Environmental Science & Technology
CRITICAL REVIEW
pubs.acs.org/est

Technical, Economical, and Climate-Related Aspects of Biochar Production Technologies: A Literature Review

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ABSTRACT: For the development of commercial biochar projects, reliable data on biochar production technologies is needed. For this purpose, peer-reviewed scientific articles on carbonization technologies (pyrolysis, gasification, hydrothermal carbonization, and flash carbonization) have been analyzed. Valuable information is provided by papers on pyrolysis processes, less information is available on gasification processes, and few papers about hydrothermal and flash carbonization technologies were identified. A wide range of data on the costs of char production (between 51 US$ per tonne pyrolysis biochar from yard waste and 386 US$ per tonne retort charcoal) and on the GHG balance of biochar systems (between −1054 kg CO_2e and +123 kg CO_2e per t dry biomass feedstock) have been 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. Above all, further field trials on the ability of different technologies to produce chars for agricultural soils and carbon sequestration are essential for future technology evaluation.

1. INTRODUCTION

In recent years, biochar application to soil has been put forward as a tool to mitigate global warming and improve soil properties.[1−3] In spite of considerable scientific work on the effects of biochar application to soil with respect to crop yields and stabilization of plant-derived carbon in agricultural soils, the commercial production of biochar for soil improvement and C sequestration is still very limited today. Parties interested in the development of commercial biochar need reliable and comprehensive data on the different technologies available for biochar production. For this reason, this paper summarizes the available peer-reviewed scientific literature (ISI Web of Knowledge) about the technological, economical, and climate-relevant aspects of carbonization technologies.

Biochar is defined as "*charred organic matter applied to soil in a deliberate manner, with the intent to improve soil properties*" in Lehmann et al.[4] Although biomass-derived char can be used as energy carrier, as adsorber, and for further applications, this paper focuses on the production of chars for the improvement of soil properties.

Carbonized organic matter can have fundamentally different physical and chemical properties depending on the technology (e.g., torrefaction (a pyrolysis process at low temperature), slow pyrolysis, intermediate pyrolysis, fast pyrolysis, gasification, hydrothermal carbonization (htc), or flash carbonization) used for its production. Research on torrefied material as soil amendment has started only recently.[5] In contrast to considerable research which has already been carried out to assess the value of charcoal as soil amendment,[6−10] no publication was identified which examines the use of chars from modern gasifiers as soil amendment. Charcoal can be produced both in traditional earthen charcoal kilns where pyrolysis, gasification, and combustion processes are carried out in parallel below the earthen kiln layer and in modern charcoal retorts where pyrolysis and combustion processes are physically separated by a metal barrier. Two papers have been published on the suitability of htc-char for the stabilization of organic carbon,[11,12] and another on the suitability of htc-char for the improvement of soil properties.[13] Only one publication is available today in the ISI Web of Knowledge on the suitability of the use of carbonized material from flash carbonization as a soil amendment.[14] It is important to be aware that the results of the indicated publications with carbonized material from torrefaction, hydrothermal carbonization, and flash carbonization did not show an improvement of plant growth after the addition of carbonized material.

As phytotoxic components have been found in torrefied material[5] and torrefied material has hydrophobic properties, this technology is treated in less detail in this review. Apart from that, all main technology routes already mentioned have been fully

Received: December 22, 2010
Accepted: September 30, 2011
Revised: September 13, 2011

Table 1. Publications Identified and Reviewed Per Category

technology type	technological maturity	profitability analyses	climate impacts
pyrolysis	2	7	6
gasification	7	2	1
hydrothermal carbonization	2	0	0
flash carbonization	1	1	0

included in this literature review as today's knowledge on the suitability of carbonized material from modern gasification, hydrothermal carbonization, and flash carbonization for the improvement of soil properties is still very limited. However, it is indispensable to further assess the ability of the different technologies to produce carbonized material suitable to increase the fertility of agricultural soils and to store carbon over a long period of time. In this context, special care has to be taken to avoid the use of chars contaminated with polycyclic aromatic compounds or dioxins for agricultural purposes. A detailed discussion of dioxin formation is presented by McKay,[12] and limits for dioxin and polycyclic aromatic hydrocarbon levels in compost and sewage sludge in European countries can be found in Libra et al.[12]

It should be noted that in field trials, often mixtures of char and compost are used with the aim to produce a soil amendment similar to the fertile Terra Preta soils in the Amazon region.[1] Though char makes up a minor weight component of this soil amendment, it is an essential part of the final product.

2. METHODOLOGY

To identify the relevant literature for this review, the ISI Web of Knowledge was explored with the following method: By searching for articles containing the keywords "pyrolysis", "gasification", "hydrothermal carbonization", and "flash carbonization" in connection with the keywords "reliability", "availability", "durability", "development + hours", and "scale up", the *technological maturity* of carbonization technologies was assessed. To retrieve publications that analyze the *economical profitability* of carbonization technologies, the keywords "profitability", "economics", "production costs + char", and "return + char" were used. Regarding the *climate impact* of carbonization technologies, the keywords "GHG balance", "LCA", "albedo", and "atmospheric soot" were selected.

The available peer-reviewed scientific literature about the technological, economical, and climate-relevant aspects of the different technologies varies considerably. This can be seen in the overview on the number of publications identified and reviewed per technology and assessment aspect (Table 1). In addition to that, information on carbonization technologies is often focused on the production of energy carriers only. This will be reflected in the following chapters.

As this paper concentrates on publications in the ISI, it cannot be excluded that additional publications are available in other scientific databases.

3. OVERVIEW OF CARBONIZATION TECHNOLOGIES

To produce carbonized organic matter, pyrolysis, gasification, hydrothermal carbonization, and flash carbonization technologies can be used. Pyrolysis can be differentiated from gasification by the (nearly) complete absence of oxygen in the conversion process.[16]

Pyrolysis technologies can be further differentiated by the reaction time of the pyrolysis material (e.g., slow and fast pyrolysis processes) and the heating method (e.g., pyrolysis processes started by the burning of fuels, by electrical heating, or by microwaves). Bridgwater[16] and IEA Bioenergy[17] differentiate pyrolysis technologies according to the temperature and the residence time of the pyrolysis process (see Table 2).

In gasification processes, the biomass is partially oxidized in the gasification chamber[18] at a temperature of about 800 °C[16] at atmospheric or elevated pressure. As already indicated by its name, the main product of this process is gas, only small amounts of char and liquids are formed.

The hydrothermal carbonization of biomass is realized by applying elevated temperature (180−220 °C) to biomass in a suspension with water under elevated pressure for several hours. It yields solid, liquid, and gaseous products.[19] Libra et al.[12] refer to hydrothermal carbonization as "wet pyrolysis". Because no oxygen is supplied to the reactor with the biomass−water suspension, this classification is justified.

For the flash carbonization of biomass, a flash fire is ignited at elevated pressure (at about 1−2 MPa) at the bottom of a packed bed of biomass. The fire moves upward through the carbonization bed against the downward flow of air added to the process. In total about 0.8−1.5 kg of air per kg of biomass are delivered to the process. The reaction time of the process is below 30 min, and the temperature in the reactor is in the range of 300−600 °C. The process results mainly in gaseous and solid products. In addition to that, a limited amount of condensate is formed. While the oxygen input into the carbonization process is a typical feature of gasification technologies, both process temperature and the product spectrum (distribution among solid, liquid, and gaseous outputs) of flash carbonization are uncommon for gasification processes. It should be noted that typical solid product yields obtained by gasification and fast pyrolysis processes are significantly lower as compared to the solid product yields of slow pyrolysis, flash carbonization, hydrothermal, carbonization and torrefaction (see Table 2).

It is important to take into account that the development history of the different technologies reviewed varies considerably: The development of coal gasification started already a few centuries ago[26] whereas the development of charcoal kilns has taken place over a time span of millennia.[21]

4. TECHNOLOGICAL MATURITY OF CARBONIZATION TECHNOLOGIES

To understand the challenges that need to be solved to ensure a high annual availability of a biochar production system, Table 3 lists technical points that need special attention to ensure a long-term operation of the respective technologies.

4.1. Pyrolysis Technologies. Bridgwater et al.[18] assumed an overall annual availability of 85% for an electricity production process based on liquids produced by fast pyrolysis. This assumption is used in a model to calculate the electricity production costs of the process. The assumption itself is based on the precondition that a buffer storage for pyrolysis liquids limits unplanned generation shutdowns. Thus, the pyrolysis process itself can have a considerably lower availability than 85%.

4.2. Gasification. Bridgwater et al.[18] assumed a mean annual availability of 80% for an electricity production process based on

Table 2. Solid Product Yields, Solid Product Carbon Content, and Carbon Yield of Different Technologies

process type	typical process temperature	typical residence time	typical solid product yield on a dry wood feed-stock basis [in mass %]	typical carbon content of the solid product [in mass %]	typical carbon yield: ($mass_{carbon, product}$/$mass_{carbon, feedstock}$)	reference
torrefaction	∼ 290 °C	10− 60 min	61−84%	51−55%	0.67−0.85	16, 20
slow pyrolysis	∼ 400 °C	minutes to days	≈ 30%	95%	≈ 0.58	16, 21
fast pyrolysis	∼ 500 °C	∼ 1 s	12−26%	74%	0.2−0.26	16, 17, 22, 23
gasification	∼ 800 °C	∼10 to 20 s	≈ 10%			15, 16
htc	∼ 180−250 °C	1−12 h	<66%[b]	<70%[a]	≈ 0.88	12, 24
flash carbonization	∼ 300−600 °C	<30 min	37%	≈ 85%	≈ 0.65	25

[a] The carbon content of 70% of the product indicated in Tsukashima[24] is related to the dry, ash-free product. [b] Lower solid product yields for htc at both shorter and longer residence times are reported by Libra et al.[12]

Table 3. Selection of Technology-Specific Challenges

technology type	technological challenges	reference
pyrolysis	• achieving and maintaining high, controlled heat rates and a correct reaction temperature; a low gas-vapor residence time at a moderate temperature • a rapid removal of char and effective liquids recovery can be challenging in fast pyrolysis systems • the release of chlorine from feedstock with high Cl content may result in corrosion of the reactor containment and in formation of deposits during pyrolysis gas conversion	Jensen et al.,[27] Bridgwater et al. [18]
gasification	• aerosol formation • soot formation due to repolymerization • dehydration of tars in the gas phase and interaction with other contaminants on fine particles • condensation of heavier tar components on cooler surfaces • blockage of particulate filters and clogging of fuel lines/injectors in internal combustion engine • corrosion caused by tars	Nunes et al.,[33] Buchireddy et al. [28]
hydrothermal carbonization	• the elasticity limit of the materials used for the pressure tank may not be exceeded during operation • feeding against pressure in continuous systems is challenging regarding material and safety aspects • a heat recovery from the hot process water and post-treatment installations for the htc-char might be necessary	Funke and Ziegler,[19] Libra et al. [12]
flash carbonization	• sudden pressure rise in carbonization container observed at ignition under specific process conditions with certain feedstock's • the elasticity limit of the materials used for the pressure tank may not be exceeded during operation	Wade et al.[29]

a dual fuel diesel engine fed by the atmospheric gasification of wood chips and diesel as auxiliary fuel. In the model, it is assumed that the ash produced from the atmospheric gasification process contains 33% char on a weight basis. Bridgewater et al.[18] further assumed the same annual availability (80%) for an electricity production process based on an integrated gas turbine combined cycle fed by the pressurized gasification of wood chips. It has to be noted that this technology is still in an early development stage.

Yin et al.[30] described a circulating fluidized bed biomass gasification and power generation system based on rice husk installed in 1998 which has been operating for 10 000 h within two years of operation. A considerable part of the char produced in the gasifier is removed from the product gas and returned to the gasifier.

According to Pröll et al.,[31] the 8 MW_{th} dual fluidized bed steam gasification plant for solid biomass in Güssing, Austria has been operated for 24 000 h between April 2002 and the end of 2006. This translates into an average plant availability of about 58%. In 2005, an average availability of about 69% was reached (6000 operation hours in one year).[32]

Table 4. Annual Availability of Electricity Production Systems

process name	annual availability	comment	reference
fast pyrolysis	>85%	model assumption	Bridgwater et al.[18]
atmospheric gasification	80%	model assumption	Bridgwater et al.[18]
pressurized gasification	80%	model assumption	Bridgwater et al.[18]
fluidized bed gasification	90%	model assumption	Yassin et al.[34]
circulating fluidized bed gasification	57%	empirical data	Yin et al.[30]
circulating fluidized bed gasification	58%; 69%	empirical data	Pröll et al.,[31] Kreuzeder et al. [32]

Nunes et al.[33] described the negative effect of tar formation on the operational availability of gasification, but do not indicate quantitative numbers on the annual availability of gasification processes.

Yassin et al.[34] assumed an availability of an electricity production system based on the fluidized bed gasification of residual waste of 90% (329 days per year) within a model to evaluate the techno-economic performance of energy from waste fluidized bed gasification.

4.3. Summary. Most information is available on gasification processes, less information is available on pyrolysis technologies (Table 4). Papers on the availability and reliability of carbonization technologies are often not based on empirical data and do not cover hydrothermal and flash carbonization technologies at all. The available knowledge is focused on systems for the production of pyrolysis oil, synthesis gas, electricity, or heat. In summary, a comparison of the technological maturity of biochar production technologies based on scientific literature in not possible at the moment. In Table 4, data on the annual availability of production processes as indicated in the reviewed papers are summarized. The difference between the assumed availability rates and the empirical data is evident.

5. PROFITABILITY ANALYSES OF CARBONIZATION TECHNOLOGIES

The focus of the literature review in this section was on publications issued not earlier than the year 2000, since profitability analyses are subject to rapidly changing economic framework conditions. Apart from that, they are often only valid for a specific project in a specific region at a specific point in time. Depending on the type of technology used, biogenic energy carriers (biogenic oil, synthesis gas), electricity, or heat are produced together with the char and constitute the main product, byproduct, or residue of the biomass conversion process. A considerable part of the described processes aim primarily at the provision of bioenergy. In these cases, the indicated economic data cannot be directly used to assess the profitability of the described technologies for biochar production. However, the indicated economic data can be used as a benchmark to assess under which conditions the production of biochar would be more (or less) profitable compared to the production of a bioenergy carrier. It is important to be aware that the (bio)energy and the biochar markets compete for the same feedstock, and that biochar-based soil amendments compete with other products (e.g., peat, pure compost) and other methods used to improve soil properties. To enable a direct comparison, the published economic data have been converted to US $ at historical exchange rates and has been inflation-adjusted to the reference year 2010 (US$$_{2010}$).

5.1. Pyrolysis. Islam and Ani[35] carried out a techno−economic assessment of fluidized bed fast pyrolysis systems with rice husk throughputs of 100 and 1000 kg/h. The systems were assumed to be installed in Malaysia in a study carried out in 2000. Since the study focuses on the production of the pyrolysis oil, production costs of 0.38 US$ (0.5 US$$_{2010}$) per kg primary pyrolysis oil [at 100 kg feed/hour] and 0.18 US$ (0.23 US$$_{2010}$) per kg primary oil [at 1000 kg feed/hour] have been calculated. Because solid char is coproduced by the fluidized bed fast-pyrolysis system, the sales price of the primary pyrolysis oil could be reduced if the char would be sold. Unfortunately, production costs for the solid char cannot be derived from this study. However, the energy value of char from fast pyrolysis within the process can be calculated. Based on the higher heating value of char from fast pyrolysis (about 28 MJ/kg)[22] and the price of wood pellets as an alternative biogenic heating fuel (0.05 €$_{2011}$/kWh; 0.0202 $$_{2010}$/MJ), the energy value of the char is as high as 560 US$$_{2010}$ /tonne. It should be noted here that the value of the char is considerably lower if a cheaper conventional fuel is replaced. For example, Badger et al.[36] calculate with residual heating oil as replacement at a price of 0.0109 $$_{2010}$/MJ.

Bridgwater et al.[18] calculated electricity production costs of 0.091 € (0.098 US$$_{2010}$)/kWh at 20 MW$_{el}$ and 0.199 € (0.215 US$$_{2010}$)/kWh at 1 MW$_{el}$ for a modeled electricity production process in UK based on liquids produced by fast pyrolysis and diesel as auxiliary fuel. Taking into account learning effects and assuming a 50% reduction of capital costs of fast pyrolysis modules after 10 installations, they calculated electricity production costs of 0.073 € (0.078 US$$_{2010}$)/kWh at 20 MW$_{el}$ and to 0.146 € (0.157 US$$_{2010}$)/kWh at 1 MW$_{el}$. In their model it is assumed that char and off-gas produced during the pyrolysis are burned to cover the internal heat demand of the installation. As calculated already above, the energy value of the char can be as high as 560 US$$_{2010}$/tonne.

Lin and Hwang[37] assessed the profitability of charcoal production from discarded Cryptomeria branches and wood tops using a still-operational earthen kiln in Taiwan. This analysis was based on empirical data combined with market research. Charcoal production cost of 3707 US$ (3747 US$$_{2010}$)/tonne can be derived from the analysis. If the revenues of selling wood vinegar are subtracted from the sum of production cost, the char could be sold at a whole-sale price of 1840 US$ (1860 US$$_{2010}$) per tonne. Considering charcoal prices in Taiwan amounted to 3030 US$ (3063 US$$_{2010}$)/tonne at the time of the analysis according to the Lin and Hwang,[37] the production process was judged to be economically feasible in their publication. However, the charcoal sales price assumed in this calculation—it is not stated in the mentioned publication if the indicated sales price is a retail price or an end customer price—is extremely high and exceeds even the end customer price for retort barbecue charcoal in Germany in 2011 (2700 US$$_{2010}$). Thus, it is doubtful whether the assumed sales price can be realized for the total production volume indicated in the calculation (13 000 kg charcoal/year). Whereas charcoal production might thus not be profitable in the described example, charcoal production for energy applications—both in simple charcoal kilns and in modern retort systems—is clearly profitable for many charcoal producers around the globe.[38] Thus, Lin and Hwang[37] might overestimate charcoal production cost in earthen-kilns. For comparison, Norgate and Langberg[39] calculated charcoal production cost of 373 US$ (386 US$$_{2010}$)/tonne based on a continuous charcoal retort.

In a very detailed assessment, Roberts et al.[40] calculated the economic viability of a modeled continuous drum kiln "slow" pyrolysis plant with a throughput of 10 tonnes dry feedstock mass per hour at a temperature of 450 °C and a drum residence time of several minutes in the United States. Aim of the process is to produce biochar for soil management and synthesis gas for heat provision. Taking into account revenues from selling the biochar (its value is calculated on basis of the potassium and phosphate content of the biochar and an improved nitrogen fertilizer use efficiency caused by the application of the char), a tipping fee for the disposal of yard waste, the sales of heat produced from the synthesis gas, avoided composting costs, and the sales of GHG offset certificates (at a price of 20 US$ per tonne CO_2), biochar produced on the basis of yard waste yields a positive return of 16 US$ per tonne dry feedstock. This calculation takes into account the opportunity costs of switching from yard waste based compost production to biochar production. Biochar produced on the basis of corn stover and switch grass cannot be produced in a profitable way under the same assumptions. For these types of feedstock, negative returns of −17 US$ to −30 US$ per tonne dry feedstock have been calculated. It should be noted here that the costs for the transportation of feedstock from dispersed locations to the pyrolysis plant can play a major role in the overall production costs of biochar. In this respect, the opportunity of sourcing biochar feedstock from a single location—e.g., from a composting collection station as assumed in the calculation cited above—can be a clear cost advantage.

Under these framework conditions, the direct production cost (not taking into account the opportunity costs for not producing and selling compost) amount to 50 US$ per tonne dry feedstock (or 172 US$ per tonne biochar at 29% wt biochar yield), while the total direct revenues (not taking into account avoided costs for composting) amount to 112 US$ per tonne dry feedstock (or 368 US$ per tonne biochar). Of the direct revenues, 35 US$ per tonne dry feedstock (121 US$ per tonne biochar) are gained by sale of heat produced from the synthesis gas of the pyrolysis process. Only 11 US$ per tonne dry feedstock (38 US$ per tonne biochar) are associated with the agricultural value of biochar. Without the revenues from the sales of GHG offset certificates, the pyrolysis process would be just at the edge of profitability. Two aspects regarding the profitability analysis of the yard waste analysis need further examination: Is it possible to create GHG offset certificates from a biochar project? Since this is not possible on the market for legally binding GHG emission reductions, only the voluntary market would offer chances to sell GHG offset certificates from biochar projects. In addition to that, potential yield increases associated with the application of biochar—yet not connected to its potassium and phosphorus content alone—have not been included yet in the value of biochar and might improve the profitability of the analyzed system substantially.

Brown et al.[38] reported total annual operating costs including fixed costs, capital depreciation, and coproduct credits of about 71 million US$$_{2010}$/year for a slow pyrolysis facility with 262.000 tonnes of biochar production per year. From these figures, the production costs for one tonne biochar can be calculated at 272 US$$_{2010}$. For a fast pyrolysis facility with an output of 172 million liters of biogenic gasoline from biooil, total annual operating costs of 67,500,000 US$$_{2010}$ and biogenic gasoline production costs of 0.39 US$$_{2010}$/liter can be derived from the study. If the indicated production cost could be realized, this facility would be highly profitable. The paper assumes that only 26% of the coproduced char is used within the fast pyrolysis process to provide heat, the remaining char is sold.

5.2. Gasification. Yin et al.[30] indicated a payback period of less than two years for a circulating fluidized bed biomass gasification and power generation system installed in 1998 in the Fujian Province of China. As already stated before, a considerable part of the char produced in the gasifier is removed from the product gas and returned to the gasifier. For this system with a throughput of 1500 kg rice husk/hour providing a power output of about 800 kW, total investment costs of 510,000 US$ (625,000 US$$_{2010}$) are necessary. However, the amount of data provided in this article to underline the claimed payback period of two years is very scarce. In addition to that, the indicated investment costs (about 640 US$ (784 US$$_{2010}$)/kW) are very low. The energy value of char from gasification within the process is calculated in the last part of this subchapter.

Bridgwater et al.[18] calculated electricity production costs of 0.1 € (0.11 US$$_{2010}$)/kWh at 20 MW_{el} and 0.22 € (0.24 US$$_{2010}$)/kWh at 1 MW_{el} installed capacity for an electricity production process based on a dual fuel diesel engine fed by the atmospheric gasification of wood chips and diesel as auxiliary fuel. They assumed electricity production costs of about 0.09 € (0.097 US$$_{2010}$)/kWh at 20 MW_{el} and of about 0.26 € (0.28 US$$_{2010}$)/kWh at 1 MW_{el} for an electricity production process based on an integrated gas turbine combined cycle fed by the pressurized gasification of wood chips. In this model, it is assumed that the ash produced from the atmospheric gasification process contains 33% wt char, resulting in an overall carbon conversion efficiency of the system of 99.5%. Thus, nearly no char is left after the biomass conversion process.

Peer-reviewed profitability analyses of gasification systems aiming at the sale of the char produced in the process are not available in the ISI to the knowledge of the authors. This can be partly explained by the development focus of this technology which is clearly set on the provision of energy, and by the technical challenges still connected with the biomass gasification technology. It is important to be aware that the operators of gasifiers will only sell the coproduced char of the gasifiers if a char price is paid which at least covers the cost for an alternative heating fuel for the gasification process. Jorapur and Anil[41] indicate a higher heating value of 18.9 MJ for gasifier char. This would correspond to an energy value of about 380 US$$_{2010}$/tonne gasifier char if wood pellets would be used to replace the char used as fuel in the gasifier.

5.3. Flash Carbonization. Antal et al.[42] stated that the actual capital investment incurred in the fabrication and setup of a flash carbonization demonstration reactor (1.73 m D × 2.74 m H) at the University of Hawaii were 270,000 US$ (290,000 US$$_{2010}$). To these costs, US$ 30,000 (32,300 US$$_{2010}$) have to be added in case a 1.27 MPa (12.7 bar) air compressor is installed to provide pressure to the reactor. In case a 2.17 MPa (21.7 bar) air compressor would be used, about US$ 120,000 (129,000 US$$_{2010}$) has to be added to the costs of the reactor. According to

Table 5. Production Costs for Char and Energy Carriers As Indicated in Reviewed Papers

process type	production costs	comment	reference
fluidized bed fast pyrolysis	0.23−0.5 US$$_{2010}$ per kg pyrolysis oil	no sales of coproduced char assumed	Islam and Ani[35]
fluidized bed fast pyrolysis	0.39 US$$_{2010}$/L biogenic gasoline from pyrolysis oil	26% of coproduced char used within the process	Brown et al.[38]
electricity production based on fast pyrolysis	0.098 US$$_{2010}$/kWh $_{el}$ at 20 MW$_{el}$; 0.215 US$$_{2010}$/kWh $_{el}$ at 1 MW$_{el}$	char used to cover the internal heat demand of the process	Bridgwater et al.[18]
fast pyrolysis	560 US$$_{2010}$/tonne char[a]	energy value of fast pyrolysis char in the process	own calculation
slow pyrolysis (earthen kiln)	3747 (*1860*) US$$_{2010}$/tonne charcoal	sales of coproduced wood vinegar excluded (*included*) in the production cost	Lin and Hwang[37]
slow pyrolysis (Lambiotte continuous retort)	373 US$ (386 US$$_{2010}$)/tonne charcoal	production costs based on wood production and wood processing (charring) cost	Norgate and Terry[39]
slow pyrolysis (drum kiln)	51 US$$_{2010}$ per tonne char from yard waste	sales of heat from syngas included in the production costs	Roberts et al.[40]
slow pyrolysis	272 US$$_{2010}$ per tonne char from corn stover	corn stover feedstock costs: 83 $/tonne	Brown et al.[38]
circulating fluidized bed gasification		investment: 510,000 US$$_{2010}$; capacity: 1500 kg feed/h	Yin et al.[30]
electricity production based on atmospheric gasification	0.11 US$$_{2010}$/kWh $_{el}$ at 20 MW$_{el}$; 0.24 US$$_{2010}$/kWh $_{el}$ at 1 MW$_{el}$	only 0.5% of the carbon in the feedstock is converted to char	Bridgwater et al.[18]
electricity production based on pressurized gasification	0.097 US$$_{2010}$/kWh $_{el}$ at 20 MW$_{el}$; 0.128 US$$_{2010}$/kWh $_{el}$ at 1 MW$_{el}$	no information on char production and char use available	Bridgwater et al.[18]
gasification	380 US$$_{2010}$/tonne char[a]	energy value of gasification char in the process	own calculation
flash carbonization	no information available	investment: 419,000 US$$_{2010}$; Capacity: 430 kg char or 1300 kg feedstock/h (at 2.17 MPa)	Antal et al.[42]

[a] Char value has been calculated based on the costs for an alternative heating fuel (wood pellets).

the authors, the 2.17 MPa systems have an output of 8.4 tonnes/day of fixed-carbon, whereas the 1.27 MPa system has an output of 6.1 tonnes/day of fixed-carbon at 24 h of operation. A rough profitability analysis is indicated in the paper with the aim to compare the two systems from an economical point of view. This analysis—which resulted in very short payback periods of 3.7 and 1.3 years for the 1.27 and the 2.17 MPa systems, respectively—however cannot be used to assess the overall profitability of the two systems due to the limited amount of cost data included in the calculation. It is possible that only little economic information on this process has been published by the authors for confidentiality reasons.

5.4. Summary. Most information is available on pyrolysis (especially slow pyrolysis) processes. Though the information provided on the economics of a slow pyrolysis system aimed at the production of heat and biochar is very detailed, it is only partly based on empirical data of an already installed system. In summary, a thorough comparison of the profitability of biochar production technologies based on scientific literature is not possible at the moment. In Table 5, data on the economic viability of the different production processes as indicated in the reviewed papers are summarized.

6. GREENHOUSE GAS (GHG) BALANCE OF BIOCHAR PRODUCTION AND APPLICATION

Before discussing the value of biochar technologies for climate change mitigation, it is important to understand the overall context of mitigation strategies. Sufficiency (lifestyle changes), efficiency, and renewable fuel switch strategies help to avoid the emission of greenhouse gases before they enter the atmosphere. Biochar systems can help to mitigate global warming also after fossil CO_2 has already been released to the atmosphere. Whereas biochar systems thus offer the opportunity to act also if other climate change mitigation strategies should fail, it is important to not weaken the necessary efforts in the field of sufficiency, efficiency, and renewable fuel strategies. This risk would become very concrete if the sale of GHG certificates from biochar projects on the carbon compliance market would enable utilities to offset their fossil fuel emissions in "temporary" emission reduction projects, instead of implementing efficiency or fuel switch measures needed in an existing cap-and-trade system. In contrast to that, trading GHG certificates from biochar projects on the voluntary market would not reduce the mitigation pressure in the carbon compliance market. For a discussion of the same mechanism in the context of forestry offset projects, see Streck et al.[43]

To fully assess the GHG balance of biochar conversion technologies, information on feedstock provision (including direct and indirect land use change effects), conversion process, byproducts use, biochar application, biochar stability in soil, influence of biochar application on soil related N_2O, CH_4, and CO_2 emissions and on plant growth—including associated impacts on land use—is needed.[12,44,45] To compare the greenhouse gas impact of the production and use of biochar to a reference scenario with an alternative use of the feedstock, it is necessary to provide detailed information on this reference scenario. To comprehensively assess the climate-related effects

Table 6. Climate Impacts of Biochar Production Technologies

GHG related impacts	**Color Code: Positive impacts**		**Color Code: Negative impacts**	
(L)arge impact:	> 500 kg CO_2e emission reductions / tonne dry feedstock		> 500 kg CO_2e emission increase / tonne dry feedstock	
M)edium impact:	> 250 kg CO_2e emission reductions / tonne dry feedstock		> 250 kg CO_2e emission increase / tonne dry feedstock	
(S)mall impact:	< 250 kg CO_2e emission reductions / tonne dry feedstock		< 250 kg CO_2e emission increase / tonne dry feedstock	
Publication	**Woolf et al. (*39*)**	**Roberts et al. (*40*)**	**Gaunt, Lehmann (*49*)**	**Searcy, Flynn (*50*)**
Process Type	Pyrolysis	Pyrolysis	Pyrolysis	Gasification
Indirect Land Use Change	Assessed, no impact assumed	(M-L), negative	Not assessed	Not assessed
Direct Land use Change	Assessed, no impact assumed	(S), positive	(S), positive	Not assessed
Feedstock Provision	(S), negative (only transport assessed)	(S), negative	Not assessed	(S), negative
Replaced Process (e.g. composting)	(S), positive	(S), positive	Not applicable	Not assessed
Conversion process	Assessed, no impact assumed	(S), negative	Not assessed	No impact
Use of byproducts (e.g. syngas)	(M), positive	(M), positive	(S-M), positive	(L), positive
Biochar Application Process	(S), negative	(S), negative	Not assessed	Not applicable
Biochar Sequestration in the soil	(L), positive	(L), positive	(L), positive	Not applicable
Increased Fertilizer Efficiency	(S), positive	(S), positive	(S), positive	Not applicable
Change of Soil CO_2 – Emissions	(S), negative	Not assessed	Not assessed	Not applicable
Change of Soil N_2O – Emissions	(S), positive	(S), positive	(M), positive	Not applicable
Change of Soil CH_4 – Emissions	Assessed, no impact assumed	Not assessed	Not assessed	Not applicable
Plant response (Carbon uptake)	Assessed, impact not included	Assessed, no impact assumed	Not assessed	Not applicable
Yield impact on land use	(S), positive	Not assessed	Not assessed	Not applicable
Non-GHG related impacts:				
Atmospheric Soot Concentration	Not assessed	Not assessed	Not assessed	Not applicable
Change of Surface Albedo	Not assessed	Not assessed	Not assessed	Not applicable

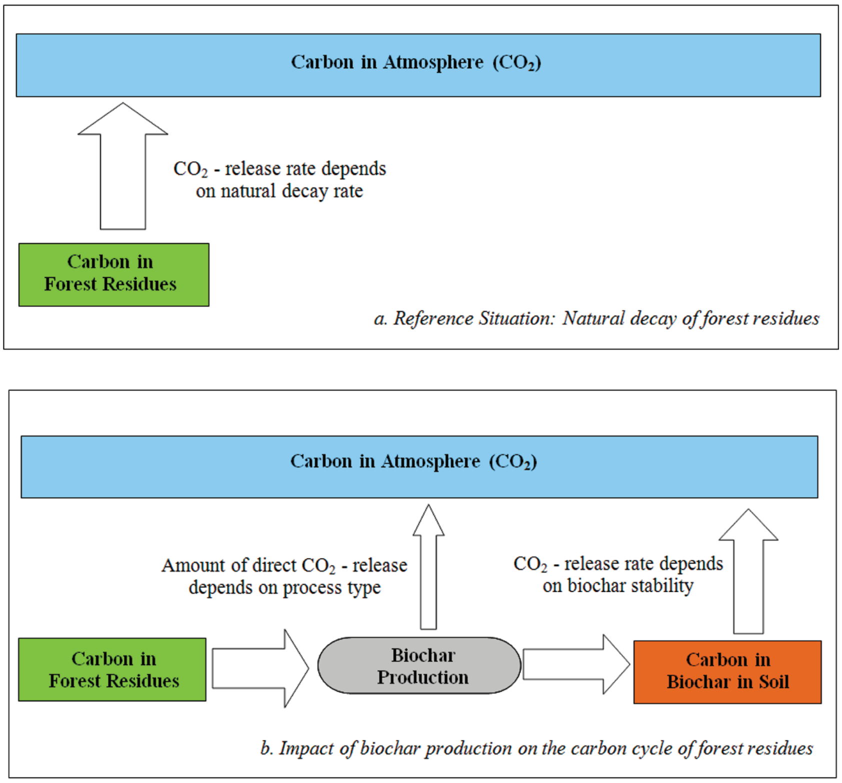

Figure 1. Impact of biochar production on the natural carbon cycle.

of biochar application, insight into the impacts of biochar application on surface albedo[46] and on black carbon concentration in the atmosphere[47] is needed in addition to the information summarized above. In the following sections it is indicated to which extent these aspects have been included in the reviewed literature articles. Table 6 gives an overview of the analyzed publications which are described in detail in the following sections.

From Table 6 it is evident that biochar sequestration in the soil is one of the main factors positively influencing the GHG balance of the biochar systems. Taking into account the variety in char yields of different technologies (see Table 2) and the differences in the long-term stability of chars made from different technologies (see Nguyen and Lehmann;[51] Steinbeiss et al.[11]), the full effect on biochar systems on the natural carbon cycle has to be understood. Whereas the production of char is in most cases slowing down the carbon cycling of the charred fraction of the feedstock (as compared to a reference situation with the natural decay of, e.g., forest residues or agricultural residues)[52] the release of CO_2 from the biomass conversion process will speed up the carbon cycle of the uncharred feedstock fraction compared to the reference situation (Figure 1). For a detailed discussion of this effect in the context of bioenergy and biochar use, see Repo et al.[53] and the supplementary information to the publication of Woolf et al.[39]

6.1. Pyrolysis Technologies. Woolf et al.[39] calculated the maximum sustainable technical global potential for the contribution of biochar systems to climate change mitigation. In this very comprehensive paper, all GHG related impacts of pyrolysis biochar production and application have been assessed. The potential impacts of biochar systems on the atmospheric soot concentration—via biomass smoke and via black carbon dust becoming airborne—and on the surface albedo are mentioned in the Supporting Information to the paper, but have not been examined in detail. In the alpha scenario of the publication, 66 Gigatonnes CO_2-C equivalent net avoided GHG emissions have been calculated over a time period of 100 years for the production and application of biochar derived from about 1.01 Gigatonnes biogenic carbon per year. Assuming an average carbon content of 50% for dry biomass, 2.02 Gigatonnes of biomass feedstock are used in the scenario for the production of biochar. As yield improvements are assumed to be triggered by biochar application, the increment in biomass production is reinvested into additional production of biochar in this scenario. Assuming a total consumption of 2.3 Gigatonnes of dry biomass feedstock for the biochar production, this scenario results in average net avoided GHG emissions of -1054 kg CO_2e/tonne dry feedstock and year.

The average avoided GHG emissions indicated above are in line with the results of a recent publication of Hammond et al.:[54] in this paper, a carbon abatement of 0.7−1.3 t CO_2 equivalent per oven dry tonne of feedstock processed has been calculated. They also fit with the calculations of Roberts et al.[40] in those of their scenarios which assume that biochar is produced from unused residues.

Roberts et al.[40] calculated comprehensive greenhouse gas balances for the production and application of biochar produced from different feedstock in a slow pyrolysis process. The authors included most of the climate-relevant factors but did not account for impact of biochar application on soil CH_4 and soil CO_2 emissions, on the surface albedo and the soot concentration in the atmosphere. The latter two aspects do not impact on the GHG balance of biochar production and application itself, but they influence the sum of climate relevant effects of biochar application. To calculate the GHG impact of the production and use of biochar, a reference scenario has to be taken into account to describe changes in emissions when the biochar system is implemented. Under the assumption used by Roberts et al.,[40] the following results have been calculated: Choosing a reference scenario in which yard waste is used for composting, 885 kg CO_2e per t dry biomass feedstock can be saved when switching from yard waste composting to the production and application of biochar. Choosing a reference scenario in which corn stover is left as residue on the field (thus not used to provide bioenergy in the reference scenario), 793−864 kg CO_2e per t dry biomass feedstock can be saved when switching to the production and application of biochar. The range of emission reduction depends on the moisture content of the corn stover used for biochar production. However, if corn stover were used to produce electricity (thereby replacing natural gas based electricity generation) in the reference scenario, GHG emissions would increase by 123 kg CO_2e per t dry biomass feedstock when switching to use the stover in a biochar system. Switching from a reference scenario with agricultural crop production to the cultivation of switch grass and the subsequent use of this feedstock for biochar production might either reduce GHG emission by 442 kg CO_2e per t dry biomass or increase GHG emissions by 32 kg CO_2e per t dry biomass, depending on the amount of GHG emissions assumed to be triggered via indirect land use change effects. Indirect land-use change effects are caused when an existing production of agricultural goods is displaced by the cultivation of energy crops on the same plot of land. As an effect of that, other land areas, e.g., primary rain forest might be converted to arable land to compensate for the decrease in the previous production of agricultural goods.

In contrast to Roberts et al.,[40] Hammond et al.[54] do not account for indirect land use change effects when assessing the GHG balance of biochar systems. Thus, the latter calculate substantial carbon abatements for biochar systems even in the case of wood chips from short rotation coppice being used for biochar production.

A less comprehensive GHG balance for a slow pyrolysis-based biochar system has been carried out by Gaunt and Lehmann.[49] The authors did not account for indirect land-use change impacts triggered by the production of energy crops, the emissions connected to the provision and the conversion of the biomass feedstock, the energy use necessary for biochar application, the impact of biochar application on plant growth and associated land use effects, soil CH_4 and soil CO_2 emissions, the impacts on the surface albedo, and the soot concentration in the atmosphere. Based on their assumptions, they calculated GHG emission reductions of 10.7 t CO_2 ha^{-1} yr^{-1} for corn stover. For direct comparison, Roberts et al.[40] calculated emissions reductions of 7 t CO_2e ha^{-1} yr^{-1} in a similar scenario for corn stover if this feedstock would have remained a field residue in the reference scenario. If corn stover and switch grass were used for pyrolysis based electricity production in the reference scenario (thereby replacing natural gas-derived electricity), switching to a pyrolysis system optimized for biochar production would reduce GHG emissions by 8.5 t CO_2e ha^{-1} yr^{-1} in the case of using corn stover as feedstock and by 7.6 t CO_2e ha^{-1} yr^{1} in the case of using wheat straw as feedstock according to Gaunt and Lehmann.[49] Because direct and indirect land-use change effects were not taken into account for using energy crops as feedstock, the calculated emission reductions for energy crop scenarios are not indicated here.

Whereas Libra et al.,[12] did not calculate a complete GHG assessment of biochar systems, they observed both a reduction in soil N_2O emission and CO_2 efflux four weeks after mixing sandy loam brown earth mixed with pyrolysis biochar.

6.2. Gasification. Searcy and Flynn[50] calculated emission reductions of switching from coal-based electricity production to a straw-based integrated gasification and combined cycle electricity production system at 839 g CO_2e per kWh of produced electricity (1680 kg CO_2e/tonne dry feedstock). It should be noted that this technology is still in an early development stage. Apart from that, no extraction of biochar out of the integrated gasification and combined cycle was assumed in this study.

6.3. Summary. Peer-reviewed greenhouse gas balances on the production and application of biochar were identified for pyrolysis technologies only. The more recent publications in this field—Woolf et al.[39] and Roberts et al.[40]—are far more comprehensive compared to older papers since they cover more GHG related impacts of the biochar systems. Depending on the types and previous use of the biomass feedstock, both reductions and increases of GHGs have been calculated for biochar systems.[39,40,49] GHG reductions are often not achieved if dedicated energy crops are used as feedstock for the production of biochar or if biomass residues are already used for the provision of bioenergy in the reference scenario. From a GHG perspective alone, the most recent studies give a clear indication under which conditions biochar systems can contribute to mitigate climate change. However, as explained above, the calculations do not yet take into account all relevant climate impacts of biochar systems: Insights into the impacts of biochar application on the surface albedo and on the black carbon (soot) concentration in the atmosphere have not been added yet to the GHG balances of the biochar systems in the publications reviewed. In this context, it should be noted that Vaccari et al.[53] reported positive soil temperature anomalies up to 2 °C in open field biochar plots during the initial phases of durum wheat production. These aspects should also be taken into account when comparing the full climate benefit of bioenergy vs biochar systems (see also Woolf et al.[39]). Last but not least—as already indicated—it is important to use biochar-based mitigation options complementary to existing mitigation strategies instead of replacing the latter.

7. OUTLOOK

The peer-reviewed papers analyzed provided valuable insights into technical reliability, economic feasibility, and climate impact of different carbonization technologies. Most papers focus on pyrolysis technologies, less information is available on gasification processes. Publications on gasification processes often do not take into account the potential suitability of the char as a product for soil improvement. Very little information about hydrothermal and flash carbonization technologies with relevance for this review has been published yet. Two comprehensive studies on the economic profitability and the GHG balance of a slow pyrolysis process have been identified which point at economic and environmental chances of biochar systems (Roberts et al.[40] Woolf et al.[39]). Data from pilot projects would be essential to further improve assessments on the technical reliability and economic profitability of biochar production technologies. To complement the assessments on the climate impact of biochar production technologies, additional information on the impact of biochar application on surface albedo, atmospheric soot concentration, and yield responses would be needed. The GHG balance of biochar systems itself has been already quite well examined in recent papers with promising results regarding climate mitigation opportunities.

In most of the studies, only one assessment dimension of a technology is analyzed. Comparisons between different technologies—see for example the papers of Bridgewater et al.[18] or Brown et al.[38]—are rare as well. Empirical data on the annual availability of technologies which (co)produce biogenic chars has only been published from gasification systems aimed at the production of electricity (in this sector, annual availability rates of 60−70% were measured). A wide range of data on the costs of char production (between 51 $\$_{2010}$ per tonne pyrolysis biochar from yard waste and 386 US$\$_{2010}$ per tonne retort charcoal) and on the GHG balance of biochar systems (between −1054 kg CO_2e and +123 kg CO_2e per t dry biomass feedstock) can be retrieved from the literature. A comprehensive assessment of the technical, economic, and environmental strength and weakness of biochar production technologies is unfortunately still not possible yet on the basis of the available scientific peer-reviewed literature. This is at least partly explainable by the fact that the production of biomass-based chars for the improvement of agricultural soils is still a relatively new topic of scientific interest. Further research of both the public and the private sector on the indicated knowledge gaps and its publication is necessary to support project developers, technology developers, and policy makers with a comprehensive and detailed picture on the different options to produce biochar for soil improvement and climate change mitigation.

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ACKNOWLEDGMENT

S.M. thanks his supervising tutors, his colleagues from Ecofys—special thanks go to Carlo Hamelinck—and three anonymous reviewers for providing valuable comments and suggestions for this work. In addition, S.M. thanks Anne for her interest in carbon stories. Finally, we thank all authors, companies, and institutions who provided the knowledge on biochar production technologies needed to compile this paper.

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