CHAPTER 11:

Biochar Production

Brennan Pecha, Karen M. Hills, Manuel Garcia-Pérez, Josiah Hunt, Tom R. Miles, Kelpie Wilson, and James E. Amonette

BASICS OF BIOCHAR PRODUCTION & CO-PRODUCTS

In production of biochar, thermochemical processes that can be used to treat biomass include pyrolysis, gasification, hydrothermal processing, and combustion. Each of these processes is defined by specific operating conditions (e.g., temperature, presence of oxygen) and feedstock requirements for optimal conversion to the product of primary interest. Each process results in varying fractions of gaseous, liquid, and solid products.

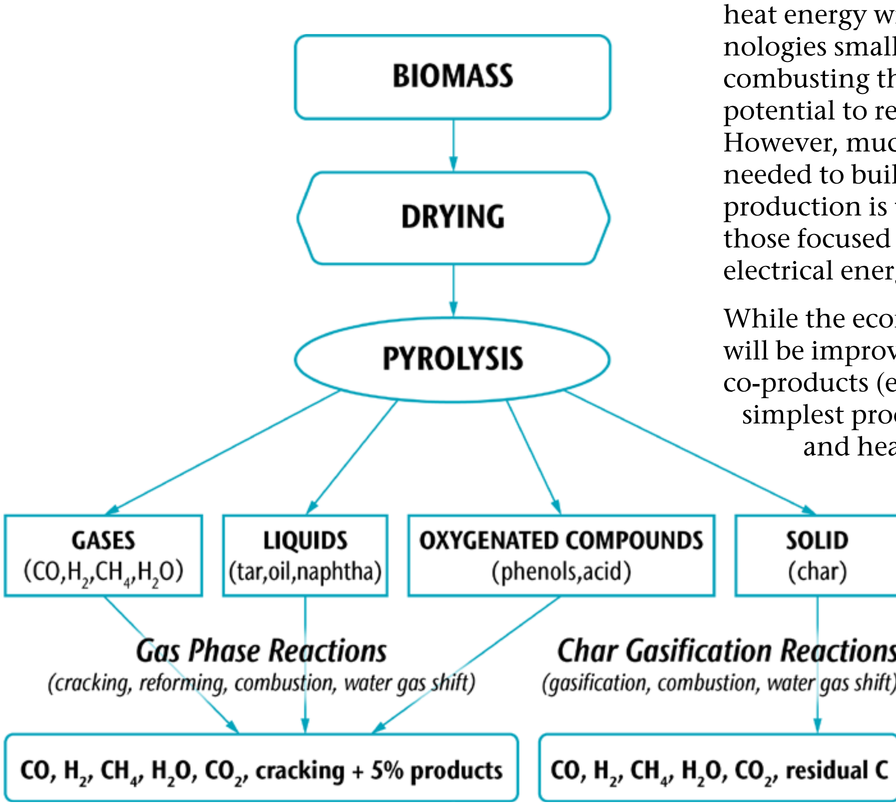

Figure 11.1. *Gasification routes. (Source: Sikarwar et al. 2016, licensed under CC BY-NC 3.0)*

Though other publications have emphasized the gaseous bio-energy products of such processes (e.g., bio-oil, synthesis gas or "syngas") with biochar as a co-product, in this discussion, we focus primarily on biochar as the main product, with heat and electrical energy as co-products of secondary interest. The reasons for this are as follows: when producing biochar, heat is the simplest form of energy to capture and utilize, electrical energy can be generated from heat energy with a wide range of available technologies small and large; rather than immediately combusting the gases released from biomass, there is potential to refine the gases into bio-oil and syngas. However, much larger investments of capital are needed to build facilities for which gaseous fuel production is the primary goal, as compared to those focused on biochar production with heat and electrical energy co-products.

While the economic viability of biochar production will be improved by production of high-value co-products (e.g., wood acids for use in pesticides), the simplest production scheme is one in which biochar and heat are the primary products. Here we aim to provide a broader overview of thermochemical processes and technologies most relevant to biochar production in its current state of commercialization.

All biochar is a result of pyrolysis (the reaction) but not all biochar is made with a dedicated pyrolysis reactor (the technology type). Further, all biochar is the result of

Table 11.1. *General conditions of pyrolysis (slow and fast), gasification, and combustion.*

	Slow Pyrolysis	Fast Pyrolysis	Gasification	Combustion
Time required for reaction	minutes - hours	seconds	seconds	seconds
Typical particle size for operation	wood chips - logs	saw dust - milled wood	milled wood – wood chips	wood chips
Temperature (°C)	300-800	400-700	750-1,000	1,000-1,200
Main product	biochar	bio-oil	syngas	heat
Biochar yield (wt. %)	35-50	15-30	5-10	<2

a lack of complete combustion (the reaction), even biochar produced in a combustion or gasification reactor (the technology type). This is an important distinction to acknowledge in the following sections in which we discuss both thermochemical conversion reactions and technology types.

THERMOCHEMICAL CONVERSION OF BIOMASS TO BIOCHAR

The progression from biomass to the resulting products is shown in Figure 11.1. Biomass moves from drying to pyrolysis, which is a thermal decomposition process in the absence of oxygen that separates components of biomass into gases, liquids, oxygenated compounds (e.g., wood vinegar), and solid (biochar). Biochar recovery occurs at this stage. Some systems capture the gases, liquids, and oxygenated compounds for making other products, while in other systems these products undergo gasification (further thermochemical conversion in the presence of oxygen).

While there are a number of thermochemical conversions that can result in biochar, here we focus on pyrolysis (slow and fast), gasification, and combustion. Torrefaction, hydrothermal carbonization, and hydrothermal liquefaction are other chemical conversion processes that have arisen from a bioenergy approach and are discussed in further detail by Brown (2019) and Clifford (2020).

Pyrolysis

Depending on the particle heat transfer rate achieved, it is possible to identify two types of pyrolysis reactors: *slow and fast pyrolysis*. Table 11.1 shows a comparison of these two processes with gasification and combustion, while Figure 11.2 offers a comparison of the distribution of resulting products.

Slow Pyrolysis

Slow pyrolysis, also called conventional carbonization, produces biochar by heating biomass at a low heating rate (around 5-7 °C per minute) for a relatively long residence time and typically uses large particles like wood chips or even whole logs. These conditions produce less liquid (30-50 by weight [wt. %]) and more biochar (35-50 wt. %) than fast pyrolysis.

Fast Pyrolysis

With fast pyrolysis, the process of heating biomass is rapid (heating rates of over 300 °C/min). Fast pyrolysis is typically used to obtain high yields of single-phase bio-oil. Fast pyrolysis uses small particles, generally smaller than 5 mm in diameter, due to the low thermal conductivity of lignocellulosic materials. High-rate heating of lignocellulosic materials typically yields 60-75% bio-oil, 15-30% biochar, and 10-20% non-condensable gas, and can be done in seconds. Most fast pyrolysis systems currently in commercial use consume the biochar that they make rather than recovering the biochar.

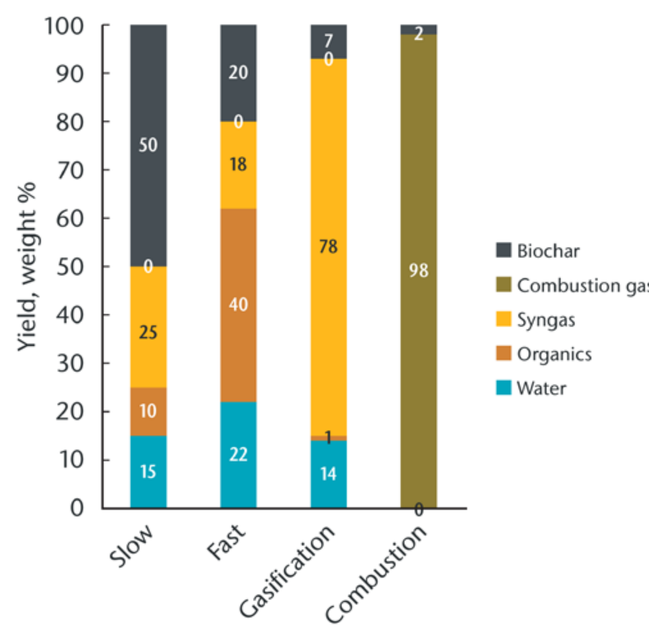

Figure 11.2. *Typical distribution of products from the three main thermochemical conversion technologies used to process low-moisture biomass feedstocks: slow pyrolysis, fast pyrolysis, and gasification. (Modified from Zhu et al. 2018)*

Gasification

Biochar can also be produced by gasification, a process that differs from pyrolysis in that some oxygen is present and much higher temperatures are used (>750 °C; Table 11.1). Gasification has been used since the 1800s in energy generation from coal and biomass. Gasification is used to convert carbon-based materials into carbon monoxide, hydrogen, and carbon dioxide (syngas or producer gas). The gas mixture can then be combusted to generate power. While gasification technologies were designed for power, rather than biochar production, biochar can be produced with this approach.

An appeal of this technology group is that there are readily available gasification units. A drawback of this technology group is that the conversion efficiency of biomass to biochar appears to be limited to relatively low levels, though conversion efficiency depends on the specific technology used. More information on gasification technologies can be found at the *Biofuels Academy website*.

Combustion

Reactors relying on combustion are primarily designed for generating heat, which is commonly used for a combination of steam turbine electrical generation and secondary heat uses such as curing lumber or drying grain. Biomass is heated in the presence of oxygen and the resulting gases are burned in the same vicinity of the biomass, thus driving the continuation of the process.

Though the word combustion seems antithetical to the production of biochar, combustion as a technology type is perhaps responsible for a majority of the biochar produced in North America. The key is that not all combustion technologies result in 100% complete combustion (which would yield ash as the solid product); in fact, the opposite statement is more accurate as combustion technologies typically do not result in complete combustion. When oxygen is present, but insufficient for complete combustion, biochar can be pulled out of the system. Combustion in a boiler will generally yield 1.5-2% biochar.

TECHNOLOGIES

Technology Considerations

Technologies for biochar production can be distinguished by mode of operation, need for pretreatment of feedstock, heating considerations, and emissions. In some cases, post-processing is used to further modify the characteristics of the resulting biochar.

Mobility

One of the most defining features of technologies is whether they are designed to be relocatable or operated at a fixed location. Relocatable technologies are generally small-moderate scale and can be operated at forest landings, lowering cost of feedstock transport.

Mode of Operation

Depending on the mode of operation, technologies can be classified as batch, semi-batch, or continuous.

Pretreatment of Feedstock

Pretreatment of feedstock improves the efficiency of pyrolysis and can include drying, size reduction (generally with a knife chipper or hammer mill; See *Chapter 10: Biomass Handling*). In general, slow pyrolysis for production of biochar and heat does not require as much pretreatment as fast pyrolysis for bio-oil production. Homogeneity in feedstock (in size and geometry) minimizes variations in dryness and off gassing of volatile organic compounds (VOCs) due to a set detention time in continuous modes of operation,

Heating

Biochar production requires heating the biomass to temperatures in which the biomass denatures moisture and volatile compounds, and the biomass is modified to amorphous and crystalline structures. In general, this is done with a flame heating the biomass, either directly or indirectly, to temperatures in excess of 400 °C. In order to create the lowest emissions profile, the biochar production equipment should be designed to operate on the synthesis gases produced for the process heat to pyrolyze or gasify the biomass. Oxygen contacting the biomass can burn off excessive carbon, but this is often a fair trade-off due to the potential for process intensification. Utilizing heat produced during biochar production can be used for drying incoming biomass which can improve overall efficiency. (See Combined Heat and Biochar, page 154.)

Emissions

Off-gas from the pyrolysis or gasification process (also referred to as syngas or producer gas) has high energy content, typically rich in mixtures of carbon dioxide (CO_2), carbon monoxide (CO), hydrogen gas (H_2), water (H_2O) and volatile and semi-volatile hydrocarbons including methane (CH_4). Combustion of the syngas can provide more than enough heat to drive the pyrolysis process, if designed into the overall process. Syngas can provide more than the amount of energy needed for drying and thermal treatment. However, a supplemental gas may be required for startup and shutdown at a minimum. Any biochar technologies need to comply with relevant regulations on emissions. Emissions issues are discussed in *Chapter 12: Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems*.

Postprocessing Technologies

Postprocessing of biochar can include a number of processes that may take place after pyrolysis including steam quench systems are applied that may include processes to further activate, or functionalize, the biochar, or physical modifications such as size reduction or pelletizing for ease of handling, blending, or application. Biochar materials can be engineered for a particular end-uses, by methods such as adding particular minerals, acids, plant nutrients, or activation with carbon dioxide to alter functional properties. Further information on engineered biochar for particular environmental services can be found in Garcia-Perez et al. (2017).

Technology Types

This section discusses some of the most commonly used types of technology for production of biochar. An in-depth understanding of the socioeconomic context of biochar production must govern specific choices of technologies. Production units should be chosen with specific context (e.g., feedstock types and amounts, products) and a clear business model in mind. Slow and fast pyrolysis reactors have been reviewed elsewhere (Garcia-Nunez et al. 2017). Specific technologies used for producing biochar at or near the forest (rather than at centralized facilities) are described further in Page-Dumroese et al. (2017). Table 11.2 provides an overview of most applicable technology types for biochar production, with text descriptions for each provided below. Table 11.3 shows further considerations in terms of categories of biochar production equipment and contexts in which each best fits.

Flame-Cap Kiln

The flame-cap kiln (or mini kiln) is a small, low-cost kiln operated by small landowners with the primary benefit of being able to be transported by one to two people. Forest residues are generally cured for a year or more prior to putting in the flame-cap kiln. Flame-cap kilns are an example of a batch system and have low rates of biochar production. Batch systems require to be lit, filled to capacity, cooled/quenched/emptied and repeat. This operation can be slower than desired, depending on biomass to be consumed and need to move on to additional treatments. This can be overcome by increasing the number of production units, but not without proportionally increasing labor logistics and costs to archive higher production rates. Therefore, flame-cap kiln production tends to remain low (McAvoy & Dettenmaier 2020). Larger flame-cap kilns (e.g., "big box" kilns) exist with larger openings that may be filled by a loader rather than by hand. For more information on types of flame-cap kilns, see Table 4.1 in *Chapter 4: Place-Based Biochar Production*.

Conservation Burn

An alternate method of constructing slash piles exists in which base logs elevate the rest of the pile above the soil and these limit soil impacts and can result in approximately 10-15% of the biomass retained as biochar (depending on pile conditions). Piles need to be quenched or built so they self-extinguish, but biochar can be made which is suitable for soil restoration in or near the piles. More information on techniques for using conservation burns to produce biochar is available in Page-Dumroese et al. (2017).

Mobile Carbonizer

The key feature of these systems is their mobility. One example of a mobile carbonizer is an air curtain burner operated in "pyrolysis mode." This technology was created as an alternative to slash pile burning (with a more favorable emissions profile) and disposal rates are typically 1-10 tons per hour. Large trees and brush can be loaded into the air curtain burner without chipping and there are relatively few moving parts. When operated in standard mode, ash results rather than biochar. However, by changing some of the operating parameters, these units can be used to produce biochar (AirBurners n.d.).

This type of modified air curtain burner has higher production capacity than the previously mentioned batch systems. They are considered "throughput systems" because biomass is introduced at one end, heated to reduce material to charcoal. Once charcoal forms on the burning biomass it is separated from the burn box and quenched at the other end. This type of production is intended to eliminate part of the batch system to increase biochar production. At least two equipment manufacturers are in the market (TigerCat & AirBurners Inc.).

Table 11.2. *Biochar production processes (Modified from Miles & Wilson 2020)*

Equipment	Processes[1]	Typical Capacity Input of Feedstock[2,3]	Typical Capacity Output of Biochar[2,3]	Status[4]	Examples
Flame-Cap Kilns	G, C	0.6 tpd/kiln × 180 days = 110 tpy/kiln[5]	2 CY/kiln/day × 180 days/yr = 360 CY/kiln/yr[5]	I	Ring of Fire, Oregon, WarmHeart, Big Box, Kon Tiki
Conservation Burn	G, C	variable[6]	Estimated 10-15% of pile volume[7]	I	Sonoma Ecology Center, Wilson Biochar Associates
Mobile Carbonizers	G, C	70 tpd × 180 days = 13,000 tpy	22 CY/day × 180 days/yr = 4,000 CY/yr	I	AirBurner, Tigercat
Combined Heat and Biochar	C, G, P	4 tpd × 310 days = 1,200 tpy	10 CY/day × 310 days/yr 3,100 CY/yr	I, Es	BET, Biomacon, Pyrocal, ICMICM
Portable Retorts	P	1.3 tpd/retort × 155 days = 200 tpy/retort[8]	4.6 CY/day/retort × 155 days = 710 CY/retort/yr[8]	I	Biochar Now
Boilers/Combustion	C	10 tpd × 310 days = 3100 tpy[9]	70 CY/day × 310 days = 22,000 CY/yr[9]	I, Es	Oregon Biochar Solutions, Pacific Biochar
Rotary Kilns	P	240 tpd × 310 days = 74,000 tpy	750 CY/day × 310 days = 230,000 CY/yr	Es	National Carbon Char Technologies, Heyl & Patterson, FEECO, Schenck Process, Sanju Environmental
Heated Augers	P	6 tpd × 310 days = 1,900 tpy	100 CY/day × 310 days = 31,000 CY/yr	Es, I	Pyreg, Artichar, VOW/Biogreen, Carbon Powdered Mineral Technology
Gasifiers	G	20 tpd × 310 days = 6,200 tpy	38 CY/day × 310 days = 12,000 CY/yr	Em, I, Es	V-Grid, KDS Systems, ICM, Ag Energy Solutions, Pyrocal, Coaltec

[1] Processes: C – Combustion, G – Gasification, P – Pyrolysis
[2] Capacity: Mobile 180 days/yr, 1,800 hrs/yr; Stationary 310 days/year, 7,440 hours/year; 200 lb dry/CY
[3] Abbreviations: CY (cubic yards), tpd (tons per day), tph (tons per hour), tpy (tons per year)
[4] Status: Em – Embryonic (bench, pilot), I – Innovative (limited adoption), Es – Established (widespread)
[5] As many as 8 flame-cap kilns can be operated by a work crew at a single site.
[6] Conservation (slash pile) burns vary widely in size, depending on whether material is gathered by hand or machine.
[7] Dumroese et al. 2017
[8] Each retort cycle requires 48 hours. Typically deployed in groups of 40 for maximum economic throughput, or 3 per trailer for short-term sites.
[9] Bioenergy facilities; assumes 2% of total biomass feedstock is added to maintain constant power output during biochar production; fraction of total biomass feedstock that converts to recoverable biochar is unknown but is significantly larger than that needed to maintain power.

Table 11.3. *Biochar equipment type considerations.*

Equipment Type	Scale[1]	Production Capacity per Unit (tons/day)[2]	# Units in Parallel	Feedstock Processing Requirement	Feedstock Transport. Distance (miles)	Integrations	Heat	Electricity	Capital Cost	Labor Needs
Flame-Cap Kiln	Place-based	0.1-1.0	8-12	cut to length	0	forest application			very low	high
AirBurner	Place-based, Moderate	0.3-7.0	1-4	cut to length, bale or chunk	0-10	forest application /biochar revenue stream			low	medium
Mobile Pyrolysis Unit	Moderate	0.3-9.0	1-40	chip, bale or chunk	0-10	biochar revenue stream			medium	medium
Industrially Integrated Unit[3]	Moderate	0.3-75.0	1-2	chip	0 (feedstock on-site for other process)	use in compost or other mfg. process on site	●		medium	medium
Combined Heat and Biochar	Moderate	0.1-1.0	1-2	chip	up to 50	biochar revenue stream	●		low to medium	low
Central Boiler	Large	5.0-10.0	1	chip	up to 50	biochar revenue stream	●	●	high	medium

[1] Descriptions of place-based, moderate, and large-scale centralized production are provided in *Chapter 1: Introduction*.
[2] Values are for biochar produced.
[3] Industrially integrated units can include gasifiers, rotary kilns, heated augers, and boilers from Table 11.2.

Combined Heat and Biochar

In the process of making biochar, thermal energy is produced which can be used for heating or cooling. Combined heat and biochar (CHAB) can be used to provide heat for a variety of purposes, for example. vermicomposting, or for heating greenhouses, for product drying, or for water heating. Capturing this heat and putting it to use improve the economic viability of the biochar operation and improve climate impacts. For more information, including a review of six systems available on the market and appropriate for CHAB, see Wilson & Miles (2020).

Portable Retorts

Historically, the term retort referred to a reactor that has the ability to pyrolyze pile-wood, or wood logs over 30 cm long and over 18 cm in diameter (Emrich 1985). In modern times it refers to a pyrolysis system (partially closed vessel of biomass heated from exterior), in which the gases released from the vessel are captured and used to provide heat for driving the reaction in the closed vessel. Some examples of portable retort types include Adam retort and screw-auger retort.

Boiler/Combustion

Conventional biomass boilers can be converted by reducing the residence time of biomass in the boiler, resulting in greater production of biochar, with a reduction in energy production. Alteration of existing boilers for producing biochar may require changes to feedstock moisture content and particle size, oxygen ratio for optimal biochar production. This type of retrofitting of boilers has occurred on a limited scale in the region and, in some cases, may be more economical than competing options. A description of modification options is offered in *Chapter 6: Centralized Biochar Production Facilities*.

Rotary Kiln

Rotary kilns were developed for large-scale forest harvest operations and can process up to 20 tons of feedstock in 24 hours. A rotating metal tube allows the feedstock (wood chips) to be rapidly heated with gas burners to 400-600 °C. The rotary kiln offers a great amount of control to the operator and is housed within a shipping container. The main product can be bio-oil or biochar, depending on the process conditions.

Heated Augers

The heated auger reactor is usually fed at one end through a hopper or a feeding screw, which carries the biomass to the hot zone of the reactor where it is carbonized. The gases and vapors are extracted and sent to a condenser (Garcia Nunez et al. 2017). Studies with woody biomass show biochar yields between 17 and 30 wt. % and yields of oil between 48 and 62 wt. % (Meier et al. 2013).

Gasifiers

Gasifiers can be either updraft (fuel enters from the top, gasifying agent from the bottom) or downdraft (both fuel and gasification agent enter from the top). *Downdraft gasifiers* (SERI 1988) can produce fuel that you can run in an engine and result in biochar yields of 2-5%. Updraft gasifiers (e.g., *the Lurgi reactor*) operate more like a furnace with biochar yields of up to 15%. While traditional updraft gasifiers are designed to burn the wood all the way to ash, they can be designed to output biochar as well.

Further reading on gasification can be found in Sikarwar et al. (2016).

This section does not contain a comprehensive list of all thermochemical conversion technologies, but instead focuses on systems that have high technology readiness levels. For further reading on the practicalities of biochar production, see Lehmann & Joseph (2015; Chapters 3 and 4).

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