Using Pyrolysis to Create Biochar

Subjects: Green & Sustainable Science & Technology

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Pyrolysis is a combustion process of woody biomass conducted under low or no oxygen conditions. It converts any kind of biomass into biochar, bio-oil, or biogas. Hence plants' woody material can also be converted into bioenergy products. Valorization of woody biomass in the form of energy-rich compound biochar is a more sustainable technique as compared to conventional burning which leads to toxicity to the environment. Innovations and the need to limit open burning have resulted in numerous mobile and fixed plant pyrolysis methods that burn a variety of woody residues.

biochar pyrolysis emissions pollutants

1. Introduction

Woody biomass is a renewable feedstock with a growing variety of applications for producing biobased products. Creating biochar under limited air conditions can release volatiles, biochar, and thermal energy. During this process, emissions of several pollutants occur such as CO, CO_2, aerosols (PM2.5 and/or PM10), NO, NO_2, and a mix of both known as nitrogen oxides (NOx), methane, NMHC, and total suspended particulates (TSP) [1]. However, agricultural residues [2] and waste timber [3] also produce these emissions.

Wood composition has little variation. It consists of 50% C, 44% O, and 6% H, and trace inorganic elements. Combinations of these elements form cellulose, hemicellulose, and lignin [4]. Wood also contains extractives that are nonstructural components of lignocellulose, such as fats, phenolics, resin acids, waxes, and inorganics. The content and character of the extractives varies from biomass to biomass and even varies between different parts of each plant [5][6].

The amount and types of pollutant emissions during the biochar production process could be explained by the variability of the biomass used. This variability is between species (trees, shrubs, grasses, and crops), chemical composition, and the harvesting conditions. Biomass composition characteristics (cellulose, hemicellulose, lignin, extractives/volatiles, and ash) and other properties, such as moisture content and material size, have influence on the biomass conversion process affecting the characteristics of the final product, and the amount of emissions depending on the type of pyrolysis system used. The three key components affecting biomass pyrolysis are ash content, volatiles, and lignin. The high ash content usually has a negative effect on biomass conversion by reducing the effectiveness of dilute acid pretreatment for biological processes and increasing char yields and sediment. Volatiles such as light organic acids (acetic acid and furans), for example, furans, can lower energy content and stability in bio-oils, and lignin can increase oil yield [7].

In pyrolysis, thermal decomposition of organic matter occurs in the absence of oxygen. The temperature at which pyrolysis occurs can be modified together with the reaction time, and the oxygen content is eliminated from the reaction medium. Performing this process allows to achieve high yields of liquid and gaseous products with high added value. Yields can be as high as 75% by weight in the liquid products [4].

According to Pecha and Garcia-Perez [5], wood combustion involves five phases when different temperatures are achieved. The process starts with evaporation of water and other volatile small molecules when temperatures of 200 °C have been reached, followed by torrefaction occurring between 225 and 300 °C, then pyrolysis occurs between 300 and 650 °C, gasification with the addition of limited air occurs between 700 and 850 °C, and finally, combustion with additional air between 450 and 2000 °C. They also pointed out that these phases occur in that order when the heating rate is very slow and an oxidizing agent is present. During the gasification process, reactions convert the char remaining from the pyrolysis step and the pyrolysis vapors into CO, H_2O, CH_4, and H_2, a gas mixture called “syngas”, which is typically produced in oxygen-starved environments. Then, pyrolysis can be summarized as the process that at moderate temperatures produces carbon, with byproducts of carbon dioxide, water, methane, and traces of carbon monoxide [8].

Regarding pollutant emissions, there are two types of pyrolysis: one of them is carbonization, where the vapors are vented to the atmosphere or fired to produce more char and ignore the vapor products, and conventional, which allows for the collection of char, oil, and non-condensable vapors (syngas) to be combusted to recover process heat and/or electricity. Usually, the yield of biochar decreases, as the syngas production increases when the temperature is increased during the pyrolysis process and when air is used to partially oxidize pyrolysis gases [5].

This characteristic of the pyrolysis process technique allows its classification as fast pyrolysis, which is a direct thermochemical process that can liquefy solid biomass into liquid bio-oil for energy production, and slow pyrolysis, where the rate of heating is less than in fast pyrolysis, with longer residence time, and the feedstock is held at constant temperature or slowly heated. The low heating rate promotes adequate heat conduction which produces higher carbon deposition and increased biochar production. In slow pyrolysis, a higher pyrolysis temperature could be used for removing volatile matter from biochar, increasing its fixed carbon [9][10][11][12]. In relationship with biomass characteristics for biochar production with less pollutants, biomass is a clean energy source appropriate for combustion because of its low nitrogen and sulfur content, which restricts the formation of SO_x and NO_x gases and lowers the residues and smells tendency [13][14]. According to Schwartz et al. [15], combusting using fast pyrolysis pine sawdust products met CO, NO_X, and SO_2 EPA’s emissions standards at 10.6 ppm, 16.8 ppm, and 2.3 ppm respectively; although PM emissions exceeded the standards, they could be met using a baghouse filter on the char burner and by adjusting the bio-oil burner air–fuel ratio. They also indicated that Cd, Pb, Hg, HCl, and dioxins/furans were not observed during testing as they typically depend on feedstock or are mostly reduced by burning liquid rather than solid fuels like dioxins/furans.

2. Mobile Biochar Pyrolysis Systems

Biochar has been made for centuries and is one of the oldest and most established processes developed by mankind [16]. Some methods use ‘slow pyrolysis’ which maximizes the amount of solid material (biochar) that is produced [17]. This method is typically what is found in mobile production units, whereas ‘fast pyrolysis’ generates syngas and bio-oil. Mobile units can produce biochar that has a carbon content of 75%–92% carbon, but the results vary by moisture content, equipment used, and feedstock type. Using slow pyrolysis, approximately 15%–20% of the original feedstock is returned as biochar. The process of making charcoal from ancient history up to now has evolved from charcoal pits, mound kilns, and retort kilns to modern technologies involving conventional technologies together with more advanced technologies such as gasification, torrefaction, microwave-assisted pyrolysis, hydrothermal carbonization, and modified traditional methods such as flash pyrolysis, vacuum pyrolysis, and microwave pyrolysis varying from simple units, like heated steel drums to fully automated and controlled processes [16][18].

The first kilns were designed as oven, furnace, or heated enclosures for processing a substance by burning, firing, or drying [19] to maximize charcoal production and were extremely polluting [20][21]. The first portable metal kiln was designed by Whitehead, but the emissions were still high and without any control system [22]. According to Fuchs et al. [23], campfires were the first step in the evolution of slow pyrolysis reactors, where a mound kiln could be considered a slow pyrolysis reactor that is similar to a campfire but covered with soil. Another cleaner type of kiln that evolved from the campfire is the so-called open fire kiln or flame cap pyrolysis technologies, defined as low technology systems, designed to restrict oxygen access to the biochar that releases low emissions as the smoke is burned in the flame [23].

Emissions associated with traditional charcoal making and kilns are usually characterized as CO, CH4, NMHC, and TSP, although NMHC regularly includes methanol, acetic acid, and other oxygenated organic compounds, which are part of the VOCs [20]. Similar to wood burning during a wildfire or prescribed fire, the emissions interact with atmospheric chemistry, producing ozone, other oxidants, and carbon monoxide. Chemistry has regional air quality implications but also could have global effects on the organic carbon budget and the global warming potential of the emitted VOCs [24]. Mobile units that use a retort design (an inner chamber filled with wood and an outer chamber to insulate) significantly decrease emissions because the pyrolysis gases are combusted internally; however, biochar yield is not great, and the cost of a retort kiln does not make them attractive for producers [25][26]. Schettini et al. [27] found that furnace kilns could reduce GHG emissions by 40.2% and increase biochar yield by 32.5% higher as compared to other kiln types used in Brazil that do not have the GHG burners.

Mobile biochar pyrolysis system could be defined as small-scale portable thermochemical conversion systems for processing forest biomass residues in situ, where the feedstock is carbonized in a controlled aerobic environment with limited oxygen at a temperature between 700 °C and 750 °C. These systems include kilns and trailer-mounted or hauled pyrolysis equipment that can be used on-site.

Kilns are still used today, and they can be of varying sizes, but the basic principles of how to burn the wood are similar. Kilns are lit at the top of the wood and there is air movement across the top to feed the flame that heats the woody biomass. Kilns lit this way develop a flame cap that helps reduce emissions and many of the emitted gases are burned while also helping to create biochar underneath the flame. The constant air flux keeps the flame going as new raw material is fed. The combustion process maintains low flame lengths and is one method to reduce embers, sparks, and gaseous emissions. In short, this type of pyrolysis takes advantage of burning pyrolysis gases to help create biochar [28][29][30][31][32].

Other kinds of more modern mobile biochar pyrolysis systems are those known commercially as air curtain burners, also known as air curtain incinerators (ACI), and carbonizers. They are based on the principle of the air curtain described above, but they have a source of air flowing continuously to create the air curtain, which works like a lid covering the opening in a firebox. Following the process described above results in a clean burn [33][34]. A grate in the firebox removes the char before it is consumed. Although an open burn pile could be used for the same purpose, the final product will not have the same characteristics because the combustion process is different. In an open burn, the char and the biomass carbon are not protected from oxidizing to CO_2 [31], and the amount of emissions is very high. **Table 1** presents the mobile biochar pyrolysis systems.

Table 1. Mobile biochar pyrolysis systems.

Mobile Pyrolysis Technology	Cost	Biochar Yield
Slash piles [1] 	Low cost—$1000 to 2000 per acre [35].	Limited biochar (1% of the initial volume is converted to biochar [31])
Kilns [1]   Ring of fire Firebox	Low cost from $2000 to $12,000 [35].	Low volume of biochar (it is estimated 25% to 50% of the initial volume is converted to char); larger kilns need a loader, water to quench the biochar [31]
Mobile systems   CharBoss [1] Tigercat Carbonator [2]	Medium from $150,000 to $700,000.	350 lb/h (160 kg/h) [36] Carbonator 6050 converts woody biomass into biochar of the initial volume to, i.e., 71% recalcitrant carbon, 91% void space, 8% ash [37]. Both systems require water for quenching in a water bath and a mini-excavator to load the woody biomass.

[1] Pictures: Carlos Rodriguez Franco, USDA Forest Service; [2] Picture: Tigercat (6050-Carbonator-4pg-1.4-0122-web.pdf (tigercat.com) (accessed on 29 December 2023)).

on system

produced. GWP indicates the amount of energy the emissions of 1 t of a gas will absorb in a given period, in relationship to the emissions of 1 t of CO_2 [38][39]. Although it is important to limit and have standards related to them, the main objective of the NAAQS is to regulate and limit the amount of emissions of pollutants that could cause impacts on human health, the environment, and property. Both the GWP and the NAAQS have in common emission factors and quantification. An emission factor is the amount of a pollutant released to the atmosphere with an activity associated with the release of that pollutant, and it is measured as the weight of the pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant [40][41] (e.g., grams of particulate emitted per kg of woody biomass processed).

Soares Neto et al. [42] in Brazil determined that one hectare of the burned forest had average emission factors for CO_2 with 1599, CO with 111.3, CH_4 9.2, NMHC 5.6, and $PM_{2.5}$ 4.8 g/kg of burned dry biomass. Assessment studies of GHG and other pollutants emitted during biochar production indicated that airborne emissions from charcoal-making kilns commonly used in Kenya and Brazil (mound kilns, and 3 Brazilian kilns) can produce rather large net GHG emissions, and have high GWPs for CO_2, CH_4, and N_2O only, with an estimated value of 0.77–1.63 kg C-CO_2 (carbon as carbon dioxide equivalents) emitted per kilogram of charcoal produced [1]. Sparrevik et al. [2] assessed the use of mound kilns and retort kilns in Zambia and concluded that when considering CO_2 sequestration and climate change effects, the use of biochar with conservation farming is more beneficial than conservation farming alone. Since earth-mound kilns produce negative effects because of the GHG emissions, especially methane, they did not completely annul the positive effect of CO_2 sequestration. However, the effects caused by the PM formation and the impact of the use of biochar produced in earth-mound kilns are inferior to conservation farming without biochar use. A similar conclusion was achieved by Sparrevik et al. [25] who tested the introduction of improved retort kilns where the pyrolysis gases are combusted internally with a significant decrease in emissions of products of incomplete combustion when using similar feedstock; as a result, the yield was not significantly higher with retort kilns, and because of their cost, they concluded that this makes it difficult for their adoption for biochar production in rural areas. Miranda Santos et al. [43] concluded that when charcoal is produced in Brazil, including furnaces, the combustion of gases reduces potential environmental impacts by approximately 90% in both a circular masonry kiln and a rectangular masonry kiln with gas combustion. In terms of climate change, the rectangular masonry kiln with gas combustion was approximately 63% less impactful than the circular masonry kiln with gas combustion. Regarding results of the emissions from all these studies, it is clear that several authors have found, in general, that emissions are reduced in comparison with wildland fires, open burning, slash pile burning, using fixed kilns that could be built on site (mound kilns and low technology brick kilns); still, those emissions are considered high and they have high GWP.

Nowadays, biochar production systems are evolving, and the development of portable biochar technologies could be a solution for rural areas without easy access as this would avoid the transportation of raw material or slash piles that could enhance fire risk, and where biochar could be part of the solution to increase CO_2 sequestration and at the same time decrease the amount of emissions during the production of biochar. This could be a good solution for an improved environment instead of leaving forest residues on piles without any use and producing GHG emissions that could exacerbate climate change, both when they are left for decomposition in the long term or when they catch fire. Lee and Han [44] compared open burning vs. ACB for disposal of forest residues and agreed with the previous statement since they concluded that ACB burning is being adopted in many forests to control emissions, smoke, and embers to improve oxygen and heat supply by the high velocity of airflow during the burn, making this technology much more efficient in reducing the negative environmental and societal impact of disposing forest residues. Susott et al. [45] found that the ACI burning technology traps unburned fine particles under the curtain in the zone where temperatures can reach up to 1000 °C, and the increased combustion time and turbulence result in more complete combustion of the forest residues. When they compared the ACI technology with open burning and slash pile burning, the air curtain incinerator (ACI) tested resulted in close to a 23-fold reduction in $PM_{2.5}$ emissions over pile burns and a 33-fold reduction over understory burns. The Oregon Department of Environmental Quality [46] conducted a source test report for 2023 with an emission factor testing mobile air curtain incinerator in Hillsboro, Oregon, with similar findings in reduction of emission to open burning, wildland fires, slash pile burning, and earth-mound kilns. **Table 2** presents a summary of several studies on air pollution emissions factors for different technologies and includes open burning and wildland fire emissions.

Table 2. Comparison of air pollutant emission factors by different sources including portable biochar kilns.

Source of Emission	Emission Factor										
	CO_2	CO	CH_4	PM_{10}	NMVOC	NO_x	NMHC *	$PM_{2.5}$	PM	Dioxins/Furan	SO
5 earth-mound kilns, (units g/kg) [1]	543–3027	143–373	32–62	-	-	NO_x 0.0054–0.13	24–124	-	13–41	-	-
Forest fires, (units g/kg) [2]	1690	63	3.4	-	-	-	2.6	7.5	-	-	-
Open burning, (units g/kg) [3]	-	50.0	-	-	Aldehyde 3.0	NO_2 2.0	7.5	11	-	-	SO_2 1.5
Open pile burning (Kg/Ton) [4]	10,618	362	17.37	-	28.96	17.37	-	-	37.65	-	-
Open burning, (units g/kg) [5]	-	34.7	1.2	3.7	-	3.1	-	-	-	0.5	SO_2 2.0
Rice residue pile burning (g kg^{-2}) [6]	-	-	-	-	-	-	-	16.9 (±6.9)	-	-	-
Slash pile burning (kg/kg) [7]	1.69	0.0653	0.00454	0.0044	0.00555	0.0025	-	-	-	-	-

Source of Emission	Emission Factor										
	CO_2	CO	CH_4	PM_{10}	NMVOC	NO_x	NMHC *	$PM_{2.5}$	PM	Dioxins/Furan	SO
Air curtain burner (kg/kg) [7]	0.78	0.0026	0.0026	0.00128	-	0.000144	-	-	-	-	-
Oregon kiln (kg/kg) [7]	0.78	0.0026	0.0026	0.00128	-	0.000144	-	-	-	-	-
Biochar Solutions, Inc. (kg/kg) [7]	2.19	0.000698	0.000152	0.00138	-	0.00196	-	-	-	-	-
All-steel kiln (g/kg) [8]	5600	38	57	22	6	0.3	-	-	-	-	-
Steel sheet soil pit (g/kg) [8]	2300	23	14	9	5	0.3	-	-	-	-	-
Soil pit (g/kg) [8]	3800	36	32	20	8	0.8	-	-	-	-	
Shallow steel pyramidal kiln (g/kg) [8]	4700	73	26	5	5	0.32	-	-	-	-	-
Average pile (lbs/t) [9]	3268	179	13.9	-	-	-	9.9	25.5	-	-	-
Average understory (lbs/t) [9]	3286	180	6.6	-	-	-	5.4	36.0	-	-	-
Average ACB (lbs/t) [9]	3616	2.6	1.4.	-	-	-	1.1	1.1	-	-	-
Incinerator (2010) (g/kg) [2]	1280	0.18	-	-	-	1.01	-	-	0.21	6.89×10^{-8}	SO_x 0.12
Japan carbonizer	43.89	0.033	-	-	-	0.43	-	-	0.015	0	SO_x 0.65

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Source of Emission	Emission Factor										
	CO_2	CO	CH_4	PM_{10}	NMVOC	NO_x	NMHC *	$PM_{2.5}$	PM	Dioxins/Furan	SO
(g/kg) [2]											
Char burner PM filter (ppm) [10] **	10.6	-	-	-	-	16.8	- [51]	-	32.6 Mg/m^3	-	2.3
EPA—OSWI (ppm) [10] **	40	-	-	-	-	103	-	-	2 30	-	3.1
EPA large—MSWI (ppm) [10] 2 **	50	-	-	-	2 - [31]	180	-	-	20	-	2 30
EPA small—MSWI (ppm) [10] **	50	-	-	-	-	500	-	-	24	-	30
air curtain incinerator BurnBoss (lbs./t) [11]	1248.5	14.2	0.668	-	1.17	1.98	1.17	-	4.25	2.88×10^{-9}	SO_2 0.24
EPA national standard, primary (p), secondary (S) [12]	- [53][54]	P 9 ppm; S 35 ppm	-	P and S 150 μg/m^3	-	-	-	P 1 year 12.0 μg/m^3; S = 15.0 μg/m^3	-	-	SO_2 0.14 ppm 24 h

The CAA Section 7429 under the category covered by solid waste incinerator units provides the regulation for air emission pollutants, and the CAA Section 7411(d) and Chapter I, Subchapter C, Part 60, Subpart B point out the standards that must include emissions limitations and other requirements applicable to new units and other requirements applicable to existing units [55].

In 2005, the EPA put into effect the OSWI's new source performance standards and emissions guidelines. This rule includes two categories for very small municipal waste combustors (VSMWC) and institutional waste incinerators (IWI), and states that pyrolysis/combustion units are two chamber incinerators with a starved air primary chamber followed by an afterburner to complete combustion [56]. EPA regulations set NSPS limits on incinerators. The current EPA regulations include rules for small MSWIs: <250 t/day, and large MSWIs: >250 t/day, and OSWIs (**Table 2**). From these regulations, it is clear that using an incineration process for solid waste disposal is a better option than open burning to decrease air pollutant emissions; however, in OSWI groups' pyrolysis with industrial waste combustion for regulation purposes, although both processes are completely different from the technical point of view, the pyrolysis process is conducted without oxygen presence during the combustion phase, and without an additional fuel source [57].

* Non-methane hydrocarbons; ** Emissions calculated on a dry basis at 7% oxygen per EPA standards. Sources: [1] [1] [2] [47]. [3] [48] [4] [49] [5] [2] [6] [50] [7] [51] [8] [29] [9] [45] [10] [47] [11] [15] [12] [52]

In recent years, EPA received inquiries about OSWI units and its regulations for pyrolysis/combustion units for a variety of process and feedstock types because of the recent market trends for plastics recycling. EPA recognized that under the current OSWI regulations, the term pyrolysis/combustion in the institutional waste incineration unit is not defined. This is based on EPA's analysis that indicated pyrolysis itself is not combustion and pyrolysis gases are not a "solid waste", so then a pyrolysis/combustion unit should not be referenced in the definition of a municipal waste combustors (MWC) unit for the OSWI rule. The EPA consistent with that technical definition proposed the revision of the MWC unit definition in 40 CFR 60.2977 and 40 CFR 60.3078 and removed the reference to "pyrolysis/combustion units" from the definition showing that those units should not be regarded as MWC units under the OSWI rule as part of the Agency's periodic review under the CAA [58].

According to Springsteen et al. [59], there are some instances where temporary operations are allowed, but most of the time, the regulations in place require that portable biochar production systems have permits. However, the regulatory agencies at state or local levels have concerns regarding the time they will be in a temporary location, frequency of movements, and areas of operation because not having this information makes the monitoring and inspection regulators' work difficult. Another barrier is the lack of land use approval for multiple locations. Mutziger and Orozco [60] also have pointed out that each air regulating district could have a different permit approach including issuing an ACI operation as open burning, engine permit, or process permit based on known criteria pollutants.

Currently, the CAA title 40, Chapter 1, Subchapter C, Part 60, and Subpart EEEE and Subpart FFFF indicate that an ACI that burns 100% wood waste, clean lumber, yard waste, and 100% percent of those three raw materials of this section are required to meet only the requirements in §§ 60.2970 through 60.2974 and are exempt from all other requirements of this subpart [61].

40 CFR 60.2971 indicates limits such as within 60 days after the ACI reaches the charge rate at which it will operate, but no later than 180 days after its initial startup, the operator must meet the two following limitations: (1) the opacity limitation is 10 percent (6 min average), except when (2) the opacity limitation is 35 percent (6 min average) during the startup period that is within the first 30 min of operation. The limitations 1 and 2 of this section apply at all times except during malfunctions. 40 CFR 60.2972 covers the periodicity of the monitoring for testing for opacity; 40 CFR 60.2973 covers the recordkeeping and reporting requirements; and 40 CFR 60.2974 indicates the specification for Title V permitting [61].

Because of all of these air pollution regulatory agencies at the state, district, and county levels plus tribal, authorities considered the permitting difficult to carry out for portable biochar systems. This situation creates a highly diverse set of permit options when some regulators do not require permits; others have the same approach as open burning (no permit required), permit as engine operation, or formal permit. For operators with high potential capacity to operate in several states, it is difficult to plan their investments and operations under these conditions. The fact that pyrolysis is not defined in the regulations also makes the permit operation process difficult, because the setup will change when this definition is included. In the case of woody biomass processing, this is important because biochar presents the opportunity to promote forest management in areas with high risk for wildland fire while using low-value biomass for biochar production.

It has been documented that biochar could improve water quality, bind or decrease concentrations of heavy metals and toxic chemicals, and improve soil health to establish sustainable plant cover, prevent soil erosion, leaching, or other unintended, negative environmental consequences. Additionally, the use of woody biomass residues to create biochar helps decreasing woody biomass to diminish the risk of wildland fires and contribute to improve forest health and forest ecosystem resilience [62]. It is also important to mention that biochar is not flammable, because of the pyrolysis process used, all the oils and other chemical substances have been consumed [63]. Biochar potential applications in waste management, renewable energy, greenhouse gas emission reduction, mine site reclamation, soil, and water remediation, enhancing soil health and crop productivity, and sequestering C within the mineral soil can be C-negative and could have major implications for the mitigation of climate change.

Nowadays, to develop the full biochar industry, there are still some barriers that have to be overcome such as woody biomass transportation costs, and the need for updated regulations among other limiting factors to increase the use of woody biomass feedstock that is both high quality and low cost. Biochar has become increasingly important for the bioenergy and bioproducts industries, especially in an era of megafires, where the conservation of natural resources for a good quality environment, and the safety of rural communities against the impacts of drought, flooding, and wildland fires require an increase in forest management activities, which will produce woody biomass residues, that if not used become an increase in wildfire risk. Here is where biochar is a great way to dispose of those residues, providing jobs for rural communities and generating additional income for the states with all the benefits already indicated.

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