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Article

A Comparison of Producer Gas, Biochar, and Activated Carbon from Two Distributed Scale Thermochemical Conversion Systems Used to Process Forest Biomass

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Abstract: Thermochemical biomass conversion systems have the potential to produce heat, power, fuels and other products from forest biomass at distributed scales that meet the needs of some forest industry facilities. However, many of these systems have not been deployed in this sector and the products they produce from forest biomass have not been adequately described or characterized with regards to chemical properties, possible uses, and markets. This paper characterizes the producer gas, biochar, and activated carbon of a 700 kg h⁻¹ prototype gasification system and a 225 kg h⁻¹ pyrolysis system used to process coniferous sawmill and forest residues. Producer gas from sawmill residues processed with the gasifier had higher energy content than gas from forest residues, with averages of 12.4 MJ m⁻³ and 9.8 MJ m⁻³, respectively. Gases from the pyrolysis system averaged 1.3 MJ m⁻³ for mill residues and 2.5 MJ m⁻³ for forest residues. Biochars produced have

similar particle size distributions and bulk density, but vary in pH and carbon content. Biochars from both systems were successfully activated using steam activation, with resulting BET surface area in the range of commercial activated carbon. Results are discussed in the context of co-locating these systems with forest industry operations.

Keywords: pyrolysis; gasification; biomass; biochar; activated carbon; synthesis gas

1. Introduction

1.1. Background

Sawmills and other wood products manufacturing facilities produce large quantities of woody biomass in the form of wood chips, sawdust, shavings and bark. These mill residues are commonly sold as raw material for the manufacture of paper and engineered wood panels (e.g., clean chips for pulp and sawdust for particle board), for landscaping applications (e.g., bark mulch), and as fuel for combustion boilers (e.g., hog fuel). The forest sector also produces millions of tons of woody biomass as a byproduct of silvicultural treatments prescribed to harvest timber, manage fire risk, improve forest health, and meet other management objectives. These forest residues include foliage, tops, limbs, unmerchantable roundwood, and stumps, which are frequently burned on site to reduce the risk of wildfires and clear growing space for regeneration. Both mill residues and forest residues are commonly used as fuel in combustion boilers to produce process heat and power for forest industry operations. More than 50% of all biomass energy in the United States is generated by the forest industry to dispose of waste and provide heat and electricity for manufacturing operations [1]. In some areas, forest biomass is also used to fuel large power plants and distributed heat and power systems [2,3].

Over the last twenty years, a complex interaction of social, political and economic factors has resulted in permanent mill closures in the interior western United States. Declining industry capacity has reduced the demand for forest biomass and increased average haul distances for timber and biomass producers in this region. For example, prior to its closure in December, 2009, the Smurfit-Stone liner board plant in Missoula, MT, used approximately 1.5 million tons of biomass annually, including wood for both pulp and energy [4]. Since the closure, one-way haul distances for mill and forest residues in western Montana have increased from 70 miles or less to 130 to 210 miles, depending on the end user. In general, high transportation costs and weak regional demand for forest biomass negatively impact the financial viability of wood products manufacturing and silvicultural treatments by turning previously marketable byproducts into waste materials with disposal costs. Furthermore, the most widely practiced method of disposal, open burning, can have negative environmental impacts including increased air pollution, establishment of invasive species, and reduced nutrient capital and soil productivity at burn sites [5,6].

Recent technical advances and public policies related to greenhouse gas emissions and energy security have spurred interest in using thermochemical conversion technologies to process forest biomass closer to harvest sites to improve transportation efficiency and produce renewable high-value

bioproducts that can be more efficiently shipped to distant markets [7]. Specifically, using heat to convert biomass into dense, value-added fuel and chemical products has the potential to improve the financial viability of biomass utilization in locations characterized by long haul distances and weak demand for biomass from pulp mills and other large facilities. Depending on substitutability for existing products, biofuels and bioproducts may also offset fossil fuel use and associated emissions with renewable forest resources, possibly at scales that are well-matched to small and medium sized operations.

In contrast to large-scale centralized facilities that require hundreds of thousands of tonnes of biomass per year, many of the advanced thermochemical technologies currently being developed are targeted at smaller-scale demand for distributed heat and power, biofuels and bioproducts production, and waste processing [8]. In delineating alternative scales of these systems, it is useful to think of distributed scale systems as small, compact, and clean units located at or near an end user of heat and power [9]. Several companies manufacture distributed thermochemical conversion systems, and some have marketed these systems for forest biomass processing [10,11]. Unlike centralized facilities that procure large volumes of biomass from many suppliers across a large geographic area, distributed systems have the potential to allow individual firms to match their byproduct and residues streams with appropriate conversion capacity to produce heat, power, and marketable products from biomass.

1.2. Objectives

It is possible to convert forest biomass into heat, producer gas, biochar, and bio-oil at distributed scales using pyrolysis and gasification technology. A large body of research is devoted to laboratory and pilot scale study of pyrolysis and gasification of woody biomass [12–14] and an increasing number of companies are developing and marketing commercial technologies for biomass conversion. However, there are gaps in our understanding of how these technologies differ with regards to outputs and how these systems might be integrated into existing forest products supply chains. Many of these systems have not been deployed in this sector and the products they produce from forest biomass have not been adequately described or characterized with regards to chemical properties, possible uses, and markets. Uncertainty about product quality and potential value represents risk to investment and presents a significant barrier to the adoption of these technologies by private companies.

The objective of this study is to compare two commercially available technologies with regards to the physical and chemical properties of their outputs and associated market products in the context of co-locating these systems with forest industry operations. Specifically, we: (1) use a gasifier and a pyrolysis system to process coniferous mill and forest residues, (2) characterize the gas and biochar produced by each, and (3) evaluate potential uses for those outputs, including the use of biochar as a precursor in the production of activated carbon (AC). This critical new knowledge is needed by technology firms, investors, and managers to evaluate potential markets for pyrolysis and gasification products and to assess the commercial potential and financial feasibility of distributed thermochemical processing deployed in the forest sector. Our results can also be used to inform analysis of the environmental costs and benefits of these products, including life cycle assessment (LCA).

1.3. Overview of Pyrolysis and Gasification Products

Thermochemical conversion can occur across broad ranges of temperature, pressure, heating rate, oxidation conditions, and residence time. Generally, pyrolysis of biomass at 200 to 300 °C (torrefaction) produces a devolatilized, hydrophobic high-carbon content product often referred to as torrefied wood. Several characteristics of torrefied wood make it more efficient to transport and store than raw biomass, including lower moisture content, higher energy density, hydrophobicity, resistance to decay, and homogenous particle size distribution [15]. It is generally considered a fuel product suitable for combustion applications, including cofiring with coal, but may also be used as a raw material in some manufacturing processes, including gasification and liquid fuel production [16].

Pyrolysis of biomass at higher temperatures (300 to 700 °C) produces recalcitrant charcoal called biochar, as well as volatile gases, a fraction of which may be condensed into liquid pyrolysis oil, also called bio-oil. Biochar can be used in its raw form as a solid fuel, or used as a feedstock for the production of other products, including chemicals, AC, and soil additives. Similarly, bio-oil can be used in its raw form as liquid fuel. However, because of its high oxygen and water content and low stability, bio-oil is generally considered a crude product to be used in the production of refined (*i.e.*, upgraded) biofuels and industrial chemicals, including liquid transportation fuels [12]. Pyrolysis in this temperature range often produces residual tars which can be a useful output or an undesirable byproduct, depending on production objectives [17].

Depending on the conditions of the reaction, specifically the composition and concentration of gas injected into the system, gasification of biomass at temperatures greater than 700 °C produces more gas (*i.e.*, producer gas or synthesis gas) and less biochar than pyrolysis, along with some ash. Depending on gas quality, gases from both pyrolysis and gasification have the potential to be used to produce heat and power in an internal combustion or gas turbine engine. The producer gas from gasification can be used to produce liquid fuels and chemicals, including methanol and hydrocarbon fuels via catalytic conversion processes [18,19]. In addition to these outputs, if conversion is co-located with wood products manufacturing, excess heat from the conversion process can be used for heating buildings, drying lumber and heat-treating products for export. The two systems evaluated in this study operate at the upper end of the temperature spectrum and produce biochar and gas, but no liquid products.

2. Methods

2.1. Biomass Feedstock

We processed mill and forest residues from Tricon Timber, LLC, Saint Regis, MT, USA. The mill residues were a byproduct of manufacturing lumber from delimbed, debarked logs, and contained negligible bark and foliage. In contrast, forest residues were produced from field-dried logging slash and included both bark and foliage. Both feedstocks were mixed coniferous species dominated by Douglas-fir (*Pseudotsuga menziesii*) and lodgepole pine (*Pinus contorta*). Both feedstocks were chipped and screened to meet particle size specifications of 0.76 cm to 1.27 cm with less than 5% size over run, and then dried in a kiln to a moisture content of 10% or less before shipping. Prepared feedstocks were shipped to study sites in Colorado and North Carolina in 55 gallon drums that were

closed but not airtight. Feedstocks in Colorado did not receive additional kiln drying, but feedstocks in North Carolina received 12 h of additional drying in two portable kilns due to concerns that ambient humidity might increase the moisture content above 10%. The moisture content of the feedstocks at the time of conversion ranged from 5.7% to 8.2% (Table 1). At 98.2% organic matter (OM), the mill residues had higher OM content than forest residues, which were 91.5% OM (Table 1). Compared to feedstocks from debarked logs, feedstocks containing bark and foliage generally have higher ash content associated with inherent inorganic compounds in the cambium and contamination from soil during harvest and transport [20]. The content of carbon, nitrogen and selected extractable alkaline metals in these feedstocks are shown in Table 1.

Table 1. Feedstock characteristics.

Feedstock	System	Moisture (%) ^b	Organic matter (%)	Mean C (%)	Mean N (%)	Total extractable cations (mg kg ⁻¹) ^a		
						Ca	Mg	K
Mill residues	TEA	8.17	98.19	47.4	0.1566	1250.0	146.5	577.5
Mill residues	BSI	7.04	c	47.4	0.2062	1919.6	296.4	781.0
Forest residues	TEA	5.71	91.51	45.8	0.2904	1299.6	396.3	898.4
Forest residues	BSI	7.25	c	48.4	0.2124	2405.8	290.5	1097.6

^a Units of mg kg⁻¹ are equivalent to parts per million (ppm); ^b Moisture content at the time of conversion. All feedstocks were kiln dried to less than 10% before shipping. Feedstocks for the TEA system received an additional 12 h of kiln drying before conversion; ^c Unknown.

2.2. Conversion

These feedstocks were processed using a prototype gasification system manufactured by Tucker Engineering Associates (TEA), Locust, NC, USA (Figure 1), and a modular pyrolysis system manufactured by Biochar Solutions, Incorporated (BSI), Carbondale, CO, USA (Figure 2, [21]).

Figure 1. The Tucker Engineering Associates (TEA) gasifier used in this study. Photo: RMRS.



Figure 2. The Biochar Systems Incorporated (BSI), pyrolysis system Beta model used in this study. The unit used in this study was fitted with a thermal oxidizer (not shown), which replaces the open flare shown on the right. Photo: BSI.



The operational dry weight feedstock throughputs of the two systems have been estimated by the manufacturers to be 700 kg h^{-1} and 225 kg h^{-1} , respectively. Biochar yields by mass are reported as between 5% and 25% for the TEA system and up to 24% for the BSI system, with the balance going to producer gas and a small fraction of ash and tar byproducts.

The TEA system was engineered to produce high-quality, high-energy gas from a wide range of feedstocks including coal, municipal solid waste, and wood waste. Biochar is considered a co-product of gas production. The TEA biochars were carbonized at $1040 \text{ }^\circ\text{C}$ in a direct heat, screw conveyor reactor heated by six tangential burners fueled with propane. With feedstock airlocks and no inputs of oxygen, steam, or carrier gas during the conversion process, oxidation during conversion was very low. The pyrolysis gas pressurizing the system is primarily carbon monoxide, nitrogen, methane, and hydrogen. Residence time is estimated at 1.5 min per run. Results for TEA biochars below are for a “double run”, where the feedstock was run through the system to produce biochar, and then the resulting biochar output was run through the system again to remove any residual volatiles and simulate a longer auger configuration, which is currently in development by TEA. Total residence time in this study was approximately 3.0 min. Samples from twelve runs were collected over six days of operation.

The BSI pyrolysis system was engineered to produce biochar from biomass, including agricultural residues and wood waste, with a focus on achieving high yields of biochar with a high percentage of stable, recalcitrant carbon. Energy gas and heat are generally considered co-products of biochar production. The BSI system uses a two-stage reactor. In the primary reactor, the feedstock is carbonized in a controlled aerobic environment with limited oxygen at a temperature between 700 and $750 \text{ }^\circ\text{C}$ for less than one minute. Then the material passes into a second reactor, where material is held in a sweep gas environment for approximately ten to fifteen minutes at a temperature between 400 and $550 \text{ }^\circ\text{C}$, before the material is removed from the machine by a liquid cooled auger with an air lock. The dust fraction of biochar present in the gas stream is collected by a cyclone trap before the gas is

evacuated from the system by a blower. Dust does not receive the same sweep gas treatment as the coarse biochar output, which receives full residence time in the second reactor. The dust fraction of production is not characterized in this study. The pyrolysis gas produced during the first stage of pyrolysis is used as sweep gas for the second stage and is pulled through the system by a blower. This gas is composed primarily of carbon monoxide, nitrogen, methane, and hydrogen, with some oxygen. Some limited oxidation occurs in the first stage, but oxidation is very low in the second stage. Samples from four runs were collected on a single day of operation.

2.3. Sampling and Laboratory Analysis

During conversion, samples of producer gas were collected in 0.5 L evacuated, inert steel canisters, which were pressurized to 15 psig (gauge pressure in pound per square inch) using stainless steel flexible tubing and a battery powered pump apparatus. Each sample generally represents about 15 to 30 s of gas flow. For both systems, tubing was attached to air-tight sampling ports located between the reactor and the downstream air lock system, which is an enclosed, pressurized water tank on the TEA system and a blower and cyclone on the BSI system. In total, twenty-five gas samples were collected from the two systems representing eight runs of each feedstock.

In the laboratory, canister samples of producer gas were analyzed for CO₂, CO, CH₄, and C₂ and C₃ hydrocarbon gases with an Agilent model 7890 gas chromatograph configured with two columns running simultaneously. Chromatogram data were collected and processed by Agilent Chem Station software. A set of gas standards bracketing the sample concentrations were analyzed with each set of samples to construct a standard curve for each compound. Based on the integrated peak areas, the sample concentrations were calculated from the standard curves and written into a spreadsheet for analysis.

For measurement of H₂ concentrations, a Trace Analytical RGA3 gas analyzer was used. A molecular sieve column and a mercuric oxide reduction gas detector were used to measure trace levels of CO, H₂ and other reduction gases. The detection limit is 0.1 ppm H₂. Data from this instrument were also collected and processed by Agilent Chem Station software. Calculations of energy content of the producer gas were made using standard stoichiometric techniques applied to the concentrations of combustible gas components.

At the time of conversion, feedstock and biochar samples were packaged in zip-type bags and shipped to the laboratory for analysis. Four 1.0 kg feedstock samples (two of each type) and fifteen 2.0 kg biochar samples were collected. Two additional biochar samples, approximately 10 kg each, were packaged for use as a precursor in steam activation trials. Feedstock moisture content was determined in the laboratory using oven drying at 103 ± 2 °C [22]. Feedstock samples were analyzed for organic matter content using loss-on-ignition methods for 8 hours duration at 400 °C [23]. To obtain nutrient information, feedstock samples were ashed for 5 h at 475 °C and nutrients were extracted with a 2N nitric acid solution. The extractable nutrients calcium, magnesium and potassium were determined by analysis with a Perkin Elmer 5100PC Atomic Absorption Spectrometer (Perkin Elmer, Inc., Waltham, MA, USA).

A sieve analysis was used to determine the particle size distribution of each biochar product. Using a mechanical shaker, a 100 g biochar sample was passed through successively smaller screens with

opening sizes ranging from 6.35 to 0.044 mm. An unconsolidated biochar sample was used to assess sample pH. A biochar-distilled water solution with a 1:4 ratio was made and pH of the solution was determined with an Orion 4-Star meter and electrode (Thermo Scientific, Beverly, MA, USA).

The determination of total carbon and total nitrogen for both the feedstocks and biochars was made by dry combustion on a TruSpec CN analyzer, which uses an infrared detector to measure carbon and a thermal conductivity cell to determine nitrogen (Leco Corporation, St. Joseph, MI, USA). Samples were dried and homogenized prior to analysis and feedstocks were ground to pass through a 420 μm screen. Biochar was ground into a fine powder. Differences in analytical methods reflect the unique composition of the samples—feedstocks were treated as organic material while the biochar was analyzed using soil (*i.e.*, mineral) methods with higher oxygen flow during the burn phase to ensure complete combustion of the material. Energy content was determined by calorimetry using a Parr bomb calorimeter calibrated with a standard of benzoic acid. Total carbon and nitrogen associated with this test was measured with a LECO CN analyzer.

Two physical activation methods were used to activate biochar outputs from the BSI and TEA systems. Biochars from both systems were activated with steam using a bench top steam activation apparatus. Activation temperature was 950 °C, with steam injected at 15 psig. In addition, the TEA system biochars were activated using a 6.5 inch internal diameter electrically heated Bartlett-Snow rotary calciner (Alstom Power, Naperville, IL, USA). The calciner has four zones along the furnace section for temperature control and the hottest zones were set at 927 °C. The calciner cylinder was nitrogen purged to maintain an inert atmosphere prior to activation and steam was injected at 815 °C. Retention time was 45 min. Unfortunately, due to cost and logistical considerations, BSI biochars were not activated using this method.

Iodine number for biochars and AC was calculated using titration methods, specifically ASTM D4607-94 [24]. Brunauer-Emmet-Teller (BET) surface area of TEA biochars and resultant AC produced from TEA biochar precursor was measured by nitrogen gas sorption analysis at 77 K using a BET-201-APC Sorptometer (Porous Materials Incorporated, Ithaca, NY, USA). Before analysis, 1.0 g samples were vacuum outgassed to 20 μm at 20 °C, with variable outgassing time. In addition to BET surface area, sorption analysis was used to calculate total pore volume, porosity, and several measures of pore diameter for TEA biochars and AC.

3. Results

For both feedstocks, producer gas from the TEA gasification system has higher energy content than that of the BSI system (Figure 3). This is a result of higher concentrations of hydrogen, carbon monoxide, and C2 hydrocarbons, including ethane (C_2H_6), ethylene (C_2H_4), and acetylene (C_2H_2 , Table 2). Among the C2 hydrocarbons, ethylene is the most prevalent C2 gas for both systems (Table 3). However, the proportion of acetylene among the three is higher for the TEA system than for the BSI system. Concentrations of methane appear similar for the two systems, as do concentrations of C3 and C4–C5 hydrocarbons, which combined are below 0.25% for both systems. Other gasses, primarily nitrogen and water vapor, account for a larger fraction of producer gas from the BSI system. For the TEA system, gas from mill residues had higher energy content than gas from forest residues,

with averages of 12.4 MJ m^{-3} and 9.8 MJ m^{-3} , respectively. Gases from the BSI system were 1.3 MJ m^{-3} for mill residues and 2.5 MJ m^{-3} for forest residues.

Figure 3. Gas energy content.

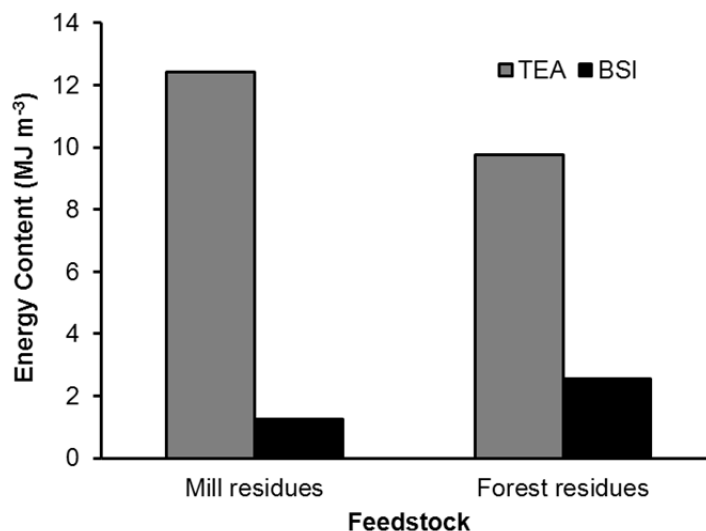


Table 2. Producer gas chemical composition.

Feedstock	Mill residues		Forest residues	
	TEA	BSI	TEA	BSI
H ₂ (%)	8.46	1.84	7.39	2.63
CO (%)	39.03	4.04	34.05	7.83
CO ₂ (%)	7.66	0.89	5.97	1.90
CH ₄ (%)	12.68	7.35	10.38	12.08
C ₂ (%)	3.43	0.24	1.63	0.64
C ₂ H ₆ (%)	0.14	0.08	0.03	0.15
C ₂ H ₄ (%)	2.77	0.15	1.18	0.44
C ₂ H ₂ (%)	0.51	0.01	0.42	0.05
C ₃ (%)	0.06	0.07	0.01	0.17
C ₄ –C ₅ (%)	0.00	0.02	0.00	0.05
Other (%)	28.68	85.55	40.57	74.69

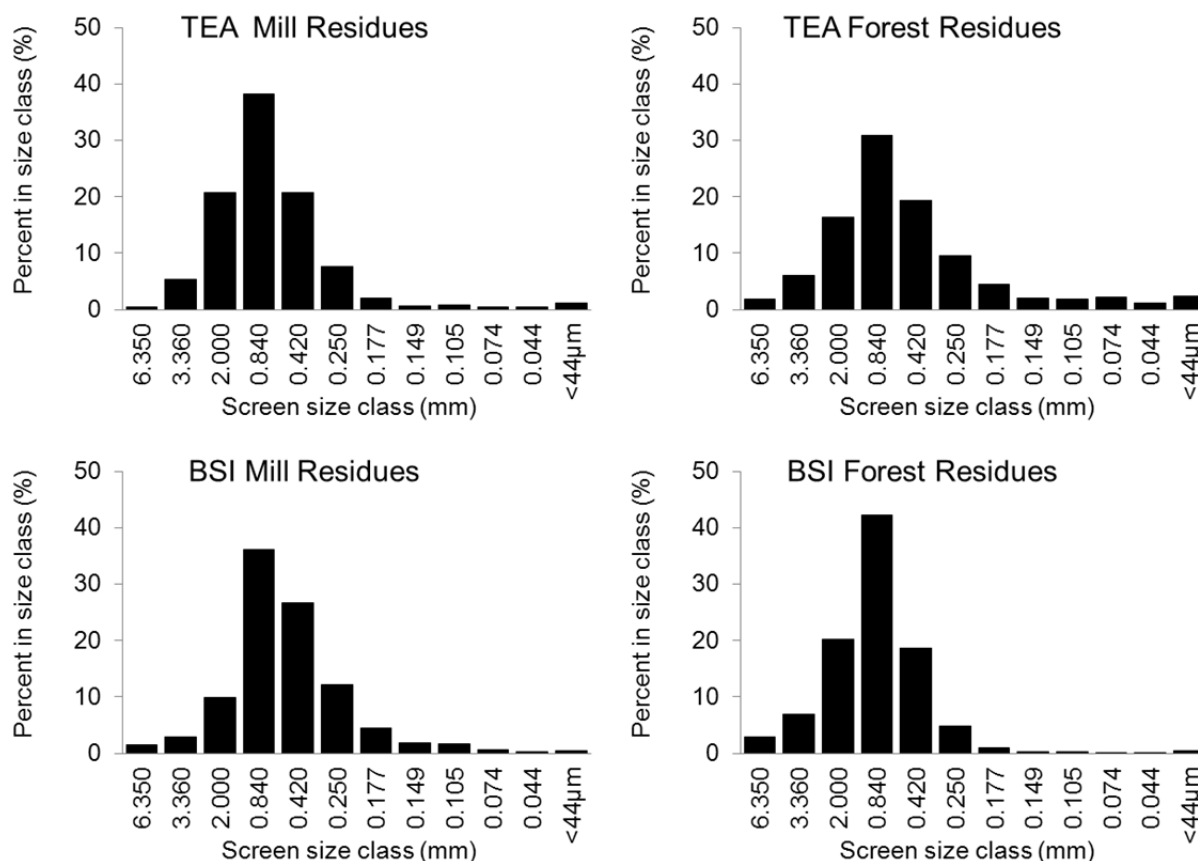
Table 3. Biochar characteristics.

Feedstock	System	H ₂ O (%)	Bulk density, dry (Mg m ⁻³)	pH	C (%)	N (%)	C:N	BET surface area (m ² g ⁻¹)	Energy (MJ kg ⁻¹)
Mill residues	TEA	2.94	0.165	10.2	91.5	0.89	102.8	15.0	33.98
Mill residues	BSI	1.31	0.150	9.0	82.1	0.83	98.9	203.0	35.71
Forest residues	TEA	1.68	0.183	8.9	70.5	0.81	87.0	11.8	33.40
Forest residues	BSI	2.23	0.131	8.7	75.9	0.45	168.7	129.0	33.46

Biochars produced by the two systems from screened feedstocks show similar particle size distributions (Figure 4), which are centered around 0.84 mm and skewed toward smaller particle sizes. TEA system biochars from forest residues appear to have a larger proportion of particles in the smaller

than 0.42 mm size classes. Bulk densities for the samples are also similar and range from 0.131 Mg m^{-3} to 0.183 Mg m^{-3} (Table 3), which are relatively low for wood biochars and reflect the low densities of the softwood feedstocks [25]. All of the biochars produced were alkaline, with biochars from mill residues having a higher pH than those from forest residues. Average pH ranges from a low of 8.7 for BSI biochar made from forest residues to 10.2 for TEA biochars made from mill residues.

Figure 4. Biochar particle size distribution.

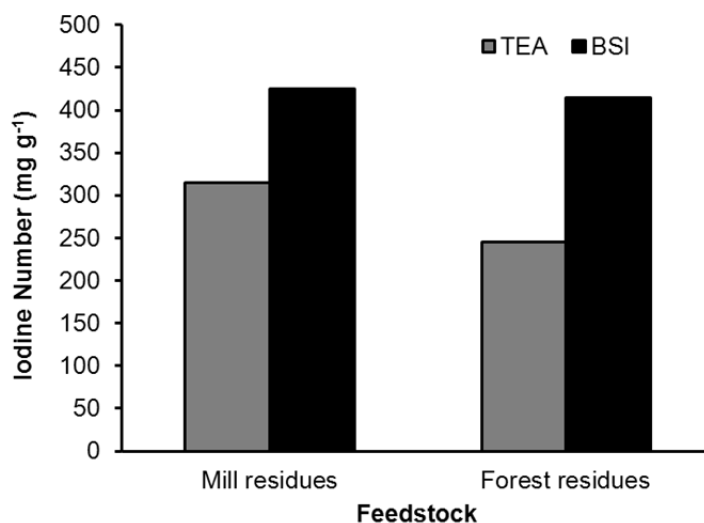


At $15.0 \text{ m}^2 \text{ g}^{-1}$ (TEA) and $203.0 \text{ m}^2 \text{ g}^{-1}$ (BSI), mill residue biochars also have slightly higher BET surface areas than forest residue biochars, which are $11.8 \text{ m}^2 \text{ g}^{-1}$ and $129.0 \text{ m}^2 \text{ g}^{-1}$ for the TEA and BSI systems, respectively. Carbon content for the TEA system biochars made from mill and forest residues are 91.5% and 70.5%, compared to 82.1% and 75.9% for BSI biochars. The carbon to nitrogen ratio for these biochars ranges from 87.0 to 168.7. The energy contents of these biochars on a dry weight basis are similar and range from 33.4 to 35.7 MJ kg^{-1} .

Pre-activation iodine numbers were 7 mg g^{-1} and 2 mg g^{-1} for TEA biochars and 142 and 82 mg g^{-1} for BSI biochars, for mill and forest residues, respectively. Following bench top steam activation at $950 \text{ }^\circ\text{C}$ with steam injected at 15 psig, iodine number ranged from 245 g cg^{-1} to 425 g cg^{-1} , indicating a significant increase in adsorption properties (Figure 5). For the bench top apparatus, AC from BSI biochars have higher iodine adsorption than AC from TEA biochars. It also appears that mill residues produce AC with higher adsorption potential. For TEA system biochars, AC iodine adsorption for mill residue feedstock is 29% higher than for forest residue feedstock. The difference is much smaller

(<3%) for the BSI system. BET surface area was not calculated for AC produced using bench top steam activation.

Figure 5. Iodine number of AC from biochar using a benchtop steam activation apparatus at 950 °C with steam injected at 15 psig.



In addition to bench top activation, TEA system biochars were activated using a Bartlett-Snow rotary calciner at 927 °C with activation by steam injected at 815 °C. Results show that this method of activation increased BET surface area from 15.0 m² g⁻¹ to 1283.0 m² g⁻¹ for biochar made from mill residues and from 11.0 m² g⁻¹ to 575.9 m² g⁻¹ for biochar made from forest residues (Table 4). The increase in surface area is reflected by the pore characteristics of the AC, with large increases in total pore volume and porosity, and a decrease in average pore diameter (Table 4).

Table 4. BET surface area and pore characteristics of TEA system biochars and AC resulting from steam activation in a rotary calciner at 815 °C.

Feedstock	Product	BET surface (m ² g ⁻¹)	Total pore volume (cc g ⁻¹)	Porosity (per g of sample)	Ave. pore diameter (Å)	Med. PV pore dia. (Å)	Med. SA pore dia. (Å)
Mill residues	Biochar	15.0	0.0161	0.0158	42.79	45.90	35.97
Forest residues	Biochar	11.8	0.0359	0.0347	122.09	175.98	60.92
Mill residues	AC	1283.0	0.9591	0.4895	29.90	48.15	26.97
Forest residues	AC	575.9	0.4441	0.3075	30.85	51.32	27.28

4. Discussion

This study examines the chemical and physical properties of the outputs of two different thermochemical conversion technologies used to process mill and forest residues, with an emphasis on potential uses and markets for those outputs. The two systems were chosen because they are commercially available, can process a wide range of woody biomass feedstocks of varying quality, and are small enough to be used in distributed applications by small and medium scale forest industry facilities. The two systems also represent different ends of the conversion spectrum, with the BSI

pyrolysis system designed to maximize biochar fixed carbon and sorption for an exothermic reaction between 350 and 750 °C, and the TEA system gasifier designed to produce high-energy gas at temperatures greater than 1000 °C. The differences between the systems are reflected in differences between production outputs and their potential uses and markets.

4.1. Producer Gas

The energy content of gas produced from forest biomass by the TEA system gasifier is somewhat higher than values reported in studies of pilot scale and laboratory systems. For example, using a Biomax-25 gasifier (Community Power Corporation, Littleton, CO, USA), Elder and Groom [26] produced gas from pine and mixed hardwood chips with energy content around 6 MJ m⁻³. Son *et al.* [27] reported syngas energy content of 4.6 MJ m⁻³ for wood chips processed in an experimental downdraft gasifier. At 12.4 MJ m⁻³, the TEA system gas produced from mill residue in this study has relatively high energy content. The energy content of BSI pyrolysis system gas is below 3.0 MJ m⁻³, which is relatively low compared to gasification systems, but similar to gas produced by pyrolysis systems operating in this temperature range [28]. It would be expected that mill residue feedstocks would result in gas with higher energy content than forest residue feedstocks because of the lower ash content and higher energy density of the raw materials, and this appears to be the case for the TEA system. However, we do not know if the seemingly contrary results of for the BSI system are within the range of variability of the system or represent a statistically significant difference between the feedstocks.

High concentrations of CO₂ and N₂ are responsible for the lower energy content of the BSI gas. However, it is also worth noting that the BSI system is exothermic and does not require any gas inputs for heating once the primary reactor is fired. By contrast, the TEA reactor is endothermic and is estimated to consume about 1500 MJ h⁻¹ in process heat, which was provided by propane in this study. Using woody biomass feedstocks, process energy needs could be met with about 15% of the gas production of the TEA system. Though the prototype is not presently configured to use producer gas as fuel for its six tangential burners, TEA is currently modifying the system to integrate this option as part of ongoing research and development.

There are some operational considerations related to air-fuel ratios and lower flame temperature, but in general retrofitting gas burners to accommodate producer gas from biomass conversion is relatively straight forward. This means that, with relatively little cost, the gas produced by these systems can be combusted to produce process heat for mill operations such as feedstock and lumber drying, heat treating, and facility heating. For example, many conversion systems require feedstock with low moisture content, but feedstock moisture content less than 10% is below what could be expected from field-dried forest residues in most parts of the country. Both systems can be configured to use waste heat and/or combustion of a portion of the gas stream to dry feedstock. BSI currently offers this option for new pyrolysis systems. Mills that dry solid wood products to meet product specifications or export requirements also have a significant need for heat.

Producer gas can also be used as fuel for electricity generation using an internal combustion or turbine engine, but this application is highly dependent on gas quality. Specifically, particulate matter and tars significantly increase engine wear and must be removed through gas cleaning. Gas quality for

use in turbine engines must be especially high, with narrow parameters for particulate matter (<30 ppm), particle size (<5 μm), and alkali metals <0.2 ppm [28]. Reductions in engine power (*i.e.*, derating) are also a challenge when substituting biomass producer gas for natural gas or liquid fossil fuel because of its lower energy density. Though we did not evaluate these gas properties in this study, the need for significant producer gas post-processing for power generation is likely. However, if power is generated, these systems provide another potential market product—electricity to the grid. If power generation meets facility requirements, excess power may be sold or credited against future power use, depending on grid infrastructure and utility sector regulation.

Biomass is the only renewable energy source that can be used as raw material in the production of liquid hydrocarbon fuels and chemicals. Thermochemical conversion systems are associated with two general types of liquid outputs: bio-oil and liquids manufactured from producer gas. Neither of the two systems in this study produces liquid output, but some pyrolysis systems do produce bio-oil, which could be shipped in its raw form to a refining facility [7]. Industrial systems for the production of methanol (methyl alcohol) from biomass producer gas with high concentrations of CO and H₂ (*i.e.*, synthesis gas) are well established [18]. Furthermore, the development of methods for the commercial production of liquid fuels and chemicals using Fischer-Tropsch (FT) synthesis of biomass producer gas is progressing [19] and even commercialized in some cases [29]. However, a variety of challenges related to economies of scale in refining operations and the technical demands of liquid fuel production make it unlikely that small-scale catalytic production of liquid fuels and chemicals will be integrated directly into these systems in the near future. For both methanol production and FT synthesis, the major barriers to integration at distributed scales are both technical and financial [19].

4.2. Biochar

Biochars produced by the TEA and BSI systems can be used as a solid fuel. Recent research on the use of torrefied wood and biochar as fuel has focused on utility applications, especially co-firing with coal [30,31]. Fossil coal energy content is generally higher than that of biochar and ranges from 28 to 40 MJ kg⁻¹, depending on coal quality. In contrast, the calorific value of fuels produced by pyrolysis of wood biomass have been reported as 20.7 MJ kg⁻¹ for torrefied wood [16], between 22.8 and 31.8 MJ kg⁻¹ for slow pyrolysis biochar (*i.e.*, charcoal, [32]), and 20 to 26 MJ kg⁻¹ for biochars made from various woody materials [33,34]. With energy content above 30 MJ kg⁻¹, the biochars evaluated in this study are higher in energy than these fuels, but lower than medium and high quality coal. This means that biochar, like biomass, is generally a poor substitute for coal in terms of energy content. However, there may be other reasons that utility companies and other coal users may want to substitute biochar for coal. Among them, co-firing biochar with coal may reduce fuel costs, reduce some types of emissions (e.g., sulfur oxide and nitrogen oxide), diversify fuel sources, and offset fossil fuels with renewable fuels [35]. In some states, cofiring may also meet requirements for renewable portfolio standards. Whether or not cofiring reduces greenhouse gas emissions depends on the source of the feedstock as well as the carbon accounting methods used, but it is clear that cofiring substitutes biogenic emissions for fossil fuel emissions. In addition, forests supplying biomass for cofiring recover emissions over time through regrowth of harvested stands, as long as forests are not converted to other land uses.

In general, these benefits are similar to those of cofiring biomass directly without conversion. Some types of coal-fired boilers, including stoker boilers and pulverized coal boilers, can substitute raw biomass for coal, often up to 20% by mass, without significant detrimental effects on system performance [36], but there may be some advantages to using pyrolysis products in these systems rather than biomass. The energy density of pyrolysis products is higher than that of biomass, which is typically around 16 MJ kg^{-1} for biomass used in cofiring [37]. In addition to improving transportation efficiency and boiler performance through higher energy density, biochar and torrefied wood have better handling and storage properties than biomass [15]. Furthermore, boiler systems that cannot cofire biomass directly, such as integrated gasification combined cycle systems, may be capable of substituting biochar directly for coal, depending on biochar properties. Based on the particle size distributions and other properties of the biochars produced in this study, we believe that they could be substituted for coal in most gasification applications.

The use of biochar as a soil amendment is the subject of intensifying scientific inquiry from researchers in agriculture, forestry, mining, and other fields. Biochar additions have received the most attention from efforts to increase carbon sequestration while reducing atmospheric carbon dioxide concentrations [38]. Increases in carbon sequestration can improve overall soil quality because of the role that carbon plays in chemical, biological, and physical soil processes [39]. Biochar has a higher surface area and greater porosity than native soil organic matter, which also helps improve soil aggregation. Application of biochar from forest biomass to forest sites can improve the nutrient and water holding capacity of the soil by altering soil texture, aggregation, and organic matter content [40,41]. Biochar can also decrease nutrient leaching and increase nutrient availability by altering soil cation exchange capacity and soil pH [42]. Understanding the interactions of biochar application and soil texture, organic matter, and pH will be the key to determining both long-term impacts and potential market opportunities.

It is difficult to evaluate the use of our biochars for soil applications because most chemical data available for biochar soil amendments are based on agricultural crop feedstocks (e.g., peanut hulls, pecan shells, apricot stones) with little information on woody feedstock biochar. As a benchmark, biochar produced from hardwood forest residues by fast pyrolysis and used in forest soil studies contained 62% C and 18% N, with a pH of 6.8 and a bulk density of 0.25 Mg m^{-3} [43]. In comparison to the biochars produced in this study, these chars have higher C, higher N, lower pH, and higher bulk density (Table 3).

The greatest impact of biochar additions to forest soil may be the liming effect that occurs as a result of increased pH. Biochar pH ranged from 8.7 to 10.2 for this study (Table 3). Forest soils generally have a pH range from 4.5 to 6.0. In this case, the liming effect may not be ideal for all forest soil types and plant communities. Many forest plants, fungi, and bacteria thrive at lower soil pH [44]; therefore altering forest soil pH through the addition of biochar may result in unfavorable shifts in above- and belowground flora. However, there are currently not any guidelines on the amounts of biochar that can be added before a resultant pH shift occurs, as this will likely be soil-specific. Low application rates (e.g., $1 \text{ to } 2 \text{ Mg ha}^{-1}$ biochar), which mimic the amount of biomass removed during harvest operations, may have little impact on soil pH, but would alter water holding and nutrient cycling conditions enough to improve forest growth. On degraded forest lands (e.g., log landings, skid trails) biochar may reduce soil bulk density and increase plant available nutrients sufficiently to

rehabilitate the soil and ensure native vegetation regrowth [45]. Though field research is progressing rapidly, markets for biochar as a soil amendment are still emerging.

In contrast, markets for AC are well developed and diverse. The chemical and physical properties of carbon that result in improved nutrient and water holding capacity in some soils are also desirable properties for industrial sorbents. High surface area and high porosity are ideal for adsorbing contaminants from both liquids and gases. Physical and chemical activation methods can significantly improve these properties in biochars, potentially adding value by meeting commercial specifications for AC used in filtering applications. Table 5 summarizes published results of BET surface areas and other properties of AC produced from fossil coal and biomass feedstocks. Pollard *et al.* [46] reported that most commercial ACs have a surface area between 400 and 1600 m² g⁻¹.

Table 5. Published BET surface areas of AC produced from fossil coal and biomass feedstocks.

Feedstock	BET surface (m ² g ⁻¹)	Pyrolysis temp. (°C)	Activat. type	Activat. temp. (°C)	Pore volume (cm ³ g ⁻¹)	Iodine # (mg g ⁻¹)	Source
Subbituminous coal	988	700–950	CO ₂	750	0.482	a	[47]
Bituminous coal	536	500	H ₃ PO ₄	50	0.030	a	[48]
Apricot stones	566	200	H ₂ SO ₄	200	a	548	[49]
Wood	1780	440	H ₃ PO ₄ + Steam	440	0.130	a	[50]

^a not reported.

In this study we show that the biochar produced by the BSI and TEA systems is suitable for physical activation using standard physical activation methods. The TEA AC is within the commercial range, and biochar from mill residue produces AC with a higher BET surface area than biochar from forest residues. This result is consistent with studies relating high ash content to lower activation levels [51]. Though we did not activate BSI biochars using the industrial rotary calciner, in laboratory activation BSI biochars were activated to a higher level than TEA biochars, as evaluated by iodine adsorption (Figure 5). This result is expected based on the temperature of pyrolysis [52]. Both biochar products could be used as a precursor for the production of AC. Though it is difficult to compete with the economic efficiency and consistency of fossil coal as an AC precursor, biochar is from renewable resources, which may be an advantage in some markets for differentiated carbon products. Further, because woody biomass is available as a byproduct of forest management and timber production in many parts of the country and pyrolysis or gasification technology performs well at distributed scales, AC can be produced from biochar in a more distributed supply chain than characterizes AC from fossil coal. Distributed production might provide advantages in transportation efficiency to some individual AC users and local markets.

Activated carbon is only one potential use and market for biochar. The range of potential market-based uses of biochar, from fuel to soil amendment to AC, can enhance product and market diversification available to producers. This offers the possibility of increasing the portfolio of value-added products that can be produced from what are now waste byproducts of solid wood products manufacturing and forest management.

5. Conclusions

Distributed thermochemical biomass conversion systems have the potential to meet a number of different operational needs associated with wood products manufacturing, including waste disposal, heat, power, and the production of marketable value-added products from woody biomass. The extent to which this potential can be achieved hinges on the qualities of the products these systems produce, potential uses for those products, and the financial viability of system integration compared to alternatives. In this study, we evaluated the outputs of two conversion systems used to process mill and forest residues and determined that the gas and biochar produced by these systems could be used to produce heat, electricity and a range of marketable products, but many questions remain.

Both of the systems examined in this paper are the subject of ongoing research. The authors and their colleagues are currently developing detailed financial models for system deployment in the forest sector based on experimental production and operations studies. Economic input-output models are being used to evaluate the potential economic benefits of co-locating these technologies with forest industry facilities in the western United States. The authors are also working to characterize gas, emissions and biochars from a wide range of woody feedstocks processed with these technologies. In particular, the variability of product quality, gas flow, and yield is being quantified in commercial settings over operational periods of days and weeks rather than hours. Additional research on the use of biochars in the production of AC is focused on chemical activation, and preliminary results using a proprietary activation process indicate that using a combination of steam and chemical activation can yield higher BET surface area AC from biochar produced by these systems than using steam activation alone.

The team is also collaborating on several lines of research to address the environmental impacts of pyrolysis conversion of woody biomass. BSI biochar has been incorporated into a number of field-based experimental studies to evaluate its effects on soil quality, soil function, and site productivity, with an emphasis on biochar application to forest soils. Broader environmental impacts are being evaluated using LCA of the TEA system and emissions analysis for both systems based on samples of gaseous and particulate matter emissions taken during testing and production runs. On the manufacturing side, both TEA and BSI are working to incorporate technical advances in producer gas utilization, feedstock drying, and biochar cooling into their systems, and have already moved beyond the prototypes examined in this study. New knowledge about the technical, logistical, economic, and environmental aspects of these and similar systems will be critical for guiding informed business and policy decisions associated with biomass conversion technologies.

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