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Is it biochar, the green engineered material from agri-waste? A promise towards technology transfer supply chain leadership for sustainable development

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Abstract: Biochar is a solid product, produced from thermal decomposition, i.e., pyrolysis, of lignocellulosic biomass generated from agricultural wastes, forest and wood residues. It is unique material for soil amendment for sustainable agricultural and many environmental applications. Biochar properties used for agriculture consist of specific surface area, total pore volume, average pore diameter, pH, electrical conductivity (EC), and cation exchange capacity (CEC). The properties that benefit the environmental purposes are the element: carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and the molar ratio of H/C, O/C, and C/N. The study found that all biochar contained suitable properties for soil amendment and carbon sequestration. However, significant differences were shown in specific surface area, average pore diameter, pH, CEC, and EC of various biochar. Based on O/C and H/C ratios, all five types of biochar persisted in soil from 100 to over 1,000 years. This paper reviews the biochar supply chain to establish a cost-effective waste management system for soil amendments. Despite enormous potential, biochars have not been used widely. This paper identifies the production process, benefits and features of supply chain for viable introduction of biochars.

Keywords: Biochar, Soil amendment, Agri-waste, Supply chain, Agricultural operations management, Technology transfer, Sustainable development, India.

1. INTRODUCTION

Biochar is a solid product, produced from thermal decomposition of biomass, a unique green material for soil amendment. Its use has been identified in Amazon fertility [65] as ancient indigenous practice. Through 'pyrolysis' (heating without oxygen) process ('pyro': caused by heat; 'lysis': dis-integration), the three types of yields are: a solid product (biochar), a gaseous product (called synthesis gas or syngas), and a liquid (bio-oil). The solid product, called biochar, is used for soil amendment. It has industrial, agricultural, and environmental applications. A common "solid char product" of pyrolysis is charcoal which often used to describe the solid char product that is burned for fuel, whereas "biochar" describes the solid char that is used as a soil amendment agent. The gaseous and liquid yields of pyrolysis have industrial uses as energy, feedstocks, and precursors (Fig. 1).

Biochars are mostly used as a soil amendment although the significance of biochars is supposed to be evaluated as a part of the pyrolysis system that coproduces biofuels.

- Biochars can improve agricultural productivity (yield) through soil amendment and increasing input use efficiency
- Biochars contribute to climate change mitigation through carbon sequestration.

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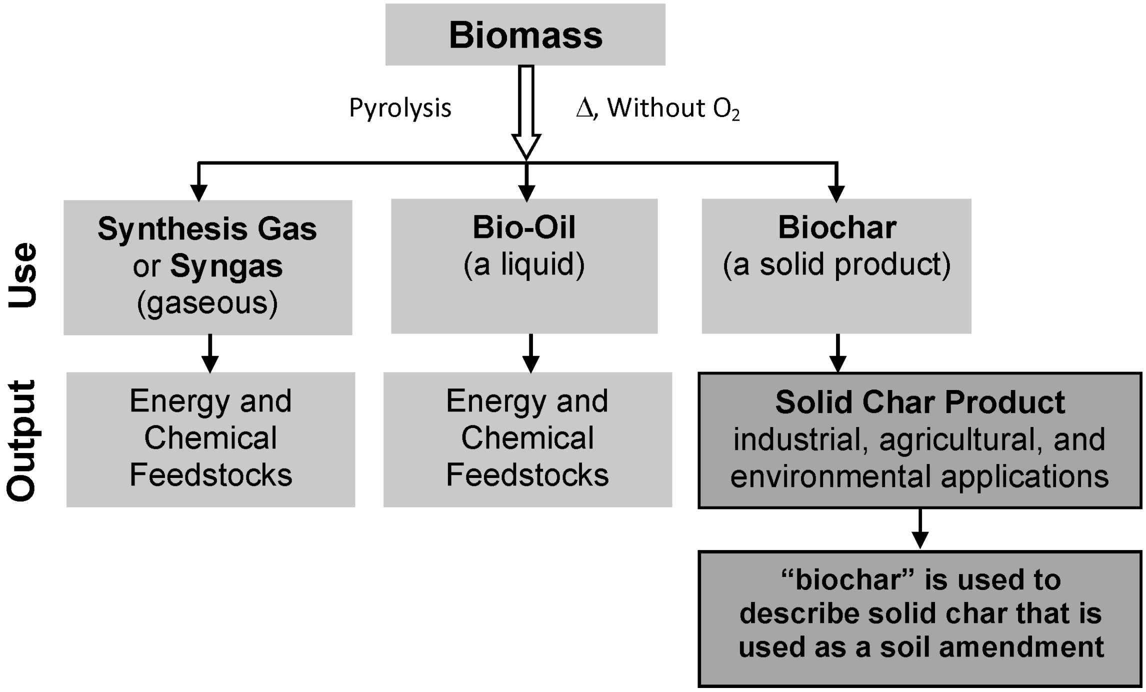

Figure 1: Biomas to biochar conversion

- Furthermore, it can provide extra benefit by contributing to fire prevention.

The impact and benefits depend on the crop and the biophysical conditions of application. Biochar is a category of heterogeneous products, depending on the feedstock and the pyrolysis technology. Conventional biochar systems follow short supply chains. This is achieved by processing local biomass by adopting simple pyrolysis which ignores gas or liquid byproducts. Thus a full economic benefit of the system is not getting realized and modern biochar production has not attained a very good commercial success, in spite of its potential to progress agricultural productivity and soil functioning, and sequesters carbon [6]. However, the dynamic effect of biochar on the use of fertilizer may be uncertain and needs further study [23, 32]. All biochars do not contribute to the reduction of nitrogen (N) loss under all soil conditions. For example, applying biochar on neutral soil often leads to a higher soil p^H, which can increase NH_3 volatilization [72]. Therefore, understanding under what conditions biochar could help reduce NH3 volatilization is crucial to maximize the benefits of biochar applications.

2. BENEFITS OF BIOCHAR IN AGRICULTURAL AND SOIL ECOSYSTEM

Agricultural ecosystems can get diversified benefits from biochar like increased soil organic matter content [12, 52, 83], improved water retention [24, 58, 68, 80], increased microbial activity [35], increased nutrient recycling and retention [34] and finally reaches to improved yields [41, 43] (Fig. 2).

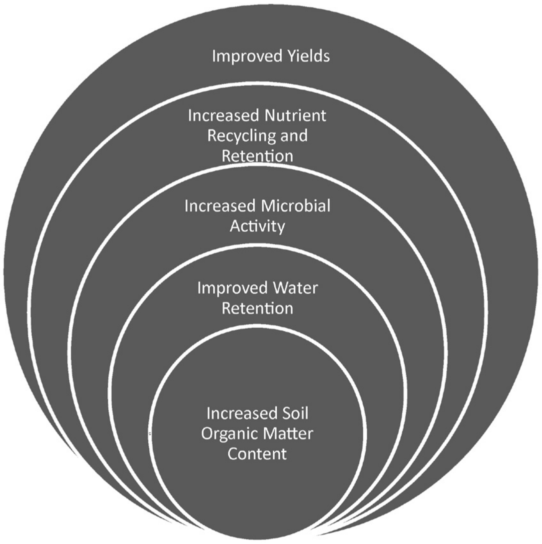

Figure 2: Various Benefits of Biochar in Agricultural Ecosystem

Close-loop waste management

Biochar also has the potential to close the loop on "waste" streams by transforming organic material from industries such as agriculture and forestry into local, low-cost soil amendments [39]. The potential benefits of different biochar categories are enumerated below.

2.1. Individual benefits: Soil functioning and improved agricultural productivity

2.1.1. Soil pH and cation exchange capacity

Long-term studies reporting yield-boosting mostly cite improvements in soil pH. Biochar has two dominant effects on soil acidity, a common limitation for agricultural production (Fig. 3, Table 1).

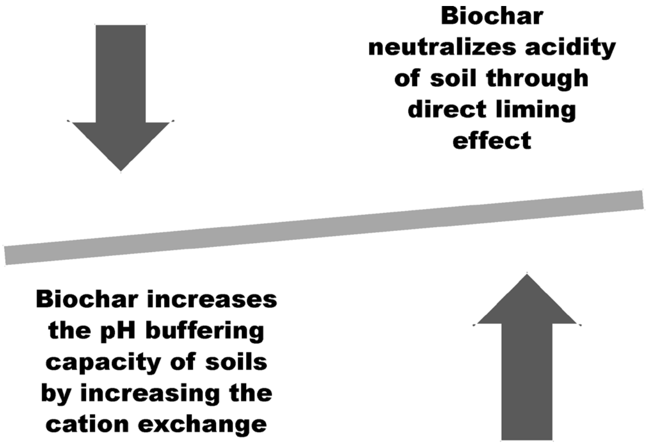

Figure 3: Soil pH and cation exchange capacity

Table 1: Function of biochar as soil amendment agent

Sl. No.	*Soil Function*	*Role of Biochar*
01.	Liming Effect	Biochar neutralizes soil acidity through a direct liming effect, improves the structure of microbial communities, controls nutrient bioavailability, retention and leaching, and causes plant toxicity above or below certain thresholds [29,53, 87].
02.	Buffering	Biochar increases the pH buffering capacity of soils by increasing the cation exchange capacity (CEC) due to negative functional groups (COO- and O-) that are bound to the biochar surfaces [89].
		Biochar increases the available reactive surface area of low-fertility soils, which in addition to increasing CEC and buffering capacity, increases porosity, water retention, and the ability of plant roots to more fully explore the soil volume [51].
		Increases in CEC after biochar application are particularly pronounced in coarse-grain or highly weathered soils [50]
03.	Both Liming and Buffering	Biochar's buffering and liming effects can improve crop productivity, especially in low fertility soils [4, 22, 66].

A global meta-analysis indicates that biochar application has the greatest impacts on soil health when applied to low pH, low cation exchange capacity, and coarse-textured soils [20] (Table 2).

A comprehensive literature review provides a descriptive statistics on the benefits of biochar with respective to the crop yield improvements. Crop yields increases by 25% on average in tropical and acidic soils [40].On the upland of China, a field-trial of 5-year explores that rapeseed production has been boosted by 17% on application of biochar produced from rice

Table 2: Impact on crop yield on application of biochar

Sl. No.	*Where*	*Parameter*	*Statistics*	*Reference*
01.	Tropical, acidic soils	Yield increase	by 25% on average	Jeffery *et al.*[40]
02.	Upland of China	biochar produced from rice straw	boosted rapeseed production by 17%	Jin *et al.* [41]
03.	Regions of tropical climate, sub-Saharan Africa (SSA)	yield increase	from 0.18 to 1.00 ton ha^{-1} year^{-1}	Dickinson *et al.*[23]
04.	Regions of temperate climate, Northwest Europe (NWE)	yield increase	from 0.07 to 0.28 ton ha^{-1} year^{-1}	Dickinson *et al.*[23]
05.	Poor soils in Labrador, Canada	forest biomass to beet field	yield from 2.9 to 11.4 Mg ha^{-1}	

straw [41]. Another global study conducted by Dickinson *et al.* [23] estimates that in a regions of tropical climate, representative in the sub-Saharan Africa (SSA), the yield increase from 0.18 to 1.00 ton ha^{-1} year^{-1}, whereas the regions of temperate climate, such as northwest Europe (NWE), it ranges from 0.07 to 0.28 ton ha^{-1} year^{-1}. An unique study conducted in Labrador, Canada on the relatively poor soils reveals that by applying biochar, produced from forest biomass, to a field of beet boosted the yield from 2.9 to 11.4 Mg ha^{-1}.

2.1.2. Nutrient supply and retention

Application of biochar has been demonstrated to improve three fundamental soil nutrient processes: nutrient supply, retention, and cycling (Fig. 4). After pyrolysis, nutrients contained in the original feedstock biomass are accumulated in biochar and added directly to the soil upon application.

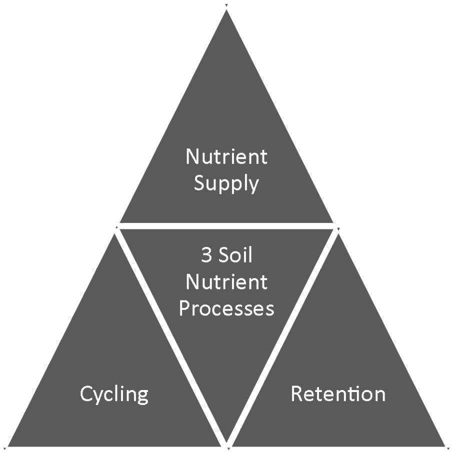

Figure 4: Soil nutrient process by biochar

Nutrient supply

Biochar has been shown to have a fertilizing effect directly and increase nutrient stocks in soil, more particularly potassium (K) and phosphorus (P) [13, 34, 74, 90]. However, low-nutrient feedstocks (hardwoods) and high-surface area biochars (produced under high pyrolysis temperatures) can have a complicated effect on the bioavailability of soil nutrient stocks. For example, biochars made from low-ash feedstocks (such as hardwood) have low levels of P and K, but a high pyrolysis temperature generally increases P and K content on a mass of biochar basis. Thus, the level of these nutrients in a biochar will depend on both the feedstock and the pyrolysis conditions (Fig. 5).

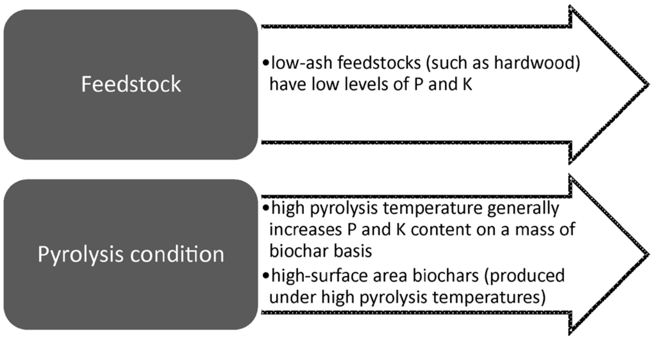

Figure 5: Effect of feedstock and pyrolysis condition on the characteristics of biochar

Nutrient retention

In addition to supplying nutrients directly, biochar can help retain critical valuable soil nutrients by decreasing losses from leaching [51]. Nitrogen leaching is decreased in temperate soils due to the adsorption by the biochar [25, 51, 77, 93]. A study, conducted by Randolph *et al.* [67] on different agricultural-waste biochars produced at various pyrolysis temperatures and rates, reveals that most of the feedstock biochars prevent NO^{-3}, Ca, Mg, and K leaching from soil. Biochar has the potential to save fertilizer through a reduction in leaching and volatilization of nitrogen. Gaunt and Lehmann [33] approximate a 10% to 30% reduction of loss in the amount of fertilizer required for a range of crops. Considering soil morphology, high-porosity and high-surface area biochars may be well suited to reduce nutrient leaching [5, 18, 34], but could also have adverse effects on nutrient supplies in low-fertility soils [9, 76, 79], illustrating how specific biochar properties must be engineered for target uses (Fig. 6).

Nutrient cycling

Biochar also alters nutrient cycling in soils, and here, we focus on nitrogen as an example. Nitrogen cycling can be altered by biochar application through a number of different mechanisms, most notably altered biological N_2 fixation [34, 63], ammonia (NH_3) volatilization [19], and denitrification [19]. Agricultural

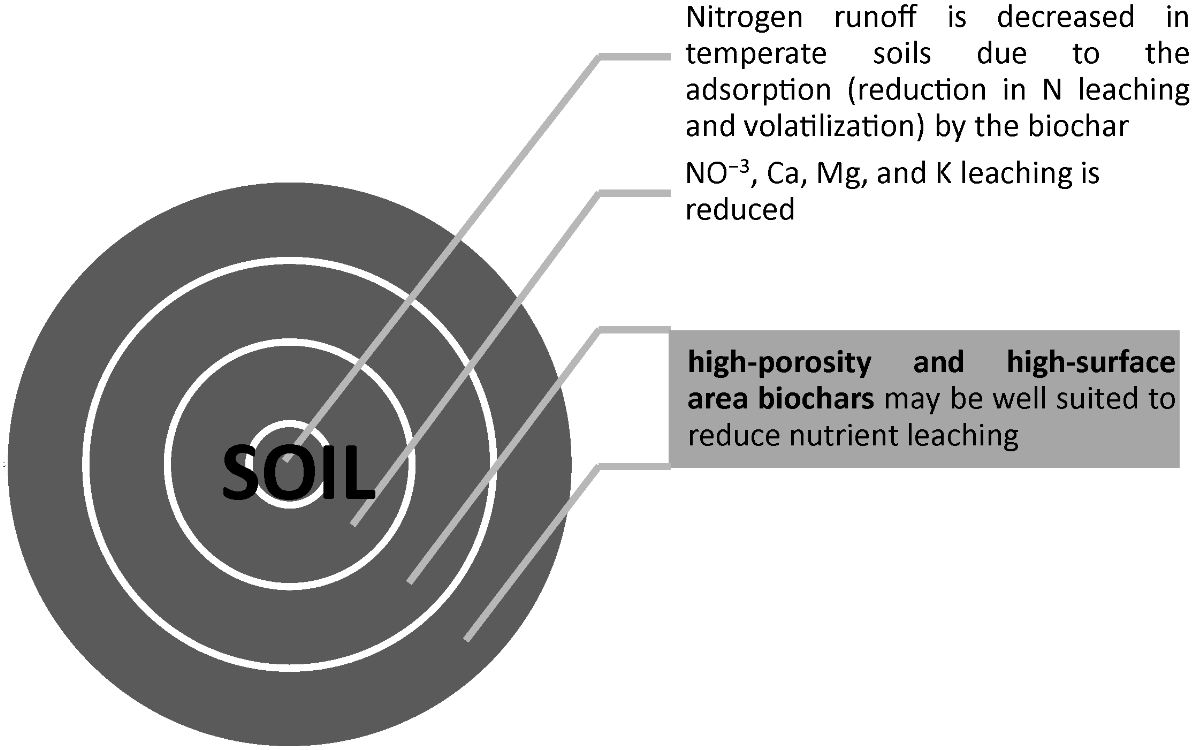

Figure 6: Retaining critical soil nutrients by decreasing losses from leaching

operations utilizing urea-based fertilizers, applying high levels of synthetic nitrogen inputs, or working in tropical, rocky, or otherwise low-fertility soils have all demonstrated a reduction in NH_3 volatilization under biochar application [1, 59, 90], making it a promising strategy for a diverse set of farmers to increase their nitrogen use efficiency.

2.1.3. Co-composting; benefits to compost production

Biochar may also be used to improve the production, input use efficiency, and efficacy of composts. Co-composting (incubation of biochar with compost) improves biochar's measured increases in crop productivity, nutrient supply and retention, and soil biological activity [1, 2, 28, 36, 42, 57, 82]. Biochar makes marked improvements to compost production and application [91], largely due to biochar's

- porous and hierarchical mesostructure
- high surface area that allows nutrients, biota, water, and organic matter to be adsorbed; hence, surface area is an important measured parameter for biochar characterization.
- In one exemplary study, total N losses were reduced by 50% from a poultry litter compost when amended with biochar [79].
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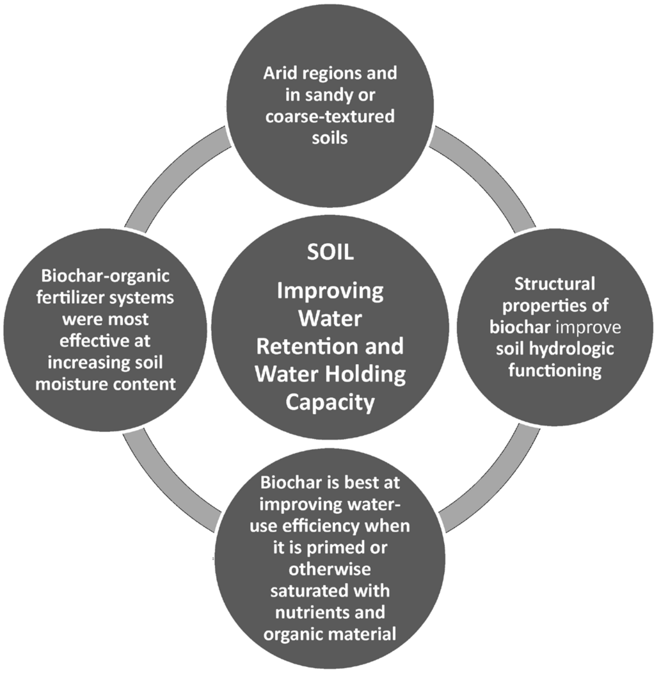

Figure 7: Improvement of water retention and water holding capacity of biochar

2.1.4. Improving water retention and water holding capacity

Biochar has demonstrated its ability to improve a range of soil-water interactions, especially in arid regions and in sandy or coarse-textured soils [24, 46, 64, 86]. A recent meta-analysis has demonstrated that the structural properties of biochar improve soil hydrologic functioning (Fig. 7) in the following context:

- on average increasing aggregate stability by 8.2%,
- available water holding capacity by 15.1%, and
- saturated hydraulic conductivity by 25.2% [64]

Field experiments have revealed that biochar is best at improving water-use efficiency when it is primed or otherwise saturated with nutrients and organic material [1, 37]. A study on peanut production in tropical soils, where a comparison of a range of biochar with co-compost amendments, found that co-composted biochar-fertilizer systems were most effective for increasing soil moisture content [1]. However, the plant available water may change with the duration the biochar has been in the soil [3, 60].

2.2. Social benefits: Climate change mitigation

As a promising carbon sequestration (CS) technology, biochar is estimated to have a maximum potential in offsetting by assuming that all sustainably harvested biomass around the globe can be converted to biochar by the high-yield, low-emission slow pyrolysis, with maximizing the yield of bioenergy [88]. Another study also calculates that biochar has a carbon sequestration potential of 0.7-1.3Gt CO_2 [76]. Biochar's climate benefits are realized mainly through sequestering carbon in agricultural application. Woolf *et al.* [88] estimate that carbon sequestration and fossil-fuel offsets are the two largest contributors to avoide emissions. The benefit of fossil fuel offsets crucially depends on the relative carbon intensity of bioenergy and the fossil fuel to be replaced. Bioenergy achieves the highest avoided emissions if coal is replaced (15%) and could increase the net emissions when replacing natural gas [88].

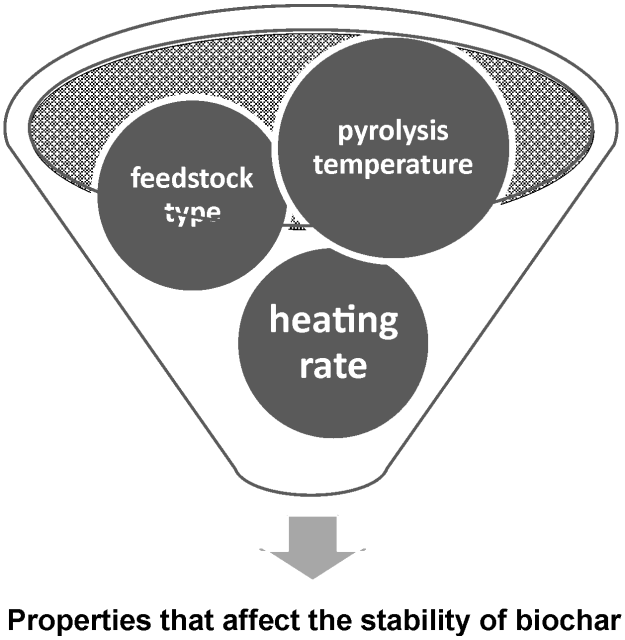

Figure 8: Parameters affecting the stability of biochar

2.2.1. Carbon sequestration

Biochar is a potential carbon storage technology because it can significantly delay carbon from returning to the atmosphere after it is captured by photosynthesis. The conversion of plant biomass to biochar during pyrolysis converts between 10% to 50% of the original carbon into a highly condensed and chemically stable form [11, 21, 55]. Understanding the stability and decomposition of biochar is critical to understand its role as a carbon storage technology. However, differences in analytical methods, environmental conditions, and biochar properties make it impossible to ascertain a single lifetime of biochar-based carbon in soils and sediments [38, 54]. The intrinsic stability of biochar carbon is a function of its properties and of the soil and climate conditions where it is applied. The primary properties that affect the stability are influenced by feedstock type, pyrolysis temperature, and heating rate [48, 80] (Fig. 8). Changes to these three production parameters yield a wide range of physicochemical properties that indicate differences in the stability of the aromatic carbon molecules that comprise char material. For example, higher peak pyrolysis temperatures generally produce more stable forms of pyrogenic carbon using hardwood feedstocks [5].

O:C Ratio, H:C Ratio and negative emission technologies (NET) for sustainable development

This is expressed in the lower O:C ratios and decreased volatile matter relative to low-temperature biochars [78]. The O:C ratios, as well as the H:C ratios, of the resultant char material, are promising metrics for evaluating the stability, volatile composition, and fixed carbon composition of biochar [78], though the latter metric is argued to be more accurate than the former [10]. Limiting global temperature rise to 1.5 °C must include large-scale deployment of negative emission technologies (NET) that capture carbon from the atmosphere [27, 31, 61, 69, 71]. Pyrolysis and the coproduction of biochar are promising candidates for negative emission technologies. Compared to other NETs, the coproduction of biochar through pyrolysis has been shown to have lower impacts on land, water use, nutrients, energy requirements, and costs [76].

2.2.2. *Land-use: Change and fossil fuel offsets*

Since biochar is an essential part of the pyrolysis system, the assessment of the benefits of biochar should consider the co-production of biofuel and biochar. The potential yield increase from biochar's application, however, could reverse the potential adverse effect as increased yield reduces the land requirement for food and energy production. Kauffman *et al.* [44] find that, assuming a 5.89% increase in corn yield above trend and a 30-year life cycle of biochar, the coproduction of biochar from corn stover and ethanol from corn grain can be carbon-neutral. More importantly, with 1% higher yield for corn, soybeans, and wheat in the United States, global land use may decline by 0.06%, or 0.47 million hectares [26].

Few important points

- Saved agricultural land may be converted to the cultivation of crops that feed the coproduction of biofuel and biochar, without hurting food production or forest systems.
- It is clear that the mitigation potential of the coproduction of biochar and bioenergy depends crucially on the soil fertility and the carbon intensity of the fuel replaced.
- Biochar helps avoid more emissions in the least fertile soils because of the greatest improvement in soil productivity and thus in the ability to capture carbon from the atmosphere.
- However, bioenergy offsets more GHG emissions when high-intensity fuels, for example, coal, are used. Woolf *et al.* [88] identify that in all soil-fuel combinations except areas of highest soil fertility and 100% coal use, biochar has a higher climate-mitigation potential than bioenergy does although this calculation ignores the fact that liquid transportation fuels (especially Jet, marine, and diesel) are critical to our economy and are not easily replaced with electricity, and that converting biomass into liquid fuels is by far the least expensive way of producing C-free liquid fuels. Considering this important role of biofuels may affect the production choices of biochar and bioenergy.

2.2.3. *Challenges of obtaining benefits of biochar*

Complexity of biochar-soil interactions has led to contradictory findings for farmers and scientists alike [40, 82]. Part of this complexity arises from the diverse properties of different biochar products and their interactions with the specific contexts of soil, crop, climate and management. "Biochar" is not a single product or amendment, but has an inherent variability governed by differences in production temperature, speed, and feedstock type [18, 48, 80]. Altering these parameters can produce a wide range of measured properties including pH, cation exchange capacity, porosity, surface area, base cation concentration, fixed carbon, etc. These diverse properties can yield diverse biochar products that serve different soil management needs. For example, woody feedstocks tend to produce higher fractions of "fixed" or recalcitrant carbon, making them well-suited for climate change intervention, but have relatively low macronutrient contents and thus limited efficacy as fertilizer [34, 35, 48]. Biochars produced from manures, by contrast, have high levels of nutrients and alkalinity but low fixed carbon, making them better suited as liming agents and for recycling nutrients and less as carbon sequestration agents [18] (Table 3).

Table 3: Variability of biochar from different feedstocks

Sl. No.	*Parameter*	*Biochar from woody feedstock*	*Biochar from manure*
01.	Outcome	woody feedstocks tend to produce higher fractions of "fixed" or recalcitrant carbon	Biochars produced from manures have high levels of nutrients and alkalinity but low fixed carbon
02.	Suitability for climate change	well-suited for climate change intervention	less impact as carbon sequestration agents
03.	Suitability for soil	relatively low macronutrient contents and thus limited efficacy as fertilizer (Gul & Whalen [34]; Gul et al.[35]; Kloss et al. [48]	better suited as liming agents and for recycling nutrients

Adding to the complexity, biochar's influence on soil functioning is highly dependent on the soil environment it is applied to, yielding often divergent trajectories for biochar-soil interactions depending on context [2, 28]. A wide range of experimental designs, analytic methodologies, and target uses have further complicated scientific research on how biochar impacts soil functioning [13, 54]. The complexity of the biochar system and uncertainty about its properties and profitability are challenges that need to be addressed by the supply system.

3. BIOCHAR SUPPLY CHAIN

Biochar supply chain consists of the cost of the main elements of the pyrolysis supply chain and scaling up and supply chain design.

3.1. The cost of the main elements of the pyrolysis supply chain

The cost of biochar system depends on the following main components:

a) Feedstock acquisition
b) Feedstock transportation
c) Feedstock pretreatment
d) Pyrolysis and operation

3.1.1. Feedstock acquisition

Multiple studies find that feedstock acquisition is one of the most sensitive factors in biochar's cost-benefit analysis [14, 73].

The cost of feedstock acquisition can be computed as either

(1) the production cost if a feedstock is produced explicitly for pyrolysis, or
(2) the opportunity cost of an existing feedstock diverted to pyrolysis [49].

For example, the cost of acquisition for corn stover is simply its market rate [81] whereas used-up grains from a brewery may be diverted to bioenergy or to livestock production, thus giving it a relatively high opportunity cost [30, 73]. On the other hand, some feedstocks may be obtained for a negative price if it is a waste stream that otherwise requires a costly treatment (e.g. municipal solid waste). Moving away from corn stover and other marketable feedstocks (e.g. brewery grain), and focusing on waste stream feedstocks (e.g. forest thinning, yard waste) may be one of the keys to a profitable pyrolysis unit. The potential synergies of biochar in the forestry context, where feedstock acquisition may incur a negative price. Biochar is most likely to be adopted in locations with marginal land and high-value crop, and near low-cost feedstock sources.

3.1.2. Feedstock transportation

Feedstock transport is a linear cost function of distance between where the feedstock originates and the pyrolysis location. Transporting biomass is costly as transportation cost could add 11% to the production cost [49]. Thus following strategic decisions are important:

- At its very initial stage of technological diffusion biochar production most likely be a highly localized market that makes the location of feedstock supply an important aspect [26].
- As mobile pyrolysers prove their functionality, feedstock proximity may become a less important factor.
- Alternatively, a firm in a complementary industry (e.g. wood and paper products) may opt to co-locate a pyrolysis unit at

their site, driving transport costs to zero [47].

In the meantime, pyrolysis projects are forced to consider only feedstocks that are proximate to their site.

3.1.3. Feedstock pretreatment

The literature on feedstock pretreatment for biochar production is perhaps under-developed. Pretreatment depends on technology available and pyrolysis process as described below:

- slow pyrolysis requires drying only
- gasification with power production requires drying and coarse chipping
- fast pyrolysis with liquid fuels production requires drying, coarse chipping and fine grinding (and to maximize bio-oil yield, the addition of acid to neutralize the catalytic effects of alkali metals, i.e. "pacification").
- If phosphoric acid is used for pacification, the cost of the acid can be recaptured in the added value of the resulting biochar, which becomes a phosphorous fertilizer product.

Most case studies acknowledge a pretreatment step (e.g. drying and chipping), but do not specify those costs, making it difficult to estimate a per-ton average [30, 70]. Campbell, Anderson *et al.* [17] considers a range of feedstock costs, where the lowest cost option is a waste stream that has yet to be chipped, and a high-cost option represents a pre-chipped and dried feedstock. Kung *et al.* [49] assumes pretreatment accounts for about 6% of total production costs across slow and fast pyrolysis processes.

One analysis that would be useful is the relative cost of drying versus chipping. These two processes are largely inversely correlated. Woody materials need not be dried much, but require a lot of mechanical energy to be chipped. Conversely, yard waste and waste sludge require a large energy input to dry, but little/no chipping.

3.1.4. Pyrolysis and operation

The actual process of pyrolysis is one of the most uncertain future costs and is where major cost reductions may be realized. We analyze simple and advanced pyrolysis separately.

Simple pyrolysis

The simplest forms of pyrolysis require zero capital input. Pit kilns and mound kilns require little more than the movement of earth to create the desired effects (e.g. minimize oxygen, contain heat) [54]. With increasing levels of capital, kilns of various complexities and sizes can be made out of brick and metal, and can include features such as continuous feed systems to increase efficiency. When we consider on-farm solutions, especially for smallholders managing their own biomass waste streams in the global south, it is safe to assume we are discussing simple pyrolysis technologies. The cost can be assumed to be the marginal cost of labor for pit or mound kilns. As we increase the capital investment, kilns start to take more concerted forms. Shackley *et al.* [73] identified 10 biochar production facilities and calculated a per-feedstock- ton cost of pyrolysis between $40 and $450. In some cases of slow pyrolysis, it may be possible to recover process heat from slow pyrolysis systems but there is little or no opportunity to capture biooil or other co-products from slow pyrolysis. When we begin describing co-product capture, we move from simple pyrolysis to advanced pyrolysis.

Advanced pyrolysis

The profitability of fast pyrolysis is most sensitive to bio-oil yield and price, as well as feedstock price, biomass collection cost, fuel yield, and fixed capital cost [14, 73]. All sensitivities are closely tied to the primary product-bio-oil. Meanwhile, profitability is relatively insensitive to biochar value which is consistent with biochar being considered a secondary product after bio-oil. Compared to gasification and cellulosic ethanol, advanced pyrolysis is advantageous in terms of the low capital costs and the lowest MFSP (minimum fuel selling price) required to be profitable across pessimistic, optimistic, and probable scenarios [8]. Therefore, one consideration is the tradeoff between the production of biochar and bio-oil, resulting from the choice of different speed and temperature of pyrolysis. Brown *et al.* [14] find that

- with a slow pyrolysis process, one can expect much more syngas and biochar (66%, 33% respectively), and virtually no bio-oil production (<1%), whereas
- a faster pyrolysis method returns over half its energy in bio-oil by weight (53%), a significant competitive advantage in future scenarios when liquid fuels are constrained.

Assuming a market-rate feedstock collection cost (i.e. corn stover), slow pyrolysis fails to be profitable. However, the study finds that fast pyrolysis can be profitable and benefits greatly from being able to sell a product on the liquid fuel market if gasoline prices are assumed to increase by 20% between 2015 and 2030, which is projected to be the case under the proposed American Clean Energy and Security Act (ACESA) (Energy Information Administration, 2009). The study also predicts that fast pyrolysis requires capital costs that are about 45% higher, which is compensated for by its higher value product. Both pyrolysis cost and costs along the supply chain are significant in the pyrolysis system. McCarl *et al.* [62] estimated that if the syngas and bio-oil were used in energy generation, of the $149.91 per ton of feedstock of the total cost, $59.44 (39.7%) comes from feedstock acquisition and $90.08 (60.1%) comes from fixed costs and operating costs of pyrolysis and electricity generation plants. Not too far away from these estimates, Dickinson *et al.* [23] also find that feedstock harvesting and transport contribute to roughly half of the total production cost, while the other half is attributed to pyrolysis.

Effect of variation in feedstock

Differences in feedstock and processing result in differentiated products which impact their values in different soil conditions. Biochar producers may benefit from horizontal integration, since differentiated pyrolysis products (fuels, pyrolytic sugar, asphalts, as well as biochar) could be produced at the same location at little additional cost of diversification just by varying feedstock, temperature, and processing technology [15].

- Biochar meets three types of needs for end use consumers: soil improvement, waste management, and climate mitigation [6]. However, biochar supply chain can be integrated to the larger set of coproducts of pyrolysis that can provide the production of liquid bioenergy fuels (jet, diesel, and marine fuels), refined from bio-oil, as well as other forms of energy production, such as process heat and syngas. Advanced pyrolysis processes are also used to produce value-added chemical products [7, 84].

3.2. Scaling up and supply chain design

Biochar can be considered to be an "early stage technology" as the global economy is yet to establish a stable and competitive market. Most of the recent works are on cost reduction components. The commercialization of biochar requires an appropriate design of supply chains for implementation [94]. Its large-scale utilization requires

- a better understanding of the properties of different categories of biochar
- their optimal utilization, and
- the design of supply chain.

However, biochar supply chains are a part of a larger pyrolysis supply chain, so the assessment of some of the benefits and costs has to incorporate these linkages.

Biochar supply chains are composed of five essential steps (Table-4, Fig.9):

1. feedstock selection and acquisition
2. feedstock transportation
3. pretreatment of feedstock
4. pyrolysis process
5. biochar products application

The complete pathway of pyrolysis has been reviewed by Campbell, Sessions *et al.* [16]; Campbell, Anderson *et al.* [17]; Galinato *et al.* [32]; Vochozka *et al.* [85], considering every element of supply chain (from feedstock to energy market). These surveys have established a comprehensible value in generating energy, production of biofuel production, waste management, and biochar sourcing in pyrolysis process. Under these studies, a few have emphasized on the decision making strategies within the supply chain

Table 4: Biochar supply chain

Feedstock Selection & Acquisition	*Feedstock Transportation*	*Pretreatment of Feedstock*	*Pyrolysis Process*	*Products*	*Biochar Applications*	*Benefits of Applications*
Forests Agricultural Land (Crops/Residues) Yard Waste Manure/Sludge	Local resource: Low cost Far from production centre: High cost	Chipping Drying Drying & Chipping	Simple Pyrolysis Advanced Pyrolysis	Biochar Bio-oil Syngas	Agricultural Land Forests Remediation Sites	Improved pH and CEC Improved nutrient cycling Improved Water Holding Capacity Carbon Sequestration

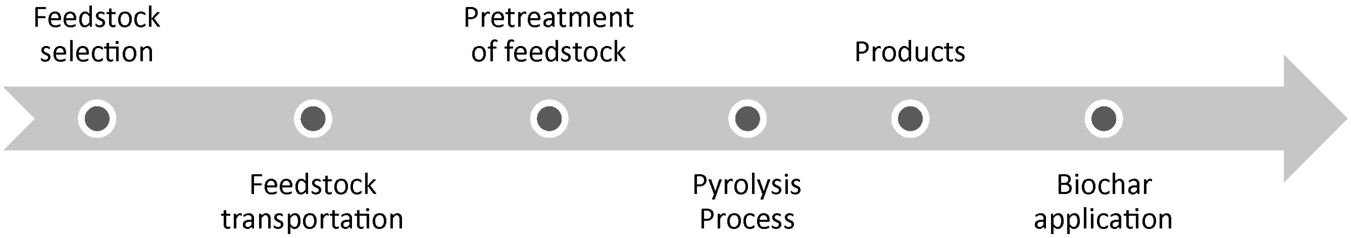

Figure 9: Supply chain of biochar

framework to assess the probability of adoption biochar as soil management technology.

4. CONTRIBUTION OF THE STUDY

This paper identifies the individual components of biochar value chain, viz., feedstock selection and acquisition, feedstock transportation, pretreatment of feedstock, pyrolysis process, biochar products application. Considering the initial investment and logistics cost the paper suggests that at the initial stage the biochar unit is supposed to be established nearby the source of biomass. Alternatively, a mobile biochar unit may be designed. In general, it is found that the biochar collection, pretreatment and transportation cost is half of the overall cost of biochar. Thus, it is suggested that if these costs are kept as low as possible, the overall productivity will be sustainable. In this study, the adoption of biochar requires a reasonably high carbon price. In cases where the yield gains are higher, modest or even zero carbon prices may lead to more adoption [45]. However, frequent fluctuations in carbon prices can defer farmers' investment decisions.

5. CONCLUSION AND FUTURE WORK: CHARACTERIZATION OF BIOCHAR

The adoption of biochar can be enhanced by compensation for carbon sequestration, further investment in research, and learning of producers to enhance efficiency of the supply chain. Characterizing a spectrum of biochar products and their specific ability to stabilize carbon is critical to understand how its production through pyrolysis can mitigate climate change and balance the global carbon budget. A proper accounting of various biochar products and their respective stabilities is also a prerequisite to the technical incorporation of biochar projects into carbon sequestration markets.

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