Performance Sensitivity to Fuel in Biomass Cookstoves

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ABSTRACT:

In this study, a commonly used char-producing cookstove design (top-lit updraft, TLUD) is compared to a pyrolysis biomass cookstove with separate combustion and pyrolysis chambers (a two-chamber stove). The impact of different types of pyrolysis fuel (hardwood, maize stover, or switchgrass pellets) on CO, NO, CO2, and particle emissions, as well as the particulate size distribution's time dependence, are measured. Tests of water boiling are carried out in a hood using pine wood as the fuel for the two-chamber stove's combustion. Reports are provided on constituent compositions, char yields, and thermal and modified combustion efficiency. Since the two-chamber stove is far less sensitive to fuel selection than the TLUD, it is an excellent alternative for difficult waste biomass fuels. While the particle emission factor (measured solely for the two-chamber stove) follows an order of hardwood < switchgrass ≤ corn stover (i.e., woody biomass < herbaceous biomass), the NO emission factors are positively correlated with the nitrogen content of biomass pellets. Seventy to eighty percent of the particles by mass are less than 0.25 μm. Throughout the water boiling test, this size range is always the majority fraction.

KeywordsBiochar;Biomasspyrolysis;Biomasscoostove;Particulates;Sizedistribution;Fuelsensitivity

1.Introduction

Woody biomass is the fuel selected by most designers of improved cookstoves and is used in the vast majority of reported tests characterizing stoves. However, agricultural residues (e.g., herbaceous biomass such as straws, husks, and corn cobs) and other waste biomass (e.g., dung) already make a major contribution to domestic biomass combustion, and have the potential to make an even greater contribution [10-16]. An effort has been made to develop efficient and low-emissions biomass cookstoves for household heating and cooking in rural areas of developing countries [1–9].Because of the significant impact that fuel selection has on stove performance, Prasad et al. [17] argued that fuel properties should be taken into account while creating a dependable stove design. Compared to woody biomass, waste biomass materials often have higher concentrations of ash and nitrogen, as well as lower bulk densities and lower energy content on a mass and volume basis [18–20]. Because of this, these fuels typically present more difficulties for maintaining combustion and frequently call for the use of specialized stoves [7, 21] or the modification of stove designs [22] in order to achieve adequate results. There are few studies that compare the emissions from a particular cookstove using woody versus herbaceous biomass fuel [13, 14, 22–25]., however they do provide some evidence that waste biomass fuels, as opposed to woody biomass fuels, are linked to increased concentrations of CO, particulates, and/or certain aromatic compounds. According to some data [24], variations in the rate of burning are what cause the variations in particle emissions between various biomass fuels.

This study's main goal is to measure how fuel selection affects the efficiency of a two-chamber stove that produces charcoal and can be easily used with a variety of pyrolysis fuels. The two-chamber stove has a central combustion chamber with wood feed and an annular pyrolysis chamber encircling it. The combustion chamber burns the volatiles once they are expelled from the pyrolysis chamber. For comparison, data from a second charcoal-producing stove—the more thoroughly researched top-lit updraft (TLUD) stove—is provided [13, 22, 25, 26]. Both stoves turn biomass into volatiles that are burned somewhere else and charcoal that can be added to soil [27–32] by creating a low-oxygen atmosphere.The geometry, modes of operation, and source of the heat that drives the biomass processes in the two stoves are different. Wood burns in the central combustion chamber of the two-chamber stove, supplying heat for the annular pyrolysis chamber to pyrolyze a second fuel. With the TLUD, autothermal heating is produced by the fuel's partial oxidation reactions when a single biomass fuel is used to power the entire stove. It is anticipated that the two-chamber stove will be insensitive to the pyrolysis fuel selection due to the difference in the heat source. Both stoves use batch methods for thermal conversion of biomass, but the two-chamber stove's semicontinuous feed wood combustion has some operating benefits.In particular, the two-chamber stove's cooking function can go on in a pure wood combustion mode once pyrolysis is finished, saving the trouble and significant emissions that come with recharging the TLUD [22]. Conversely, the drawback of the two-chamber stove is that, in addition to the pyrolysis fuel, it needs a significant amount of wood for burning.Wood is used as the combustion fuel in the two-chamber stove. As pyrolysis fuels, three main types of biomass pellets are used: pellets of woody biomass (hardwood pellets), pellets of herbaceous biomass (panicum virgatum) and pellets of maize stover (leaves, stalks, and cobs of Zea mays), which represent crop leftovers. Switchgrass shares similarities with straws and other waste biomass materials in terms of its nitrogen and ash content, while being an energy crop rather than a waste biomass species [19, 33, 34]. A more restricted fuel comparison is done between hardwood and switchgrass pellets for the TLUD, which uses one fuel at a time.

There are numerous procedures available to assess cookstove performance, from water boiling tests with pollutants gathered and quickly diluted in a hood [3, 4, 7, 40–45] to indoor pollutant measurements in kitchens under uncontrolled cooking settings [35–39]. The water boiling test method with a hood is used in this study, which is suitable for assessing a new biomass cookstove's performance. For both stoves, particulate emissions factors, the particulate size distribution and emission rate at various stages of the pyrolysis process, and emission factors for CO, CO2, and NO are derived.

As far as we are aware, a time-sensitive evaluation of the Studies on cookstoves have rarely reported on the size distribution of particles [46]. There aren't many research on NO emissions [15, 47–50] or particulate size distribution [3, 24, 38, 41, 42, 51–54] in cookstoves. This work is one of them. Additionally presented is the distribution of carbon and nitrogen between the gas phase and the solid residue.In this study, we refer to the modest amounts of charcoal created from the combustion fuel of the two-chamber stove as wood charcoal and the charcoal produced in the TLUD or in the pyrolysis chamber of the two-chamber stove as "biochar."

2. Materials and methods

2.1. Fuel selection and analysis

The three pyrolysis fuels and one combustion fuel selected for the two-chamber cookstove are biomass pellets of hardwood (Dry Creek brand), switchgrass and corn, and dowels (a triangular prism with a side length of 1.5 cm and a height of 11.5 cm) of pine wood, respectively, and these fuels are denoted as HWP, SGP, CP and PW. Upon completion of pyrolysis and combustion processes, the pyrolysis fuel leaves behind biochar as its solid residue, and the combustion fuel leaves behind ash and small amounts of wood charcoal. The two fuels selected for the TLUD cookstove are biomass pellets of hardwood (Instant Heat brand, here denoted as IHWP), and switchgrass. The basic fuel information is listed in Table 1. The detail of the moisture content of biomass fuels, the elemental composition and heating value of biomass fuels, biochar and wood charcoal, and the standard deviations are listed in Supplementary Tables SM-1, SM-2, SM-5 and SM-6. Note that both cookstoves use the same switchgrass pellets. The pyrolysis characteristics of the biomass samples are determined via thermogravimetric analysis (TGA), as described in the Supplementary Material.

2.2. Two-chamber cookstove and hood system

A photograph and a schematic diagram of the two-chamber cookstove are shown in Supplementary Fig. SM-1. The pyrolysis chamber has an inner diameter of 180 mm, an outer diameter of 280 mm, and a height of 200 mm. The inlet for wood feeding has a width of 100 mm and a height of 75 mm. The outer shell has a diameter of 350 mm and a height of 400 mm. The two-chamber stove differs from pure combustion stoves in several important ways. First, the geometry of the stove creates an oxygen-starved heated zone for pyrolysis fuel as well as a combustion zone where volatiles burn. Second, unlike many combustion stoves, the two-chamber stove is generally tolerant of a range of biomass fuels, allowing the utilization of waste biomass such as crop residues as a replacement or supplement to wood. Finally, the batch nature of the pyrolysis process leads to more complex time-dependent behavior than is seen in pure combustion stoves. The hood and testing system used with the two-chamber cookstove are shown in Fig. 1. The corresponding information for the TLUD cookstove is presented in Supplementary Section 5.1.

Table 1

The elemental composition, proximate analysis, and higher and lower heating values (HHV, LHV) of biomass fuels for the two-chamber stove and the TLUD stove.

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The elemental composition, proximate analysis, and higher and lower heating values (HHV, LHV) of biomass fuels for the two-chamber stove and the TLUD stove.

Sample	Elemental Composition (% w/w, dry basis)					Proximate analysis (% w/w, dry basis)		HHV (kJ/kg, dry basis)	LHV (kJ/kg, dry basis)
	C	N	H	O	Ash	Volatile matter	Fixed carbon	$Q_{gr,d}$	$Q_{net,d}$
Pyrolysis fuel for the two-chamber stove or the TLUD stove									
HWP	55.63	0.18	5.92	43.80	0.48	83.21	16.31	19581	18324
SGP	52.44	1.43	5.82	42.67	3.98	80.25	15.77	18717	17482
CP	51.29	1.80	6.13	43.48	6.09	-	-	18460	17159
IHWP	54.57	0.11	6.48	44.61	0.58	84.25	15.17	18865	17490
Combustion fuel for the two-chamber stove									
PW	57.64	0.07	6.19	42.13	0.20	86.11	13.69	19550	18237

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Figures:

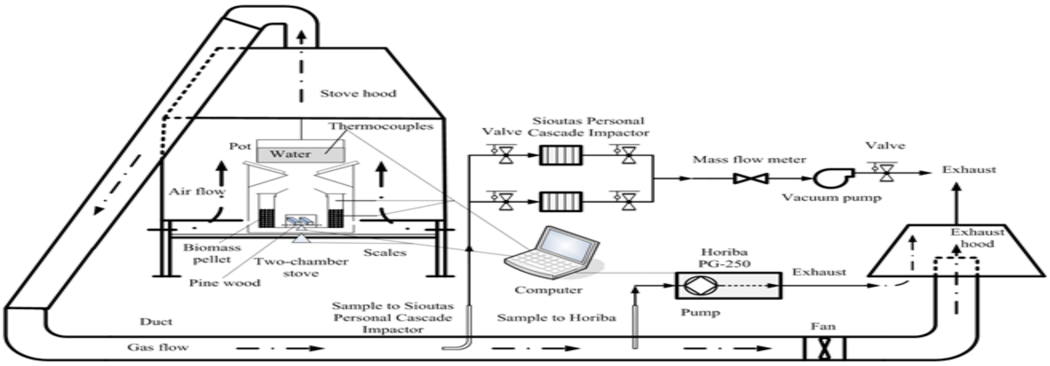

Fig. 1. The hood and testing system for the two-chamber stove experiments.

The performance evaluation tests of the cookstoves are based on Version 4.2.2 of Water Boiling Test (WBT) [55] and Stove Manufacturers Emissions & Performance Test Protocol (EPTP) [56]. Changes are introduced to the water boiling test because of the batch operation of the cookstoves. The test is adapted in different ways for the two cookstoves. Thus intra-stove comparisons of fuel effects are more valid than inter-stove comparisons of stove performance with a given fuel.The two-chamber cookstove is tested using the equipment and procedure described in Supplementary Sections 2.1 and 2.2. For that cookstove, pollutants are sampled through a quartz probe from a well- mixed duct location downstream of the canopy hood. Molar dilution ratios are between 21 and 24, similar to those used elsewhere [24]. The dilution ratio is estimated from the elemental composition of fuels, biochar and wood charcoal, the mass of fuel consumed, and the flow rate in the duct, assumingcomplete combustion. The TLUD cookstove is tested using the equipment and procedure described in Supplementary Sections 5.2 and 5.3. In those tests, the pollutant sampling is done through a quartz probe hanging in the center of the canopy hood, 20.5 cm above the top of the pot. A primary air inlet, 5 cm in diameter, provides the biomass bed with a limited flow of oxygen. The performance evaluation tests for the TLUD cookstove are conducted with restricted and unrestricted primary air flow, which are denoted as 'restricted mode' and 'unrestricted mode', respectively. In the restricted mode, a cap is placed onto the primary air inlet, reducing the diameter to 2 cm to further reduce the oxygen availability. For each cookstove/biomass pellet type combination, the tests are performed three times to ascertain repeatability.

2.3. Gas and particulate emissions monitoring

For both cookstoves, the concentrations of CO, CO_2 and NO are measured continuously with a PG-250 Portable Gas Analyzer (Horiba Instruments Inc., USA). For the two-chamber cookstove experiments only, the size-resolved particulates are monitored by the Sioutas Personal Cascade Impactor (SKC, USA). To obtain a time-resolved size distribution of particulate, five impactors are used and replaced in succession. During one whole test, each of the first four impactors serves for 24 min, and the last one serves for the remainder of the test. Particulates with aerodynamic diameters of >2.5, 1.0−2.5, 0.5−1.0, 0.25−0.5, and <0.25 µm are collected by four 25-mm polytetrafluoroethylene (PTFE) filters (SKC, USA) with pore size of 0.5-µm, and one 37-mm PTFE filter (SKC, USA) with pore size of 2.0-µm, respectively. The weights of unloaded and loaded filters are measured after they were conditioned in a desiccator for more than 10 days to a constant weight. The particulate sampling probes isokinetic, and the mass flow rate of sampling gas is maintained at 0.194 g s-1, which is the recommended operating flowrate for the impactor.

2.4. Data analysis

The data analysis for the two-chamber cookstove is presented below, while the corresponding information for the TLUD cookstove is described in Supplementary Section 5.4. The data processing methods differ because of the differences in sampling method, and more assumptions are required for processing the TLUD data. To develop confidence that the different methods do no change results significantly, the two-chamber stove data is reprocessed using the TLUD data processing method. The reprocessed emissions factors (not presented here) differ on average from the original values by less than 3%, and the maximum observed difference is 16%.

For the two-chamber stove, the equivalent dry fuel consumptions of pyrolysis and combustion fuels, $m_{equ,py}$ and $m_{equ,co}$ (kg), are defined as [22]

$$m_{equ,py} = m_{py}(1 - \frac{MC_{py}}{100}) - m_{py}\frac{MC_{py}}{100}[Cp_w(T_b - T_a) + L]/LHV_{py} - m_{bc}LHV_{bc}/LHV_{py} \quad (1)$$

$$m_{equ,c} = m_c(1 - \frac{MC_c}{100}) - m_c\frac{MC_c}{100}[Cp_w(T_b - T_a) + L]/LHV_c - m_{cc}LHV_{cc}/LHV_c \quad (2)$$

where m_{py} and m_c are the masses of pyrolysis and combustion fuels consumed (kg), MC_{py} and MC_c are the moisture contents of pyrolysis and combustion fuels (%), Cp_w is the specific heat of water (kJ kg^{-1} K^{-1}), T_b and T_a are the boiling temperature of water and the room temperature (°C), L is the latent heat of water (kJ kg^{-1} K^{-1}), m_{bc} and m_{cc} are the masses of biochar and wood charcoal at the end of the test (kg), LHV_{py}, LHV_c, LHV_{bc} and LHV_{cc} are the lower heating values of pyrolysis and combustion fuels, biochar and wood charcoal (kJ kg^{-1}, dry basis), respectively.

Emission factors for gas pollutant i and particulate, EF_i and EF_p (kg kg-1), can be calculated from

$$EF_i = \frac{\frac{MW_i}{MW_{gas}} \int_{t_o}^{t_o+\Delta t} m^{\cdot}_{gas} X_i dt}{m_{egu,py} + m_{egu,c}} \qquad (3)$$

$$EF_p = \frac{m_p}{m_{egu,py} + m_{egu,c}} \qquad (4)$$

where MW_i and MW_{gas} are the molecular weights (kg mol-1) of gas pollutant i and of gas, $m^{\cdot}_{gas}$ is the mass flowrate of gas in the duct (kg s-1), t_o is the time at the beginning of an experiment, Δt is the time

interval of the experiment (s),Xi is the mole fraction of gas pollutant i (dimensionless), mp

is the mass of particulates collected (kg). EF values are multiplied by 1000 to express them in g kg-1 units.The thermal efficiency (calculated with energy credit for remaining biochar and wood charcoal) of the cookstove, ? (%), can be calculated from [22]

$$\eta = \frac{\sum_{j=1}^{3} (Cp_w m_{wij}(T_b - T_{ij}) + L(m_{wij} - m_{wfj}))}{LHV_c m_{equ,c} + LHV_{py} m_{equ,py}} \times 100 \qquad (5)$$

where m_{wij} and m_{wfj} are the initial and final weights of water in pot j (kg), T_{ij} is the initial temperature of water in pot j (°C).

The modified combustion efficiency of the cookstove, MCE (%), can be calculated from [57-59]

$$MCE = \frac{M_{CO_2}}{M_{CO} + M_{CO_2}} \times 100 \qquad (6)$$

where M_{CO_2} and M_{CO} are the molar quantities of CO_2 and CO (mol), respectively.

3. Findings and conversation

3.1. The insensitivity of emissions and efficiency to fatigue

Emission factors (Figs. 2a and 2b) generally indicate that the two-chamber stove is less sensitive to the choice of pyrolysis fuel than the TLUD stove. The choice of fuel has no bearing on the CO and CO2 emission factors in the two-chamber stove. On the other hand, using the TLUD stove, the kind of fuel and the ventilation mode (limited vs. unconstrained airflow) affect the CO and CO2 emission factors. In contrast to what is expected for waste biomass, switchgrass pellets have CO emission factors that are almost 50% lower than those of wood pellets in a particular TLUD stove ventilation mode.The switchgrass fuel has CO2 emission

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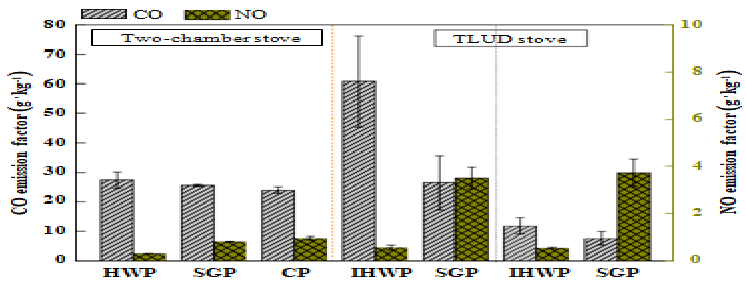
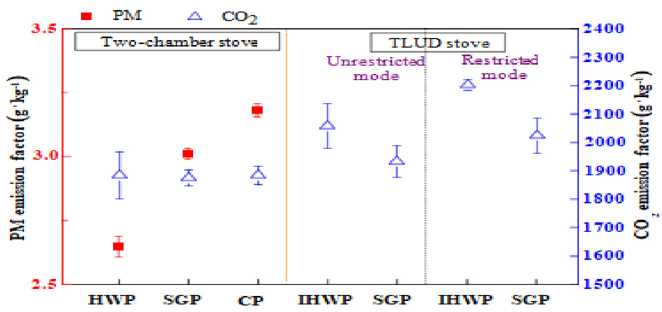
factors that are about 10% lower than those of the wood fuel. In the two-chamber stove, the modified combustion efficiency—which is derived from CO and CO2 readings—is independent of fuel and is higher for switchgrass than for wood pellets in the TLUD. For both stoves, overall efficiency is mostly unaffected by the fuel selection; however, for the TLUD, it is reliant on air flow restriction.



(a) CO and NO emission factors of two-chamber and TLUD stoves



(b) PM and CO_2 emission factors of two-chamber and TLUD stoves

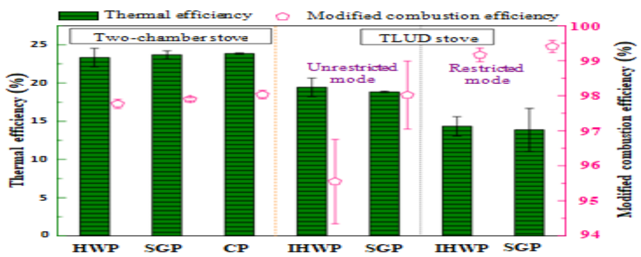


Fig. 2. Gas and PM emission factors and thermal and modified combustion efficiencies of cookstoves.

NO emission factors (Fig. 2a) are higher for the higher-nitrogen-content fuels in both stoves, consistent with the hypothesis that NO is formed from fuel nitrogen, rather than thermal or other mechanisms [60]. TLUD ventilation restrictions have essentially no impact on NO emission factors. NO emission factors are considerably higher for both fuels in the TLUD stove than in the two-chamber stove, and the dependence of emission factor on fuel type is considerably stronger in the TLUD than in the two-chamber stove.

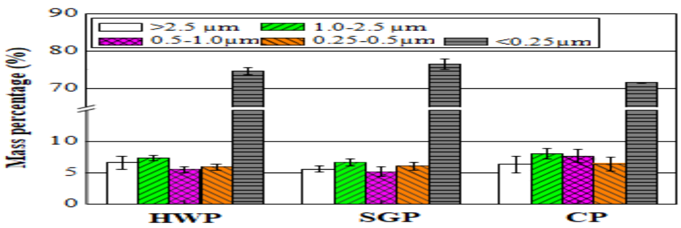


Fig. 3. Mass percentage of particulate in different size ranges for the whole two-chamber stove test.

Particulate emission factors (Fig. 2b) are determined only for the two-chamber stove. They show a moderate dependence on pyrolysis fuel type. The PM2.5 emission factors are, respectively, 15% and 20% higher for switchgrass and corn pellets than for wood pellets. That is to say, herbaceous materials have higher particulate emission factors than woody material does. The distribution of particle sizes (Fig. 3) is essentially the same for the different fuels.The relatively weak dependence of CO, particulate, and NO emissions on fuel type in the two-chamber stove contrasts with the behavior of the TLUD emissions and with literature on the substitution of a high-ash fuel for wood in TLUDs and other combustion devices. Chandrasekaran et al. [61] found that substituting grass pellets for wood pellets in residential-scale boilers and furnaces had a dramatic effect on emission factors for PM2.5, NO, and especially CO. CO emissions were attributed to the poor combustion conditions with high-ash fuel. In a study of six different devices from the US and Europe, these factors increased by an average of 80%, 60%, and 160%, respectively when grass pellets were used in place of wood pellets. Prior literature of TLUD and related stoves [22, 25] also shows strongfuel impacts on emissions. Several models of TLUD stoves had CO and particulate emissions increasing by factors of 2 to 47 when herbaceous biomass fuel was substituted for wood pellet fuel, while one stove model showed decreased emissions with a herbaceous biomass fuel [22], as observed for CO in the TLUD in the current study. Fuel substitutions (dung or coal vs. applewood chips or chunks) produced large increases in CO, NO and particulate levels (not emission factors) in TLUD experiments of Patel et al. [25]. The qualitatively different impacts of fuel substitution in different TLUD stoves are surprising. Evaluating fuel impact is complicated by the fact that different fuels have significantly different physical form (size, density) in the literature studies.

Two factors may account for the low sensitivity of the two-chamber stove emissions to the choice of pyrolysis fuel: (1) the contribution of the combustion fuel to emissions, and (2) the fact that external heating initiates and sustains pyrolysis. It is likely that both of these factors are important. In the two- chamber stove, the combustion fuel, wood, is present for all tests; thus the change from high-ash to low- ash pyrolysis fuel affects only part of the emissions. Over the entire test period, pyrolysis fuel accounts for only 54%−58% of the carbon released and 69%−73% the energy released. Thus the impact of changing the pyrolysis fuel may be “diluted” substantially by the contributions of the combustion fuel. This “dilution” effect may provide the main explanation of the weak dependence of PM2.5 and NO emission factors on fuel.

The second factor, external heating of the pyrolysis chamber, appears to be important in explaining the total independence of CO emission factors on fuel choice. High carbon monoxide emissions are often associated with poor combustion conditions, which tend to occur with the lower-energy-content high-ash fuels [61]. The two-chamber stove, unlike the TLUDs or domestic heaters and boilers used in literature studies, the combustion fuel (wood) provides a steady source of heat in all cases. Thus, the two-chamber stove does not require a self-sustaining combustion process for the pyrolysis fuel, and for that reason does not suffer from poor combustion described in other devices' operation with high-ash fuel [61]. Evidence for the importance of the combustion fuel in governing the reaction process can be seen in the timing of the fuel usage. In the two-chamber stove, combustion proceeds on a timetable largely dictated by the combustion fuel feed rate.

Although the different pyrolysis fuels have different kinetics (Fig. SM-10 in the Supplementary Material) and slightly different thermochemistry (Table SM- 2 in the Supplementary Material), the two-chamber stove timescales are essentially independent of pyrolysis fuel: times to boil each pot of water agree almost to within the experimental repeatability (Table SM-4 in the Supplementary Material). In contrast for the TLUD stove, under unrestricted mode, switchgrass pellets require 60% more time than hardwood pellets to heat the water to 90 °C (Table SM- 7 in the Supplementary Material). That is to say, the TLUD boiling time depends strongly on the choice of fuel, with less vigorous reaction occurring in the cases with the higher-ash fuel.3.2. Fuel sensitivity of partitioning of mass, carbon and nitrogen

Biochar yields and nitrogen partitioning into biochar, NO and other (unidentified) compounds for the different stoves and different pyrolysis fuels are reported in Table 2. The measured NO may originate from the nitrogen in the pyrolysis and combustion fuels or from the combustion air. For the purposes of calculating yields, NO is assumed to be released only from the nitrogen in the pyrolysis and combustion fuels; this assumption is reasonably accurate because temperatures in the stove are too low for the thermal NO formation mechanism to be active [62].

Switchgrass pellets have the highest biochar yields. For all biomass pellets, 44%−52% of the fuel nitrogen is retained in the biochar, whereas 37%−51% of fuel nitrogen is released in unidentified gas or particulate form. Carbon partitioning into biochar, wood charcoal, CO, CO2, PM and other (unidentified) compounds for the three pyrolysis fuels is also listed in Table 2. The total carbon includes the carbon in the pine wood and the carbon in the biomass pellets, with the biomass pellets accounting for 19.40% to 21.24%. For all biomass pellets, the largest fraction of carbon is released as CO2, followed by carbon retention in the biochar. Even with an assumption that PM is pure carbon, PM represents a very small fraction of the initial carbon.

Table 2

Biochar yields (wt %, dry), and nitrogen and carbon partitioning (wt %).

	Two-chamber cookstove			TLUD cookstove			
				Unrestricted mode		Restricted mode	
	HWP	SGP	CP	IHWP	SGP	IHWP	SGP
biochar yields	32.9±1.9[a]	37.0±0.4	33.0±1.3	19.0±2.7	20.2±3.3	33.0±1.3	26.3±0.3
nitrogen partitioning[b]							
biochar	52.7±5.2	51.8±2.3	44.4±4.1	20.9±4.9	25.2±2.3	33.0±1.3	44.7±1.2
wood charcoal	0.85±0.31	0.18±0.05	0.15±0.06	N/A	N/A	N/A	N/A
NO	9.28±0.22	4.38±0.18	4.11±0.27	16.10±3.69	8.25±1.18	12.90±1.29	7.37±1.45
other[c]	37.2±5.0	43.7±2.6	51.4±3.9	63.0±8.5	66.5±2.8	42.4±1.7	52.8±1.3
carbon partitioning[d]							
biochar	21.2±1.1	21.2±0.4	19.4±1.2	28.2±3.4	26.9±4.9	36.8±0.4	37.9±1.1
wood charcoal	2.02±0.76	2.47±0.62	2.61±0.99	N/A	N/A	N/A	N/A
CO	1.64±0.12	1.54±0.02	1.51±0.08	3.53±1.11	2.18±0.91	0.81±0.07	0.75±0.44
CO_2	71.8±1.0	71.9±0.8	75.3±0.9	67.4±2.3	70.2±5.4	62.0±2.8	60.2±2.8
PM[e]	0.34±0.01	0.39±0.01	0.43±0.01	0.79±5.24	0.69±0.22	0.42±3.19	1.13±2.40
other[c]	2.99±2.70	2.41±0.92	0.76±1.11				

[a] Standard deviation.
[b] Mass of nitrogen in a given product, normalized by mass of nitrogen initially present in combustion fuel and/or pyrolysis fuel.
[c] Unidentified.
[d] Mass of carbon in a given product, normalized by mass of carbon initially present in combustion fuel and/or pyrolysis fuel.
[e] Assuming particulates are pure carbon.

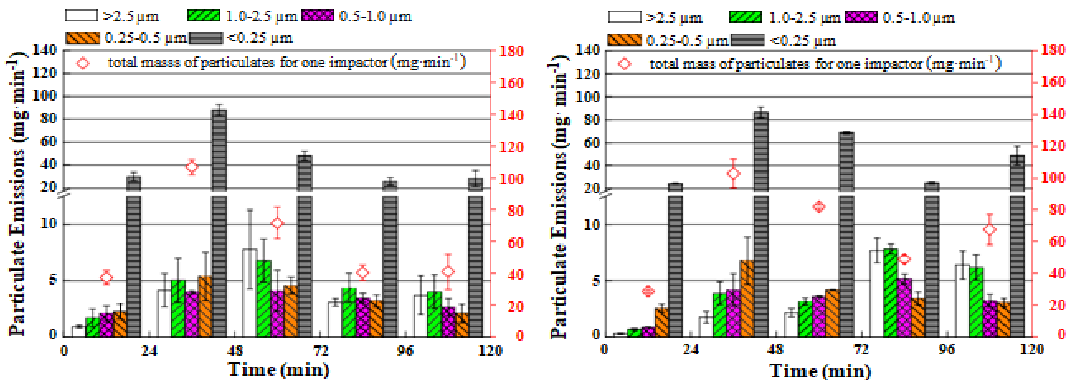
Table 2

Biochar yields (wt %, dry), and nitrogen and carbon partitioning (wt %).

Besides heat, the two-chamber stove can also produce biochar, which can be used as a soil amendment to improve the water retention and productivity of soils [63, 64]. Mass yields of biochar (Table 2) are distinctly lower for unrestricted-mode operation of the TLUD than for the other TLUD modes or the two-chamber stove. This difference makes sense because the presence of more O2 in the unrestricted mode of the TLUD, resulting in more oxidation of char that has been created earlier. Yields of char vary somewhat with fuel. According to Tables SM-2 and SM-6 (Supplementary Material), enrichments of nitrogen and carbon in the biochar occur for both stoves and for all fuels except for IHWP for the TLUD in unrestricted mode. For biochar, these enrichments may have a positive effect on the soil environment [65, 66], though the extent of nitrogen availability for plant uptake is unclear [67]. The enrichment of carbon in the char also indicates that the stoves receive cooking energy from a lower- carbon source (the volatiles from the pyrolysis process), reducing the carbon emissions to the atmosphere.

3.3. Details of PM emissions, two-chamber stove

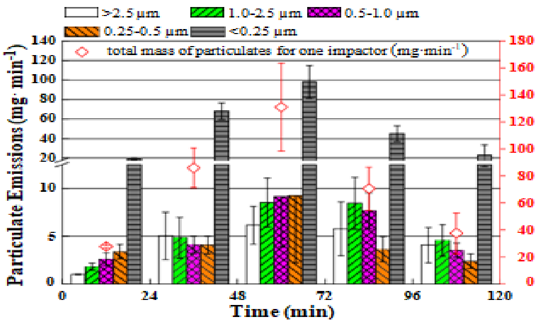
The mass of particulates emitted during different time periods (corresponding to different impactors) is shown in Fig. 4 for the two-chamber stove operated with different pyrolysis fuels. The time interval of the last time period is different from those of the first four time periods. For more meaningful comparisons, the mass of particulates collected is normalized by the time interval of each time period. The mass percentage of particulates of different sizes is displayed in Supplementary Fig. SM-6. For all biomass pellets, particulate mass increases as pyrolysis proceeds, and then decreases.From Fig. 4, it can be seen that for each time period, particulates smaller than 0.25 μm are the dominant fraction for all biomass pellets. The proportion in this mass bin is greatest in all time periods. For switchgrass pellets, this bin exceeds 84%. Fig. 3 shows the mass percentage of particulate with different sizes for the entire test. 70%−80% of mass of the particulates has a size of less than 0.25 μm. Other size bins account for only 5%−10% each. This general size distribution is typical of solid-fuel combustion sources [61, 68]. In studies of Venkataraman and Rao [42], and Habib et al. [24], a similar hood system was built and a different impactor was used to examine the size-resolved particulate frombiomass combustion in cookstoves. The size distribution of particulates in both of these studies was unimodal, peaking at 0.47−0.78 μm or 0.42−1.31μm [24, 42], much larger than the peak seen in the current study. A possible reason for this difference is their use of a dilution plenum to provide additional residence time (200−420 s, which is similar to a coal boiler) for thorough quenching after the gas was sampled via an isokinetic probe. The condensation of semivolatile compounds might have the potential to increase the particulate size [42]. Armendáriz-Arnez et al. [38] and Huboyo et al. [54], used a similar impactor as our study to monitor size distributions of particulates emitted from combustion of wood or Jatropha curcas seeds in cookstoves under indoor conditions. These two studies found that particulates smaller than 0.25 μm accounted for 55%−67% [38], and 60%−80% [54] of total PM mass, respectively. These findings are comparable to ours, though with a slightly lower mass fraction of particulates of less than 0.25 μm. One reason for this discrepancy could be the difference between hood and indoor methods. Stove differences, especially the pyrolysis process could also affect the production of particulates.



(a) Hardwood pellet

(b) Switchgrass pellet

I



(c) Corn pellet

Fig. 4. Mass of particulates emitted during different time periods (normalized by the time interval of each time period)

4. Conclusion :

Water boiling test with hood: This method is used to assess the fuel sensitivity of a two-chamber biomass cookstove. Various biomass pellets are mixed with one combustion fuel (pine wood) to serve as pyrolysis fuels. The pellets are typical biomass resources that are woody and waste (herbaceous). The impact of fuel type for pyrolysis on efficiency, emissions of gases and particulates, and the time-resolved size distribution of particulates is investigated. The two-chamber stove's results are contrasted with those obtained from measurements made using a TLUD cookstove running on two different kinds of biomass pellets and with those reported in the literature [22, 25]. Both types of cookstoves generate carbon- and nitrogen-enriched biochar, which can be added to soil in addition to providing heat.The fuel sensitivity comparison demonstrates the advantages of using waste biomass as a supplementary fuel (as in the two-chamber stove) rather than as the sole fuel for a cookstove (as in the TLUD stove). The two-chamber cookstove thermal performance, duration of pyrolysis, time required for boiling water, and CO emission factors are not affected by the choice of pyrolysis fuel, while the PM2.5 and NO emission factors are less fuel-dependent that observed in other biomass combustion devices. By combining pyrolysis of a waste biomass fuel with combustion of wood, the two-chamber stove can make use of variety of biomass materials without modification. The two-chamber stove differs from the TLUD stove in that it controls the rate of combustion largely through periodic feeding of wood. Because the TLUD stove uses only one fuel both to sustain combustion and to produce biochar, its emissions and combustion timing are considerably more dependent on the choice of fuel. While the two- chamber stove provides benefits in terms of fuel flexibility, it is important to emphasize that it relies on a combination of wood and pellet fuels, rather than on pellet fuel alone. Thus it allows waste biomass to supplement wood, but not to operate as the only fuel.One cause of concern with the two-chamber stove is the size distribution of the emitted particulates. Like many other biomass combustion devices, this stove produces particulate emissions that dominated by the small size range (< 0.25 µm), especially when pyrolysis is active. The harmful health effects of fine particulates point to a need for further design improvements. Particulate measurements were not performed for the TLUD stove in the current study.

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