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Sustainable Technologies for Small-Scale Biochar Production—A Review

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Abstract

Charcoal has found enormous application in both agriculture (AKA biochar) and other sectors. Despite its potential benefits, small scale technologies relevant for its production remain a challenge. Technologies striking a balance between user friendliness, energy efficiency, ease of adaptation and limited emissions could easily be integrated into the local community for the sustainable production of biochar answering both technical and socio-economic aspects. These technologies can be customized to recover the produced heat alongside biochar and the producer gas. The purpose of this work is to review the state of the art in small scale technologies, their associated risks and challenges as well as research gaps for future work. Factors affecting biochar production have been discussed and temperature is known to heavily influence the biomass to biochar conversion process. Based on the reviewed work, there is a need to develop and promote sustainable and efficient technologies that can be integrated into biochar production systems. There is also further need to develop portable, economically viable technologies that could be integrated into the biochar production process without compromising the quality of produced biochar. Such technologies at midscale level can be channeled into conventional small scale farmer use in order that the farmers can process their own biochar.

Keywords

Biochar, Technologies, Small Scale, Sustainable, Farmers

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1. Introduction

Biochar is the carbon-rich product obtained when biomass is heated in a closed container with little or no available air through a process called pyrolysis [1]. Biochar is a pyrogenic black carbon that has attracted increased attention in both political and academic arenas [2]-[12]. The ability to attract such a global attention is due to biochar's potential to mitigate climate change [3] [13] provide food security [14] as well as providing an alternative for organic waste management [2]. Application of biochar to soils is currently gaining considerable interest globally due to its potential to improve soil nutrient retention capacity, water holding capacity and also to sustainably store carbon, thereby reducing greenhouse gas (GHG) emissions [1] [2] [15] [16]. Farmers will be motivated to apply biochar on their farms if these benefits can be demonstrated explicitly through various farming methods such as mixing the biochar with fertilizer and seed, applying through no till systems, uniform soil mixing, deep banding with plow, top-dressed, hoeing into the ground, applying compost and char on raised beds. However, the type of application of biochar to soil depends on the farming system, available machinery and labor [16]. Biochar has the potential to mitigate climate change because the inherent fixed carbon in raw biomass that would otherwise degrade to greenhouse gases is sequestered in soil for years. Assessments of the realistic potential for biochar in carbon abatement have converged on a figure of about 1 GtC yr^{-1} [15] presenting a potential wedge for climate change mitigation. It can act as a soil amendment tool because of its beneficial impact on cation exchange capacity (CEC; 40 to 80 meq per 100 g, high surface area (51 to 900 $m^2 \cdot g^{-1}$), which leads to increased soil pH and water holding capacity, and affinity for micro- and macro-plant nutrients [1] [9] [15]. The use of biochar as a soil amendment has been investigated since the early 1800's [1]. A number of studies have suggested that terrestrial application of biochar could effectively sequester carbon in soils and thus mitigate global warming [7] [17] reveals that applying biochar to agricultural soil is proposed for three reasons:

1) Only the soil seems to have a capacity sufficient to accommodate biochar at the scale relevant to the long-term mitigation of climate change;

2) There is potential for biochar to enhance soil function for agricultural productivity and thus offset the opportunity cost associated with its residual energy value, and;

3) The possible suppression of methane and nitrous oxide release would increase the value of biochar as a means to offset agricultural GHG emissions. In their study on biochar and its function in soil, [7] assert that a strategy to deploy biochar on a large scale would divert a portion of the existing global carbon flux that resides within managed ecosystems or to intercept enhanced net primary productivity production in the form of increased harvest or waste biomass. This reveals the great need and potential for technologies relevant for sustainable biochar production. Pyrolysis of the biomass feedstocks enables the biomass conversion to biochar whose subsequent application to soil is in a more stabilized form. When little or no oxygen is supplied, biochar is formed under the pyrolysis process, and with a controlled amount of supplied air, it is formed under the gasification process. The later optimizes the gaseous phase of biomass conversion while the former optimizes char yield. Biochar is currently the accepted term for pyrolysis-derived charcoal when used as a soil amendment [7]. The quest for a good biochar suitable for soil application is largely attributed by a number of social, technological as well as the environmental factors. It is the purpose of this work to review a state of the art technologies and how they are integrated in the biochar manufacturing niche.

Properties of Biochar

Characterization of biochar for proximate and ultimate analysis reveals the different biochar properties. Important physico-chemical properties include porosity, surface area and pH which all have an effect on its application to soil. Biochar is made up of elements such as carbon, hydrogen, sulphur, oxygen, nitrogen as well as minerals in the ash fraction. The properties of biochar will thus vary depending upon the production conditions and the nature of the feedstock used. For example, during the thermal oxidation of biomass to produce biochar, the inherent carbon is lost in the forms of CO_2, CO, CH_4 and various hydrocarbons. Also, there is more cracking and devolatilization creating bigger pore holes inside the biochar if produced at higher temperatures. Results from [18] for biochar BET analysis revealed that samples with low surface area seem to have large, flat surfaces that have partial cracking, compared to the higher surface area samples, for which the cracking is further developed and there are more individually shaped spherical particles. Biochar surface area increases directly with treatment temperature due to increased volatilization of organic material, leaving a porous structure consisting of the mineral and carbon-based vascular tissue but if volatilization is allowed to continue beyond the optimum, the pores

become wider and a drop in BET surface area may be observed [19]. Thus, a biochar with desirable properties can be deduced from both its proximate and ultimate analysis. The lower the O/C and H/C ratios, the higher is the loss of oxygen and hydrogen during the combustion process [20] producing a product richer in higher elemental carbon. The International Biochar Initiative (IBI) recommends a maximum value of 0.7 for the molar H/C ratio [20] to distinguish biochar from biomass that has not been or only somewhat thermo-chemically altered. Thus suitable working conditions and technologies must be selected in order to produce a biochar of high quality.

2. Small Scale Technologies for Biochar Production

Technologies producing biochar are designed and optimized to produce char ahead of liquid tars and pyrotic gases (Table 1). The common processes include slow and fast pyrolysis, and the most successful approach for high-yield biochar production is via slow pyrolysis (Table 1). Under slow pyrolysis, a biochar yield between 25% - 35% can be reproducibly produced. During slow pyrolysis, the residence time of the feedstock is longer and the temperatures are lower than 700˚C. This allows all the volatile components to escape leaving a chary solid behind. Table 1 shows that a yield of 35% biochar is feasible via slow pyrolysis. Such a yield may vary depending on the nature of the feedstock, reactor type as well as the degree of operating conditions optimization. [21] revealed that pyrolytic gasification is an example of indirectly heated processes which utilizes an external vessel to burn portion of the fuel and uses the heat to pyrolyze the biomass producing medium-energy gas with significant fraction of tars. Such a design has great prospects for modification to produce biochar because the movement of the ignition front leaves char behind. The current position of pyrolysis in the context of a range of other biomass conversion processes is shown in Figure 1.

As shown in Figure 1, fast pyrolysis processes aim at production of bio-oil and the amount of biochar formed is a small fraction of nearly 12% of the total biomass (Table 1). To obtain a high bio-oil yield, biomass fast pyrolysis needs to satisfy four conditions namely, a medium temperature (450˚C - 600˚C), high heating rate (103 - 104 K/s), short vapor residence time (<2 s) and fast condensation of vapors [22]. This implies that although a series of biomass materials can be used to produce biochar, the yield largely depends on the method of production as well as the operating conditions. Such conditions include temperature, particle size, moisture content, feedstock type, nature and type of the reactor, and mode of operation. The small scale technologies available can be either manually operated or automatically run. In these technologies, it is possible to control some of the variables that affect the yield of biochar while it is not possible to directly control some operating conditions. The mode of operation also varies with reactors designed for either autothermal or allothermal mode.

2.1. Autothermal Reactors

Autothermal reactors provide the necessary heat of reaction by means of partial oxidation of the biomass within the reactor. The heat produced is sufficient to drive the endothermic reactions within the reactor to produce biochar, bio-oil and syngas [22]. Air is generally employed as the oxidation agent. The yield largely depends on the reactor design, operating conditions and physico-chemical properties of the biomass. Such designs include top lit updraft gasifiers (TLUG) [23], natural draft [24]. The TLUG is a "tar burning, char making" gasifier which has the advantage that tar is much lower, due to flaming pyrolysis of the biomass and the gases then passing

Table 1. Fate of initial feedstock mass between products of pyrolysis processes [16].

Mode	Condition	Liquid (bio-oil)	Solid (biochar)	Gas (syngas)
Fast pyrolysis	Moderate temperature (~500˚C) Short vapor residence time (<2 s)	75% (25% water)	12%	13%
Intermediate pyrolysis	Low-moderate temperature Moderate hot vapor residence time	50% (50% water)	25%	25%
Slow pyrolysis	Low-moderate temperature Long residence time	30% (70% water)	35%	35%
Gasification	High temperature (>800˚C) Long vapor residence time	5% tar (55 water)	10%	85%
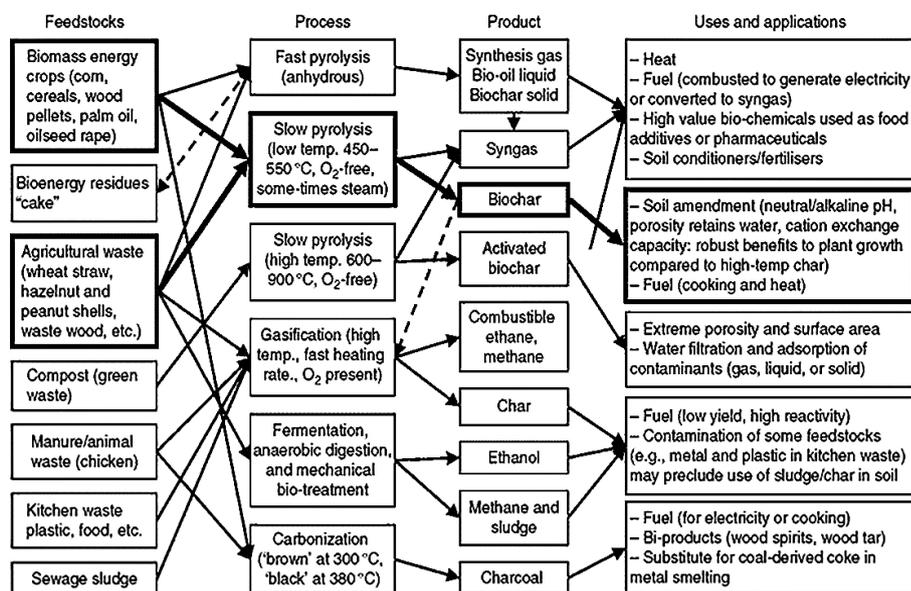
Figure 1. Biochar and other products of thermal conversion of biomass according to available technologies and feedstocks [7].

through a layer of charcoal on the top [23]. TLUG are easily adaptable and can be used for small scale char production because of their ease of operation, simple technology with ease of fabrication, ease of operation as well as the ability to generate a substantial char yield [25].

2.2. Allothermal Reactor

Allothermal reactors require the heat-of-reaction from an external heat source into the reactor. External heat sources include biomass as well as non-renewable fuels. Allothermal reactors have not found wide use for small-scale application because they are not easy to implement due to larger investment costs [22].

Commonly Used Technologies for Biomass Pyrolysis

[26] proposed the following technologies for biomass pyrolysis which have been extensively used although their application is limited due to their respective drawbacks hence a quest for more unlimited applications. Amongst these conventional pyrolysis units include:

- Fixed beds: These have been used for the traditional production of charcoal. They are poor in heat and mass transfer because the bed is stationary in one position and there is no uniform mixing inside the reactor.
- Fluidized beds: These reactors are more effective with gasification reactions because there is effective heat and mass transfer. Within fluidized bed reactors, the biomass is mixed with a hot sand bed fluidized by a gas which keeps the mixture rotating within the reactor. The attrition between biomass particles and sand particles doesn't make fluidized beds a better choice for biochar production because there is a higher carbon conversion to gases than to solid char.
- Augers: In this technology, hot sand and biomass particles are fed at one end of a screw which mixes the sand and biomass and conveys them along. This process works best when pyrotic gases are the major product because it avoids the dilution of the pyrotic products with the carrier gases. Reheating of sand must be done in a separate vessel and mechanical reliability is a concern.
- Ablative technologies: During ablative processes, biomass particles are moved at high speed against a hot metal surface. Ablation of any char forming at a particle's surface maintains a high rate of heat transfer. This can be achieved by using a metal surface spinning at high speed within a bed of biomass particles, which may present mechanical reliability problems but prevents any dilution of the products.
- Rotating cone: Pre-heated hot sand and biomass particles are introduced into a rotating cone. Due to the rotation of the cone, the mixture of sand and biomass is transported across the cone surface by centrifugal force.
- Circulating fluidized beds: Biomass particles are introduced into a circulating fluidized bed of hot sand. Gas,

sand and biomass particles move together, with the transport gas usually being a recirculated product gas, although it may also be a combustion gas. High heat transfer rates from sand ensure rapid heating of biomass particles and ablation stronger than with regular fluidized beds. A fast separator separates the product gases and vapors from the sand and char particles. The sand particles are reheated in a fluidized burner vessel and recycled to the reactor. Although this process can be easily scaled up, it is rather complex and the products are much diluted, which greatly complicates the recovery of the liquid products.

- Chain grate: Dry biomass is fed onto a hot (500˚C) heavy cast metal grate or apron which forms a continuous loop. A small amount of air aids in heat transfer and in primary reactions for drying and carbonization. Volatile products are combusted for process and boiler heating.

2.3. Processes and Parameters Affecting Biochar Production in Stoves

[27] revealed that there is indeed tremendous potential for both localized "intensive" benefits and also global "extensive" advantages emanating from scaled up carbon-financed ICS (improved cook stove) programs. [28] reported that a lot of effort has been devoted over the past decades to develop improved stoves, which reduce fuel use by 40% to 50% with equivalent reduction in associated emissions and are now in production at a value greater than 100,000 units per year. [18] proposed an alternative method of biochar production with a much simpler and accessible process design: a gasification cook stove where biochar can be created under atmospheric conditions because the cook stove is designed so that continuous combustion is kept spatially separated from where pyrolysis of the feedstock occurs. Fan-assisted stoves require an electricity source such as PV-powered batteries [29], the grid or through the use of thermo-electric (TE) devices which convert some of the heat generated by the stove into electricity [28] though TE devices require considerable further development and cost reduction. One advantage with producing biochar in cooking stoves is that it can run under atmospheric conditions and does not require the use of any inert gas. It can be scaled up and configured to run with a continuous stream of feedstock and has a greater throughput than batch methods [30]. For biochar to be produced in improved autothermal TLUD cooking stoves, a defined amount of sub stoichiometric air is supplied which induces a moving counter current bed whose combustion characteristics are greatly influenced by the amount of air supplied. The amount of air has a direct effect on the temperature gradient inside the reactor, the movement of the fuel bed, reaction kinetics and the total gasification time. The practitioner refers to the reaction kinetics as the specific gasification rate which is defined as the rate of mass loss per unit area and unit time. The initial heat is supplied by firing the fuel on top of the bed with the combustion zone moving downwards in presence of the continuous oxygen supplied. The heat generated within the combustion zone is transferred by conduction, convection and radiation throughout the stove. This allows for drying, pyrolysis, and gasification of biomass as well as removal of volatile gases from the stove through forced air supply. Because the heterogeneous char oxidation is relatively slow and the oxygen supplied is limited, carbonized particles (char) remain behind the ignition front. When the combustion zone reaches the grate, all original biomass has been pyrolyzed and from now on only char oxidation takes place turning char to ash if supply of oxygen continuous. Hence, the reactor is typically stopped at this stage to avoid the unwanted char oxidation during biochar production.

2.3.1. The Chemistry of Gasification and the Effect of Production Conditions on Biochar

The major processes that take place during gasification of biomass include drying at nearly 105˚C where water is driven off. The dried material undergoes pyrolysis as shown in Equation (2-1) through which volatile components are released [31]. Subsequently, the combustion process occurs as carbon matter reacts with oxygen to form CO_2 and CO, shown in Equations (2-3), (2-4) respectively which provides heat for the subsequent gasification reactions. Letting C represent a carbon-containing compound, the gasification process occurs as the char reacts with CO_2 and steam to produce CO and H_2 (Equations (2-5), (2-6)) respectively. In addition, the reversible gas phase water gas shift reaction in Equation (2-10) reaches equilibrium very fast at temperatures of 800˚C. This balances the concentrations of CO, CO_2 and H_2 within the system. Generally, a small amount of air (Equation (2-8)) introduced into the reactor allows some of the organic material to be burned to produce CO and energy which drives the process that converts further organic material to H_2 and additional CO_2. Consequent reactions occur when the formed CO and residual water from the organic material react to form CH_4 and excess carbon dioxide (Equation (2-11)). Details of these reactions are illustrated in **Table 2**. The kinetics of these reactions depends on the operating conditions under play. This subsequently affects the quality and quantity of the

Table 2. Gasification reactions [43].

Nature of reaction	Reaction	Reaction number
Pyrolysis	$Biomass + heat + air \leftrightarrow Char + H_2 + CO_2 + CH_4 + CO + C_mH_n + H_2O + N_2 + O_2$	(2-1)
Tar cracking	$C_mH_n \rightarrow H_2 + CO + CO_2 + \cdots$	(2-2)
Heterogeneous reactions	$C + 1/2O_2 \rightarrow CO$	(2-3)
	$C + O_2 \rightarrow CO_2$	(2-4)
	$C + CO_2 \rightarrow 2CO$	(2-5)
	$C + H_2O \rightarrow CO + H_2$	(2-6)
	$C + 2H_2 \rightarrow CO + CH_4$	(2-7)
Homogeneous reactions	$CO + 1/2O_2 \rightarrow CO_2 \,(combustion)$	(2-8)
	$H_2 + 1/2O_2 \rightarrow H_2O$	(2-9)
	$CO + H_2O \leftrightarrow CO_2 + H_2 \,(Water\text{-}gas\ shift)$	(2-10)
	$CH_4 + H_2O \leftrightarrow CO + 3H_2 \,(Methane\ reforming)$	(2-11)
	$CO + 3H_2 \rightarrow CH_4 + H_2O$	(2-12)
	$2C + 2H_2O \rightarrow CO_2 + CH_4$	(2-13)

gasification products. Production conditions influence char properties, fixed carbon as well as its stability in the soil [32]. A good biochar produced under optimal conditions should be recalcitrant in the soil for longer residence times [33]. Such conditions include temperature [32] [34]-[36] nature of feedstocks [37], particle size [38], heating rate [35], heating source [39], reactor type [40], gasification time [41], equivalence ratio [42] as well as pressure [31].

H_2 (Equation (2-10)), and CO (Equation (2-11)) and a significant amount of CH_4 (Equation (2-13)), CO_2 (Equation (2-10)), H_2O (Equation (2-13)), and N_2 (Equation (2-1)) are always present in the producer gas (Equation (2-1)), together with organic (tar) and inorganic (H_2S, HCl, NH_3, and alkali metals) impurities and particulates [44]. The tars formed are organic impurities comprising a range of low to high molecular weight hydrocarbons which condense under ambient conditions. The product content of these undesirable contaminants can be reduced by careful control of the operating conditions (temperature, biomass heating rate, etc.), appropriate reactor design and suitable gas conditioning systems [45].

2.3.2. Effect of Feedstock Type on Biochar Yield

Biomass consists of three major components (hemicellulose, cellulose, and lignin) together with trace amount of extractives and minerals [46]. Due to these constituents, which vary in composition according to biomass type, the pyrolysis and gasification behavior of lignocellulosic biomass (LB) depends upon these main components of cellulose, xylan (hemicelluloses), and lignin. Proportions of hemicellulose, cellulose, and lignin content appear to influence the ratio of volatile carbon in oil and gas and the proportion of carbon stabilized in biochar [7]. In **Table 3**, varying char yields were obtained from different biomass species because of the difference in composition of the biomass feedstocks. The higher the lignin content (which normally corresponds to the lower content of cellulose), the lower the pyrolysis weight loss [47]. Feedstocks with high lignin content generate high yields of biochar when pyrolyzed at temperatures of approximately 500˚C [48] [49].

2.3.3. Effect of Temperature on Biochar Yield and Carbon Stability

In a study conducted by [53] lab-scale pyrolysis to produce biochar at three temperatures between 350˚C and 550˚C from selected feedstock (pine, mixed larch and spruce chips, softwood pellets), showed that despite an increase in the stability of biochar with increasing pyrolysis temperature, the yield of stable biochar is nearly independent of temperature. These results indicate that from the point of view of sequestering maximum amount of carbon per unit of feedstock, low-temperature conversion processes might perform as effectively as higher

Table 3. Effect of feedstock type on char yield.

Agricultural Waste Type	Lignin Content %	Hemicellulose (Xylan) Content %	Cellulose Content %	Ash Content %	Biochar Yield %	Fixed Carbon %	Reference
Red oak	19.58	20.45	30.02	2.24 ± 0.04	Cellulose char 4.45%, xylan char 1.89%, lignin char 41.43%	20.55 ± 0.13	[50]
Empty fruit bunch	24	43	26	na	Hemicellulose char (20 wt%), lignin char 60%, cellulose char 7 wt%	na	[46]
Sawdust	28.9	29.3	41.8	0.6	13.8%	na	[51]
Willow	19.6	na	na	1.3	20.9	na	[52]
Switch grass	8.6	na	na	4.3	24.7	na	[52]
Straw	7.5	na	na	6.3	29.9	na	[52]
Reed canary grass	9.3	na	na	5.1	24.4	na	[52]
Rice husk	24.4	28.6	28.6	17.9	~30	9.3	[47]
Rice straw	22.3	35.7	32.0	10.1	~22	15.2	[47]
Corncob	15.0	31.0	50.5	0.9	~10	16.2	[47]

na: not available.

temperature pyrolysis processes. By using an accelerated ageing technique to determine the stability of biochar, [54] showed that the fraction of recalcitrant carbon in biochar increases with increasing pyrolysis temperature. This means that biochar exposed to higher pyrolysis temperatures contains a higher proportion of the stable fraction than biochar produced at low temperatures. Since the primary objective of biochar is to store carbon, it is the yield of carbon contained in the solid product that is important, rather than the yield of biochar itself. Reporting experimental results from pyrolysis experiments aimed at biochar production only in terms of biochar yields without data on fixed organic carbon yields is not sufficient as it does not provide a true picture of the effectiveness of the process in terms of carbon sequestration potential. In a different study by [36], Conocarpus sp. wastes were pyrolyzed at different temperatures (200°C - 800°C) to investigate their impact on characteristics and chemical composition of biochars. As pyrolysis temperature increased, ash content, pH, electrical conductivity, basic functional groups, carbon stability, and total content of C, N, P, K, Ca, and Mg increased while biochar yield, total content of O, H and S, unstable form of organic C and acidic functional groups decreased while the ratios of O/C, H/C, (O + N)/C, and (O + N + S)/C tended to decrease with temperature. Similarly, these results suggested that biochar pyrolyzed at high temperature may possess a higher carbon sequestration potential when applied to the soil compared to that obtained at low temperature. Furthermore, [32] conducted a study to investigate the influence of pyrolysis temperature on production of wastewater sludge biochar and evaluated the properties required for agronomic applications through pyrolysis in laboratory scale reactor and found that by increasing the pyrolysis temperature (over the range from 300°C to 700°C) the yield of biochar decreased. The biochar produced at low temperature was acidic whereas at high temperature it was alkaline in nature. Subsequently, the concentration of nitrogen was found to decrease while micronutrients increased with increasing temperature. All authors agreed that biochar yield decreases linearly with pyrolysis temperature. The effect of operating conditions on the quality of biochar produced is further detailed in **Table 4**.

2.3.4. Effect of Pressure on Biochar Yield

During an experiment conducted by [58] a factorial design of experiments was used to investigate the effect of absolute pressure (in the range 0.1 - 1.5 MPa) and peak temperature (in the range 400°C - 550°C) on the pyrolysis behavior of two-phase olive mill wastes (TPOMW). From results of regression analyses, they concluded that 1) biochar yield from pyrolysis of TPOMW decreases when both peak temperature and pressure increases; 2), an increase of both peak temperature and pressure results in a higher fixed carbon yield; and 3), a significant increase of the overall devolatilization rate was observed for experiments conducted at intermediate pressure values (0.8 MPa). The effect of pressure on biochar yield and other gasification products are further detailed in the

Table 4. Effect of operating conditions on the char yield and stability.

Study objective	Operating condition	Feedstock type	Observation	Reference
To determine the influence of production conditions on the yield and environmental stability of biochar	pyrolysis temperatures: 350˚C - 550˚C; heating rate: 8˚C min^{-1}; holding time: 60 min	pine, mixed larch and spruce chips, softwood pellets	• biochar stability increases with increasing pyrolysis temperature; • the yield of biochar decreases with the peak pyrolysis temperature	[53]
To investigate the effect of pyrolysis temperature and heating rate on biochar from pyrolysis of safflower seed press cake	temperatures:400˚C, 450˚C, 500˚C, 550˚C and 600˚C heating rates: 10˚C, 30˚C and 50˚C min^{-1} 20 g of biomass samples (SPC)	safflower seed press cake	• at 600˚C biochar has highest fixed carbon content, FC (80.7%), carbon (73.8%), higher heating value, HHV (30.3 MJ·kg^{-1}) and lowest volatile matter content, VM (9.80%); • biochars had low BET surface areas (1.89 - 4.23 m^2/g) containing predominantly aromatic compounds; • biochar yield decreased linearly with increasing temperature; • increase in heating rate reduced VM, FC and BET surface area but had no clear effect on HHV, elemental composition and pH	[55]
To determine the physical and thermochemical characterization of rice husk char as a potential biomass energy source	temperature: 200˚C - 650˚C heating rate: 50˚C holding time: 60 min	rice husk	• 400˚C the optimum temperature with char having moderate HHV; • order of reaction in combustion zone was ~1, the activation energy 73.4 kJ/mol with pre-exponential factor 4.97×10^4 min^{-1}	[56]
Characterization of char from rapid pyrolysis of rice husk	• temperature: 1200˚C • rice husk particles injected into the centre of the reactor at extremely high heating rates ($\approx 1 \times 104$˚C/s), short residence times under a N$_2$ environment at atmospheric pressure	rice husk	• based on SEM, pore surface of char particle became increasingly rough in the middle of pyrolysis; • the surface area of char increased with pyrolysis process to a maximum value of 56.95 m^2/g at pyrolysis reaction ratio (Rp = 0.90); • the H/C, O/C and N/C ratios of the char changed with different trends when the pyrolysis reaction ratio increased; • FTIR studies indicated a gradual decrease in the intensities of OH, C-H and C-O stretches with pyrolysis process	[57]
Characterization of biochars to evaluate recalcitrance and agronomic performance	• pyrolyzing the feedstocks in 50˚C increments from 300˚C to 600˚C • holding at the target temperature: 15 - 20 min • about 3 kg of feedstock manually placed into main chamber purged with N$_2$ while running the mixer	Bull manure, corn, dairy manure, hazelnut, oak, pine and poultry manure	• biochar ash contents varied from 0.4% to 88.2%, VM from 13.2% to 70.0%, and fixed carbon from 0% to 77.4% (w/w); • pyrolysis temperature and FC increase proportionally for low-ash biochars, but decrease for biochars with >20% ash; • nitrogen recovery varied depending on feedstock used at a pyrolysis temperature of 600˚C; • at 600˚C, fixed carbon production ranged from no enrichment in poultry biochar to a 10-fold increase in corn biochar; • woody feedstock demonstrated the greatest versatility with pH values ranging from 4 to 9	[37]

Table 5. The major observations reveal that using smaller particles, operating under high pressure and at high peak temperature is the best way to maximize the pyrolysis gas production but not the char yield. The absolute pressure decreased the tar content in the producer gas at the outlet of a secondary cracking reactor [59].

2.3.5. Effect of Reactor Type on Yield and Biochar Properties

The nature and type of the reactor has an effect on the yield and the properties of the biochar produced. [62] conducted a study that compared slow pyrolysis and microwave (MW) pyrolysis of two different feedstocks

Table 5. Effect of pressure on biochar yield.

Biomass type	Process type	Yield	Operating conditions	Main findings	Reference
Olive mill waste water (OMW)	hydro thermal carbonization (HTC)	~30%	• catalyst: citric acid; • temperature: 180˚C or 220˚C; • residence time: 14 h; • pressures: 9 bar (180˚C) and 24 bar (220˚)	• the organic carbon content of the biochar is enhanced with increasing HTC temperature and pressure; • mass balance considerations confirm that the yield of biochar is associated with a low fraction of carbohydrates in OMW	[60]
Two-phase olive mill waste (TPOMW)	TGA	~22.4%	• pressure: 0.1 - 1.5 MPa; • peak temperature: 400˚C - 550˚C; • heating rate: 5 K·min⁻¹	• biochar yield from pyrolysis of TPOMW decreased when both peak temperature and pressure increased; • an increase of both peak temperature and pressure results in a higher fixed-carbon yield and devolatilization rate	[58]
Sunflower husks	thermochemical liquefaction	574 $g_{char} \cdot kg^{-1}$ husks	• temperature: 280˚C; • feed rate 30 g·kg⁻¹; • solvent: distilled water, methanol, ethanol, isopropanol and n-butanol	• HHV of the biochars were higher than that of the feedstock; • biochars compared favorably with coal on a Van Krevelen diagram; • at temperatures below 280˚C, the charring of the biomass is not complete, with some of the cell wall lignin still intact	[61]
Vine shoots-derived biochar	laboratory-scale fixed-bed slow pyrolysis	na	• heating rate: ~5 K·min⁻¹; • pressure: 0.1 - 1.1 Mpa; • temperature: 400˚C - 600˚C	• particle size the most significant factor in determining the potential stability of biochars; • operating at higher peak temperatures leads to the production of more stable materials; • the absolute pressure decreased the tar content in the producer gas; • no statistically significant effects of increasing pressure on the aromaticity of biochar	[59]

(willow chips and straw), with particular focus on physical properties of the resulting biochars and their relation to biochar soil function. In these experiments, slow pyrolysis laboratory units at the University of Edinburgh and the MW pyrolysis units at the University of York were used to produce biochar from identical feedstock under a range of temperatures. Physical properties and stability of produced biochar from both systems were then analyzed and compared. The results showed that using MW, pyrolysis can occur even at temperatures of around 200˚C, while in the case of conventional heating a higher temperature and residence time was required to obtain similar results. Researchers revealed that the low pyrolysis temperature in MW is possible due to the differences in the temperature of decomposition, heating rates and requirement for feedstock pre-processing (e.g. shredding or drying) [63]. Microwave heating offers several advantages over conventional heating, as it is often more controllable [64]. The difference in attaining pyrolysis temperatures between the different reactors can subsequently produce chars of different properties as well as the yield. This is because of the difference in the rates of thermal decomposition. Detailed results on gasification products from different production methods are shown in **Table 6**. In general, the yield and biochar characteristics are dependent on the maximum attainable temperatures within the biochar production system. Systems with high energy efficiency have the potential to produce a good biochar.

2.3.6. Effect of Moisture Content on Biochar Yield

The quality of the fuel depends on the moisture content, which affects the heating value [68]. The moisture content in the biomass is one of the important parameters that affects the performance of the gasifier through the variation in the producer gas composition and conversion efficiency [69]. The amount of moisture content may be due to the inherent water content in the raw biomass specie or due to prevailing weather conditions. The amount of moisture present leads to loss of heat (quenching) as a matter of evaporating off the water and super heating of the vapor. A moisture content higher than 67% (on dry basis) makes the product gas too lean for ignition [21]. The presence of moisture during gasification reduces the thermal energy and subsequently forms more

Table 6. Effect of pressure on biochar yield.

Study	Production method	Main findings	Reference
MW and slow pyrolysis biochar	slow pyrolysis and MW pyrolysis	• MW assisted pyrolysis starts at 200˚C, while in case of conventional heating a higher temperature and residence time was required to obtain similar results	[62]
Production of solid biochar fuel from waste biomass	HTC	• energy density of biochar increased with increasing hydrothermal temperature • most hemicellulose and cellulose were decomposed below 250˚C while the degradation of lignin only occurs at higher temperatures • biochar yield decreased rapidly with increasing temperature	[61]
Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties	slow pyrolysis	• the production method showed strong effect on biochar properties. • higher pyrolysis temperatures produced higher thermal stability biochars • biochar yields decreased with increasing temperature and when peak temperature rose from 200˚C to 600˚C, carbon contents increased and oxygen and hydrogen contents decreased	[65]
Comparison of kiln-derived and gasifier-derived biochars as soil amendments in the humid tropics	kiln-produced biochar	• highest estimated temperature reached inside the kiln was 400˚C and 600˚C at the top and between 600˚C and 800˚C at the bottom • biochar yields were 140 - 290 g·kg^{-1} of the initial biomass weight for eucalyptus, 240 - 250 g·kg^{-1} for maize cobs, 450 - 490 g·kg^{-1} for rice husks, 360 - 430 g·kg^{-1} for coffee husks, and 290 - 320 g·kg^{-1} for groundnut shells	[66]
Production and characterization of bio-oil and biochar from rapeseed cake	fixed bed pyrolysis	• H/C: 0.47, O/C: 0.27, AC: 17.6%, VM: 18.7%, FC: 63.7% • biochar obtained are carbon rich, with high heating value and relatively pollution-free potential solid biofuel	[67]

CO_2 because the water gas shift reaction is favored at lower temperatures. This leads to formation of low calorific value gas as more CO is consumed while more CO_2 is formed. The presence of high moisture during biochar formation would lower the temperatures for biochar producing char with low fixed carbon. As detailed in **Table 7**, the presence of high moisture content increases biomass fuel density which makes biomass transportation quite difficult.

2.3.7. Effect of Equivalence Ratio on Biochar Yield

The ratio of actual air flow to the theoretical airflow needed for stoichiometric combustion of the biomass is referred to as equivalence ratio (ER), which indicates the extent of partial combustion [43]. The process rates are classified into three successive regimes depending on the air flow rate: Oxygen-limited, reaction-limited and extinction by convection regimes [72]. The propagation of the ignition front is controlled by the amount of oxygen and the process rates are linearly proportional to the air flow rate. The process rates are limited by the reaction rate of the fuel in the reaction-limited regime. As the ER increases, the convective cooling of particles around the ignition front slows down the process and finally causes extinction of the flame [42]. To ensure the high temperature for gasification, air/oxygen is usually used as agent [39]. [73] asserts that gasification requires moving significantly lower quantity of air or oxidizer per unit weight of fuel based on the optimum operating range of 0.2 to 0.4 air ER as opposed to combustion which occurs around the stoichiometric region, typically at plus or minus 2% excess air. The amount of air supplied per unit mass of dry fuel can determine if the process condition or the stoichiometry of reaction is at or near the combustion range or within the optimum gasification range, it also determines the propagation of reaction front throughout fuel bed as well as determine the quality and quantity of gasification products. Results obtained by [74] performed using a cyclone gasifier concept with biomass micron fuel revealed that higher ER led to higher gasification temperature and contributed to high H_2-content, but too high ER lowered fuel gas content and degraded fuel gas quality. The effect of ER on biomass gasification is detailed in **Table 8**. Authors reported an increase in gas formation as ER increases but the effect of ER on char properties is still poorly understood. Using gasification has significant processing advantages; it can be carried out in normal atmospheric conditions, eliminating the use of inert gas, is more amenable to scale up and provides heat that can be used to generate power and/or help recoup processing costs [18].

Table 7. Effect of moisture content on the yield of gasification products.

Study	Operating conditions	Main findings	Reference
Effects of moisture content, torrefaction temperature, and die temperature in pilot scale pelletizing of torrefied Norway spruce	• moisture content: 11% - 15% • torrefaction temperature: • 270˚C - 300˚C • die temperature :60˚C - 105˚C • bulk densities: 630 - 710 kg/m^3	• at too high moisture contents, other problems such as low bulk density and feeding problems predominate • pellet moisture contents were decided by torrefaction temperatures, and not by ingoing material moisture contents • working at high die temperatures is a promising alternative	[63]
Implications of fuel moisture content and distribution on the fuel purchasing strategy of biomass cogeneration power plants	• assuming the fuel cost followed by detailed engineering design, project cost estimation and economic analysis • developing mathematical models of fuel cost incorporating various fuel parameters and power plant operating parameters	• the maximum affordable fuel cost depend on the fuel moisture content, area-base annual availability, the required financial return, size of the power plant, and the operation of the power plant	[68]
Effect of initial moisture content on the yields of oily products from pyrolysis of biomass	• size range : 0.180 - 0.250 mm • heating :298 - 825 K • dried samples (0% moisture), air • dried samples, wet samples and in nitrogen medium	• yields of total oily products increased with increasing pyrolysis temperature • presence of moisture influenced significantly the thermal degradation degrees of the biomass samples during pyrolysis due to quenching	[70]
Effects of compressive force, particle size and moisture content on mechanical properties of biomass pellets from grasses	• biomass samples compressed with five levels of compressive forces (1000, 2000, 3000, 4000 and 4400 N) and three levels of particle sizes (3.2, 1.6 and 0.8 mm) at two levels of moisture contents (12% and 15%) (wet basis)	compressive force, particle size and moisture content significantly affected the pellet density of barley straw, corn stover and switchgrass. As moisture content of biomass increased, pellet density decreased.	[71]

2.4. Traditional Kilns and Retorts

Producing charcoal using traditional kilns liberates greenhouse gases, particularly methane and nitrous oxide, conserves relatively small proportions of carbon in the feedstock [79] and wastes the heat energy created during production. Controlled pyrolysis stabilizes some carbon in solid form and also captures energy-rich liquids and gases which can be used to drive the pyrolysis reactions or used elsewhere [7]. Retort methods are effective at excluding oxygen to facilitate pyrolysis but can be costly during scale-up because of the need to control the atmosphere with sealed systems in conjunction with the use of inert gas [18]. Retort technology is the standard method of production for industrial charcoal in western countries, but due to high investment costs, it is not viable for traditional charcoal makers in the so called south countries [80]. Pyrolysis could be more efficient in terms of carbon emissions (CO_2 MJ^{-1}) and production of biochar carry greater abatement potential than biomass combustion, provided there is an overall adequate supply of feedstock and storage for the biochar product. Producing biochar using kilns is a simple technology and easy to adopt. The limitation attached to this method is the significant feedstock burn off, lower char yields and no heat recovery within the kiln system. The advantages derived from a given technology are rooted in its mode of operation and design concept. In general, the thermochemical conversion of organic biomass is influenced strongly by the production technologies. This was shown by the fundamentally different resulting chemical properties of biochars and hydrochars produced with gasification, pyrolysis and hydrothermal carbonization [20]. During their study these authors found that hydrochars have a less stable structure (dominated by alkyl moieties) than biochars (dominated by aromatics). Biochar should thus be produced under promising technologies not to compromise their stability in the soil. **Table 9** compares the various reactors and the numerous advantages and disadvantages arising from them.

2.5. Choice for Selection and Design of a Gasification System

The ease to adopt a technology for biochar production is based on a number of major engineering as well as socio-economic factors [81] such as:

Table 8. A summary of relevant literature investigating effect of ER on biomass gasification.

Study type	Type of gasifier	Operating conditions	Particle size	Main findings	Reference
Experimental investigation and modelling study of long stick wood gasification in a top lit updraft fixed bed gasifier	TLUG	MC: 25%, 180 W of blower power air supply, T: 432˚C - 936˚C ER: 0.26 - 0.43 H: nd D: nd	sticks with length ~68 cm and diameter ~6 cm	• measurement of the ER is a simple way of analyzing the behavior of the gasifier • TLUG gasified 90 kg of wood for 10 h in two batches per day	[23]
Low temperature gasification of olive kernels in a 5-kW fluidized bed reactor for H_2-rich producer gas	5-kW fluidized bed reactor	MC: 10%wt - 12%wt T: 750˚C - 850˚C and ER: 0.2 - 0.4 H: 1400 mm	Bulk density (kg/m³): 573 size fraction of olivine (500 - 425 µm)	• increase in ER deteriorated producer gas quality, decreased H_2 content and favored CO_2, thus lowering producer gas heating value	[75]
An experimental study on biomass air-steam gasification in a fluidized bed	a fluidized bed reactor of atmospheric pressure	T: 700˚C - 900˚C in 50˚C increments Biomass feed rate: 0.445 kg/h; air: 0.5 m³/h; steam rate: 1.2 kg/h ER: 0.22; S/B: 2.7	size: 0.3 - 0.45 mm, silica sand (particle size 0.2 - 0.3 mm) as bed material	• the LHV of fuel gas decreased with ER • the introduction of steam improved gas quality compared to biomass air gasification but excessive steam would lower gasification temperature and so degrade fuel gas quality • smaller particle more favorable for higher gas LHV and yield	[76]
Experimental investigation of a downdraft biomass gasifier	a blow-type downdraft gasifier	H: 2.5 m ID: 600 mm ER: 0.268 - 0.43	size of the biomass material (wood chips and furniture wood + charcoal) used was equivalent to 50 mm cube	• calorific value of the producer gas increases with ER initially, attains a peak and then decreases with the increase in ER • the gas flow rate per unit weight of the fuel increases linearly with ER • complete conversion of carbon to gaseous fuel did not occur even for the optimum ER • optimum ER (0.38) for the best performance of the downdraft biomass gasifier	[77]
Scale-up of downdraft moving bed gasifiers (25 - 300 kg/h)-design, experimental aspects and results	downdraft moving bed gasifiers	H_1: 1050 mm and H_2: 1800 mm • Feed: 5 - 6 kg unchanging air flow: 100 N·m³/hr, FCR: 50 kg/h and SGR: 0.283 kg/s·m²	Particle size: 84% between 0.5 and 16 mm	• air flow is an influential variable and it determines the biomass consumption and the gas and solid production • mass conversion efficiency (MCE) and cold gas efficiency (CGE) values increase with ER	[78]
Effect of pyrolysis temperature and heating rate on biochar obtained from pyrolysis of safflower seed press cake	fixed-bed reactor	H: 104 mm ID: 70 mm feed: 20 g • inert gas (nitrogen) • T = 400˚C, 450˚C, 500˚C, 550˚C and 600˚C heating rates: 10˚C, 30˚C and 50˚C·min⁻¹	average particle size: 1.8 mm	• biochar yield and quality depend principally on the applied temperature where pyrolysis at 600˚C leaves a biochar with higher fixed carbon (80.7%) and relative carbon content (73.8%), and higher heating value (30.3 MJ·kg⁻¹) in comparison with the original feedstock (SPC) and low VM content (9.80%) • the biochars had low surface areas (1.89 - 4.23 m²/g) and contained predominantly aromatic compounds	[55]
Simplifying pyrolysis: Using gasification to produce corn stover and wheat straw biochar for sorptive and horticultural media	top-lit updraft cookstove	• average temperatures CS: 520 ± 150 WS: 550 ± 25 WS + GT: 595 ± 80 • gasification time: 30 min H: nd ID: nd ER: nd	pellets size: 6 mm diameter by 8 - 10 mm long	• biochar from the gasification process had carbon content > 70% and an ash content of 25% which was equal or better than the same biochar produced using the retort oven • the same biochar showed successful use as a peat moss replacement in horticultural applications • gasification is a simpler, more cost-effective means to produce biochars and should be considered for horticultural and other similar applications	[18]

nd: no details; H: height; ID: internal diameter; CS: corn stover; WS: wheat straw; MC: moisture content.

Table 9. Comparison of various types of reactors for biochar production [16].

Process type	Reactor type	Examples of equipment manufacturers	Advantages	Disadvantages
Batch	Earth pits and mounds Brick, concrete and double metal kilns Retorts		Simple technology, cheap and portable	Inefficient leading to low yield; no heat recovery, significant feedstock burn off; release of pyrolysis gas and vapors to atmosphere resulting in environmental pollution
Continuous	Retort	Lambiotte retort	The operating time for the retort-kiln is much shorter, about 12 h (plus about 12 h for cooling)	High investment costs and not viable for traditional charcoal makers in the so called south countries
	Multiple hearth reactors			
	Screw type pyrolysers	Pyro-7 by Pro-Natura; Biofuel Energy Systems Ltd.	Higher yields; feedstock flexibility; heat integration; possible cogeneration of char and energy; easy to operate, relatively proven technology; combined char and energy generation; available as either portable or stationary unit (depending on size)	More complex systems; more expensive than batch processes; No usable by-products
	Paddle drum type reactors	BEST Energies, Australia	Relatively proven technology; feedstock flexibility; combined char and energy generation; available as either portable or stationary unit (depending on size); higher yields, heat integration and possible cogeneration of char and energy	More complex systems; more expensive than batch processes

- Effectiveness: The reactor should use chemical and thermal energy efficiently to produce a maximum amount of biochar in an environmentally friendly manner.
- Fuel flexibility: Reactor should be able to pyrolyze a variety of biomass feedstocks.
- Operation: Reactor should be easy to start up and control during operation.
- Mobility: Reactor should be low-weight and of simple design to allow for ease of translocation between farmer fields.
- Prestige: The reactor should be attractive and able to give pride to the user.
- Time-saving: Reactors with long holding times or low throughput capacity are likely not of interest to farmers.
- Quality: The quality should be customized to meet the end user's ability to procure.
- Spare parts and maintenance: The ease to replace broken material is a very attractive engineering tool in designing the reactor.
- Health and safety: Reactor must be safe to operate. Pressure build-up should be avoided by installing pressure relief valves if required. Hot reactor surfaces should be avoided by good thermal insulation to minimize risk of skin burns. Release of toxic or irritant smoke must be minimized by ensuring complete combustion of pyrolysis gases.
- Familiarity: Users ease to adopt and familiarize with the reactor is an important ingredient in the design.
- Affordability: Whereas other parameters are pretty important, the price of the reactor has to be tailored to meet the users' ability. An expensive reactor may not be easily adopted and so is a very cheap one.
- Consumer-driven technologies: The reactor should be in position to solve a problem that attracts its design. This will add value to attracting the consumers to adopt it due to its ability to meet the end users goal.

The design of biomass gasifiers is thus an emerging concept aimed at providing solutions to a number of engineering problems. [82] designed, evaluated and optimized the performance of an energy efficient biomass gasifier-based cookstove using babul wood (*Prosopis julliflora*), goundnut (*Arachis hypogaea*) shell briquettes, sawdust briquettes and cashew nut (*Anacardium occidentale*) shells. A 35% thermal efficiency with 1.53 to 1.76 kW of power rating and a maximum flame temperature of 763˚C was recorded when cashew nut shells were used as feedstock. [83] designed, manufactured and evaluated the performance efficiency of the house hold gasifier

stove. The gasifier reactor had an internal diameter of 24 cm and an overall dimension of 30.4 cm diameter by 70 cm height and a specific fuel consumption of 1.3 kg/hr. The performance efficiency of the stove was evaluated using water boiling test and a thermal efficiency of 17.2% was obtained. Their results showed that the gasifier performance and operating conditions were good and the stove could provide modern energy services for basic needs and productive applications in the rural areas. [84] developed an 11.2 kW laboratory scale updraft gasifier that was tested using sawdust and palm kernel shell (PKS) as feedstock. The gasifier performance for both sawdust and PKS comprised of chemical energy inputs of 28,125 and 31633.06 kJ, power input of 7.81 and 8.79 kW, power output of 5.47 and 6.15 kW and the respective gasifier efficiencies of 93% and 67.4% and would meet various applications of heating, electricity supply and could be used to generate the needed combustible gases during fuel scarcity. From the reported literature above, it is important to note that the performance of the gasifier is feedstock-specific. This is due to differences in particle density and the minimum amount of air allowed for gasification. Notwithstanding the efforts from previous researchers, the prospect for available gasifiers to process biochar remains missing. There is need to design and test gasifiers with available feedstocks putting emphasis on biochar production. This will provide an innovative means for producing biochar and making it more accessible to the users.

3. System Energy Efficiency and Economics

A system is a group of devices or objects whose interaction serves a common purpose. It is possible to have an energy efficient system during biochar production through effective thermal insulation to avoid heat losses, ensuring an effective ignition system during start up as well as proper direction and use of the generated heat during biochar production. The energy efficiency of a biochar manufacturing technology is a critical ingredient as a choice for a biochar system. As the energy efficiency decreases, emissions increase due to incomplete combustion products. It is thus important to consider a system whose energy efficiency is well maintained with lesser or no energy losses during the thermo-chemical processes. Although a certain amount of fossil fuel may be needed at some stages of the biochar making process such as for the ignition processes, systems that require more fossil fuel offer less greenhouse abatement benefits and are less energetically desirable [85]. Fossil energy savings and GHG mitigation will be increased if the technology is vertically integrated to use process residues internally to run the biomass conversion plant [86]. The technology that has the potential to provide both ecological and economic benefits of the system will make its application more sustainable. The technology producing more than one product through the coproduction of usable bioenergy in addition to biochar, instead of simply flaring the gases and oils produced from the process is more promising because the raw material is split between more products. Technologies with broad feedstock specifications with respect to particle size distribution, chemical composition (ash content), and moisture content will be the most flexible [85] and marketable. By executing measuring, monitoring and verifying (MMV) protocols for all energy inputs required by the technology accounts for GHG reduction purposes. It is thus important for all biochar related works to advocate for energy efficient technologies as well as biochar projects should source technologies that employ energy efficiency practices to mitigate the environmental risks associated with a particular process.

3.1. Use of a Hood for Emission Monitoring in Stoves

The use of a hood has been extensively used for a number of studies in emission factor measurements [87]-[92]. The basic concept of the hood is to construct it above the tested device to capture all the emissions, making the unvented stove as if a ducted emission source [90]. [88] revealed that the presence of an extraction hood could change combustion characteristics of the stove because it could change the fuel combustion characteristics independent of the stove type and the stove air inlet could be influenced by the forced extraction. To avoid large measurement errors, this method requires a constant and steady exhaust flow rate during the entire burning test as well as the isokinetic sampling for larger particles [90]. By directly measuring the air flow in the hood, problems that make emission monitoring difficult can be avoided [92]. By performing a study to investigate and quantify fire power, fire temperatures, thermal efficiencies, and emissions, the influence of reasonable hood extraction levels on the performance of a number of cooking device, the potential for the forced extraction of flue gases to change the combustion characteristics of unvented biomass-burning cooking devices was assessed [88]. The performance of three stoves with different air inlet characteristics was measured using three hood extraction rates. These extraction rates were selected between the boundaries of being sufficiently low to have no visual

impact on a flame at the height of the stove and being high enough to capture all emissions. Fire power, fire temperature and thermal efficiency were found not to be affected by the hood extraction rates. Sulphur dioxide and total suspended particles showed no significant effect of extraction at a 95% confidence level while a measurable influence of extraction on carbon monoxide emissions was detected, but this was considerably smaller than the effect of the stove. There was no detectable interaction between stove type and extraction level indicating that the influence of the extraction on emissions is independent of the type of stove. The authors concluded that, provided the extraction level does not change between tests and falls between their tested boundaries, it is possible to use an extraction hood to compare emissions from different stoves. **Table 10** summarizes pollutant emission factor monitoring studies from biomass gasification. From these studies it can be inferred that biomass must be gasified under optimized conditions to minimize these emission factors. It is feasible that comparisons between emissions from different cooking devices may be made without the aid of air-flow measurements thereby significantly simplifying and reducing the cost of emission assessment in the stove design. For the hood design methodology, [93] proposed a hood which was described in details by [94]. The tower is in the form of an inverted funnel with a cylindrical bottom, 1.0 m in diameter and 1.9 m high. From the top of the cylinder, the tower decreases to 0.2 m in a length of 1.0 m and is topped with a stack 1.2 m in height. This design has the potential to vent out the flue gases at turbulent flows because of the decreasing diameter of the inlet and outlet. Sampling of gases at turbulent flow ensures a representative sampling of the emissions coming out from the stove.

Table 10. Emission factor monitoring studies from biomass gasification.

Study type	Major parameters	Main findings	Reference
Thermal performance and emission characteristics of unvented biomass-burning cook stoves: A proposed standard method for evaluation	• measure emissions of air pollutants	• emission factors for the three metal stoves tested burning *Acacia nilotica* ranged between 13 and 68 g·kg^{-1} for CO and between 1.1 and 3.9 g·kg^{-1} for total suspended particulates and to increase with increasing thermal efficiency both within and across stoves	[91]
Major gaseous and PAH emissions from a fluidized-bed combustor firing rice husk with high combustion efficiency	• investigate CO, NO$_x$ and PAH emissions from a 400 kW$_{th}$ fluidized-bed combustor with a cone-shaped bed, over 99%, combustion efficiency	• excess air had substantial effects on the axial CO and NO$_x$ concentration profiles • the total PAHs emission was predominant for the coarsest ash particles • the highest emission was shown by acenaphthylene, 4.1 µg/kWh, when the total yield of PAHs via fly ash was about 10 µg/kWh.	[95]
Emissions from multiple-spouted and spout-fluid fluidized beds using rice husks as fuel	• investigate emissions of CO and CO$_2$ on different configurations of spout-fluidized beds • vary level of excess air, different primary-to-secondary air ratios at each level of excess air and method of feeding	• emission of CO seemed to be lower with under-bed feeding of the rice husk fuel compared to over-bed feeding • CO$_2$ emissions independent of method of feeding • changes in excess air levels influenced the emissions of CO and CO$_2$ within the excess air range investigated • emission of CO was less at 10% excess air with over-bed feeding; emission of CO in the case of under-bed feeding was lowest at 20% excess air level • emission of CO was less in the spout-fluid bed than CO in the multiple-spouted bed.	[96]
Combustion and emission characteristics of a swirling fluidized-bed combustor (SFBC) burning moisturized rice husk	• the swirling fluidized-bed combustor was tested at a constant fuel feed rate (of about 80 kg/h) for six fuel-moisture contents (from 8.4% to 35%)	• with increasing fuel-moisture content, the emission of NO from the combustor apparently reduced, while the emission of CO was adjusted at a quite low level due to the effects of secondary air • effective least-cost control of both NO and CO emissions with over 99% combustion efficiency are achievable when firing moisturized rice husk	[97]
GHG emission mitigation potential of rice husks for An Giang province, Vietnam	• to evaluate the GHG emission mitigation potential of rice husk utilization through life cycle inventory analysis	• CH$_4$ and N$_2$O emissions from open burning contribute largely to the current GHG emissions • briquettes can contribute to GHG emission mitigation as the production is more efficient than rice husk burning or dumping • Gasification the most efficient GHG mitigator	[98]

3.2. Economics of Biochar Production

A number of studies are geared to verifying the economic value of biochar in crop production and carbon sequestration [40] [99]-[103] (**Table 11**). The investigations by [99] [101] [103] suggest that the economic viability of the pyrolysis-biochar system is largely dependent on the costs of feedstock production, pyrolysis, and the

Table 11. Economic studies related with biochar production.

Study type	Economic variables	Main findings	Reference
Biomass availability, energy consumption and biochar production in rural households of Western Kenya	• on farm assessment of the energy consumption for food preparation, the biomass availability relevant to conventional and pyrolytic cook stoves and the potential biochar generation in rural households of western Kenya	• biomass availability for pyrolysis varied widely from 0.7 to 12.4 Mg·ha^{-1}y^{-1} with an average of 4.3 Mg·ha^{-1}y^{-1}, across all 50 studied farms • the introduction of a first-generation pyrolytic cook stove reduced wood energy consumption by 27% while producing an average of 0.46 Mg·ha^{-1}y^{-1} of biochar	[100]
Economics of charcoal production in miombo woodlands of eastern Tanzania: some hidden costs associated with commercialization of the resources	• assigning monetary values to commercial production of charcoal (using traditional earth kilns) in the miombo woodlands surrounding Kitulanghalo Forest Reserve in eastern Tanzania, through cost-benefit analysis (CBA)	• the profit from charcoal production is attributable to very low capital outlays, "free" own labor, "free" raw materials, lack of concern about associated external costs and high demand for charcoal • when the cost of labor, raw materials and opportunity costs were considered, the NPV value was negative (US $−868 ha^{-1}), indicating that profit realization is accomplished at the expense of other potential uses of the woodlands • although commercialization of wood resources provides tangible monetary benefits, it contributes to the resource depletion that threaten their long-term survival	[101]
Techno-economics of rice husk pyrolysis, conversion with catalytic treatment to produce liquid fuel	• Fluidized Bed Fast Pyrolysis (FBFP) and Fluidised Bed Fast Pyrolysis with Catalytic Treatment (FBFPCT)	• FBFP was economically better than FBFPCT for the production of primary pyrolysis oil that could be used as boiler fuel oil and for the production of catalytically treated upgraded, liquid-products • The FBFP 1000 kg/h plant unit appeared to be economically feasible, with the lowest unit production cost of primary pyrolysis oil	[102]
Technical, economical, and climate-related aspects of biochar production technologies: A literature review	• carbonization technologies (pyrolysis, gasification, hydro-thermal carbonization, and flash carbonization)	• a wide range of data on the costs of char production (between 51 US $ per ton pyrolysis biochar from yard waste and 386 US $ per ton retort charcoal) and on the GHG balance of biochar systems (between 1054 kg CO$_2$e and +123 kg CO$_2$e per t dry biomass feedstock) were published • more data from pilot projects are needed to improve the evaluation of biochar production technologies • additional research on the influence of biochar application on surface albedo, atmospheric soot concentration, and yield responses is necessary to assess the entire climate impact of biochar systems • further field trials on the ability of different technologies to produce chars for agricultural soils and carbon sequestration are essential for future technology evaluation	[40]
Life cycle assessment of biochar systems: Estimating the energetic, economic and climate change potential.	• using life cycle assessment to estimate the energy and climate change impacts and the economics of biochar systems • agricultural residues (corn stover), yard waste, and switch grass energy crops were used	• the economic viability of the pyrolysis-biochar system is largely dependent on the costs of feedstock production, pyrolysis, and the value of C offsets • biomass sources that have a need for waste management such as yard waste have the highest potential for economic profitability (+$69 t^{-1} dry feedstock when CO$_2$e emission reductions are valued at $80 t^{-1} CO$_2$e) • the transportation distance for feedstock creates a significant hurdle to the economic profitability of biochar-pyrolysis systems • biochar may at present only deliver climate change mitigation benefits and be financially viable as a distributed system using waste biomass	[103]

value of C offsets. It may be profitable to apply biochar as a soil amendment under some conditions if the biochar market price is low enough and/or a carbon offset market exists. [104] further proposed that the price of biochar has a bearing in accordance with its production temperature. Profitability was sensitive to the biochar selling price with a break-even at a biochar price of about $220/t for the pyrolysis at 300°C and about $280/t for pyrolysis at 450°C. Economic biochar renders financial benefits to the user which includes increased production and reduced fertilizer requirements. In addition, the biochar producer or user may benefit from carbon credit under an emissions trading scheme. The producer could receive credits for stabilizing organic carbon, avoiding emissions from decomposition; alternatively, the landholder may receive credits for increasing the soil carbon stock in his field where biochar is applied. With the growing cost of waste disposal and implementation of renewable energy targets, the production and application of biochar and waste management will become more economically viable. Numerous studies have focused on the properties and application rates of biochar and their impacts on agricultural productivity [1] [2] [15] [16], while others examined biochar's potential in sequestering carbon [8] [33] [40] [101] yet there is a gap to link biochar production from portable midscale reactors if conventional farmers are to produce their own biochar. The economic feasibility for using a biochar production system is important for product commercialization. Factors such as operational costs, fixed costs and revenues from biochar production and sales must be considered [105].

4. Biochar Production and Forest Security

Although the application of biochar to soil has great environmental and agricultural contributions, controversy related to its application does exist, especially if timber is cut from forests specifically for use as a biochar feedstock material. If timber is primarily cut for biochar production, this could lead to deforestation and subsequently threaten food security since this could compromise on the amount of rainfall useful for agriculture. However, this can be avoided if biochar is produced from waste material such as waste wood, saw dust, rice husk, rice straw, empty fruit bunches, etc. instead of merely burning them. Slash and char can keep up to 50% of the carbon in a highly stable form [1]. Thus biochar production from agricultural wastes must be encouraged to avoid the extinction of forests.

5. Conclusion

Based on the reviewed work, there is need to develop and promote efficient technologies that can be integrated into biochar production systems. Such technologies should be easily adaptable to enable sustainable, low emission biochar production for both the users and the environment. There is need to develop mobile but economical technologies at midscale levels that can be adopted by small scale farmers. Economic technologies striking a balance between good technical performances and mobility could easily be adopted into the local community for sustainable biochar production. Most studies have focused on the properties and application rates of biochar and their impacts on agricultural productivity while others examine biochar's potential in sequestering carbon. There is lack of understanding on how a particular biochar technology impacts biochar production costs as well as biochar properties. It is thus important to investigate on how change in ER affects rice husk char properties for autothermal gasification systems. Linking rice husk biochar production with the costs involved makes the research path more certain with prospects for investments. Thus, the need to develop and test portable but economically viable rice husk gasification technologies remains relevant.

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