

Review

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Review

Mobile Biochar Production and the Clean Air Act of 1990

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Abstract: Pyrolysis is a combustion process of woody biomass conducted under low or no oxygen conditions. New innovations and the need to limit open burning has resulted in numerous mobile and fixed plant pyrolysis methods that burn a variety of woody residues. Production technologies that reduce the need for open burning, the main source of potential pollutants, fall under the regulations in the Clean Air Act of 1990. This Act is the legal instrument to regulate air pollution at its source across the United States of America and it is implemented and enforced through the Environmental Protection Agency, in coordination with sister agencies. One newer innovation for reducing woody residues and emissions is an air curtain incinerator. Currently, the Clean Air Act regulates stationary solid waste incinerators, and this is also applied to mobile air curtain incinerators burning woody biomass. However, other woody biochar production methods (*e.g.*, flame cap kilns) are not subject to these regulations. Discrepancies in the interpretation of definitions related to incineration and pyrolysis and the myriad of differences related to stationary and mobile air curtain incinerators, type of waste wood from construction activities, forest residues, and other types of clean wood make the permitting regulations confusing as permits can vary by jurisdiction. This review summarizes the current policies, regulations, and directives related to in-woods biochar production and the required permits.

Keywords: biochar; pyrolysis; Clean Air Act; emissions; pollutants; mobile biochar production systems

Article Highlights

- Portable biochar producing technologies could help to decrease wildland fires risk in overstocked forest stands under forest management.
- Applying consistent policies, regulations, and directives at different jurisdictional levels could increase biochar production on-site.
- Air pollution producing biochar on-site decreased potential CO₂ emissions caused by wildland fires or slash pile burning.

1. Introduction

In United States of America (USA) woody biomass biochar is an emerging industry product with high potential for a wide variety of applications. Biochar is made from non-merchantable wood residues which presents an option to decrease the risk of wildland fire to rural communities, helps to promote sustainable forest management providing alternative silvicultural systems to manage fuels

and conduct salvage practices or thinnings that will increase the resilience of standing trees and contribute to using and developing smart climate forest operation tools.

At current forest management levels in the USA, the potential for biochar production derived from woody biomass residues are described in the Billion Ton report (Langholtz et al., 2015) and which indicates the potential availability of 334 million dry metric tons of forest wastes and residues that could be sustainably produced each year in the USA. This gives forest managers an opportunity to create biochar in-woods and use it for restoration, to work with industry partners to increase production of biochar, bioenergy, or wood chips from slash piles that consist of small-diameter trees, branches, shrubs, and twigs that are created when forests are thinned to reduce excess fuel and lower fire danger and during conventional harvest operations.

Biochar made from woody residues can improve both forest conditions (e.g., reduced wildfire threat) and ecosystem services (e.g., water quality, nutrient retention, reduced compaction) when applied back to forest soils. On-site biochar production is a very good alternative to utilize low cost, low quality raw material to provide an important economic source for jobs and rural development, decrease the intensity of wildland fires, promote forest productivity, and enhance carbon sequestration by sequestering carbon in the soil with biochar and in increased growth efficiency of the remaining trees. Currently, there is an emphasis on increasing forest management activities to decrease the amount of biomass that fuels wildland fires. With a reduce risk of wildfire comes the additional benefits of decreased greenhouse gases (GHG) emissions, Global Warming Potential (GWP), and air pollutants. Biochar production can be an attractive option when done in the woods with mobile pyrolysis systems. Using portable biochar production systems and applying the biochar on-site reduces the need for long haul distances of raw material which can lower costs, but these methods also can reduce the GWP by 2-40 times net CO₂e as compared with open slash pile burning (Puettmann et al. 2020).

In spite of these advantages, the use of mobile pyrolysis equipment in the woods can be limited in some states because of the complexity and cost to obtain air quality permits. To develop sustainable forest operations that facilitate forest residues utilization, develop new markets, sequester carbon, promote innovation, and support resilient forests, there is a need to develop consistent air quality permitting policies, regulations, and directives at national, state, and local government levels with streamlined administrative processes specific to in-woods biochar production using a variety of techniques (e.g., kilns, air curtain burners, portable pyrolysis).

The short-term goal of reduced wildfire risk must dovetail with the long-term goal of increasing carbon sequestration in forest soils and improving forest resilience to a changing climate. Given this challenge, this article describes the current policies, regulations, and directives related to in-woods biochar production and the required permits. This analysis recognizes that long-term healthy forests are essential for promoting sustainable forest management across the USA.

2. The Clean Air Act Background

2.1. Clean Air Act scope

Congress enacted air pollution legislation in 1963 and amended it in 1970 establishing the (42 U.S.C. §7401 et seq. (1970)) Clean Air Act (CAA) (U.S. Government Publishing Office, 2010). Since its inception, the CAA has had a large impact on the lives of Americans and is the sole federal authority for regulating GHG emissions (Domike and Zacaroli 2016). The CAA is also the primary federal law that regulates air emissions from stationary and mobile sources. The CAA is environmental legislation that dates back to the 1970s and describes uniform national standards for a wide range of air pollutants and sources, through different mechanisms (e.g., power plants, incinerators, mobile burners; U.S. Environmental Protection Agency, 2023). Enactment of the CAA was designed to develop a national-level response to environmental concerns (air pollution). The CAA was revised in 1977 and 1990 to improve its efficacy targeting new air pollution problems including acid rain and damage to the stratospheric ozone layer (U.S. Environmental Protection Agency, 2023a).

The Environmental Protection Agency (EPA) was given authority to set and changes regulations to enforce compliance with the CAA. The EPA, therefore, was charged with establishing national ambient air quality standards (NAAQS) for six common pollutants known as “criteria pollutants”. The common pollutants are distributed widely across the country and because they can cause damage to human health, environment, and property. The common pollutants are particulate matter (PM), ozone (O₃), sulfur dioxide (SO₂), nitrogen dioxide (NO₂), carbon monoxide (CO), and lead (Pb) (U.S. Environmental Protection Agency, 2023b).

The NAAQS involve an integrated science assessment, risk/exposure assessment, policy assessment, and rulemaking. Rulemaking requires 1) the EPA to develop and publish a notice of proposed rulemaking that communicates the Administrator’s proposed decisions regarding the review of the NAAQS; 2) a public comment period, with public hearings; 3) a publication of the notice of proposed rulemaking; 4) review and consideration of received comments; and 5) EPA issues a final rule (U.S. Environmental Protection Agency, 2023c).

After EPA has issued a final rule, States and Tribes then assess their areas to determine whether it is in attainment with the standard. States and Tribes use available air quality data collected from approved monitors, emissions inventory data, and modeling to measure compliance. Based on those results States and Tribes then submit recommendations to the EPA of those areas that are not in compliance with the standard, and the EPA will "designate" an area based on whether or not it is meeting the standard. Exception event demonstrations can also be submitted to EPA in an effort to remove certain air quality data from having regulatory implications. Exceptional events (EE) are unusual or naturally occurring events that can affect air quality, such as wildfires, volcanic eruptions, dust storms, and certain types of emissions that are not typically included in regulatory assessments.

State and Tribal areas which meet or are cleaner than the national standard are designated as “attainment area.” Areas that do not meet the national standard are designated as “nonattainment area”, and when the EPA is not able of define the designation status for an area, based on the available information, that area is designated as "unclassifiable." Following EPA’s designations, the states have to develop state implementation plans (SIPs), indicating how areas will attain and maintain the standards by reducing air pollutant emissions. Although, the Tribes are not required to develop an implementation plan, they could decide if they want to do it. (U.S. Environmental Protection Agency, 2023d).

2.2. State Implementation Plans (SIPs)

State Implementation Plans (SIPs) are developed to bring areas under their jurisdiction into attainment of the NAAQS. These plans are developed by State and local air quality management agencies and proposed to the EPA for approval. The main SIPs objectives are to make sure that the State has a well-established air quality program and that they are capable of implementing a new or revised NAAQS for emissions control. The main highlights to develop a SIP are presented in Table 1(U.S. Environmental Protection Agency, 2023d).

Table 1. Main highlights for State Implementation Plans*.

SIP process	State role	EPA role
In a period of two years after EPA has set a new NAAQS or an existing standard.	States and Tribes must provide input	EPA based on the newest set of air monitoring or modeling data must designate attainment areas or not nonattainment areas.
In a period of three years after EPA has set a new NAAQS or an existing standard.	States must submit SIPs to implement, maintain, and enforce a new or revised national ambient air quality standard as specified in Clean Air Act Code §7410 sections (a)(1) and (a)(2). These SIPs are known as Infrastructure SIPs.	When the State air agency has submitted to the EPA one or more infrastructure SIP submissions, EPA will evaluate the submission(s) for completeness. The EPA's criteria for determining completeness of

		<p>a SIP submission are codified at 40 CFR part 51 appendix (https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-51/appendix-Appendix%20V%20to%20Part%2051).</p>
		<p>EPA must take final decision within 1 year after the submission is determined to be complete.</p>
		<p>When the EPA decides an affirmative finding that the SIP submission is complete, the date of the finding establishes the completion date. This decision does not indicate that the submission has been approved. It only indicates that the air agency has provided information sufficient to commence formal EPA review for approvability.</p>
In a period of 18 to 24 months after EPA designation.	<p>Nonattainment area SIPs are due based on the designation date and vary by pollutant and area classification. A period of 18 months are given for nonattainment areas for sulfur dioxide (SO₂), nitrogen dioxide (NO₂), coarse particle pollution (PM₁₀), fine particle pollution (PM_{2.5}), and lead (Pb) for sulfur dioxide (SO₂), nitrogen dioxide (NO₂), coarse particle pollution (PM₁₀), fine particle pollution (PM_{2.5}), and lead (Pb). A period of 24 months is for ozone (O₃) and carbon monoxide (CO) nonattainment areas. must outline the strategies and emissions control measures that show how the area will improve air quality and meet the NAAQS. In addition, the Clean Air Act mandates that areas adopt certain specified control requirements</p>	<p>When the EPA makes no affirmative completeness finding, then the submission is deemed complete by operation of law on the date 6 months after the State’s submission date. A finding that an infrastructure SIP submission is complete does not necessarily mean that the submission is approvable; the completeness review only addresses whether the air agency has provided information sufficient to commence formal EPA review for approvability.</p>
The SIP implementation process may apply under the Tribal Authority Rule in 40 CFR part 49 to an Indian Tribe that has received delegation of federal authority by the EPA to administer CAA programs in the same manner as states, over all air resources within the exterior boundaries	<p>Tribes when opt to implement their own air permitting programs, should follow up the same process and periods of time to submit their Tribal Implementation Plans.</p>	<p>When the Tribe opts not to implement their own CCA programs the EPA has promulgated regulations establishing permit requirements for major sources in attainment areas, and issued Prevention of Significant Deterioration permits to new or modifying major sources (40 CFR 52.21). Nevertheless, the EPA has not promulgated regulations for a permitting program in Indian country for either minor or major sources of air pollution emissions in nonattainment areas (Federal Register, 1998).</p>

of a reservation for such programs (federal Register, 1998).		EPA reviews the SIP submission and proposes to approve or disapprove all or part of each plan. Then proceeds to have a public consultation. The public has an available period for comments submission on EPA's proposed action. EPA considers public input before taking final action on a state's plan. If EPA approves all or part of a SIP, those control measures are enforceable in federal court.
SIPs approval or disapproval	SIPs must be developed with public input, and formally adopted into state law, and being submitted to the EPA by the Governor's designee.	
State fails to submit an approvable plan or EPA disapproves a plan.		EPA is required to develop a federal implementation plan (FIP).

*Based on information from the following sources: U.S. Environmental Protection Agency, 2023d; U.S. Environmental Protection Agency, 2015; and U.S. Environmental Protection Agency, 2013.

2.3. Solid waste incineration

One of the amendments to the CAA was to facilitate the implementation of sound solid waste management systems. The CAA regulates emissions for municipal waste incinerators and landfills. High CAA standards for monitoring, controlling, and reporting emissions made waste incineration highly specialized and expensive (Louis 2004). Although the CAA was meant to deal with municipal solid waste, it also applies to mobile incinerator units.

In the case of biochar production from mobile air curtain incinerators, emissions are regulated under the category covered by solid waste incinerator units in section 7429 of the CAA and directs the EPA Administrator to develop regulations for each category of solid waste incineration units. The standards must include emissions limitations and other requirements applicable to new units and guidelines under CAA section 7411(d) and other requirements applicable to existing units, and, Chapter I, Subchapter C, Part 60, Subpart B- Adoption and Submittal of State Plans for Designated Facilities (U.S. Code, 2010).

The CAA Section 7411(d) prescribes regulations which must establish a procedure similar to those under the CAA section 7410 and each State submits a plan that establishes performance standards for any existing source of air pollution

The new source performance standards (NSPS) and emission guidelines (EG) to reduce air pollution from commercial and industrial solid waste incineration (CISWI) units, for Subparts CCCC, DDDD, EEEE, and FFFF of part 60 were developed in accordance with sections 7411(d) and 7429 of the Clean Air Act (CAA) and applied to incinerators burning solid waste. The limiting emissions are for nine air pollutants (i.e., particulate matter, CO, dioxins/furans, SO₂, NO_x, HCl, Pb, Hg, and Cd) from four categories of solid waste incineration units: municipal solid waste; hospital, medical and infectious solid waste; commercial and industrial solid waste; and other solid waste. The NSPS and EG were designed to significantly reduce emissions of a number of harmful air pollutants such as lead, cadmium, mercury, and dioxins/furans, which are suspected of causing adverse health and environmental damages (U.S. Environmental Protection Agency, 2023e).

This very important to be considered ,because of the definition of "solid waste" for example wood appears both in the definition of woody waste and solid waste in subpart EEEE. Some districts have interpreted wood pyrolysis as solid waste which requires that a small pyrolyzer for converting clean woo waste to biochar is classified as a solid waste incinerator.

Regarding the woody biomass biochar production and the biochar production systems. The main regulated pollutants by the EPA are those classified as criteria pollutants and hazardous pollutants.

The EPA has developed the NAAQS for the group of six common pollutants known also as criteria pollutants in outdoor air. NAAQS are designed for PM, O₃, SO₂, NO₂, CO, and Pb based on characterizations from the latest scientific information regarding their effects on health or welfare. Particulate matter and ground-level ozone pollution are considered by the EPA the most widespread health threats. Volatile organic compounds (VOCs), carbon containing compounds involved in ozone formation, are also under regulation (U.S. Environmental Protection Agency, 2023f).

Other set of regulated contaminants are those named hazardous pollutants, also known as toxic air pollutants, that are suspected to cause cancer or other serious health effects, such as reproductive effects, or adverse environmental effects. The EPA has classified 188 toxic air pollutants, among those are metals such as cadmium (Cd), mercury (Hg), chromium (Cr), and lead (Pb) compounds (U.S. Environmental Protection Agency, 2023g).

2.3.1. Particulate Matter

Several authors agreed that air pollution is caused by a complex mixture of gaseous and particulate components from varied amount of sources (citations for the several authors at the start of this sentence). Those components are the main cause of detrimental effects on human health. One of the modifiable components of air pollution is PM, PM is classified according to its origin and components. When PM is directly emitted into the air, it is classified as primary, and when it is formed indirectly from emissions from fuel combustion and other sources is classified as secondary. Primary pollutants include carbonaceous materials (soot and organic) particles, elemental carbon (according to Middlebrook et al (2012) elemental carbon is a PM from a petroleum oil fire, that is composed of small elemental carbon particles that, due to intense heat produced, will initially loft high into the air in a plume of black smoke), organic carbon (OC), and NO₂ and SO₂ oxides emitted directly into the air by combustion of fossil fuels. Main sources of NO₂ are vehicles, heavy equipment, forest fires, some industrial processes and burning waste. Secondary pollutants are formed in the atmosphere from other components. One of them is ozone, which is result of complex photochemical reactions of NO_x and volatile organic components (SO₂, NO₂, ammonia (NH₃), and organic carbon emissions) (U.S. Environmental Protection Agency, 2012; Newby et al., 2015; Hamanaka and Mutlu, 2018).

PM is subdivided by particle size as coarse (PM₁₀) with diameter less than 10µm, fine (PM_{2.5}) with diameter less than 2.5µm, and ultrafine (PM_{0.1}) with diameter less than 0.1µm. PM₁₀ particles derive from numerous natural sources (soil erosion, sand, volcanic ash and woodsmoke) and other industrial sources. PM₁₀ particulates in general do not penetrate beyond the upper bronchus. Fine and ultrafine particles are product of the combustion of carbon-based fuels and fossil fuels and are a major threat to human health than coarse particles because they are inhaled deep into the respiratory system. PM_{2.5} has been constantly correlated with negative cardiovascular consequences regardless of location, especially for people with susceptibility and vulnerable conditions like asthma, pneumonia, diabetes, and respiratory and cardiovascular diseases. (Brook et al., 2010; Miller, Shaw and Langrish, 2012; U.S. Environmental Protection Agency, 2012; Newby et al., 2015; Hamanaka and Mutlu, 2018; Manisalidis et al., 2020).

2.3.2. Volatile organic compounds and ozone

VOCs are specifically regulated as a class of ozone precursors for major source purposes under the 40 C.F.R. § 51.165, § 51.166, § 70.2. VOCs are defined under 40 C.F.R. § 51.100(s), which defines them as "any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, which participates in atmospheric photochemical reactions." A number of compounds are deemed to have "negligible photochemical reactivity," and are therefore exempt from the definition of VOC. The Federal definition of VOC does not specify how to measure the mass of the organic compound being emitted to the air (U.S.

Environmental Protection Agency. 2000). Ozone is a secondary pollutant formed in the atmosphere from complex photochemical reactions of nitrogen oxides and volatile organic components (Stanek et al., 2011; Newby et al.,2015). The two types of chemicals that are the main ingredients in forming ground-level ozone are called volatile organic compounds (VOCs) and nitrogen oxides (NO_x). VOCs are released by vehicles, oil refineries, chemical plants, and other industrial facilities. Ozone at ground level is a primary component of smog. Ground-level ozone can cause human health problems and damage forests and agricultural crops. Several studies have shown that exposure to ozone increases the susceptibility and can aggravate respiratory diseases like asthma and increase respiratory infections and lung inflammation, it also has been associated with cardiovascular morbidity and mortality (Brook et al., 2002; U.S. Environmental Protection Agency, 2007; Razza et al., 2013; Newby et al., 2015; Hamanaka and Mutlu, 2018; U.S. Environmental Protection Agency, 2021).

2.3.3. Carbon Monoxide

Manisalidis et al (2020) pointed out that CO is produced by fossil fuel when combustion is incomplete. CO pollution mostly comes from emissions produced by fossil fuel-powered engines, including motor vehicles and non-road engines and vehicles. CO affects human health, and the symptoms of poisoning due to inhaling carbon monoxide include headache, dizziness, weakness, nausea, vomiting, and, finally, loss of consciousness. Poisoning may occur in people exposed to high levels of carbon monoxide for a long period of time may cause the loss of oxygen as a result of the competitive binding of carbon monoxide causing hypoxia, ischemia, and cardiovascular disease. CO is unlikely to be at very high levels outdoors. Though, when CO levels are elevated outdoors, people with some types of heart disease can be affected (U.S. Environmental Protection Agency, 2023h).

CO emissions influence global and regional air quality. These emissions contribute indirectly to global climate change through its influence on tropospheric O₃ and atmospheric oxidants. CO is also formed by photochemical reactions in the atmosphere from methane and non-methane hydrocarbons (NMHC), and other volatile organic hydrocarbons, and organic molecules in surface waters and soils. CO affects the greenhouses gases that are tightly connected to global warming and climate (Fry et al., 2013; California Air Resources Board, 2023).

2.3.4. Hazardous air pollutants

The CAA section 7412 addresses emissions of hazardous air pollutants (HAPs). The CAA Amendment of 1990 instructed exposure standards for 187 compounds grouped as HAPs or urban air toxics, and emissions control strategies of 30 or more compounds that present the greatest risk to public health. The EPA defines toxic air pollutants or hazardous air pollutants, are those substances that are harmful to humans and cause or may cause cancer or other serious health effects, or adverse environmental and ecological effects. Nowadays, the list of HAPs covers 33 pollutants (Table 2) (U.S. Environmental Protection Agency, 2023i).

Table 2. List of EPA defined toxic air pollutants or hazardous air pollutants.

HAPs posing the greatest potential health threat in urban areas		
Acetaldehyde	Dioxin	Mercury compounds
Acrolein	Propylene dichloride	Methylene chloride (dichloromethane)
Acrylonitrile	1,3-dichloropropene	Nickel compounds
Arsenic compounds	Ethylene dichloride (1,2-dichloroethane)	Polychlorinated biphenyls (PCBs)
Benzene	Ethylene oxide	Polycyclic organic matter (POM)
Beryllium compounds	Formaldehyde	Quinoline
1,3-butadiene	Hexachlorobenzene	1,1,2,2-tetrachloroethane
Cadmium compounds	Hydrazine	Tetrachloroethylene (perchloroethylene)

HAPs posing the greatest potential health threat in urban areas		
Chloroform	Lead compounds	Trichloroethylene
Chromium compounds	Manganese compounds	Vinyl chloride
coke oven emissions*	1,2-dibromoethane*	carbon tetrachloride*

* HAPs are not generally emitted by area sources (They are not included as greatest potential health threat) (Source: U.S. Environmental Protection Agency, 2023i).

HAPs are released into the air by urban activities like vehicles, power generation, use of solvents, industrial manufacturing, and wood burning. In addition to release into the air and secondary formation, volatile HAPs enter the atmosphere through intermediate transport. Even if a chemical is released initially into water, soil, sediment, or biota, when is volatile it will enter the atmosphere at some point through evaporation from water or soil (Leikauf, 2002; Kim et al., 2021).

Section 7430 of the CAA directs the administrator to conduct a review, and when there is a need revise, the methods used to estimate the quantity of emissions of carbon monoxide, volatile organic compounds, and oxides of nitrogen from sources of such air pollutants (including area sources and mobile sources). Additionally, the Administrator must establish emission factors for sources for which no such methods have previously been established ((U.S. Code, 2010).

2.3.5. CAA Title V permitting

The CAA 1990 amendments direct the EPA to develop and enforce rules and regulations for industries and other entities that emit toxic substances into the air, and required the EPA to establish the operating permits program to assure that source operators know what air pollution control requirements apply, improve compliance, and resolve applicability questions. Operating permits are required for major sources and other sources subject to acid rain control requirements, new source performance standards, hazardous air pollutant standards, and permitting requirements under Title I of the Act U.S. Environmental Protection Agency, 2013a).

Operating permits contain information about the pollutants that are being released, the amount and limits of how much pollutants may be released, and what kinds of steps the source’s owner or operator is required to take to reduce the pollution. Permits also have to include plans to measure and report the air pollution emitted, and sources must provide a monitoring report every six months. States and tribes governments are in charge of issuing operating permits under EPA approved programs. States must submit permit applications, proposed permits and final permits to EPA for review, and notify of each permit application or proposed permit to nearby states. EPA can object the issuance of a state proposed permit that is not consistent with the CAA; if EPA does not object, any person may petition the EPA Administrator to make such an objection. These programs are required to charge permit fees sufficient to cover the costs of the permit program, and permits are issued by a fixed term of five years (U.S. Environmental Protection Agency, 2013a).

Under the CAA the EPA has authority for ensuring compliance and for pursuing enforcement actions against those who are in violation of the CAA. States that have programs approved or delegated by EPA under various provisions also have the authority to implement and enforce those programs.

3. Emissions from burning woody biomass

Open burning (e.g., wildfire, prescribed fire) is one of the largest sources of atmospheric traces gases and this has a major impact on air quality (Knorr et al. 2012). Open burning is the main source of black carbon (59%), and of primary organic aerosol emissions (89%); (Andreae, 2019). Open vegetation fires represent about one-third global CO and 62% of OC emissions (Wiedinmyer et al., 2011). Vegetation fires are also a major source of GHG, CO₂, and CH₄ (Friedlingstein et al., 2022). This has become a concern at the local, regional, national, and international scale because of the large wildfires here and abroad that threaten community health. Because of the wildfires, many human health recommendations were issued to keep people safe, especially those susceptible to pollution

and with medical respiratory diseases. For this reason, is important take into consideration the pollution caused by open burning versus burning wood under controlled conditions (e.g., stoves, air curtain incinerators, bioenergy plants). Controlled burning is one method to create a high-quality biochar by-product.

Open burning releases soot and PM that are visible as a smoke plume, CO, CH₄ and other light hydrocarbons, volatile organic compounds VOCs such as benzene, and semi-volatile organic compounds (SVOCs) like polycyclic aromatic hydrocarbons (PAHs) such as benzo[*a*]pyrene. According to the burned materials, varying amounts of metals for example Pb or Hg may be discharged. Polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (PCDDs/Fs) or polychlorinated biphenyls (PCBs) can be released as well. Biomass open burning sources usually emits less VOCs, SVOCs and PAHs than anthropogenic sources on a mass emitted per mass burned basis (Lemieux et al., 2004).

When VOCs are released during wildfires, there can also be secondary pollutants such as ozone and fine particles (Sekimoto et al (2018). The main source of VOCs are from wood polymers such as cellulose, hemicellulose, and lignin. Commonly during a wildfire, biomass is heated to temperatures ~1100 °C and a large fraction of the wood is often gasified at a high rate (Greenberg et al., 2006). Burning at different temperatures will result in different VOCs. At high-temperatures VOCs consist of aliphatic unsaturated hydrocarbons, (polycyclic) aromatic hydrocarbons, terpenes (emitted from distillation), HCN, HNCO, and HONO and are often from coniferous trees. At lower temperatures, burning wood emits aromatic oxygenates, furans, and NH₃ (e.g., from chaparral vegetation). These results can explain in average 85 % of the VOC emissions across various fuels representative of the western USA. However, the results of studies can be variable depending on wood type and conditions of burning (Sekimoto et al. 2018; Estrellan and Line 2010).

In uncontrolled burns, some of the emissions are captured by the standing vegetation, but smoke and particulates are still a major concern for inhabitants. When the woody biomass is burned using incinerators to obtain biobased products (e.g., biochar, biofuel) it is generally considered safer to burn under regulated pollutant emissions standards, as those established under the CCA. This is confirmed by Garcia-Perez et al (2010), who found that emissions from burning wood can be controlled during continuous production of biochar because the composition and the emissions flow rate is more constant, burners and cyclones control emissions from continuous multiple hearth kilns, and burners can improve emissions recovery resulting in decreased PM, CO and VOCs of up to 80%.

4. Using pyrolysis to create biochar

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, CO₂, aerosols (PM_{2.5} and/or PM₁₀), NO, NO₂, and a mix of both known as nitrogen oxides (NO_x), methane, NMHC, and total suspended particulates (TSP) (Pennise et al., 2001). However, agricultural residues (Sparrevik et al 2013) and waste timber (Sørmo 2020) 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 (Ribeiro et al, 2018). 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 (Pecha and Garcia-Perez, 2020, Yang and Lu, 2021).

The amount and types of pollutants 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, 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 (Williams et al., 2017).

In pyrolysis, thermal decomposition of the 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 75% by weight, in the liquid products (Ribeiro et al, 2018).

According to Pecha and Garcia-Perez (2020) 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, H₂O, CH₄, and H₂, 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 (Antal and Grønli, 2003).

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 that 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 oxidized pyrolysis gases (Pecha and Garcia-Perez, 2020).

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 (Mohan et al., 2006; Itoh et al., 2020; Yaashikaa et al., 2020; Safarian, 2023). 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 sulphur content, which restricts the formation of SO_x and NO_x gases and lowers the residues and smells tendency (Anand et al., 2023; Mishra et al., 2023). According to Schwartz et al (2020) combusting using fast pyrolysis pine sawdust products met CO, NO_x, and SO₂ 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.

4.1. Mobile Biochar Pyrolysis Systems

Biochar has been made for centuries and is one of the oldest and most established processes developed by mankind (Hornung et al., 2020). Some methods use ‘slow pyrolysis’ which maximizes the amount of solid material (biochar) that is produced (Sohi et al., 2010). 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 charcoal making from the ancient history up to now has evolved from charcoal pits, and 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 full automated and controlled processes (Gabhane et al., 2020; Hornung et al., 2020).

The first kilns were designed as an oven, furnace, or heated enclosure for processing a substance by burning, firing, or drying (Merriam-Webster, 2023) to maximize charcoal production and were extremely polluting (Brown et al., 2015; Plaza et al., 2019). The first portable metal kiln, which was designed by Whitehead, but the emissions were still high and without any control system (Whitehead, 1980). According to Fuchs et al (2014) 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 release low emissions, as the smoke is burned in the flame (Fuchs et al., 2014).

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 (Brown et al., 2015). Similar wood burning during a wildfire or prescribed fire, the emissions interact with atmospheric chemistry, producing ozone, other oxidants, and carbon monoxide. The 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 (Greenberg et al., 2006). Mobile units that use a retort design (an inner chamber filled with wood and an outer chamber to insulate) significantly decreases 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 (Sparrevik et al. 2015;Nsamba et al.2015) Schettini et al (2022) found that furnace kilns could reduce GHG emissions by 40.2 % and the increase biochar yield by 32.5 % higher as compared to other kiln types used in Brazil that do not have the GHG burners.

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 feed. 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 (Schmidt and Taylor, 2014; Cornelissen et al., 2016; McAvoy, 2019; Wilson, 2021; and Bindar et al., 2023).

Another kind of more modern mobile biochar pyrolysis systems are those known commercially as the air curtain burners, also known as air curtain incinerators (ACI), and the carbonizer. They are based on the principle of the air curtain described above, but they have source of air flowing continuously to create the air curtain, where it works like a lid covering the opening in a FireBox and following the process described above resulting in a clean burn (Air Burners Technology, 2022; Tigercat, 2022). A grate in the firebox removes char before it is consumed. Although, open burn pile could be used for the same purpose the final product won't have the same characteristics, because the combustion process is different. In an open burn the char and the biomass carbon are not protected of oxidizing to CO₂ (Wilson, 2021), and the amount of emissions is very high.

Life cycle analysis studies relate the emissions towards a Global Warming Potential (GWP) of the production system because, it reflects the amount of GHG emitted through the supply chain of

the specific product being produced. GWP indicates the amount of energy the emissions of 1 ton of a gas will absorb on a given period of time, in relationship to the emissions of 1 ton of CO₂ (Vallero, 2019; U.S. Environmental Protection Agency, 2023j), 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 the 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 pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (Mareddy, 2017; U.S. Environmental Protection Agency, 2023k) (e.g., grams of particulate emitted per kg of woody biomass processed).

Soares Neto et al (2009) in Brazil determined that one hectare of burned forest had average emission factors for CO₂ with 1,599, CO with 111.3, CH₄ 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 CO₂, CH₄, and N₂O only, with an estimated value of 0.77-1.63 kg C-CO₂ (carbon as carbon dioxide equivalents) emitted per kilogram of charcoal produced (Pennise et al, 2001). Sparrevik et al (2013) assessing the use of mound kilns and retort kilns in Zambia concluded that when considering CO₂ 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 CO₂ sequestration. However, the effects caused by the PM formation, the impact of the use of biochar produced in earth-mound kilns is inferior to conservation farming without biochar use. Similar conclusion was achieved by Sparrevik et al (2015) testing the introduction of improved retort kilns where the pyrolysis gases are combusted internally with a significant decreasing of emissions of products of incomplete combustion when using similar feedstock, as a result that the yield was not significantly higher with retort kilns, and because of their cost, they concluded that makes difficult their adoption for biochar production in rural areas. Miranda Santos et al (2017) 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 portable biochar technologies could be a solution for rural areas with not easy access, and for avoiding transportation of raw material or slash piles that could enhance the fire risk, and where biochar could be part of the solution to increase CO₂ sequestration and at the same decrease the amount of emissions during the production of biochar. This could be a good solution for 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 on the long term, or when they caught fire. Han and Lee (2017) comparing open burning vs ACB for disposal of forest residues agreed with the previous statement since they concluded that ACB burning is being adopted in many forests to control emissions, smoke, and embers improve oxygen, and heat supply by high velocity of airflow during the burn, making this technology much more efficient reducing the negative environmental and societal impact of disposing forest residues. Susott et al (2017) found out 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 results 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 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 (2023) conducted a source test report for 2023 emission factor testing mobile air curtain incinerator valley environmental Hillsboro, Oregon with similar findings in reduction of emission with respect to open burning, wildland fires, slash pile burning and earth mound kilns. Table 3 presents a summary of several studies on air pollution emissions factors for different technologies and includes open burning and wildland fire emissions.

Life cycle analysis have indicated that portable biochar production system as an efficient way to decrease the impacts of climate change and decrease air pollutant emissions. Puettmann et al (2015) found out that in general the production of biochar from forest residues reduced GHG emissions 2–40 times lower net CO₂eq (-0.3 to -1.83 tons of CO₂eq./dry ton of forest residues) compared to pile burn when using the ACI, the Oregon Kiln (OK) and the Biochar solutions Inc mobile downdraft gasifier (BSI). In addition, the OK had the lowest GWP, emitting 0.11-ton CO₂eq./ton of fixed carbon in biochar, followed by the ACI with 0.16-ton CO₂eq./ton, and the GWP of the BSI gasifier varied from 0.25–0.31-ton CO₂eq./ton of fixed carbon in biochar which was in function of depended on feedstock characteristics and the electrical power generator used at the remote site (Wilson, 2021).

Table 3. 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	NMVO C	NO _x	NMH C*	PM _{2.5}	PM	Diox ins/F uran	SO _x	SO	Lead (Pb)	O ₃
Pennise et al (2001) g/kg														
5 earth mound kilns, beehive-shaped brick kiln, Brazilian round brick (surface), and Brazilian rectangular with tar recovery (metal and brick).	543 to 3027	143- 373	32 - 62	-	-	NO ₂ 0.011-0.30 and NO _x 0.0054- 0.13	24-124	-	Total Suspende d matter 13-41	-	-	-	-	-
Estrellan and Lino (2010) (g/kg)														
Forest fires	1690	63	3.4	-	-	-	2.6	7.5	-	-	-	-	-	-
Vallero (2008) (g/kg)														
Open burning	-	50.0	-	-	Aldehyd es and ketones 3.0	NO ₂ 2.0	Total Hydro carbon s 7.5	11	-	-	SO ₂ 1.5	-	-	-
Springsteen et al (2011) (Kg/Ton)														
	10,618	362	17.37	-	28.96	17.37	-	-	37.65	-	-	-	-	-
Sparrevik et al (2013) g/kg it also includes PAHs with 18.6 and VOC with 4.0														
Open burning	-	34.7	1.2	3.7	-	N ₂ O 0.07 NO _x 3.1	-	-	-	0.5	SO ₂ 2.0	-	-	-
Lasko and Vadrevu (2018) (g Kg ⁻²)														
Rice residue burning	-	-	-	-	-	-	-	16.9 (±6.9) for pile burning 8.8 (±3.5) for non- pile burning	-	-	-	-	-	-

Puettmann et al (2020) (kg/kg)														
Slash Pile Burning	1.69E+00	6.53E-02	4.54E-03	4.40E-03	5.55E-03	2.50E-03	-	-	-	-	-	-	-	-
Air Curtain Burner	7.80E-01	2.60E-03	2.60E-03	1.28E-03	-	1.44E-04	-	-	-	-	-	-	-	-
Oregon Kiln	7.80E-01	2.60E-03	2.60E-03	1.28E-03	-	1.44E-04	-	-	-	-	-	-	-	-
Biochar Solutions Inc.	2.19E+00	6.98E-04	1.52E-04	1.38E-03	-	1.96E-03	-	-	-	-	-	-	-	-
Cornelissen et al (2016) (g/kg)														
All steel deep octagonal	5600	38	57	22	6	0.3	-	-	-	-	-	-	-	-
Steel sheet soil pit	2300	23	14	9	5	0.3	-	-	-	-	-	-	-	-
Soil Pit	3800	36	32	20	8	0.8	-	-	-	-	-	-	-	-
Shallow steel pyramidal and octagonal	4700	73	26	5	5	0.32	-	-	-	-	-	-	-	-
Susott et al (2017) (lbs/ton)														
Average Pile	3268	179	13.9	-	-	-	9.9	25.5	-	-	-	-	-	-
Average Understory	3286	180	6.6	-	-	-	5.4	36.0	-	-	-	-	-	-
Average ACB	3616	2.6	1.4	-	-	-	1.1	1.1	-	-	-	-	-	-
Estrellan and Lino (2010) (g/kg)														
Incinerator	1280	0.18	-	-	-	1.01	-	-	0.21	6.89E-08	0.12	-	-	-
Japan Carbonizer	43.89	0.033	-	-	-	0.43	-	-	0.015	0	0.65	-	-	-
Schwartz et al (2020)** (ppm)														
Char Burner PM Filter	10.6	-	-	-	-	16.8	-	-	32.6 Mg/m³	-	-	2.3	-	-
EPA Other Solid Waste Incinerators (OSWI)	40	-	-	-	-	103	-	-	30	-	-	3.1	-	-
EPA large Municipal Solid Waste Incinerators (MSWI)	50	-	-	-	-	180	-	-	20	-	-	30	-	-
EPA small MSWI	50	-	-	-	-	500	-	-	24	-	-	30	-	-
Oregon Department of Environmental Quality (2023) (lbs./ton)														
Air Curtain Incinerator (ACB - Burn Boss T24)	1248.5	14.2	0.668	-	NMHC/ NMVOC 1.17	1.98	NMH C/NM VOC 1.17	-	4.25	2.88E-09	SO2 0.24	-	1.30E-04	-
U.S. Environmental Protection Agency (2023l)														
EPA National Standard	-	Primary (P) 8 hrs. 9 ppm	-	P and S 24 hrs. 150 µg/m³	-	-	-	P 1 year 12.0 µg/m³	-	-	-	SO2 0.14 ppm 24-hour and 0.03 ppm annual P 1 hr. 75 ppb S 3 hrs. 0.5 ppm	P and S 3 Mon ths aver age 0.15 µg/m³	P and S 8 hrs. 0.070 ppm

35
μg/m³

*Non-Methane Hydrocarbons; **Emissions calculated on a dry basis at 7% oxygen per EPA standards;.

4.2. Permitting for Mobile Biochar Pyrolysis Systems in the USA

The EPA defined incineration as the process of oxidizing combustible hazardous materials (solid waste) at high temperatures above their ignition point in the presence of oxygen to destroy contaminants and maintaining it at high temperature for sufficient time to complete combustion to carbon dioxide and water. It is conducted in a type of furnace designed for burning hazardous materials in a combustion chamber, known as incinerator. EPA requires that an incinerator can destroy and remove at least 99.99 percent of each harmful chemical in the waste it processes (U.S. Environmental Protection Agency.2009; U.S. and Environmental Protection Agency, 2012a).

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, (U.S. Code, 2010).

In 2005, EPA put into effect the OSWI new source performance standards and emissions guidelines. This rule includes two categories very small municipal waste combustors (VSMWC) and institutional waste incinerators (IWI) and stated that pyrolysis/combustion units as two chamber incinerators with a starved air primary chamber followed by an afterburner to complete combustion (U.S. and Environmental Protection Agency, 2023m). EPA regulations set NSPS limits on incinerators. The current EPA regulations include rules for small MSWI <250 tons/day, and large MSWIs, >250 tons/day, and OSWIs (Table 3). 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, 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 additional fuel source (Vallero, 2019a).

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” then a pyrolysis-combustion unit should not be referenced in the definition of municipal waste combustors (MWC) unit for the purposes of the OSWI rule. EPA consistent with that technical definition, proposed to revise the MWC unit definition in 40 CFR 60.2977 and 40 CFR 60.3078, and remove 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 (U.S. Environmental Protection Agency, 2020).

In this same review EPA decided to address the regulatory requirements of the 2005 OSWI rule, regarding ACIs that burn only wood waste, clean lumber, and yard waste to respond to several states request that considered the title V requirements as unnecessary burdensome and expensive for states to maintain, and results of available data, showed that ACIs that burn exclusively wood waste, clean lumber, and yard waste are commonly located at facilities that would not otherwise require a title V operating permit. However, in this rule EPA considered that a title V permit was necessary to assure compliance with the opacity and other requirements established for such incinerators, and because such units are not considered solid waste incineration units under section 129 (U.S. Environmental Protection Agency, 2020). The regulation provides special provisions for ACI burning wood waste. Stationary pyrolysis systems may be permitted differently according to their configuration and the rules of the air quality district.

According to the EPA after this review proposal issued an advance notice of proposed rulemaking titled “Potential future regulation addressing pyrolysis and gasification units” soliciting

information and requesting comments for the potential development of regulations for pyrolysis and gasification units that are used to convert solid or semi-solid feedstocks, including solid waste, biomass, plastics, tires, and organic contaminants in soils and oily sludges to useful products such as energy, fuels and chemical commodities. However, the EPA received significant adverse comments on the proposed provision (U.S. Environmental Protection Agency. 2021a) and on May 2023 withdrew the proposed provision that would have removed pyrolysis/combustion units from the other solid waste incineration (OSWI) standards under the Clean Air Act, and the current OSWI definition of “municipal waste combustion unit” will continue to include pyrolysis/combustion units (U.S. Environmental Protection Agency. 2023n).

The previous considerations for OSWI and ACIs are applied for stationary incinerators with different amounts of waste processing capabilities. In the case of portable ACIs the OSWI regulation is applied for some mobile biochar pyrolysis systems (Air Curtain Burners), but not for the flame cap carbonizers for biochar production in the forest, because it is not defined, making the permit regulations to be considered different and varying according to the jurisdiction where operations are going to be conducted.

According to Springsteen et al (2021) 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 these information makes the monitoring and inspection regulators work difficult. Other barrier is the lack of land use approval for multiple locations. Mutziger and Orozco (2021) also have pointed out that each air regulating district could have different permitting approach including issuing an ACIs operation as open burning, engine permit, or process permit based on known criteria pollutant.

Currently the CAA title 40, chapter 1, subchapter C, Part 60, and subpart EEEE and subpart FFFF indicates that ACI that burn 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 (U.S. Environmental Protection Agency, 2023).

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-minute average), except when 2) the opacity limitation is 35 percent (6-minute average) during the startup period that is within the first 30 minutes 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 (U.S. Environmental Protection Agency, 2023).

Because of all of these air pollution regulatory agencies at State, District and county level plus Tribal authorities considered the permitting difficult to be carried out for portable biochar systems. This situation creates a highly diverse set of permit options when some Regulators do not require permits, other have the same approach as open burning (not permit required), permit as engine operation, or formal permit. For operators with high potential capacity to operate in several States is difficult to plan their investments and operations under these conditions. The fact that pyrolysis is not defined in the regulations also makes difficult the permit operation process, because the set up will change when this definition is included. In the case of woody biomass processing this 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.

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 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 of updated regulations among other limiting factors to increase the use of and 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 the natural resources for a good quality environment, and safety of rural communities against the impacts of drought, floodings and wildlands fires require an increase of forest management activities, which will produce woody biomass residues, that if not used become an increase of 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.

5. Conclusions and perspectives

Portable biochar producing technologies are a potential tool to be considered to decrease the risk of wildland fires in overstocked forest stands when forest management and restoration activities are carried out.

Pyrolysis life cycle analysis results have demonstrated that disposing of forest residues for biochar production on site results on decrease of pollutant emissions and this combustion process is much more efficient compared with the disposal of forest biomass with open burning, or slash piles burn.

Air pollution producing biochar decreased potential CO₂ emissions to the atmosphere caused by wildland fires or slash pile burning and brings associated benefits result of the biochar incorporation to the soil as amendment increasing CO₂ sequestered and other additional benefits, including increase of water retention and other improvement of soil characteristics, including the decreasing of CH₄ emissions from open burning.

It is clear that to achieve the benefits of biochar production on site with portable production technologies there is a need for designing and the application of consistent policies, regulations, and directives at national, state, and local government levels with streamline administrative processes in place to facilitate and promote innovation and decrease pollutant emissions.

Barriers, challenges and research needs for portable systems should be considered, among them there is a need to conduct more research about sustainable woody feedstocks for biochar production, biochar characterization from these technologies, economic analysis of different portable systems, including the life cycle analysis. To facilitate the streamline for operation of portable biochar technologies there is also need of air emission pollution assessments.

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