on crops and soils (Schmidt et al. 2021).

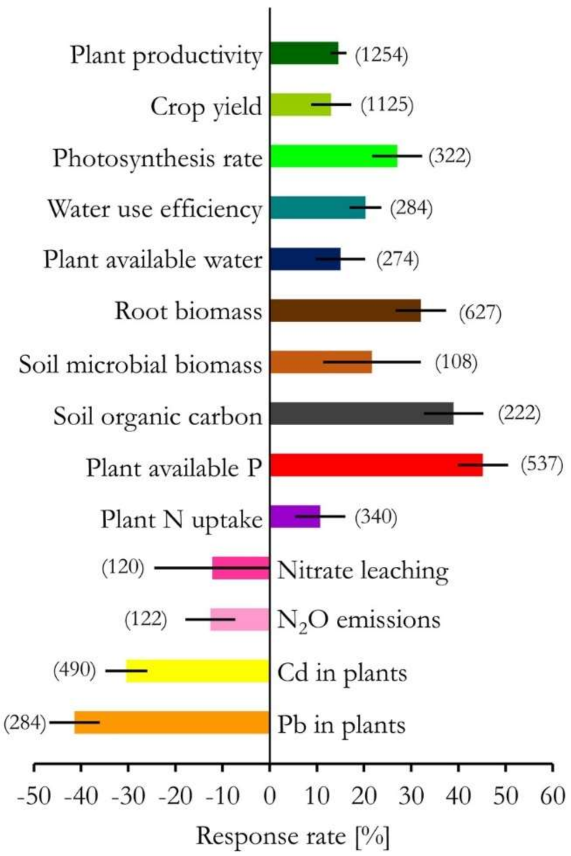

Figure 1: *Impact of biochar application on plant productivity and soil parameters as collated from global meta-analyses after Schmidt et al. (2021). Colored bars indicate the level of impact in % relative to respective control trials. Error bars (in black) indicate the 95% confidence interval.*

Crop yields have increased significantly worldwide after biochar application to soils across a comprehensive range of crops, vegetables, soil types, climates, biochar properties, and soil management (Table 1). The IPCC (2019) estimated an average increase in crop yield of 25% in tropical regions, consistent with the range indicated in the meta-analyses listed below in Table 1. IPCC (2019) stated that biochar application improved a number of soil properties and helped to augment crop yields particularly on highly weathered soils and attributed medium confidence to those finding listed in the IPCC report.

In tropical regions, crop yield increases are far more pronounced than in temperate climates, as shown by the meta-analyses undertaken by Jeffery et al. (2017) and Ye et al. (2019), which list crop yield increases pooled across tropical regions of 25% and 40%, respectively. For temperate climates, Jeffery et al. (2017) noted a slight reduction in crop yields, while Ye et al. (2019) found an increase of 20%. This is underlined by Biedermann and Harpole (2013), who showed that above-ground biomass production increases in the tropics (relative to control plots), but reduces and turns partly negative when moving to temperate climates. These findings are in line with those articulated by the IPCC (2019). In a field study undertaken in Germany, Haider et al. (2017) did not find any evidence of a crop yield increase after biochar application.

Differentiated by soil properties, biochar application shows its greatest impact on crop yield increases in coarse textured, highly-weathered, nutrient-poor, and acid soils, as illustrated in Figure 2 (Jeffery et al. 2011, Jeffery et al. 2017, Ye et al. 2019). Biochar application results in the doubling of crop yields on sandy textured soils, whereas there is a crop increase of merely 20-40% on fine-textured (loam to clay) soils (Ye et al. 2019). With regard to soil acidity, biochar's impact on crop yield increases the lower the soil pH (Jeffery et al. 2017, Ye et al. 2019, Bai et al. 2022). As outlined above, crop yield increases were found across a wide range of biochar application dosages, including the more realistic lower dosages of 1 t/ha to 10 t/ha, as illustrated by a meta-analysis undertaken by Jeffrey et al. (2011), whereby application rates of 100 t/ha averaged in a crop yield increase of approximately 40%, while 135 t/ha averaged in an increase of approximately 25%, and an application rate of 10 t/ha resulted in an average of approximately 10% increase. The data compiled by Ye et al. (2019) showed a decreasing crop yield response, with biochar application rates increasing from <5 t/ha to 20 t/ha (Figure 2). Applying biochar by itself showed a much weaker response on crop yields (approximately 10% yield increase) compared with a biochar application followed by application of inorganic fertilizer (approximately 50% yield increase) (Figure 2). This finding was confirmed by a meta-analysis from Bai et al. (2022). This clearly indicates that biochar is not a replacement for fertilizer; when biochar is charged with fertilizer, better yield results are obtained. Please note that these numbers represent averages over a wide range of different crops and field sites.

Differentiated by major crops in the tropics and subtropics, maize yields respond most favorably to biochar application, while rice yields showed a weak and somewhat insignificant response to biochar addition, as listed in Table 2 and shown in Figure 2. Conversely, Agegnehu et al. (2017) showed a higher crop yield increase following biochar application to soils when compared to the use of fertilizer alone.

The maize and soybean yield increases of 117% and 43%, respectively (Table 2), are averages over ten years, achieved after an initial biochar application of 100 t/ha combined with annual N-P-K-fertilizer application in a field trial in Kenya (Kätterer et al. 2019). Another field trial in Kenya, (Mahmoud et al. 2019) found an increase in maize yields by 31% in the first year and by 47% in the second (Table 2) after an initial biochar application of 2.8 t/ha on average. In this study based upon on-farm trials, farmers applied between 1 t and 10 t biochar per ha; a strong correlation was found between the amount of biochar applied and crop yield response.

Furthermore, biochar application improved yields in a variety of vegetables: radish yields increased by more than 20% (meta-analysis by Jeffery et al. (2011)), as did cabbage and kohlrabi yields by 60% and 62%, respectively, in on-farm field trials in Bangladesh (Sutradhar et al. 2021).

Such positive responses in crop yields are the result of the impact that biochar exerts on the soil's physical and chemical properties. Biochar has a considerable inner surface area, a feature that enables it to absorb copious amounts of water as well as plant nutrients. Its ability to absorb thus improves the soil's water-holding capacity and increases the amount of water available to plants, notably in sandy soils, while its capacity to store boosts the soils' ability to absorb plant nutrients and make them available to plants. Biochar thus assumes the function of organic matter in the soil in terms of nutrient and water storage, thereby boosting its fertility.
Both the water holding capacity and the amount of water available to plants is substantially increased in coarse-textured (sandy) soils after biochar application. There is a much weaker response, however, in medium and specifically in fine-textured soils (Omondi et al. 2016, Blanco-Canqui 2017, Razzaghi et al. 2020). This partially explains the stronger response in crop yields following biochar application to sandy soils when compared with loamy, silty, and clay soils.

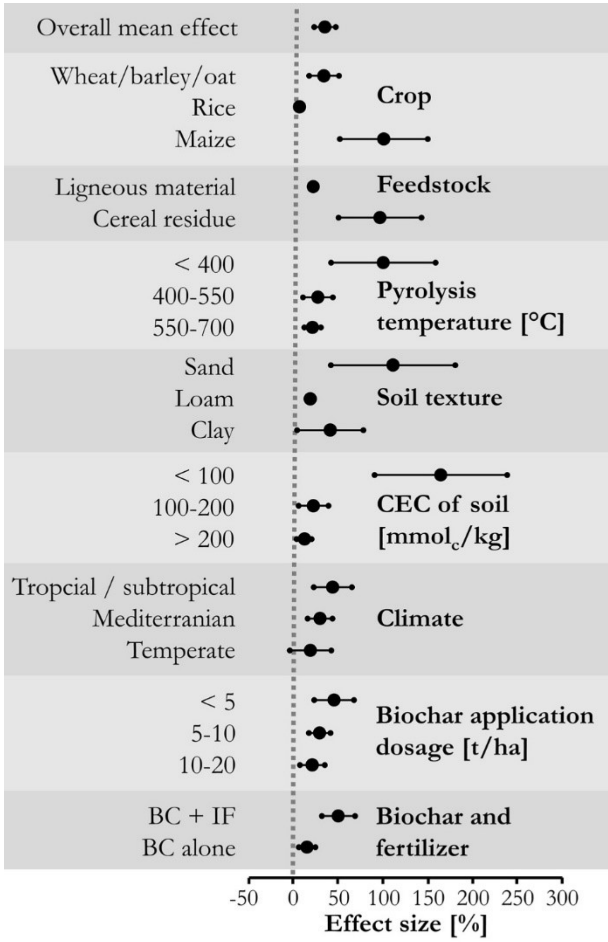

Figure 2: *Impact of biochar application on crop yields in soils with different pH, soil types, climatic conditions, feedstocks, pyrolysis temperatures, and fertilizer treatment following Ye et al. (2019). CEC: cation exchange capacity; BC biochar: BC+IF: biochar followed by inorganic fertilizer application. Dots indicate the level of impact in % relative to respective control trials. Bars indicate the 95% confidence interval. Where the left side of the error bar intersects the dotted line (zero % effect), no significant yield increase has been observed.*

Figure 3 shows a significant increase of 24.3% in water available to plant over the controls in coarse-textured soils, though the biochar doses needed to achieve these effects were higher than the doses needed to achieve effects on plant nutrition (Figure 2). It also indicates that much lower and no significant increases were to be observed in medium and fine-textured soils, respectively (Omondi et al. 2016). These findings are consistent with the meta-analysis by Razzaghi et al. (2020), which revealed that plant available water significantly increased by 45% in coarse-textured soils, compared with increases of 21% and 14% in medium- and fine-textured soils, respectively, whereby those values

Table 2: Yield increases [% relative to control] and 95% confidence interval of selected crops revealed by meta-analyses and selected field studies. The yield increases represent grand means, i.e., all the compiled data from a given meta-analysis across crop, soil type, climate, biochar properties, and soil management.

Yield increase [%]	95% confidence interval [%]	Number of single data points (studies) included	Source
		Maize	
6	-2 – 14	194 data points from 54 studies	Jeffery et al. 2011
90	50 – 140	30 studies	Ye et al. 2019
28		1 field study	Farhangi-Abriza et al. 2021
117		1 field study	Kätterer et al. 2019
31 and 47		1 field study	Mahmoud et al. 2019
		Soybean	
13	2 – 24	64 data points from 8 studies	Jeffery et al. 2011
43		1 field study	Kätterer et al. 2019
		Wheat	
5	-2 – 12	116 data points from 21 studies	Jeffery et al. 2011
30	15 – 45	42 studies	Ye et al. 2019
13		1 field study	Farhangi-Abriza et al. 2021
		Cowpea	
17	-7 – 41	26 data points from 6 studies	Jeffery et al. 2011
		Rice	
4	-7 – 15	125 data points from 39 studies	Jeffery et al. 2011
5	-1 – 11	43 studies	Ye et al. 2019
10	5 – 15	70 studies	Awad et al. 2018

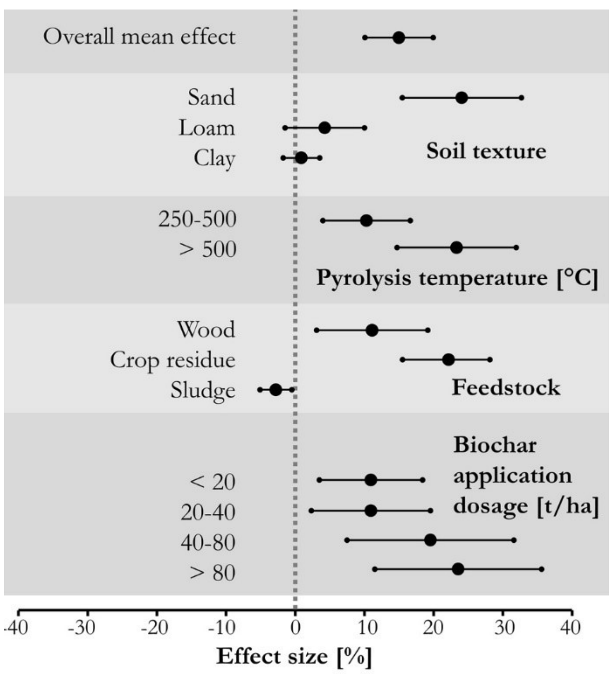

***Figure 3:** Changes in plant available water levels in soils following biochar application differentiated by soil texture, biochar production, and biochar application dosage (Omondi et al. 2016). Dots indicate the impact level in % relative to the respective control trials. Bars indicate the 95% confidence interval. Where the left side of the error bar intersects the dotted line (zero % effect), no significant yield increases were observed.*

represent averages over a range of biochar application dosages. Figure 3, however, shows a significant increase of plant available water of 10.6% at biochar application rates of below 20 t/ha. This increase of plant available water combined with crop yield responses frequently results in greater crop water use efficiency on account of biochar application (Gao et al. 2020).

Applying biochar to soils results in a reduction of the soil's bulk density while increasing its porosity (Omondi et al. 2016, Razzaghi et al. 2020) across different biochar application dosages. The increased porosity, in turn, make it easier for water to infiltrate the soil and for plant roots to penetrate greater soil areas in order to tap water and nutrients. This increased amount of plant available water is critical for rain-fed agriculture in climates with protracted dry seasons and irregular rainfall given that the soil is then able to deliver water more reliably and over more extensive timespans (Ding et al. 2016, Blanco-Canqui 2017).

Biochar generally boosts the soil's ability to retain nutrients and make them available to plants. This can be explained by the improved soil chemistry and, where nutrient rich biochar is applied, on account of the nutrients added along with the biochar application. The soil's chemical composition can be improved with the help of both nutrient-poor as well nutrient-rich biochar, resulting in what is referred to as a greater cation exchange capacity (CEC), increased soil pH, and chemical bonds between biochar and soil minerals (Spokas et al. 2012, Jindo et al. 2020). In practical terms, this improved soil chemistry means that biochar produced from wood or crop residues will enable soils to make better use of plant nutrients derived from either chemical or organic fertilizers. Hence, biochar produced from wood or crop residues is a soil conditioner, though it is not a fertilizer. In itself, biochar has a high CEC, fostered by its large surface area. When biochar is applied to soils, it increases the soils' CEC, which, in turn, improves the soils' ability to absorb ammonium, potassium, calcium, magnesium and other cations, retaining them as plant available nutrients (Spokas et al. 2012, Nguyen et al. 2017). This impact explains the strong response in crop yields after biochar application in those soils that often have a low CEC, such as sandy and many tropical soils.

Considering its ash content, biochar generally has a high pH; this will help boost soil pH after biochar application. This soil pH increase, the so-called liming effect, translates most strongly into crop yield increase on acidic soils. This liming effect improves environmental conditions for the crops' and plants' root systems due to the fact that it reduces aluminum toxicity and phosphorus fixation, notably in acidic tropical soils, and contributes to increasing the CEC in soils, given that clay minerals and native soil organic matter gain more exchange places for cations (Biedermann and Harpole 2013, Jindo et al. 2020). Thanks to an increase in the soil pH, biochar application often translates into an increase of legumes' biological nitrogen fixation (Nguyen et al. 2017, Liu et al. 2018, Jindo et al. 2020).

Applying biochar enhances the availability of phosphorus to plants (Gao et al. 2019, Glaser and Lehr 2019); this is helpful for those tropical soils suffering from a high degree of phosphorus fixation. Some of biochar's organic matter binds with aluminum and iron ions, thus blocking the phosphorus fixation sites in such soils (Jindo et al. 2020). Under reduced conditions (i.e. the absence of oxygen) in submerged rice paddies, soil pH is generally high and phosphorus availability improved given that iron oxides are reduced and thereby partly dissolved, a process that sets the phosphates free. The relative impact of biochar application to soils is thus less pronounced in rice paddies when compared with dry upland soils (Ye et al. 2019).

Finally, biochar reduces nitrate leaching, because it offers absorption places for nitrate. Furthermore, the enhanced water holding capacity reduces water infiltration below the soil profile (Borchard et al. 2019, Jindo et al. 2020). In coarse-textured soils, nitrate leaching is reduced by 25-30% (Borchard et al. 2019).

4 Biochar production and its impact on soils and crops

Depending on the type of feedstock used and pyrolysis temperature, biochar contains varying amounts of nutrients, as will be explained below. This particularly applies to potassium and phosphorus (Biedermann and Harpole 2013, Jindo et al. 2020). As a general rule, biochar produced from wood or straw will have a lower nutrient content than biochar derived from nutrient-rich feedstocks such as animal manure or organic urban waste. Hence, as indicated by Glaser and Lehr (2019), biochar from wood shows little effect on phosphorus availability (1.5 times increase), while biochar from crop residues resulted in a 3.5-times increase of phosphorus availability, and biochar derived from animal waste increased phosphorus availability 6.5 times. At the same time, however, after applying biochar, particularly a nutrient-rich variant thereof, the amount of available nitrogen – as ammonium (NH_4^+) and as nitrate (NO_3^-) – is significantly reduced by approximately 5% and 15%, respectively (Liu et al. 2018), notably in sandy and acidic soils (Gao et al. 2019). This can be explained by the fact that phosphorus introduced into soils by such nutrient-rich biochar triggers the growth of soil bacteria, which, while growing, absorb ambient nitrogen and thus remove it from the pool of plant available nitrogen. However, nutrient-rich biochar results in higher crop yield increases than nutrient-poor types, as revealed by meta-analyses listed in Table 3. It has to be noted, however, that those meta-analyses do not include long-term studies of the impact to soils after biochar has been applied and therefore only reflect its short-term impact.

Table 3: *Biochar properties depending on feedstock*

Feedstock	
	Impact of feedstock on crop yield in % compared with control without biochar (across all climate types) (Jeffery et al. 2011)
Wood	7
Poultry litter	22 to 26
Biosolids	-26
Nutrient status of feedstock	Impact of feedstock on crop yields in % compared with control without biochar only in tropical climate (Jeffery et al. 2017)
Nutrient-poor	18
Nutrient-rich	70
Ligneous vs. cereal feedstock	Impact of feedstock on crop yields in % compared with control without biochar (only for trials shorter than one year) (Ye et al. 2019)
Ligneous	15
Cereal	90
	Impact of feedstock on plant available water in % compared with control without biochar (Omondi et al. 2016)
Wood	12
Crop residues	25
Sludges	-5

Once biomass is subjected to pyrolysis, a typical chain of decomposition reactions of the biomass compounds unfolds, along with a corresponding increase in pyrolysis temperature. First, cellulose and hemi-cellulose start to decompose (at temperatures of 100-300°C), followed by lignin (at temperatures of 300-500°C) (Hassan et al. 2020). During these processes, oxygen (O_2), hydrogen (H_2), nitrogen (N_2), and part of the carbon from the initial biomass feedstock are emitted, whereby carbon is primarily emitted as CO_2 and methane. Depending on the device used, methane and hydrogen combust during the pyrolysis process, which keeps it running. Part of the methane and hydrogen can be recovered as raw material in order to generate electricity. As the pyrolysis temperature increases, the carbon that remains as biochar from carbon rich structures is increasingly arranged in benzene polymers (Hassan et al. 2020). These benzene polymers render biochar recalcitrant against decomposition in soils (Spokas et al. 2012). This turns biochar derived from high pyrolysis temperatures of more than 600-700°C into a carbon stock with a long-term presence in soils (this biochar's half-life value is approximately a 1000 years), as reviewed by Li et al. (2019).

Yields from biochar production depend on pyrolysis temperature; they decrease with increasing pyrolysis temperature (Li et al. 2019), as shown in Table 4.

With increasing pyrolysis temperatures, nitrogen initially valorizes, already at temperatures of 300°C. This is followed by hydrogen and oxygen valorizing, while carbon remains in the resulting biochar. Biochar produced at temperatures of below 300°C thus has a carbon content of approximately 60% and an oxygen content of approximately 40%, whereas biochar produced at 400°C has a carbon content of 60-80% and an oxygen content of approximately 20%. In biochar produced with a pyrolysis temperature of more than 800°C, carbon content reaches 90-95%. Furthermore, phosphorus and metals such as potassium, calcium, and magnesium remain in the biochar at increasing pyrolysis temperature as well (Hassan et al. 2020). These changes in element contents, chemical and physical structures, and increasing pyrolysis temperatures result in higher ash contents, higher pH values, and a higher inner surface area of biochar. After applying biochar derived from higher pyrolysis temperatures (Table 1), this higher inner surface area is in line with overall improved soil physical properties such as plant available water. Conversely, biochar's cation exchange capacity decreases with increasing pyrolysis temperature, because the negatively charged exchange places containing oxygen are

Table 4: *Biochar properties depending on pyrolysis temperature*

Pyrolysis temperature [°C]	
	Biochar yield in % of initial feedstock mass, average across all feedstocks (Li et al. 2019)
300	60
500	40
800	30
	Carbon content of biochar produced from herbaceous material (crop residues) in % of biochar mass (Li et al. 2019)
300	60
500	75
800	90
	Approximate carbon in biochar produced from herbaceous material such as crop residues in % of initial feedstock mass, calculated after Li et al. (2019)
300	36
500	30
800	27
	Impact of pyrolysis temperature on crop yields, in % compared with control without biochar (Ye et al 2019)*
< 400	95
400-550	25
550-700	15
	Impact of pyrolysis temperature on plant available water in % compared with control without biochar (Omondi et al. 2016)
250-500	10
>500	25

* note: these represent short-term effects from studies of less than one year after biochar application

destroyed as a result of increasing pyrolysis temperatures (Nguyen et al. 2017).

Finally, increasing pyrolysis temperatures produce biochar that reduces nitrous oxides (N_2O) emissions more efficiently, from -25% at <460°C to -45% at >780°C (Borchard et al. 2019).

The impact on phosphorus availability decreases with increasing pyrolysis temperature (Gao et al. 2019, Glaser and Lehr 2019). This can be is explained by how the phosphorus contained in feedstocks is converted into more stable phosphorus minerals at higher pyrolysis temperatures; those phosphorus minerals are less readily available to plants (Jindo et al. 2020). Furthermore, with higher pyrolysis temperature, biochar's potassium content increases, while, on the other hand, nitrogen is lost from the biochar at pyrolysis temperatures approx. 400°C, as reviewed by (Gao et al. 2019).

As a feedstock, crop residues yield biochar that increases plant available water in soils more so than biochar produced from wood. Biochar derived from sludges, on the other hand, reduces the plant available water content in soils. Biochar produced at pyrolysis temperatures of more than 500°C increases the plant available water content more than biochar from pyrolysis temperatures of below 500°C (Figure 2). Blanco-Canqui (2017), however, did not find a consistent relationship between pyrolysis temperature and plant available water or its water holding capacity.

With regard to pyrolysis temperature, there is an overall trade-off between a higher CEC and a higher nitrogen content at lower pyrolysis temperatures as against improving the soil's physical properties and increasing recalcitrance as pyrolysis temperatures rise.

At the fairly regular pyrolysis temperatures of 300-600°C, dioxines are formed, if chloride is present. Biomass from saline soils subjected to biochar production thus bears the risk of emitting dioxins in amounts above environmental thresholds (Wiedner et al. 2013). If feedstocks contaminated with heavy metals are used, these pollutants remain in the resulting biochar. If potentially contaminated waste material such as urban waste is used, the resulting biochar needs to be thoroughly analyzed in order to avoid contaminating the targeted soils (Verheijen et al. 2009).

As a general rule, fine dust particles can be emitted at any pyrolysis temperature; hence, care must be taken to avoid such emissions.

Biochar production from urban waste has been increasingly gaining attention as a pathway to treat such waste material and recycle plant nutrients as well as carbon back to agriculture (Box 1).

BOX 1

Waste treatment through biochar

(López-Cano et al. 2018) analyzed the properties of biochar from different feedstocks (wood, horticultural crop residues, municipal waste from parks and urban gardens, pig manure, urban organic waste pretreated by anaerobic digestion, and urban waste composed from household, commercial, and industrial waste) with respect to their suitability as a soil amendment in agriculture. The former two feedstocks yielded premium quality biochar according to (EBC 2012), while the biochar from the latter cannot be recommended according to (EBC 2012). The reason is a too high concentration of heavy metals due to contamination of the feedstock. The presence of poly-cyclic aromatic hydrocarbons (PAHs) did not exclude any of the tested biochar from agricultural use. The latter four biochar types had pH values of more than 10 so that acid soils can be improved, while during their application on non-acidic soils care must be taken not to increase the pH to undesirably high values which impede crop growth. In general, the biochar from wood-rich feedstock has higher CEC, a higher water holding capacity, but lower plant available N and P than biochar from urban waste with lower amounts of wood. Still, the CEC of the biochar from the urban waste feedstocks was between 148 and 679 mmolc/kg, which is in the range of clay minerals of temperate soils. In total, all biochar types improved plant growth (López-Cano et al. 2018).

(Goldan et al. 2022) reviewed the application of biochar made from sewage sludges and concluded that pyrolysis removes pathogens, destroys organic pollutants, and immobilizes heavy metals, while the resulting biochar improves the soils properties and return nutrients to the soils.

BOX 2

Gasifier stoves and biochar application on farms in Kenya

In Kenya, on-farm experiments have tested the use of locally manufactured gasifier stoves that produce biochar. These biochar-producing stoves run on pyrolysis of wood or other farm residues and make use of the pyrolysis' process excess energy for cooking purposes in households. These gasifiers can produce char when used for cooking; this can either serve as another energy source or be applied to the farmers' lands as a soil amendment (Njenga et al. 2017, Gitau et al. 2019, Sundberg et al. 2020b, Njenga et al. 2021). Compared with the widely used three-stone open fire, the use of these gasifiers has reduced the demand for wood fuel by 32% when domestically produced char was used as charcoal to provide energy. If that charcoal was used as biochar and applied to soils, the demand for fuel wood dropped by 18% compared with the three-stone open fire (Gitau et al. 2019). Thus, the pressure on woodlands and forests has been reduced, given that households can reduce their consumption of wood fuel and commercially produced charcoal, which is a major factor behind Kenya's woodland and forest degradation (Ndegwa et al. 2020). Most households appraised the use of gasifier stoves in a positive way, primarily because it cooks faster and causes less air pollution indoors. It also uses less fuel, a reality that lightened women's workload substantially. On the other hand, the stoves were negatively perceived on account of the fact that feedstock, mostly wood, had to be cut into small pieces approximately 20 cm long (Mahmoud et al. 2021).

Maize yields increased significantly on all farms on those field plots where homemade biochar was applied. Yields increased from an average of 0.9 t/ha without biochar application to approximately 2 t/ha with biochar application rates of 1-2 t/ha and approximately 5 t/ha with biochar application rates of 10 t/ha (Sundberg et al. 2020b, Kätterer et al. 2022). Feedstocks consisted primarily of branches from farmhold trees that had been pruned. Farmers can administer 0.1 ha to 0.15 ha per year with an amount of homemade biochar equivalent to an application rate of 2 t/ha. Given that the soil amendment effect on soils persists over long periods, small holders are able to upgrade their land year upon year. Even minute quantities of biochar can impact crop yields: farmers are thus advised to use even such small quantities and thereby to gradually improve their farm's soil. At some point in the future, higher crop yields will enable farmers to plant more trees, either to diversify farm income or to collect more feedstock from those trees. Greenhouse gas emissions per household dropped from 19 t CO_{2eq}/year when using the three-stone open fire to less than 3 t CO_{2eq}/year, when using the gasifier and applying homemade biochar to the soil.

5
Biochar application to soils – diverse management options

Biochar is applied to soils by mixing it into the topsoil down to a depth of 5 cm (e.g. Major et al. 2010) to 20 cm (e.g., Kätterer et al. 2019). Before applying biochar, it is crushed into small pieces of between 20 mm and even down to 1 mm or smaller (Kimetu et al. 2008). Across the various field studies, the amount of biochar applied ranged from 0.5 t/ha to over 100 t/ha in tropical and subtropical regions, as reviewed by Glaser et al. (2002). Recent field trials on farms in Kenya used application dosages of between 1 t/ha and 10 t/ha in order to operate in a range of biomass that is realistically available to farmers for biochar production (Sundberg et al. 2020b), as illustrated in Box 1 (Njenga et al. 2021). The meta-analysis carried out by Ye et al. (2019) focused on application dosages below 20 t/ha; they did not find any increase in crop yields with a dosage beyond 5 t/ha within one year of the biochar being mixed into the soil.

As a general rule, biochar is applied evenly over a given field plot. In recent field trials, however, farmers have been applying biochar only to the seeding rows (in the case of maize) or around planting holes (in the case of vegetables such as cabbage) in order to reduce the amount of biochar needed (Sutradhar et al. 2021).

Applying pure biochar to soils results in lower crop yield increases compared with a combined application of biochar and fertilizer or the use of so-called charged biochar. The meta-analysis carried out by Ye et al. (2019) across different climate types, soil types, and crops, and Kätterer et al.'s (2019) long-term study in Kenya have revealed that, depending on farming practices, an application of chemical fertilizer compared with a control trial had a similar impact on crop yields, as did the application of pure biochar. When biochar and chemical fertilizer were applied together, crop yields increased significantly, if compared with treating the soil only with fertilizer or only with biochar. Similar results were shown by Kimetu et al. (2008), Major et al. (2010), Haider et al. (2017) and Kätterer et al. (2019). This can be explained by the fact that by itself biochar only improves the soil's physical properties, particularly in that it increases its water retention capacity and plant available water (Omondi et al. 2016, Gao et al. 2020, Razzaghi et al. 2020), all of which help the soil to become more productive. It should be noted, however, that with the exception of such nutrient-rich types of biochar produced from animal manure, biochar is not a fertilizer, for it does not contain any substantial amount of plant nutrients.

a) Biochar from wood or crop residues combined with chemical fertilizers

This management option considers biochar as an agent or an investment that will improve the soil's physical and chemical properties, thus enabling it to better store plant nutrients from fertilizers in plant available forms. This option has been examined in Kenya in the long-term experiment by Kätterer et al. (2019) with maize and soybean. In this experiment, one initial application of biochar (100 t/ha) in 2006 helped to significantly improve the soil's properties, to such an extent that normal farming practices, including fertilizer application, have resulted a threefold increase in yields of maize and a twofold increase in soybeans over the last fifteen years. Smaller dosages had a similar impact as a soil conditioner, as described in Box 1. This management option uses biochar from nutrient-poor feedstocks such as wood and crop residues.

b) Biochar from wood or crop residues charged or combined with organic fertilizers

While analogous to the previous management option, in this case organic fertilizers are mixed into the soil after biochar has been applied. Alternatively, biochar can be mixed with manure, urine, or compost before applying it to the soil (Agegnehu et al. 2017, Wang et al. 2019, Sutradhar et al. 2021). Another option is to add biochar to compost while the composting process is ongoing (Agegnehu et al. 2017, Wang et al. 2019). Using this strategy, plant nutrients as available from the manure, urine, or compost are absorbed by the biochar, the so-called charged biochar, and thus stored and slowly released after being applied to the soil. For this management option, it is recommended to use nutrient-poor feedstocks in order to produce biochar, while composting nutrient-rich biomass. If nutrient-rich biomass is used to produce biochar, plant nutrients, particularly nitrogen would be lost. Composting, on the other hand, preserves nitrogen. Finally, co-composting with biochar reduces N_2O emissions from the composting process, as can be concluded from Liu et al. (2018), Borchard et al. (2019) and Wang et al. (2019). In addition, the meta-analysis by Zhou et al. (2022) revealed that methane emissions were significantly reduced during this co-composting.

c) Use of biochar from nutrient-rich feedstocks such as animal manure

Nutrient-rich biochar, produced from animal manure and other nutrient-rich feedstocks, both supplies plant nutrients and acts as fertilizer, more so with regard to phosphorus and potassium, but less so for nitrogen. Nevertheless, biochar derived from nutrient rich-feedstocks can achieve significant crop yield increases, as shown by Jeffery et al. (2011), Jeffery et al. (2017) and Ye et al. (2019). If this management option of using nutrient-rich feedstock in biochar production is followed, repeated application of biochar will be necessary in order to replace those nutrients that have been extracted during the crop harvest.

Given its positive impact on animal health and growth, biochar has been garnering more attention as an additive to animal feed, as reviewed by Schmidt et al. (2019). If manure from animals fed with added biochar is applied to soils, the biochar will impact those soils in a manner described above. The quantities of biochar that end up in soils by means of animal feed will be small if compared with direct application, for only 10-20 g of biochar is added to animal feed per one head of cattle (Schmidt et al. 2019).

BOX 3

Making use of residual and waste biomass by converting them into biochar

In India, huge amounts of crop residues are burnt each year. In 2019, the total amount equaled 48 million tons of crop residues from maize, rice, sugarcane, and wheat, which nearly equals the entire crop residues burnt across the African continent. (http://www.fao.org/faostat/en/#data/GB). This practice releases vast quantities of greenhouse gases into the atmosphere, thereby contributing to air pollution over large Indian cities such as the capital Delhi. Attempts have been made to use this huge amount of currently unused biomass in order to produce bioenergy. Combined production of biochar and energy is also being piloted by a number of governmental and non-governmental actors across India, as for example currently by CIFOR-ICRAF in cooperation with the Indian Institute of Soil Sciences and various NGO partners. In conjunction with local farmers, these NGOs have been experimenting with biochar production and its application and have achieved crop yield increases, while sequestering carbon in soils. In an Indian context, where proper disposal of residues and waste biomass from the agricultural sector and from the urban conglomerations pose significant problems, conversion of these bioresources into biochar offers a solution both for resource recovery and efficient waste management. Emissions from burning residues and waste biomass is thus avoided, while soils can be improved and carbon can be sequestered.

BOX 4

Restoring grasslands and increasing climate resilience: Biochar production in Namibia

Namibia faces the challenge of bush encroachment in previously open semi-arid savannah ecosystems, especially in the central north of the country. It is estimated that more than 45 million ha of grassland is bush encroached, entailing negative effects on groundwater recharge, leading to a decline of biodiversity and reducing the productivity of the affected areas on a massive scale. It is too costly just to remove this excess biomass. Therefore, GIZ's Bush Control and Biomass Utilisation (BCBU) Project (https://www.giz.de/en/worldwide/28648.html), among others, promoted production of biochar to turn this biomass into a marketable resource. So far, few entrepreneurs have been looking into biochar from a commercial perspective in Namibia and farmers have started produce biochar with Kon-Tiki kilns or Top Lit Up-Draft Gasifiers to apply biochar to their own horticulture. Due to the immense Namibian livestock industry, slurry from cattle farming has been widely available and used for charge the biochar with nutrients before applying it to soils. Also, chicken manure has been proven to be equally effective and been mixed in a 4:1 ratio with biochar and kept moist in large drums for 14 days to ensure charging and inoculation before applying to the soil.

6 Carbon sequestration and climate change mitigation through biochar use

Worldwide, the technical mitigation potential through biochar use is estimated 2.6 (0.2-6.6) Gt CO_{2eq}/year. The economic mitigation potential with costs up to 100 USD/tCO_{2eq} is 1.1 (0.3-1.8) Gt CO_{2eq}/year (IPCC 2022), both until 2050. These numbers position biochar application in the same order of magnitude as agroforestry and nearly the two-fold of soil carbon sequestration of croplands. Its mitigation potential is considered high, while its adaptation potential is judged very high – the same ranking as for agroforestry deployment. And yet, given that feedstock for extensive biochar production would need up to 20% of the planet's croplands, large-scale application of biochar runs the risk of competing for land. Agroforestry or carbon sequestration of croplands would not bear a similar risk. Considered from the perspective of land competition, biochar might have comparable impacts as large-scale afforestation, reforestation, or the production of feedstock for Bioenergy with CO_2 Capture and Storage (BECCS) (IPCC 2019). In order to derive optimal benefits from biochar in climate change mitigation, whatever biomass is used in the process needs to be produced sustainably and the pyrolysis process should be efficient both in terms of emissions and quantities of feedstock used (Sundberg et al. 2020a).

Table 5: *Labile and stabile pool of biochar carbon and their related mean residence time in soils (Wang et al. 2016)*

Biochar carbon pool	Size [%]	Mean residence time
Labile C pool	3 ± 0.6	108 ± 196 days
Recalcitrant C pool	97 ± 0.6	556 ± 483 years

Once applied to soils, biochar remains there for extensive periods given that it is hardly decomposed by bacteria if compared with other soil organic matter. In stark contrast to most soil organic matter inputs derived from waste refuse, compost, or animal manure, biochar consists of inherently stable forms of carbon that are recalcitrant against decomposition by soil microbes. Biochar's recalcitrant carbon can primarily be attributed to the presence of benzene polymers. This carbon in biochar is thus stored in soils for decades or even centuries (IPCC 2021). As a co-benefit to its betterment of soil properties and to its increasing crop yields, applying biochar to soils also sequesters carbon in soils, thus contributing to climate change mitigation (Verheijen et al. 2009, Gurwick et al. 2013, Kuzyakov et al. 2014, Wang et al. 2016).

Only a limited number of studies have investigated the residence time of biochar carbon under field conditions, as reviewed by Gurwick et al. (2013) across different regions and biochar types. The mean residence time of carbon ranged from 8.3 years to more than 1000 years, with the longest mean residence time being reported in rice paddies, where decomposition of all organic matter is slowed down due to the absence of oxygen. Further indications for residence times of several hundreds of years have come from field observations of soils with biochar containing soil horizons in conjunction with historical findings such as for terra preta [Amazonian dark earth] in Latin America, as reviewed by Glaser et al. (2002). A meta-analysis on biochar stability, mainly based on lab experiments by Wang et al. (2016), concluded that biochar has a mean residence time of several centuries in soils and that only 3% of the biochar carbon is subject to decomposition over a short timespan (Table 5). In that meta-analysis, the maximum amount of rapidly decomposed carbon was 10% of the initial biochar. Smith et al. (2014) reported that 3%-12% of the biochar C were rapidly decomposed, whereby fast pyrolysis lead to higher proportions of labile biochar C. If the biochar yields and carbon contents from Table 4 and the fraction of the recalcitrant carbon are taken into account, one ton of carbon in an average feedstock biomass will result in a carbon sequestration in soils of 0.53 to 0.72 t C. A number of life-cycle analyses focusing on biochar use in Kenya (Whitman et al. 2010, Sieber 2016, Sujessy 2018, and Sundberg et al. 2020b) assumed that 80% of the biochar carbon are stable over several centuries (Baldock and Smernik 2002).

Beyond long-term carbon sequestration, biochar reduces N_2O emission from soils (Nguyen et al. 2017, Liu et al. 2018, Borchard et al. 2019, and Zhang et al. 2020). A correlation clearly exists between increasing biochar application dosage and a lowering in N_2O emissions, with a reduction of approximately 3% at 10 t biochar per ha and more than 60% at biochar application rates of more than 40 t/ha (Borchard et al. 2019). In combination with fertilizer use, N_2O emissions were significantly reduced by 20-30% following biochar application; no significant changes were observed when fertilizer was not applied (He et al. 2016). In contrast to N_2O, no significant changes of methane emissions were registered following biochar application (He et al. 2016, Jeffery et al. 2016, and Zhang et al. 2020). However, in rice paddies or other water submerged conditions, applying biochar results in a significant decrease of methane emissions (IPCC 2021), while methane emissions substantially increased on upland soils following its application (Jeffery et al. 2016).

Biochar application reduces the overall greenhouse gas emissions per unit of harvest by 27% compared with respective controls across crops, biochar and soil types (Liu et al. 2019). This effect is significantly stronger on dryland soils (reduction by 41%) than in rice paddies (reduction by 17%). In line with the reduction of N_2O emissions after applying biochar to soils, this overall reduction in greenhouse gas emissions only becomes significant when used in combination with nitrogen fertilizer (Liu et al. 2019). In terms of global warming, applying biochar reduces the global warming potential per unit of yield (Zhang et al. 2020).

As explained in Box 1, the use of small gasifiers in households substantially lessens the demand for fuel wood, thus contributing to reducing forest degradation, given that less fuel wood is being extracted from forests and woodlands. This household-based biochar production thus contributes to climate change mitigation, for forests and woodland with their concomitant carbon stocks are preserved, while at same time the burden placed upon women in gathering wood is reduced. Compared with an open fire, greater use of the gasifier will lessen household air pollution indoors, thus representing an efficient strategy to reduce climate impacts associated with cooking with biomass (Njenga et al. 2016, Sundberg et al. 2020a). Such cleaner biomass cooking practices also mitigate against health problems associated with harmful fumes in the kitchen, a condition that leads to over four million premature deaths worldwide, and one which disproportionately impacts women and children (Lim and Vos 2012).

As can be observed in India (Box 2) and Namibia (Box 3), biochar production can moreover serve as an alternative to burning crop residues or vegetation encroachment and thus avoids CO_2 emissions. Instead, a substantial part of the carbon stored in the crop residue biomass will be stored in soils.

The newly developed carbon certification standard for biochar (VERRA 2021) follows this logic and assumes that the carbon from residue biomass, which otherwise would be decomposed, instead is stored in soils over long time periods and thus can be certified. Though, this standard rests on more conservative residence times of the biochar carbon compared to the studies of the previous paragraphs. For biochar produced through so-called pyrolysis equipment, which controls the pyrolysis temperature and uses the exhaust methane gas, a default is given that 74% of the initial biochar carbon will remain in soils over 100 years. In contrast, that default is only 56% for biochar that results from simple kilns (so-called low-tech by that standard) which cannot control the pyrolysis temperature. In addition, that standard assigns methane emissions of 0.09 t CH_4 per ton biochar to biochar production by low-tech facilities. This methane emissions often would over-compensate the emission reductions by the carbon storage through biochar. These assumptions clearly direct into the application of pyrolysis devices which use methane to generate electricity or heat.

7
Recommendations

In the previous sections, it has been shown that applying biochar to soils both improves the soils' properties and helps to increase crop yields, notably in the tropics and subtropics. Its efficiency is more pronounced in semi-arid to arid conditions rather than in humid conditions. Biochar application thus has a significant role to play in the process of sustainable intensification. Concurrently, large parts of biochar carbon are sequestered in soils for extensive periods following biochar application. Furthermore, biochar application reduces the levels of N_2O emissions from upland soils and methane emissions from rice paddies, which, in turn, further contributes to climate change mitigation. Biochar is recommended as a soil amendment on condition that its feedstock is available without compromising other biomass needs, as for example providing fodder or construction material (Table 6) In order to avoid competition with croplands, land must not be specifically allocated for biochar feedstock production (IPCC 2019, Tisserant and Cherubini 2019).

Biochar can help to bridge dry spells, as it improves infiltration of water and is able to store more of the infiltrated water than unamended soils. It has to be noted that small amounts of biochar, which can be produced from the biomass amounts that are realistically available to farmers, have a significant effect on plant nutrient availability, whereas significant effects on water infiltration and retention need larger amounts or a higher number of repeating biochar applications with smaller doses.

In terms of development cooperation, when deciding to produce and apply biochar for agricultural use and climate protection, which is the focus of this paper, priority should be given to the potential to increase soil productivity and crop yields in order to improve farmers' livelihoods. Climate protection should be considered as a significant co-benefit. Where only carbon sequestration would take place and no substantial crop yield increases could be expected following biochar application, priority should be given to use biomass for other products such as timber for house construction or oriented strand boards (OSB), which can store the carbon directly (Churkina et al. 2020).

It is recommended that carbon certificate schemes include biochar (VERRA 2021), given that the carbon stock in any given soil can be built up more rapidly compared with humus formation from biomass. Biochar carbon remains much longer in the soil than carbon derived from other organic matter in soils. Once biochar has been mixed into a given soil, most of its carbon will remain there regardless of future land use changes, with the exception of land uses that incur erosion. The issue of permanence (the long-term storage of carbon in soils) can be more easily treated than in carbon certification schemes that rely on humus formation. Furthermore, issuing carbon credits can be justified when biochar is applied to the soil, because that is the point when the carbon is actually sequestered in a given soil.

Adding biochar to animal feed is also recommended, although this cannot be considered a substitute for applying biochar directly to soils.

Under those conditions marked + in Table 6, biochar application is generally recommended. In those instances, without a clear recommendation, such as biochar application on loamy soils, field trials over one, or even better two, seasons are recommended, before applying biochar on large areas in order to avoid any adverse effects following its application. Such detrimental impacts are potentially long-term, given that biochar remains in the soil for extensive periods and cannot be removed once applied. Below, the entries (+), (-), and − in Table 6 are briefly explained.

Climate

Biochar application significantly increases crop yields in tropical climates (cf. Section 3), but not in temperate climates. In humid climates, its positive impact to soil chemistry is pronounced. In semi-arid or arid climates, however, the beneficial impact of biochar on the soil's physical properties such as improved water retention play an increasingly significant role for crop yield increases. In semi-arid or arid temperate climates, biochar application might become beneficial due to greater water retention capacity and plant available water, both determining factors in the growing risk of drought worldwide on account of climate change. Furthermore, if specific objectives in temperate climates are to be reached, such as reducing nitrate leaching, biochar application might be beneficial.

Soils

Compared with its application to sandy soils, biochar's application to loamy and clayey soils did not show any substantial crop yield increases. In contrast to sandy soils,

***Table 6:** Recommendations with regard to biochar application:*
+ : biochar application is fully recommended,
(+) : biochar application is partly recommended; limitations explained below,
(-) : biochar application is not recommended apart from exceptions explained below,
− : biochar application is not recommended in any circumstances.

Parameter	Level of Recommendation
Climate:	
Tropical and subtropical	+
Temperate	(+)
Semi-arid and arid	+
Soil texture:	
Sand	+
Loam	(+)
Clay	–
Soil acidity:	
Acid soils	+
Slightly acid to neutral soils	(+)
Alkaline soils	–
Feedstock:	
Feedstock source:	
Unused farm residues	+
Biomass with potential for higher value use	(-)
Biomass from areas designated for biochar feedstock production	–
Biomass from saline areas	–
Feedstock type:	
Wood	(+)
Crop residues	+
Animal (farm) manure	(+)
Sludges	–
Pyrolysis temperature:	
Below 500°C	+
Above 500°C	(-)
Biochar dosage:	
Small dose (< 10 t/ha)	+
Large dose (> 10 t/ha)	(+)
Soil management:	
Biochar uniquely	(+)
Biochar + inorganic fertilizer	+
Biochar + organic fertilizer	+
Application to upland soils	+
Application to rice paddies	(+)

biochar application to loamy and clayey soils did not significantly raise levels of plant available water (cf. Section 3). Before applying biochar to fine-textured soils, it is thus recommended to consult scientific case studies that correspond to the climatic, soil, and land use conditions similar to those in the targeted area, or alternatively to carry out field trials before going to scale with biochar.
Biochar has a liming effect on account of its own high pH (cf. Section 3). While this is a desired impact on acidic soils, it might impede crop growth on neutral soils, given that the resulting pH following biochar application might reduce the availability of plant nutrients, or even create toxic conditions for plants' root systems. If biochar is to be applied on slightly acidic to neutral soils, as for example to improve the soil's physical properties, biochar with a high ash content (animal manure) should be avoided.

Feedstock and biochar production

Feedstock from saline soils must be avoided, given that biomass grown on such soils contains chloride, which would lead to the risk of dioxins in the biochar end-product (as shown in Section 4).

Wood as a feedstock produces good biochar; its use results in improved soil properties and crop yields. While not attaining similar crop yield increases as biochar derived from crop residues (cf. Sections 3 and 4), if woody biomass is available and other conditions suggest amending soils which need to be charged with plant nutrients through biochar, then biomass derived from woody material can be recommended.

Where animal manure, feces, or urban waste are available, it is preferable to compost it and add biochar produced from nutrient-poor feedstock to the compost heap (cf. Section 5), provided that those materials do not contain pollutants or pathgens. Given that composting does not valorize nitrogen, it remains available to plants when the compost is applied to soils (cf. Section 4). Co-composting with biochar immediately charges the biochar with plant nutrients; they become available to plants once the co-compost is applied to soils. Furthermore, co-composting reduces N_2O emissions from the composting process. The pyrolysis destroys pathogens and most organic pollutants so that a larger range of waste materials can be treated by pyrolysis and converted into biochar.

Biochar produced from animal manure contains potassium and phosphorus, thus functioning as a fertilizer, notably for those two plant nutrients. If animal manure cannot be composted or needs to be converted into biochar for other reasons, nitrogen from an additional source needs to be supplied in order to unlock the biochar amended soil's potential.

Biochar produced through a pyrolysis temperature of over 500°C generally attains weaker crop yield responses than biochar generated from lower pyrolysis temperatures (cf. Section 4). Pyrolysis temperatures of below 500°C are more realistic for biochar production units in rural households or rural communities. Pyrolysis temperatures of more than 500°C are only recommended, if the soil's physical properties are specifically addressed.

Biochar dosage

With biochar applications of below 10 t/ha, increasing biochar dosages will translate into higher crop yields. If more than 10 t/ha of biochar is applied, however, increasing biochar dosages will only sometimes result in higher crop yields. The highest increases are seen at low dosages, if compared with soils where no biochar has been applied. If large amounts of biochar, which could be applied at amounts of more than 10 t/ha, are available, it is recommended to amend a larger area with the available biochar rather than applying a high dosage to a smaller area.

Soil management

Where biochar is available and other conditions suggest its application, its use is recommended, even where fertilizer is not available. When used by itself, biochar has a positive impact on crop yields, given that it improves the soil's physical properties and stimulates the release of plant nutrients during the initial decomposition of the labile carbon fraction. Biochar's full potential, however, is unlocked when applied together with a fertilizer. In this case, biochar enables the soil both to store larger amounts of nutrients and to supply them to plants. Considering that its impact persists over extensive periods, fertilizer can be added at a later stage and will still unlock biochar's full potential. Where the soil's physical properties are being specifically addressed, as for example improved water retention, the use of biochar by itself is recommended (cf. Section 3).

When applied to rice paddies, biochar results in a weaker crop yield increase if compared with upland soils. Applying biochar is only recommended in such circumstances if the rice paddies are being used as part of a crop rotation during which those crops grown under upland conditions can profit from biochar application. Where methane emissions from rice paddies are addressed, biochar can be recommended (cf. Section 3).

8
Knowledge gap

To date, several hundred studies on biochar and its usages have been published, as reflected in the meta-analyses to which the previous sections refer. Knowledge gaps remain, however; these still need to be addressed by donors in development cooperation and research.

The most pressing knowledge gaps revolve around biochar's long-term impact on soils. As outlined in Section 1, very few experimental studies have monitored biochar and its impact on soils and crops alike for a timespan of more than three years. Ongoing field trials thus need to be continued for as long as possible in order to lay the foundation for a better understanding of the long-term behavior and ramifications of biochar in soils. Furthermore, funding agencies need to go beyond the typical project cycles and provide more long-term funding in order to enable extensive trials that will help to improve soil management through proper applications of specific types of biochar for different crops and soils.

Given that the decomposition of biochar's labile fraction takes place shortly after its application, and that soil water dissolves minerals from the ash fraction shortly after biochar application, it can be concluded that old biochar in soils has different properties than freshly applied biochar. Not only are plant nutrients from biochar available for just a short period, its liming effect will become weaker over time, whereas biochar's structure and surface area and therefore its impact on CEC and soil water persist for long time periods. These changes in biochar and biochar amended soils that are beyond the timeframe of many project cycles thus require more exhaustive research in the future.

With regard to biochar's future development, further studies are needed in order to better understand and develop sustainable ways of producing biomass and its processing technologies. Such research will help build strategies to avoid any detrimental impact on landscapes and the climate.

To date, scientific studies have not adequately covered the socio-economic embedding around biochar production and its application. This includes the cost of biochar production as well as those changes of farm livelihoods over the course of biochar application.

9
Biochar: actors in the field

International Biochar Initiative:
https://biochar-international.org/

European Biochar Certification:
https://www.european-biochar.org/en

Ithaka Institute for Carbon Intelligence:
https://www.ithaka-institut.org/en/

Journals:
Biochar:
https://www.springer.com/journal/42773

The Biochar Journal:
https://www.biochar-journal.org/en

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