Performance and Emissions Control of Commercial-Scale Biochar Production Unit

M. A. Severy, D. J. Carter, K. D. Palmer, A. J. Eggink,
C. E. Chamberlin, A. E. Jacobson

Abstract. *Two commercial biochar production machines – a single-auger unit and a larger dual-auger version – were operated to evaluate feedstock specifications, biochar quality, throughput rates, and emissions profiles. Biochar was produced from woody biomass feedstocks of various species, contamination levels, comminution methods, and moisture contents. Feedstocks with ash content exceeding 15% dry basis or moisture content exceeding 25% wet basis were observed to decrease fixed carbon content of biochar and to increase the labor effort required to operate the machine. The dual-auger version of the machine was able to process 380 kg h^{-1} of biomass feedstock (dry basis) to produce 63 kg h^{-1} of biochar with a mean electricity demand of 4.5 kW. Average CO, propane, NO_x, and SO_2 emission rates from the flare of this machine were measured to be 160, 120, 51, and 43 g h^{-1}, respectively, with total particulate matter (PM), PM_{10}, and $PM_{2.5}$ emission rates of 380, 40, and 4.5 g h^{-1}, respectively. Results from these experiments indicate that high-quality biochar can be produced from a variety of feedstocks, including forest residuals, as long as the ash and moisture content are within the specifications. Future research and development should focus on increasing the throughput of the machine, implementing an automated control system to reduce the operational effort, and improving safety and product consistency.*

Keywords. *Biochar, Biomass, Biomass conversion technology, Carbon sequestration, Forest residuals, Gasification, Pyrolysis.*

Biochar is a carbonaceous material, or char, that can be produced from biomass feedstocks such as forest residues through gasification or pyrolysis of biomass in an oxygen-limited environment. During the production process, biomass is decomposed at elevated temperatures to produce a gas, mainly comprised of hydrogen carbon monoxide and carbon dioxide, and a solid product. The residual, carbonaceous, solid material is biochar.

Biochar is used primarily as a soil amendment to improve soil fertility. Blending biochar into soils increases the moisture retention capacity and reduces nutrient leaching (Lehmann and Joseph, 2012) due to its high surface area and pore distribution (Mukhergee et al., 2014). Other benefits to biochar application in soils include increased health and efficiency of soil microbial life (Steiner et al., 2007) and increased cation exchange capacity (Liang et al., 2006). The effects of these soil properties have been shown to improve plant growth and productivity (Graber et al., 2010), but longer term field studies are required to confirm the results of lab scale tests (Jones et al., 2012). Application of biochar has also shown the potential to mitigate the effects of climate change (Woolf et al., 2010) both by decreasing N_2O emissions from soils (Kammann et al., 2012) and sequester recalcitrant carbon in soils (Brassard et al., 2016). Although most research for biochar applications focuses on its use as a soil amendment, biochar can also be used for remediation of contaminated soils (Beesley et al., 2011), for water treatment (Mohan et al., 2014), and as the base material for activated carbon (Han et al., 2013).

Characteristics of biochar, such as carbon mineralization (long-term carbon sequestration), surface area, and cation exchange capacity are dependent on several factors, primarily feedstock type and quality and reactor time and temperature (Zhao et al., 2013, Enders et al., 2012). The ability to determine biochar properties, particularly carbon stability, and beneficial applications based on feedstock type and processing technique has been the subject of a significant amount of research. A long-term carbon mineralization rate model developed by Zimmerman (2010) shows a linear relationship between biochar volatile matter (VM) (wt. %) and the 100-year carbon loss rate. According to this model, carbon loss was less than 5% at 20% VM and less than 10% at 40% VM (Zimmerman, 2010). The International Biochar Initiative (IBI) and the European Biochar Foundation (EBF) have worked to define standard biochar properties. The first and primary property for both IBI and EBF standards is a determination of carbon stability via ultimate analysis where organic carbon must be ≥60% (class 1, IBI), or ≥50% (EBF), with a maximum H/C_{org} ratio of 0.7 (EBF, 2013). Recently,

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The authors are **Mark A. Severy,** Research Engineer, **David J. Carter,** Managing Research Engineering, **Kyle D. Palmer,** Research Engineer, **Anthony J. Eggink,** Research Engineer, **Charles E. Chamberlin,** Professor, and **Arne E. Jacobson,** Professor, Schatz Energy Research Center, Humboldt State University, Arcata, California. **Corresponding author:** Mark A. Severy, 1 Harpst St., Arcata, CA 95521; phone: 707-826-4345; e-mail: mark.severy@humboldt.edu.

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Klasson (2017) developed a correlation that accurately classifies biochar and biochar stability based on proximate analysis and the mass fractions of VM, fixed carbon, and ash content when biochar was produced at ≥400°C. In the present article, fixed carbon content will be used as a simple indicator of biochar quality and long-term stability of biochar in soils.

The most common methods for biochar production include gasification (Shackley et al., 2012, Pereira et al., 2016) and pyrolysis (Lee et al., 2013, Tripathi et al., 2016). Gasification and pyrolysis are differentiated by the reaction temperature and amount of oxygen in the reactor; pyrolysis occurs at a temperature range of 300°C to 600°C in the absence of oxygen, and gasification occurs around 800°C with limited small amounts of oxygen (Meyer et al., 2011). Heat for pyrolysis reactions must be externally supplied or, in some cases, the energy requirements can be met from combustion of the gases evolved during the reaction (Xu et al., 2011). During gasification, the heat demand is met through the reaction of oxygen and the biomass feedstock in the reactor, resulting in lower char yield for gasification systems (~10%) compared to pyrolysis (~35%) (Shackley et al., 2012).

Various reactor designs are available for biochar production including batch, semi-batch, or continuous operation (Garcia-Perez et al., 2010). Biochar kilns are a simple, low-cost method to produce biochar but often have low production, higher uncontrolled emissions, and produce biochar of inconsistent quality (Garcia-Perez et al., 2010). Gwenzi et al. (2015), for example, used kilns to assess the suitability for biochar production and application in sub-Saharan Africa. Continuous laboratory-scale pyrolysis systems have also been studied to determine biochar quality and uses (Jenson et al., 2000; Xu et al., 2011; Agrafioti et al., 2013; Mašek et al., 2013). Due to their small scale, however, these studies provide limited context to evaluate the techno-economic potential of biochar production for a commercial system. As noted by Meyer et al. (2011), more data from pilot-scale systems are required to allow for better technologic and economic assessment of biochar production. Few studies have reported data from pilot or commercial-scale biochar production systems. Shakley et al. (2012) provided biochar yield and quality analysis from a gasifier electricity generation system deployed in Cambodia, and Kim et al. (2015) reported on the economic performance of a continuous biochar production unit manufactured by Biochar Solutions, Inc. (BSI, Carbondale, Colo.) based on data collected over 25 days of production using sawmill residues.

The objective of this article is to add to the limited available literature to provide detailed production and operational data from pilot scale biochar production machines. The results from this study can be used as inputs for techno-economic assessments and lifecycle analyses to evaluate the economic and environmental performance of biochar production at a commercial scale. This study provides results from field testing of two machines manufactured by BSI. The first machine, designated as the single-auger unit, was designed to reduce the operation and maintenance costs and improve the safety of the machine tested by Kim et al. (2015). The second machine, designated as the dual-auger unit, was designed to increase the throughput capacity and improve the emissions profile relative to the single-auger unit.

In addition to evaluating production potential, the other objectives of this study were to 1) determine the range of acceptable feedstocks for the biochar machine with respect to moisture content, ash content, and particle size; 2) observe how feedstock quality influences biochar quality based on proximate analysis of the materials; and 3) evaluate emissions profiles of the machines.

Methods and Materials

Experiments were conducted with two separate biochar production machines produced by Biochar Solutions Inc. (BSI) of Carbondale, Colorado (Biochar Solutions, 2017). The first phase of testing was conducted on the single-auger version of BSI's biochar machine to investigate the relationship between feedstock and biochar quality and determine the feedstock specifications. Based on the results from testing the single-auger unit, the manufacturer designed and fabricated a larger dual-auger machine to improve the performance and increase the throughput. This slightly larger, second machine used two processing trains exiting a single reactor rather than one. The second machine was tested with the objective of evaluating potential increases in the throughput rate and reductions in the emissions.

Feedstock Description

Seven combinations of feedstock species, comminution methods, and contaminants were tested in the single-auger unit (table 1). The feedstocks were selected to be representative of forest residuals including large chips and ground material, as well as feedstock contaminated with tops and soil. The dual-auger machine was tested using a single feedstock, medium conifer chip, as noted in row 4 of table 1. Pueblo Wood Products, Co. (Pueblo, Colo.) and Summit Logging, LLC (Pueblo, Colo.) supplied the feedstocks. The feedstocks originated in southwest Colorado, but the exact origin was undisclosed. Proximate analyses, bulk density (BD), and higher heating value (HHV) for the feedstocks are presented in table 1 for each feedstock and its replicate. The feedstock moisture content ranged from 10% to 37% wet basis (w.b.) and ash content ranged from 0.3% to 26% dry basis (d.b.), with medium conifer chip having the highest moisture content (25% and 37% w.b.) and pinyon-juniper being the most contaminated (21% and 26% ash content d.b.).

The particle size distributions of the ground and chipped feedstocks used in the single-auger unit are presented in figure 1 as the cumulative mass percent passing through a sieve. The table on the bottom of figure 1 provides a breakdown of the particle size distribution into three categories of fine, medium, and large particles. The pinyon-juniper feedstock contained a high percentage of fine soil and dust after harvesting and displayed the largest fraction of very fine particles (13%), which pass through a 1 mm sieve, as seen on the intersection of the left axis in figure 1. Also notable is that the medium conifer chip has a very narrow range of particle

Table 1. Feedstock description and properties. Two rows are presented for each feedstock type referring to replicates _1 and _2, respectively.

Test ID	Species	Comminution Method	Contaminant	MC[a] % w.b.	Ash % d.b.	VM % d.b.	FC % d.b.	BD[b] kg m^{-3}	HHV[b] MJ kg^{-1}
Cg	Conifer	ground	none	15%	2%	85%	12%	178	20.3
				19%	2%	86%	13%	173	20.4
Cg-T	Conifer	ground	33% tops	17%	7%	86%	7%	162	18.8
				15%	2%	82%	16%	154	18.2
Cg-C	Conifer	ground	9% soil	14%	13%	77%	10%	145	17.1
				16%	14%	72%	14%	157	16.4
Ccm[c]	Conifer	chip, medium	none	37%	1%	87%	13%	147	20.0
				25%	0%	88%	12%	149	20.0
Ccs	Conifer	chip, small	none	22%	3%	86%	12%	167	19.2
				20%	3%	85%	12%	131	20.7
Hg	Hardwood	ground	none	15%	0%	94%	6%	190	18.6
				16%	1%	87%	11%	218	18.7
PJg	Pinyon-juniper	ground	as received[d]	10%	26%	67%	7%	220	18.0
				10%	21%	72%	7%	163	16.6

[a] MC = moisture content; VM = volatile matter; FC = fixed carbon; BD = bulk density; HHV = higher heating value.
[b] These measurements use mass on a bone-dry basis.
[c] Ccm was used for all tests on the dual-auger unit.
[d] PJg was contaminated with soil and bark as received.

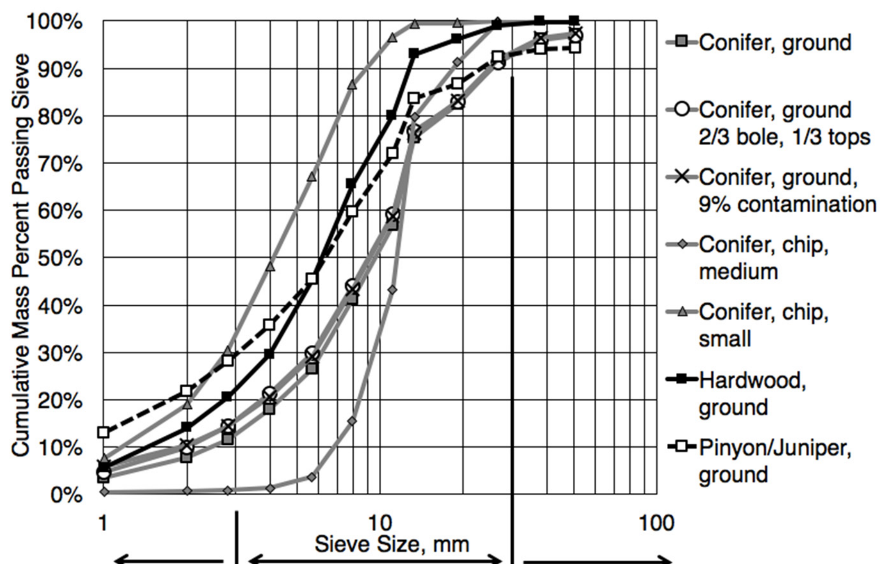
sizes, indicated by its steep slope in figure 1, with 99% of its mass falling between 3 and 12 mm.

System Description

The single-auger unit and the dual-auger unit both operate following the same principles. Annotated images of the single-auger unit are shown in figure 2 accompanied by an explanation of the process flow. The modifications incorporated in the dual-auger unit are described at the end of this subsection.

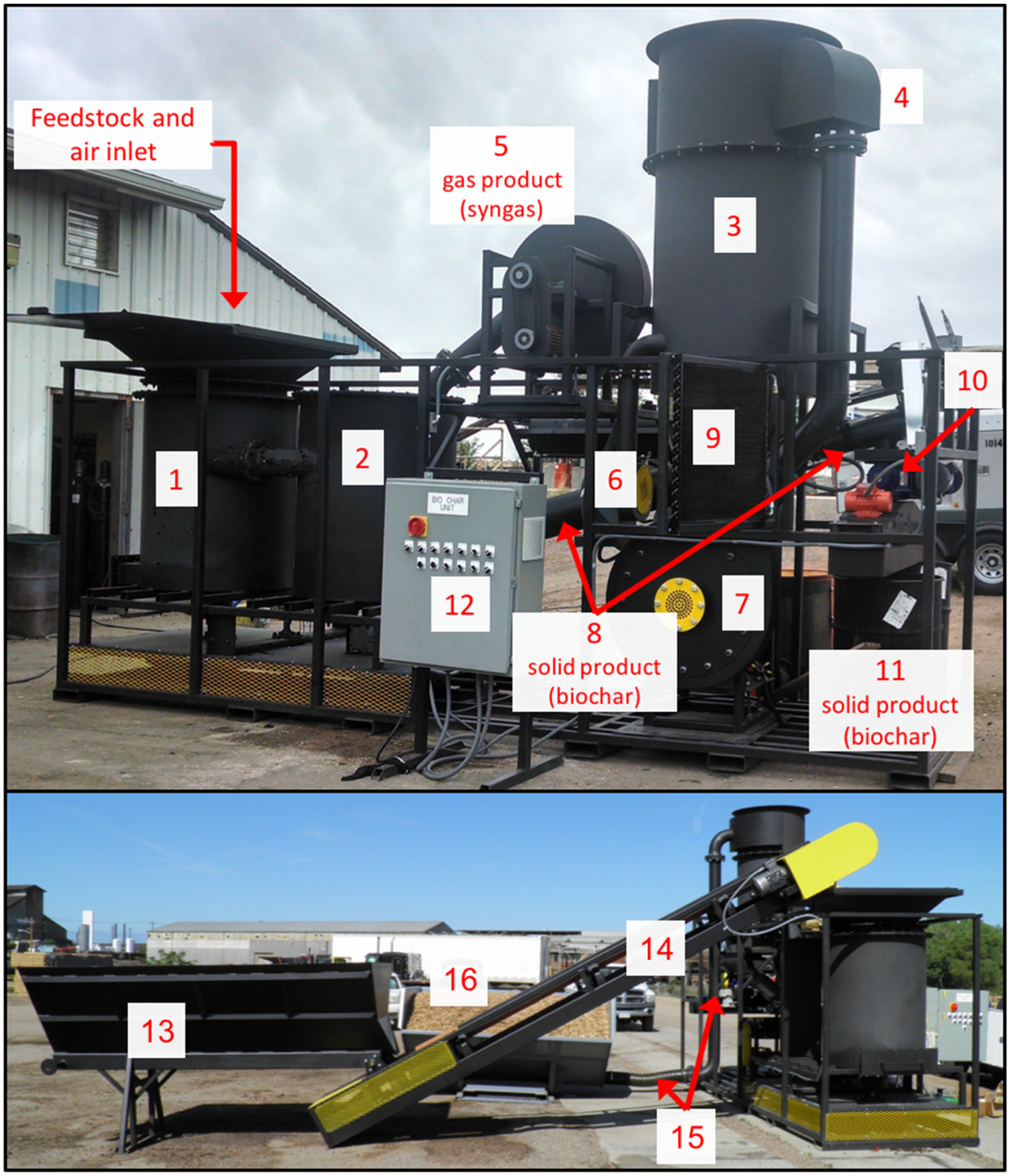
Average biomass input rates for the single-auger unit are 316 kg h^{-1} d.b. (385 kg h^{-1} w.b.) with 14% biochar yield based on dry mass input. Referring to figure 2, feedstock biomass is loaded into the feed hopper (13) and transferred onto the conveyor (14), which moves feedstock into the reactor (1). The reactor consists of two concentric cylinders with a gap between the two cylinder walls and an approximately 0.15 m tall gap between the bottom of the inner cylinder and the bottom of the outer cylinder. Feedstock is loaded into the inner cylinder to maintain a bed depth between 0.5 and 2.5 m. Rotating bars in the reactor slowly stir the bed. Biomass loaded into the top of the reactor is heated by partial combustion of feedstock as it moves downward through the reactor. As oxygen levels are depleted towards the bottom of the bed, biomass is converted into biochar through gasification.

After biochar is formed, the reactor blower (5) pulls it through the gap between inner and outer reactor cylinders



	Fine (-3mm)	Medium (-12mm/+3mm")	Coarse, (+12mm)
Conifer, ground	12%	80%	9%
Conifer, ground 2/3 bole, 1/3 tops	14%	77%	9%
Conifer, ground, 9% contamination	14%	77%	8%
Conifer, chip, medium	1%	99%	0%
Conifer, chip, small	31%	69%	0%
Hardwood, ground	20%	79%	1%
Pinyon/Juniper, ground	28%	64%	8%

Figure 1. Cumulative particle size distribution of different feedstock mixtures plotted on a log scale.



1: Reactor	**2: Dropbox**	**3: Flare**	**4: Heat exchanger**
5: Reactor blower	**6: Flare air blower**	**7: Heat exchanger inlet blower**	**8: Biochar cooling auger**
9: Cooling auger radiator	**10: Air lock**	**11: Biochar collection drum**	**12: Control panel**
13: Feedstock hopper	**14: Conveyor**	**15: Heat exchanger outlet**	**16: Dryer hopper**

Figure 2. Annotated images of a single-auger biochar production unit.

and into the dropbox. Biochar and syngas are drawn by vacuum from the reactor into the dropbox where they encounter a baffle, which drops the biochar to the bottom of the dropbox while syngas exits through a pipe in the top of the dropbox. The syngas flows through the main blower and into the flare. An air blower (6) introduces fresh air into the flare, creating a combustible mixture of syngas and oxygen, which is burned in the flare before the product gases exit through the top of the flare stack.

The biochar, which has dropped to the bottom of the dropbox, enters an auger (8) that is cooled by an external water jacket. The closed-loop auger cooling system rejects heat to the environment through a radiator (9). Biochar exits the auger through an air lock (10), which prevents large backflows of air into the system while allowing solid biochar to exit, and is collected into metal drums (11).

Instrumentation was installed on the single-auger unit to measure mass and energy flows at throughout the system. Instruments included thermocouples (Omega Engineering, Type K, Norwalk, Conn.) pitot tubes (Nailor, 36FMS, Houston, Tex.), a power meter (Continental Control Systems, WNB-3D-240-P, Longmont, Colo.), and an emissions gas analyzer (Enerac, M700, Holbrook, N.Y.).

The dual-auger unit was designed to increase biochar production capacity by connecting a second processing train to a single reactor. An additional dropbox, reactor blower, and biochar auger were connected to the reactor in parallel as shown by the dashed lines in figure 3. Furthermore, the size of the flare was increased, and two larger flare air blowers were used instead of one. The biomass feeding system was automated by installing an auger in the feedstock hopper that loaded feedstock onto the conveyor based on a limit switch in the reactor. The manufacturer eliminated some electrical components on the dual-auger machine, which reduced the overall load despite increasing the capacity. The biochar auger cooling system, the vibrating motor at the biochar exit, and the biomass drying system including the heat exchanger blower were deemed nonessential and removed from the system. In addition, the blowers provided the same flow at lower motor speeds, which contributed to lowering the overall electrical load.

PRODUCTION TEST METHODS

The operational test methods are described below for the single-auger unit and the dual-auger unit.

Single-Auger Unit

Testing occurred in Pueblo, Colorado during August 2014 using seven feedstocks including different species, moisture contents, contamination levels, particle size distributions, and comminution methods. The objectives of these tests were to determine how feedstock type influences the throughput capacity, emissions profile, biochar quality, and electricity demand of the machine by evaluating data and samples collected during steady state operation. The duration of the steady state periods ranged from 0.67 to 2.5 h consuming between 290 and 700 kg of biomass. Duplicate tests were performed for each feedstock.

To begin each test, feedstock from piles stored on site were weighed using a truck scale and staged in tared self-dumping hoppers. The feed hopper on the biochar machine was initially loaded with enough of the same material to achieve steady state operation. Feedstock was manually transferred from the feed hopper onto the conveyor, which moved material into the reactor. As the reactor began to fill up with feedstock, the blowers, stirrer, auger, and other electrical components were turned on. Next, a propane tank and torch were used to ignite the initial feedstock in the reactor. After thick smoke began to rise from the stack, the propane torch was used to ignite the syngas and air mixture evolving in the stack. The system was deemed to be in steady state when the flare remained lit, the motor speeds were fixed, the bed depth in the reactor was constant, and the output of biochar was consistent. After reaching steady state at the start of each test, the feeder hopper was emptied of the start-up biomass. The feedstock in the staged dumper hopper was loaded into the feeder hopper to begin the testing period, and empty barrels were placed under the biochar output chute to receive the product. To the best of their ability, the operator(s) maintained consistent operational parameters and biochar production throughout the steady state period. This occasionally led to inconsistent feedstock input rates during the tests and a varying bed depth. Although this was not the desired operational procedure, it was required to keep the machine running consistently.

Data were collected throughout steady state operation. All the data acquisition parameters were written to an electronic data file every five seconds. Other parameters were manually observed and recorded during each run such as flare conditions, start and end time, propane consumption, and operator's comments.

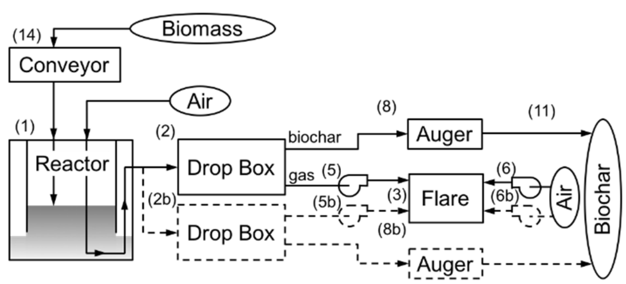


Figure 3. Simplified process flow diagram for single-auger unit (solid lines only) and dual-auger unit (solid and dashed lines). The numbers in parentheses refer to the annotations in figure 2; annotations appended with 'b' indicate additional equipment for the dual-auger unit.

Dual-Auger Unit

The dual-auger unit was tested in Pueblo, Colorado, in November 2016 over two days using a single feedstock. The objective of these tests was to measure the throughput rates and gather gaseous and particulate matter emissions data from the stack to perform a comparison to the single auger unit. Operator functions were similar to the single-auger unit except feedstock was automatically loaded from the feedstock hopper onto the conveyor rather than being manually transferred. The machine was operated for two 8-h work days while a third-party agency, Air Pollution Testing, Inc. (Arvada, Colo.), sampled the gases emitted from the flare. Emissions were determined by conducting three 1-h long sample runs when the biochar machine was operating at steady state on each day. Due to the expense and operating duration required for particulate matter sampling procedures, duplicate tests of a single feedstock were performed rather than conducting a full suite of tests as with the single-auger unit. The feedstock was selected to meet the specifications outlined from testing the single-auger unit and provide a useful comparison between the machines.

SAMPLING PROCEDURE

Feedstock and biochar samples were collected during each test and stored in airtight plastic bags before further analysis. The feedstock sample was gathered from a staged dumper hopper immediately prior to loading the feedstock hopper. Biochar samples were taken intermittently at the exit of the airlock throughout the test, allowed to cool, and then mixed together for each steady state period. Typically, four 1-L biochar samples were taken during each test and combined to create a composite sample representative of the steady state testing period.

OPERATOR EFFORT

Operator effort was assessed qualitatively by observing the functions and requirements for the machine operators.

The single-auger unit testing was conducted by one biochar operator and three researchers. The researchers helped operate the machine and also monitored the data collection instrumentation. The dual-auger unit testing was conducted by one biochar operator with two researchers observing production and managing emission testing logistics. During the dual-auger testing, the researchers did not perform any functions required to operate the machine.

MATERIAL ANALYSIS METHODS

Material samples were analyzed in the lab to determine several parameters using the methods described below:

- Ash content – measured following ASTM Method E 1534-93 (ASTM Standards, 2006a).
- Bulk density – measured by following the procedure of SCAN-CM 46:92 (SCAN Standards, 1992) but using a device that deviated in dimensions from the protocol.
- Fixed carbon – calculated using ASTM E870-82 (ASTM Standards, 2006b).
- Gross calorific value – measured using a bomb calorimeter (Parr Instruments, Model 1241, Moline, Ill.).
- Moisture content – measured following ASTM Method E871-82 (ASTM Standards, 2006c), deviating by drying samples in a 105°C oven rather than at 103°C.
- Particle size distribution – Measured by separating a sample through two sets of sieves in a mechanical shaker for four minutes: a coarse mesh 203 mm (8 in.) diameter set and a finer mesh 305 mm (12 in.) diameter set. The 203-mm diameter set used mesh sizes of: 50.8 mm, 38.1 mm, 26.7 mm, 19 mm, 13.3 mm, and pan. Material collected in the pan was placed into the 305-mm set of sieves with mesh sizes of: 15.9 mm, 7.9 mm, 5.6 mm, 4 mm, 2.8 mm, 2 mm, 1 mm, and pan. After shaking, the mass retained on each sieve was measured to the nearest ±0.1 g (Ohaus, Brain-Weigh B 3000D, Florham Park, N.J.).
- Volatile matter – measured using ASTM Method E 872-82 (ASTM Standards, 2006d) using a muffle furnace in place of a vertical electric tube furnace.

EMISSIONS MEASUREMENTS

Emissions from the single-auger unit were measured with a continuous gas analyzer (Enerac, M700, Holbrook, N.Y.) equipped with electrochemical sensors for O_2, NO, NO_2, SO_2, and CO (low range) and non-dispersive infrared (NDIR) sensors for CO (high range), CO_2, and unburned hydrocarbons (measured as propane). Emissions rates were determined with gas composition and volumetric flow rate measured by a pitot tube (Nailor, 36FMS 18 in., Houston, Tex.).

Emissions from the dual-auger unit were measured by a third-party testing agency, Air Pollution Testing, Inc. of Arvada, Colo., in accordance with EPA Methods 1, 2, 3A, 6C, 7E, 10, and 25A. Total particulate matter was determined by gravimetric analysis. The particle size distribution of particulate matter collected on filters during each hour-long test was measured by laser diffraction liquid dispersion by Particle Testing Laboratory in Downers Grove, Illinois.

RESULTS

Results from tests on the single-auger and dual-auger units are presented below. Results are presented for feedstock and biochar quality, throughput rates, energy consumption, and emissions profile.

SINGLE-AUGER UNIT

The single-auger unit was tested with a variety of feedstocks to determine their impact on biochar quality, energy usage, and emissions as discussed below.

Biochar Quality

Results from the proximate analysis of the biochar samples are listed in table 2. Biochar moisture content was less than 3% w.b. with a wide range of ash content from 3% to 77% and fixed carbon from 14% to 83% d.b. depending on the feedstock.

Biomass input rates for the single-auger unit averaged 316 kg h^{-1} d.b. (385 kg h^{-1} w.b.) with 43 kg h^{-1} d.b. biochar production, which is an average 14% yield based on dry mass input. Figure 4 shows the throughput rates for all tests on the single-auger unit. The mass throughput rates of contaminated feedstocks, however, are skewed by high mass fractions of ash or moisture in the feedstock and biochar. The pinyon-juniper (PJg), for example, displays high biochar production and yield rates, but the biochar was very low quality due to high ash content that was, in turn, the result of its contamination with soil and bark. To remove ash content from the results, the fixed carbon throughput rate is shown in figure 5 with percent of fixed carbon lost in the process displayed above the bars in the chart. The loss of fixed carbon is important for two reasons: 1) fixed carbon content is a simple metric to indicate the quality of biochar and 2) the loss of fixed carbon indicates how much of the energy was consumed to provide heat to the gasification reactions. Greater loss of fixed carbon indicates that more energy was consumed in the biochar production process. Feedstocks with high levels of moisture and ash content had more fixed

Table 2. Proximate analysis, bulk density, and heating value of biochar from single-auger unit.

	MC % w.b.	Ash % d.b.	VM % d.b.	FC % d.b.	BD[a] kg m^{-3}	HHV[a] MJ kg^{-1}
Cg_1	2.3%	5%	16%	79%	96	30.5
Cg_2	2.2%	8%	15%	78%	95	29.4
Cg-T_1	2.6%	18%	17%	65%	118	28.9
Cg-T_2	1.6%	12%	23%	65%	107	29.6
Cg-C_1	1.7%	14%	19%	67%	101	26.9
Cg-C_2	2.0%	33%	17%	50%	112	26.4
Ccm_1	2.7%	3%	55%	43%	105	25.3
Ccm_2	2.2%	5%	12%	83%	86	32.3
Ccs_1	2.5%	14%	34%	52%	88	28.0
Ccs_2	3.3%	13%	19%	68%	106	27.8
Hg_1	1.8%	8%	22%	70%	137	29.5
Hg_2	1.9%	3%	24%	73%	110	30.4
PJg_1	0.6%	77%	10%	14%	428	6.3
PJg_2	0.0%	53%	12%	35%	142	18.8

[a] Values provided using the oven dry mass basis.

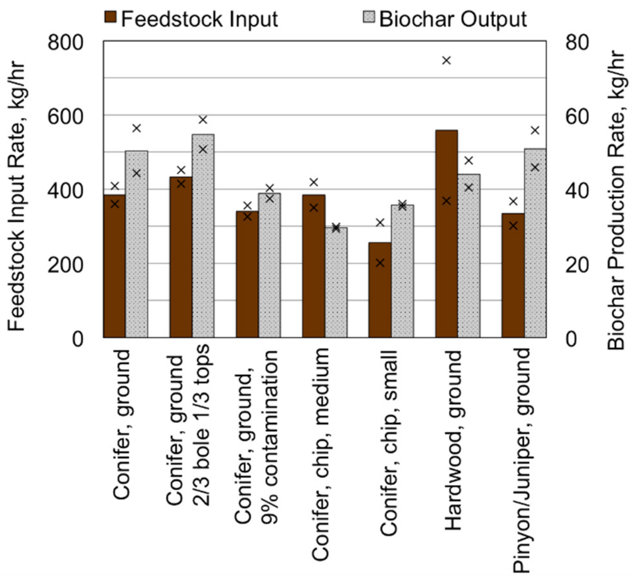


Figure 4. Average feedstock input and biochar production rates with various feedstocks. The black 'x' symbols represent the values from replicate test runs, and the height of the bar shows the average.

carbon consumed in the process to convert biomass into biochar. The three feedstocks with the largest loss of fixed carbon – ground conifer with contamination (Cg-C), medium conifer chip (Ccm), and pinyon-juniper (PJg) – have the highest levels of ash and moisture content. Figure 6 shows the relationship between percent loss of fixed carbon versus the sum of feedstock moisture and ash content. This chart shows that lower levels of moisture and ash content will allow the machine to produce biochar with a higher fraction of fixed carbon.

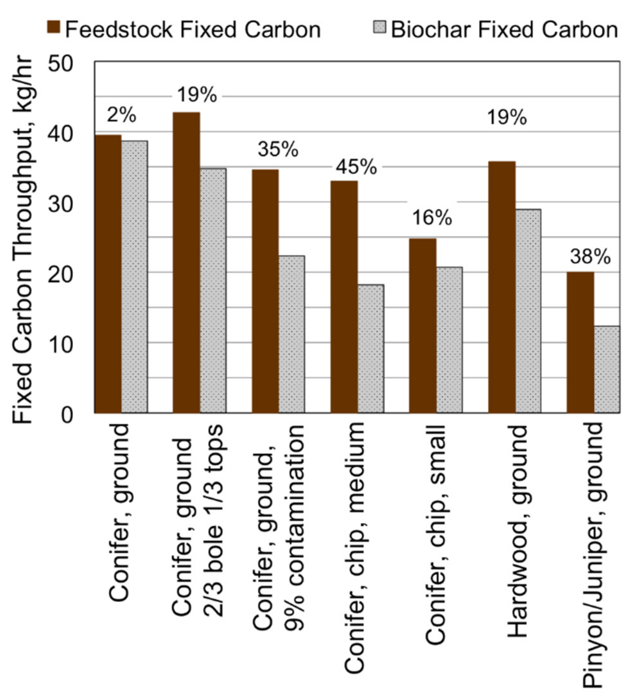


Figure 5. Fixed carbon input and output rates. The percentage value above each set of bars indicates the percent of fixed carbon lost on a wet basis.

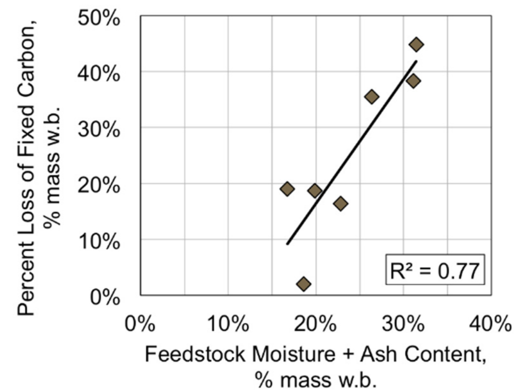


Figure 6. Fixed carbon loss versus the sum of feedstock moisture and ash content.

In addition to increasing the amount of stable carbon in biochar that can be sequestered in soils, higher fractions of fixed carbon content increase the heating value of biochar. The relationship between biochar calorific value and fixed carbon content is plotted in figure 7. Biochar's heating value on a mass basis (table 2) is comparable to coal, which ranges from low-quality lignite (12 MJ kg^{-1}) to high-quality anthracite (34 MJ kg^{-1}) (Mitchell, 2017).

Energy Consumption

The biochar production machine requires both electricity and propane to operate. Steady state electricity consumption on the single-auger unit displayed a wide range from a minimum of 2.3 kW to a peak demand of 26 kW. Mean electrical demand during the steady state ranged from 7.3 to 19 kW. Strong correlations between electricity demand and other measured parameters were not discovered. Electricity demand is hypothesized to be dependent on the reactor bed depth, which influences the load on the reactor blower and stirrer motors. Higher bed depths cause the reactor blower to overcome a larger pressure drop and the stirrer motor must rotate a greater mass, both of which increase the electricity demand. The bed depth varies between runs and throughout an individual test based on the speed at which feedstock is loaded into the reactor by the operator. The relationship between bed depth and electricity demand cannot be confirmed because the operator manually controls the bed depth and the bed depth is not consistently recorded. Future work should investigate this relationship further by adding level sensors

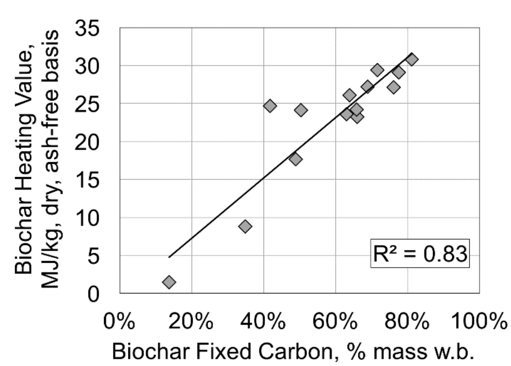


Figure 7. Biochar higher heating value on a dry, ash-free basis versus fixed carbon content.

to the reactor or automated feedback control to identify optimal bed depths with respect to electricity demand and biochar production rate.

A small amount of propane is required to operate the machine. During steady state operation with a good quality feedstock, external heat is not necessary because the gasification reaction is auto thermal. Thermal input is required during startup to initiate combustion in the reactor and to ignite the flare. Propane is also occasionally used during steady state operation to add heat to the reactor or relight the flare. Propane consumption was found to be a function of feedstock moisture content, as shown in figure 8. The clear outliers are the pinyon-juniper tests, which were relatively dry but required more propane than would be expected due to their high level of contamination and difficulty of operation.

Emissions

Emissions at the exit of the stack of the single-auger unit were high in unburned hydrocarbons (UHC) and carbon monoxide (CO) and low in oxygen content, indicating incomplete combustion and insufficient air supply into the flare. Poor combustion in the stack was observed from the gas analyzers installed on the single-auger unit during each test. A separate experiment was conducted to determine the appropriate level of combustion air intake for the flare. In this experiment, a second blower was connected to the flare to augment the combustion air supply, and the air flow was gradually increased while emissions data were recorded. Results from this experiment are shown in figure 9a. Normal operating conditions occur at approximately 11,000 standard liters per minute (SLM) of air from the original flare air blower. Air flow was measured with a pitot tube (Nailor, 36FMS 4") and converted to standard conditions at 20°C and 1 atm. As the supplemental air blower speed was increased, the UHC (measured as propane) and CO emissions decreased while the oxygen content began to rise after 23,000 SLM of air is supplied to the flare. For air flows of at least 23,000 SLM, the gas analyzer no longer detected UHC emissions, and by air flows of at least 31,000 SLM the CO emissions had fallen below detectable limits. Using data from these tests, the manufacturer selected an appropriately sized combustion air blower for the flare on the next iteration of the machine – the dual-auger unit. Figure 9b shows that as the temperature of the stack gas initially increased from 840°C to 930°C, then dropped to 740°C with the addition of more air. Even though the temperature decreased, the amount of waste heat exiting the exhaust stack, including both thermal and chemical power in the exhaust gases, increased from 300 kW to a maximum of 490 kW at 34,000 SLM of air supply.

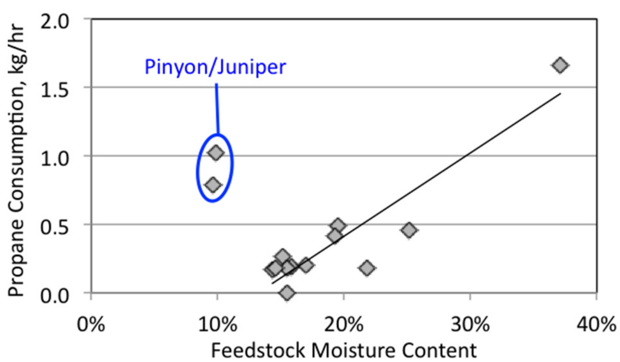


Figure 8. Propane consumption vs. feedstock moisture content on a dry basis.

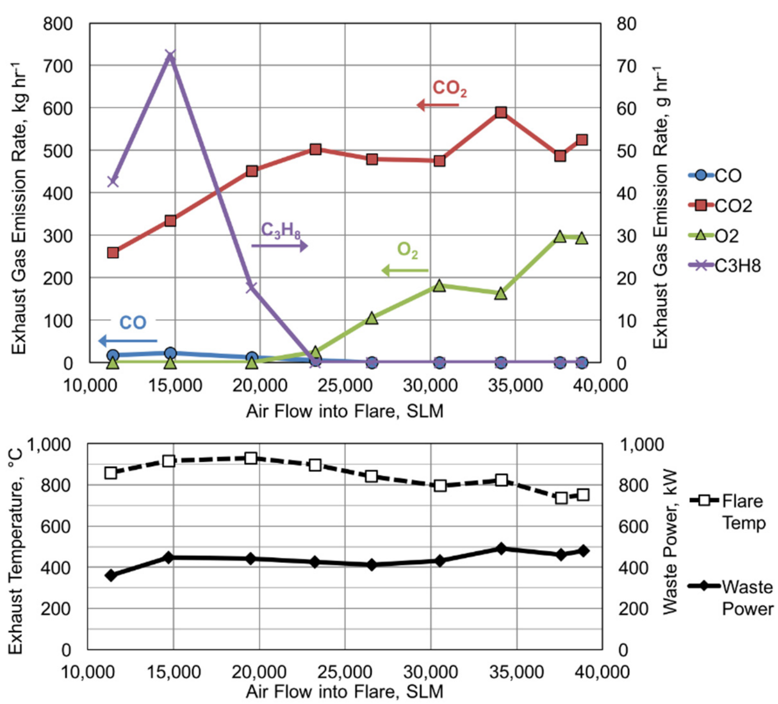


Figure 9. (a) Gas emissions and (b) temperature and waste heat from the flare with supplemental combustion air. The colored arrows in the upper plot indicate which y-axis is used with each of the respective exhaust gas concentration values.

DUAL-AUGER UNIT

The dual-auger machine was designed to increase the biochar production capacity while maintaining the same labor requirements of one operator per machine. In addition, the flaring system was redesigned to facilitate more complete combustion of the syngas and tars. The feedstock throughput on a dry basis increased by 21%, the biochar production rate increased by 45%, and the yield increased by 21% over the single-auger unit, while both the average and peak electrical demand decreased dramatically by removing nonessential loads (table 3).

Emissions Rate Comparison

Emissions of CO and propane were significantly reduced in the dual-auger unit following the redesign of the flare to provide more combustion air and a longer residence time in the stack. A higher concentration of excess oxygen was detected at the exit to the stack in the dual-auger unit (average 12% instead of 4% by volume, table 4), indicating that the redesigned flare was not oxygen limited and more complete combustion could occur, converting CO and UHCs into CO_2 and water vapor. Emission rates from both machines are normalized by biochar production rate and compared in figure 10. Emission rates of CO, UHC (as propane) decreased on the dual-auger machine. SO_2 emissions are primarily a function of feedstock sulfur content. The reductions in SO_2 emissions shown for the dual-auger machine are a result of averaging data for all the feedstocks on the single-auger machine, which included many high ash content feedstocks, and comparing it to SO_2 emissions from lower ash content medium conifer chip used on the dual-auger machine. Only the NO_x emissions increased in the redesigned flaring system, which is likely due greater thermal NO_x formation at the higher flame temperatures in the flare of the dual-auger machine. The emission rate of CO_2 increased slightly, as expected, following more complete combustion. Emissions results are shown in table 4 for replicate tests using medium conifer chip on both machines. Particulate matter (PM) emissions are measured for the dual-auger machine only. Total PM, PM_{10} and $PM_{2.5}$ averaged 375, 39.5, and 4.5 g h^{-1}, respectively.

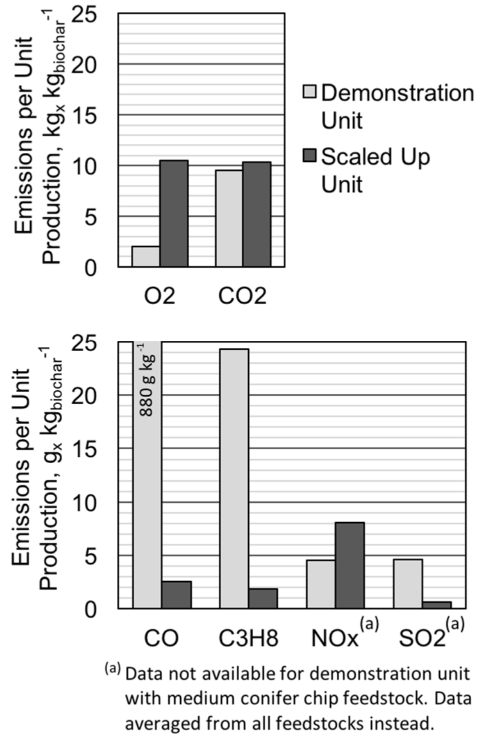


Figure 10. Comparison of emissions averaged from all feedstock types on the single-auger unit (light bar) and both tests of the dual-auger unit (dark bar).

OPERATOR EFFORT

During biochar production, the operator's tasks include loading feedstock, monitoring the reaction conditions, monitoring and relighting the flare, watering biochar, sealing and removing barrels of biochar, and clearing clogs and jams within the system. The extent and effort required for these tasks was influenced by feedstock quality.

Testing the single-auger unit with a variety of feedstocks indicated that high levels of moisture or ash content in the feedstock increased the amount of operator effort. High moisture content feedstocks need more energy to remove feedstock moisture in the reactor and combust the wet syngas in the flare. With wet feedstock such as Ccm_1, first, the operator had to provide extra effort to apply propane to the reactor to maintain proper reactor conditions. Second, the operator needed to reignite the flare multiple times to maintain steady combustion of the wet syngas in the flare. Operator effort is also increased with feedstock ash content. Ash,

Table 3. Throughput rates and electrical demand of the single-auger and dual-auger units.

	Single-Auger Unit	Dual-Auger Unit	Percent Change
Feedstock Input Rate, kg h^{-1} d.b.	316	381	+21%
Biochar Production Rate, kg h^{-1}	43	63	+45%
Yield Rate, mass% d.b.	14%	17%	+21%
Average Electrical Demand, kW	12	4.5	-61%
Peak Electrical Demand, kW	26	18	-32%

Table 4. Stack gas emissions from single-auger and dual-auger units using medium conifer chip.

	Single-Auger Unit		Dual-Auger Unit	
	Test 1	Test 2	Test 1	Test 2
Stack Temp, °C	553	821	713	609
O_2, mole%	7.3%	1.1%	14.1%	10.0%
CO_2, mole%	11.2%	17.7%	6.6%	10.6%
CO_2, kg h^{-1}	206	366	500	810
H_2O, mole%, w.b.	20%	12%	12.3%	10.8%
Flow, m^3 s^{-1}	0.483	0.526	1.126	1.120
NO_x, ppm			51.2	80.4
NO_x, kg h^{-1}			0.40	0.62
CO, ppm	28,000	13,900	39.2	30.4
CO, kg h^{-1}	33	18	0.18	0.14
SO_2, ppm			0.8	6.9
SO_2, kg h^{-1}			0.009	0.077
TVOC, ppm as C_3H_8	634	101	14.77	15.22
TVOC, kg h^{-1} as C_3H_8	1.17	0.21	0.11	0.12
PM, g m^{-3}			1.1	1.6
PM, kg h^{-1}			0.30	0.45
$PM_{2.5}$, g m^{-3}			0.001	0.002
$PM_{2.5}$, kg h^{-1}			0.003	0.006
PM_{10}, g m^{-3}			0.1	0.2
PM_{10}, kg h^{-1}			0.036	0.043

rock, and mineral from the feedstock accumulates in the bottom of the reactor and must be removed. Typical removal frequency is once per 20 hours of operation, but high ash content feedstocks, such as the pinyon juniper mixture, required cleanout once per every four hours of operation. If cleanout frequency is neglected, the biochar removal auger and gas flow passages can become clogged, which requires an extra 30 to 60 minutes of effort to clear. Whether through a clog or more frequent cleanouts, biomass with higher ash content requires more labor to process the same amount of feedstock.

Next, automating key processes on the machine can reduce the labor requirements. The single-auger unit required the operator to manually load feedstock onto the reactor inlet conveyor and monitor the bed depth in the reactor by sight. One operator was required to manage the feedstock and reactor while at least one other operator was required to monitor the flare and manage biochar production. The dual-auger unit reduced labor effort by automating the reactor loading system. A rotary paddle level sensor was added to the reactor to monitor bed depth and automatically operate an auger to load feedstock into the reactor. This removed the requirement for an operator dedicated to managing the feedstock and reactor loading system and reduced the labor requirements for the dual-auger unit.

Discussion

The results are interpreted in the section below to provide a discussion of the required feedstock specifications and to assess any improvements between the single and dual-auger machine designs.

Feedstock Specifications

The interaction between feedstock characteristics and biochar quality can be determined by comparing the proximate analyses presented in table 2. First, high moisture or ash content in the feedstock decreases biochar quality as evaluated by fixed carbon content. Notice that the moist, medium conifer chip and contaminated pinyon-juniper feedstocks produce biochar with the lowest fixed carbon content (table 2). In the case of the first medium conifer chip experiment (Ccm_1) where the feedstock moisture content was 37%, the resulting biochar yielded only 42% fixed carbon and had the highest volatile matter content of all the tests. During this test, a disproportionate amount of energy in the reactor was used to vaporize the moisture in the feedstock, and there was not enough energy or time to volatilize the short-chain carbon compounds, as in the other tests. This resulted in a low-quality biochar with high volatile matter, low fixed carbon, and low heating value. High feedstock ash content also reduces biochar fixed carbon because the minerals, ash, and soil from the biomass are not separated from the biochar in the machine and exit into the biochar collection barrels. Thus, the biochar is higher in ash and subsequently lower in fixed carbon on a mass basis.

The operator noted the difficulty of running the machine with the pinyon-juniper and medium conifer chip and said they would not use these feedstocks to operate the machine on a daily basis because of the increased maintenance and operator effort. Due to its high bulk density and ash content, the pinyon-juniper feedstock caused clogs in the reactor during steady state operation because heavy ash, minerals, and rocks were not pulled out of the reactor by the suction of the main blower. As material built up in the bottom of the reactor and in the ducting on the machine, gas flow became obstructed and the flow rate of syngas to the flare decreased sharply, causing the flare to go out due to lack of fuel and smoke to rise from the stack. Without an exit for the gas, combustible mixtures of syngas and air would form within the system and, after coming in contact with a spark or ignition source, would backfire and force hot feedstock and char upwards out of the reactor inlet. Additionally, ash and mineral accumulation within the reactor formed into clinkers requiring more frequent removal and cleaning of the reactor clean-out, necessitating a complete shut-down of the system to allow it to cool. Lastly, the biochar that was separated in the dropbox was so dense because of its high ash content that it stalled the biochar auger motor and clogged the biochar outlet system. Because of the increased labor effort, maintenance, and safety concerns, the pinyon-juniper feedstock is not feasible to operate because of the high ash content (21% and 26% d.b. for replicate tests). The ground conifer with 9% soil contamination (13% and 14% ash content d.b.) did not create any of the difficulties experienced with the pinyon-juniper. Thus, a maximum limit of 15% ash content (d.b.) should be tentatively set for all feedstocks entering the machine.

Secondly, feedstocks with moisture contents above 25% (w.b.) also make the machine difficult to operate. Wet feedstocks require additional heat from propane ignition during operation to maintain a stable reaction. As shown in figure 8, the medium conifer chip with 37% moisture content (Ccm_1) required over 200% more propane than any other feedstock. In addition, moist feedstocks create a syngas with higher moisture content, making it more difficult to maintain steady combustion in the flare because more energy is required to heat up and ignite the effluent gases. When using feedstocks over 25% moisture content (w.b.), both igniting the feedstock bed in the reactor and tending to the flare system increase the operator labor effort to a degree so as to require a second operator to complete necessary operation tasks. Other feedstocks with moisture contents below 25% (w.b.) did not cause a sharp increase in operator effort. Thus, a maximum limit of 25% moisture content (w.b.) should be tentatively set for all feedstocks entering the machine without a feedstock dryer.

Finally, feedstock particle size distribution and species did not appear to significantly influence the quality of the biochar. The range of particle sizes and comminution methods tested with the single-auger unit would all be feasible for commercial operation. Similarly, the species was not a main factor driving the biochar quality; rather, ash and moisture content have more influence on the quality and operability of the biochar machine.

Improvements to Dual-Auger Machine

The dual-auger biochar machine with an automated feeding system displayed notable improvements over the single-auger unit, including greater feedstock throughput, increased biochar yield, lower emissions, lower peak and average electrical demand, and decreased labor effort per unit output. First, the biochar output rate increased by 45% to 63 kg hr^{-1} due to the addition of a second biochar processing train attached to the reactor. Secondly, emissions of CO and UHC were decreased by increasing the flow of combustion air into the flare to allow for more complete combustion. Although a few additional electrical loads were added to the dual-auger biochar machine, all the blower motors were operated at lower speed on VFD control, which required substantially less power. Additionally, a few auxiliary systems (i.e., the biochar auger cooling system, the vibrating motor at the biochar exit, and the heat exchanger and blower) were removed from the biochar machine since the manufacturer deemed them unnecessary. With these changes, the biochar machine's average electrical load decreased by a surprising 61% despite an increase in production rate. The peak electrical demand observed during testing also decreased by 32%. Therefore, while electricity costs are expected to be lower on the dual-auger machine, they may not decrease in proportion to the energy savings (i.e., in proportion to the average power) because the maximum power demand typically also influences the electricity costs either through a peak-demand charge from the utility or by requiring the purchase of a larger generator to meet the maximum load in off-grid systems. Lastly, the addition of an automated feeding system reduced the operator's effort to input the feedstock into the reactor and decreased labor hours per unit of biochar output.

Conclusion

We determined the throughput rate, emissions profile, and feedstock specifications for two biochar machines. A wide range of feedstock species, contamination levels, and comminution methods can be processed with this equipment, but as the ash and moisture contents exceed 15% and 25%, respectively, the quality of biochar degrades and the machine becomes exceedingly difficult to operate. After making improvements to the machine's design following testing of the single-auger unit, the larger dual-auger unit was able to process 380 kg hr^{-1} (d.b.) to produce 63 kg h^{-1} of biochar with an average electricity demand of 4.5 kW.

Future work to develop this biochar production system should focus on decreasing the operator effort, improving operator and site safety, and increasing the production rate. Controls and instrumentation could be added to the machine to maintain stable condition in the reactor and continuous operation of the flare. Automating these tasks would save the operator a significant amount of effort and substantially reduce the operator's risk of being exposed to flames or explosions. Further increases in production rate may be realized by increasing the diameter of the reactor; future iterations should fabricate and test a larger reactor size.

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