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Fuel sensitivity of biomass cookstove performance

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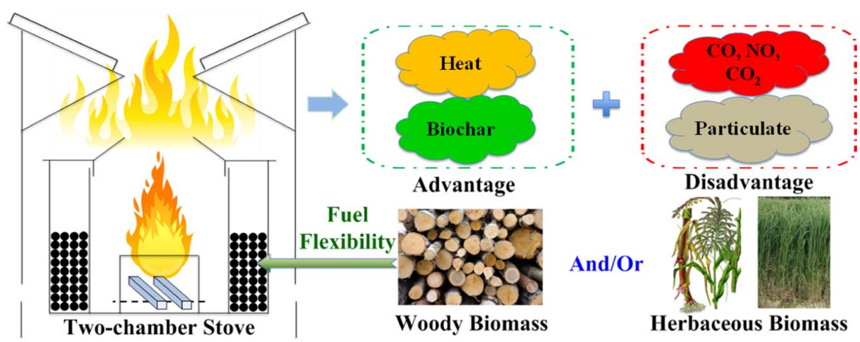
HIGHLIGHTS

- Fuel sensitivity is far lower in the two-chamber stove than in the TLUD stove.
- The NO emission factor is positively related to the nitrogen content of biomass.
- The PM emission factor is greater for herbaceous biomass than for woody biomass.
- The two-chamber stove produces biochar with nitrogen and carbon enrichments.
- By mass, 70 – 80% of PM produced in the two-chamber stove is smaller than 0.25 μm.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a pyrolysis biomass cookstove with separate combustion and pyrolysis chambers (two-chamber stove) is investigated and compared to a widely-used char producing cookstove design (top-lit updraft, TLUD). The influence of pyrolysis fuel type (pellets of hardwood, corn stover, or switchgrass) on CO, NO, CO_2 and particulate emissions, and the time dependence of particulate size distribution are quantified. Water boiling tests are conducted in a hood with pine wood as the combustion fuel for the two-chamber stove. Thermal and modified combustion efficiencies, and char yields and elemental compositions are reported. The sensitivity to fuel choice is far lower in the two-chamber stove than in the TLUD, thus making the two-chamber stove design well suited to challenging waste biomass fuels. The NO emission factors are positively related to the nitrogen content of biomass pellets, whereas the particulate emission factor (measured only for the two-chamber stove) follows an order of hardwood < switchgrass ≤ corn stover (i.e. woody biomass < herbaceous biomass). By mass, 70 – 80% of the particulates are smaller than 0.25 μm. This size range is the dominant fraction at all times during the water boiling test.

1. Introduction

Efforts have been made to develop efficient and low-emissions biomass cookstoves for household heating and cooking in rural areas of developing countries [1–9]. Woody biomass is the fuel chosen by most designers of improved cookstoves, and is used in the vast majority of

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reported tests characterizing stoves. But 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].

The choice of fuel influences stove performance, and the magnitude of this effect led Prasad et al. [17] to assert that fuel characteristics must be considered in producing a reliable stove design. Waste biomass materials generally have higher levels of nitrogen and ash, lower energy content on a mass and volume basis, and lower bulk densities, than woody biomass does [18–20]. For that reason, these fuels generally pose greater challenges for sustaining combustion, and often require either specialized stoves [7,21] or else stove design modifications [22] for satisfactory performance. Studies comparing the emissions from a given cookstove with woody versus herbaceous biomass fuel are limited [13,14,22–25], but they provide some indications that waste biomass fuels are associated with higher levels of CO, particulates and/or certain aromatic compounds in comparison to woody biomass fuels. Some evidence [24] suggests that differences in the burning rate are responsible for differences in particulate emissions among different biomass fuels.

The primary objective of the current study is to quantify the effects of fuel choice on the performance of a two-chamber charcoal-producing stove that can be operated readily with a range of pyrolysis fuels. The two-chamber stove features an annular pyrolysis chamber surrounding a central combustion chamber equipped with wood feed. Volatiles are released from the pyrolysis chamber and burned in the combustion chamber. Data from a second charcoal-producing stove, the more extensively studied top-lit updraft (TLUD) stove [13,22,25,26], is presented for comparison. Both stoves use a low-oxygen environment to convert biomass to volatiles that are burned elsewhere, and to charcoal, which can be used as a soil amendment [27–32].

The two stoves differ in their geometry and operation, and in the origin of the heat responsible for the biomass reactions. In the two-chamber stove, wood burns in a central combustion chamber and provides heat to pyrolyze a second fuel in the annular pyrolysis chamber. In the TLUD, the entire stove is loaded with a single biomass fuel, and the partial oxidation reactions of the fuel produce autothermal heating. The difference in the source of heat is expected to make the two-chamber stove insensitive to the choice of pyrolysis fuel. Thermal conversion of biomass occurs as a batch process in both stoves, but the semicontinuous-feed wood combustion occurring in the two-chamber stove offers some operational advantages. Specifically, a cooking task in the two-chamber stove can continue beyond the completion of pyrolysis, in a pure wood combustion mode, avoiding the inconvenience and high emissions associated with refueling the TLUD [22]. On the other hand, the two-chamber stove has the disadvantage of requiring a substantial amount of wood as its combustion fuel, in addition to the pyrolysis fuel.

For the two-chamber stove, wood is the combustion fuel. Three different types of biomass pellets are used as pyrolysis fuels: woody biomass is represented by hardwood pellets, and crop residues are represented by pellets of two types of herbaceous biomass: switchgrass (*panicum virgatum*), and corn stover (leaves, stalks, and cobs of *zea mays*). While switchgrass is an energy crop rather than a waste biomass species, its nitrogen and ash content are similar to those of straws and other waste biomass materials [19,33,34]. For the TLUD, which uses a single fuel at a time, a more limited fuel comparison is made: between hardwood pellets and switchgrass pellets.

Several tests are available to evaluate cookstove performance, ranging from indoor pollutant measurements in kitchens under uncontrolled cooking conditions [35–39] to water boiling tests with pollutants collected and rapidly diluted in a hood [3,4,7,40–45]. The current study uses the water boiling test method with a hood, which is appropriate for performance evaluation of a new biomass cookstove. Emission factors for CO, CO_2, and NO are obtained for both stoves, along with particulate emissions factors and the particulate size distribution and emission rate at different times in the pyrolysis process for the two-chamber stove only. To our knowledge, a time-resolved assessment of the size distribution of particulates has seldom been reported in cookstove studies [46]. The current study is one of only a small number of studies addressing NO emissions [15,47–50] or particulate size distribution [3,24,38,41,42,51–54] in cookstoves. The partitioning of nitrogen and carbon between the solid residue and the gas phase is also reported.

In this paper, we refer to the charcoal produced in the TLUD or in the pyrolysis chamber of the two chamber stove as “biochar”, and refer to the small amounts of charcoal produced from the combustion fuel of the two-chamber stove as wood charcoal.

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.

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.

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	19,581	18,324
SGP	52.44	1.43	5.82	42.67	3.98	80.25	15.77	18,717	17,482
CP	51.29	1.80	6.13	43.48	6.09	–	–	18,460	17,159
IHWP	54.57	0.11	6.48	44.61	0.58	84.25	15.17	18,865	17,490
Combustion fuel for the two-chamber stove									
PW	57.64	0.07	6.19	42.13	0.20	86.11	13.69	19,550	18,237