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Cristian Birzer, Paul Medwell, Gregory MacFarlane, Matthew Read, Josh Wilkey, Matthew Higgins, Tomas West

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A biochar-producing, dung-burning cookstove for humanitarian purposes

Cristian Birzer*, Paul Medwell, Gregory MacFarlane, Matthew Read, Josh Wilkey, Matthew Higgins, Tomas West

The School of Mechanical Engineering, The University of Adelaide, Adelaide, 5005, Australia

Abstract

Over three billion people worldwide cook with traditional stoves, which typically consist of three stones and an open fire. The harmful emissions produced from these types of stoves are known to cause fatal illnesses. Traditional stoves claim the lives of up to 4 million people every year and cause the death of more children under the age of five than any other single cause. In addition, widespread land degradation and deforestation have resulted from inefficient fuel consumption of traditional stoves. In order to address these issues, investigations into the use of dung-burning top-lit up-draft (TLUD) microgasifier cookstoves, that produces biochar as a byproduct, have been conducted at the University of Adelaide. Results indicate that dung from various grazing animals burnt in the TLUD stove have similar heating properties, implying that the stove is applicable to a wide client-base. Additionally, biochar from cow-dung combustion is as good, if not better than some commercially available biochar.

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1. Introduction

Domestic energy consumption in the developing world is still largely dependent on biomass such as wood, dung and agricultural waste: fuel sources that are typically burned in traditional stoves. Unfortunately, these types of stoves produce high levels of air pollution, which results in increased risk of acute respiratory infection and lung diseases, especially for women and young children. Emissions produced by traditional stoves and cooking fires in

* Corresponding author. Tel.: +61 8313 3148; fax: +61 8313 4367.
E-mail address: cristian.birzer@adelaide.edu.au

the developing world cause illness that results in approximately 1.6 million deaths every year [1], although more recent data indicates up to 4 million deaths every year [2]. Harmful emissions from traditional stoves and cooking fires are reported to claim the lives of more children under the age of five years than any other single cause [3]. The combustion of renewable fuels such as dung and wood can result in a depletion of natural fertilizers, deforestation and soil erosion. The ash that remains after combustion has little use, and can be detrimental to agriculture if mixed with soil. However, under certain combustion conditions biochar, which can be used as a soil enhancer, can be produced. Developing affordable cleaner-burning systems for cooking that also produce biochar can not only help save millions of lives every year, but also improve quality of agriculture and life in general.

Three-stone fires are the most commonly used cooking method in developing communities. They consist of three stones placed in a ring on the ground with fuel in the centre of the ring. They are made from, and fuelled by, material collected in the local environment and rarely incur financial cost. The most commonly used fuel is wood, although dung and agricultural waste are also widely used. Emissions from inadequate biomass stoves are linked to adverse health effects including acute lower respiratory infection, chronic obstructive pulmonary disease and lung cancer in women and children [4, 5]. Many significant health, productivity and environmental benefits may result from replacing traditional cooking fires with modern cooking stoves [6]. However, approximately 3 billion people in developing countries still rely on traditional stoves [1]; this is due to the expense and unavailability of modern sources [7]. Alternatives to three-stone fires that can be easily implemented are necessary for improved cookstove combustion.

Due to limited budgets, solid fuels such as wood, crop residue and animal dung are used throughout the developing world [8]. Dung is a commonly used biomass fuel. Dung produces higher amounts of poisonous CO emissions compared to wood and agricultural residues. The release of CO is one of the most hazardous products from biomass combustion stoves [9]. The production of CO is directly related to the burn rate [10]. Stove users generally utilize burn rate to control the power output of the stoves with an increase in burn rate resulting in an increase in power output [11]. Therefore, burn rate is of critical importance in any stove design.

Microgasification prior to combustion can reduce harmful emissions production, and also promotes the production of biochar. Biochar is the term used to describe charcoal that is added to soil as a soil enhancer. It is formed when biomass is heated in a low oxygen environment. Biochar has the potential to boost agricultural production through increased soil moisture retention, reduced nutrient leaching, increased microbial activity and increased soil pH [12]. Biochar is also an effective way of sequestering carbon from the atmosphere, making biochar cook stoves an important tool in combating rising atmospheric CO₂ concentrations [13].

One particular stove design that can reduce harmful emissions and produce biochar from solid-fuel combustion is a top-lit up-draft (TLUD) microgasifier stove (Fig 1). The combustion process of a TLUD stove can produce fewer harmful emissions and preserves the charcoal as biochar for use as an organic soil enhancer [14]. This technology can be applied to a stove to burn almost any solid biomass fuel, including wood pellets, nut shells, crop residues, textile waste and animal dung, thereby reducing the depletion of wood resources [15]. Work by [16] presents some of the advances made for TLUD stoves, but more scientific information is required for design optimization of these types of stoves.

The combustion process of a TLUD stove is shown diagrammatically in Fig 1. These stoves utilize pyrolysis: a thermo-chemical decomposition of biomass at elevated temperatures in a low oxygen environment [17] to separate solid biomass into charcoal and volatiles. Once the volatiles have been released, they travel up through the stove. Air is drawn in through the air inlets and enters the fuel chamber as either primary air that passes through the packed fuel, or secondary air that mixes with volatiles before combustion.

The motivation of the current work is focused on developing affordable and sustainable bio-char producing clean-burning cooking systems for the developing world. The aim of the current paper is to further the knowledge of TLUD designs for improved combustion and biochar production.

2. TLUD Design

The TLUD stove used for the current work is detailed in Birzer et al. 2013. It is made from readily available recycled parts, in order to ensure that the final design can be made at little, if any, monetary cost. The stove body is made from a 10 L paint tin (donated by Solver Paints) with the base removed. The stove adaptor is made from a

second 10 L paint tin and has 16 x 20 mm diameter secondary air inlet holes. The diameter of the TLUD is 200 mm. The chimney is made from a tomato can with diameter of 140 mm. The cooking pot is located 45 mm from the top of the chimney.

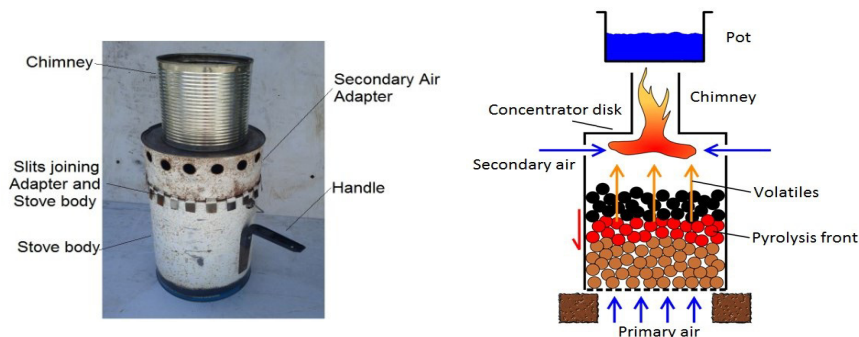


Fig. 1. Photo of TLUD stove (left) Schematic diagram of the TLUD operation.

3. Testing

For the current work, tests were conducted on the power output of fuel, as well as the quantity and quality of biochar produced. Power output was measured using a modified water boiling test (WBT). In this test, a fixed mass of fuel (1800g plus 50g of ethanol as starter fluid) was ignited. Once the flame was established and stabilized, a 1 L pot of water was placed above the stove and heated until the flame changed color from yellow/orange to blue, indicating combustion of the char and incorrect TLUD operation. During the tests, water temperature measurements were taken at regular time intervals. After combustion, the biochar was weighed and samples were tested to assess biochar quality.

Two separate aspects of the biochar quality were assessed: carbon hydrogen nitrogen (CHN) content and adsorption capacity. These tests were only conducted on cow-dung. A specific analyzer of carbon hydrogen and nitrogen (CHN) was used to determine the percentage of carbon and nitrogen present. This helps assess whether a biochar is better as a soil enhancer or is better at sequestering carbon in the soil over a long term time period [18].

The adsorption capacity, as well as ash content, of biochar was evaluated using a gas adsorption test. This test was conducted by Alterna Biocarbon Inc in Massachusetts, USA.

The amount of biochar produced as a percentage of the initial fuel mass in the cow dung burning TLUD stove was tested for varying burn times. Five WBT were conducted but stopped at different periods and not strictly when char oxidization began. The burn time of each successive test was increased by four to five minutes, and the weight of biochar produced was recorded.

4. Fuel

A range of different animal dungs were tested to identify the applicability of the dung burning TLUD stove throughout the developing world. Dung fuel types of differing size, shape and heating value including zebra, giraffe, rhinoceros and American bison were tested. Although dung from these creatures may not be commonly burned in many communities, these tests give an indication of the sensitivity of the stove performance with different fuel types. For reference purposes, cow dung was also tested. The fuels are all quite distinct in both size and shape, however, have unknown energy densities. These dung fuels were collected from Monarto Zoo in South Australia. Their diet consists of grasses and hay, similar to that of wild populations. The tests give an indication of how the TLUD stove design burns fuels of different composition and how easily the stove could be adapted to burn dung across the developing world.

5. Results

5.1. Dung combustion

The heating profiles of the water for different dung types and total burn times are illustrated in Fig 2. In general, the rates at which the water heats up to 100°C are similar, although giraffe and cow dung depart from the trend slightly. More important is the duration of combustion. For a given mass of fuel, the duration of combustion ranged from 700 seconds (11.7 minutes) for rhinoceros dung to 2700 seconds (45 minutes) for giraffe dung. This is important in the application of cooking food and boiling water. Insufficiently cooked food can result in food poisoning. As the TLUD cookstove design is a batch-feed fuel system, it can not be refueled during combustion.

American bison dung was similar in size and shape to cow dung. While a fuel canister of both dung types had approximately the same mass, the bison dung may have a higher energy content due to differences in diet. The American bison had a diet rich in lucerne hay, whereas the free grazing Angus beef cattle used for cow dung were occasionally fed meadow hay. This slight difference in diet likely had a marginal effect on the heating value of each dung because both fuels produced flames with similar characteristics. The flame produced by the bison dung surrounded the bottom of the pot, producing smoke and blackening the pot. It was also observed that air was not induced through the secondary air inlet holes, suggesting the stove was not operating as a microgasifier. It is likely that air was induced through small gaps between the secondary air adapter and the fuel chamber, reducing the effect of secondary air holes on the combustion process.

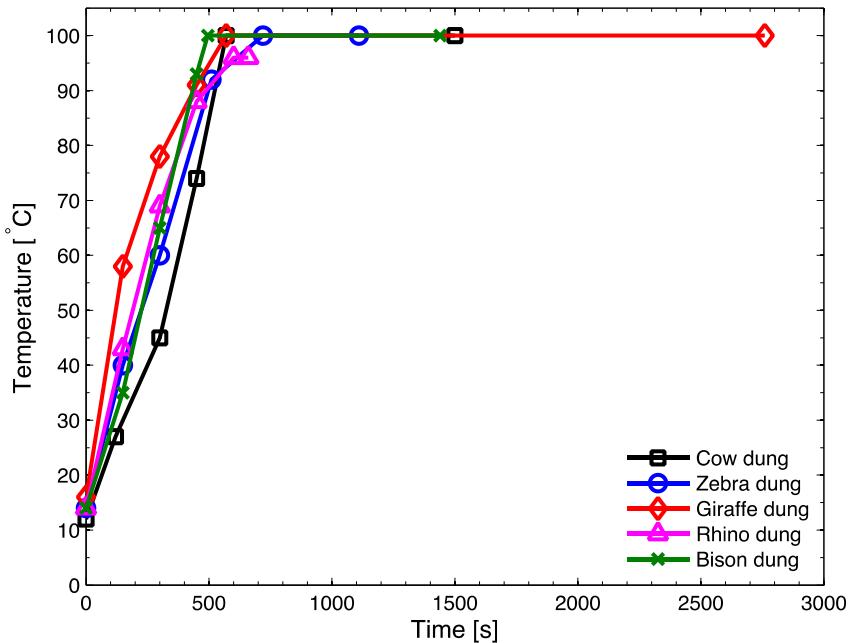


Fig. 2. Temperature profile and burn time of the dung burning TLUD stove with different types of animal dung.

Zebra dung produced a flame that only just reached the bottom of the pot. Consequently, there was little visible smoke produced from the stove during operation. This fuel type has a much lower bulk density than cow and bison dung, so the mass of fuel in one fuel canister was significantly lower. As a result, the zebra dung produced a short burn time. When the pyrolysis front reached the bottom of the fuel bed the flame was blown out, indicating a weak natural draft induced at the end of the burn.

The giraffe dung took a similar time to boil water compared to other fuels, but had a significantly longer burn time. The bulk density of giraffe dung was about 30% greater than that of cow and bison dung. In addition to a

higher density, the giraffe dung had a longer burn time because the size and shape of the fuel reduced primary air flow. Small, spherical shaped pieces of dung formed by the giraffe are ideal for TLUD stoves as they allow primary air to flow evenly up through the fuel and better sustain the movement of the pyrolysis front down the fuel bed. These desirable fuel characteristics were evident in the performance of the TLUD stove. Visually giraffe dung was the cleanest burning fuel of any type tested. This fuel was clean burning not only because the flame did not interact with the pot, but also because it correctly operated as a microgasifier.

Rhinoceros dung had the lowest bulk density of all fuels tested and, as expected, a short burn time. It burned for only 11 minutes in the dung burning TLUD stove. The poor performance of this fuel was also related to the large size of each fuel piece, which was too large for ideal TLUD stove operation. Furthermore, these fuel pieces also contained loose hay which propagated the flame down through the fuel chamber without an even pyrolysis front. The operation of the stove in this instance was a conventional combustion device where both volatiles and char oxidization occurred simultaneously. A large quantity of smoke was produced both because of the combustion process and due to quenching the flame on the pot. In general, the production of soot and smoke during the cooking cycle is strongly time-dependent [19, 20] and so further testing would be required to quantify the smoke emissions from the TLUD stove, across the range of different fuels.

5.2. Biochar

Biochar yield is defined as the final weight of the charred fuel as a percentage of the initial fuel mass. The biochar yields from cow dung combustion for five different burn time are presented in Table 1, this value includes the ash content that was found through testing to be 24%. This value is higher than commercially available biochars; however, this is because the ash content of cow dung is naturally higher than that of biochars produced from woody biomass.

It is evident that as the burn time increases biochar yield decreases. There is a direct compromise between the amount of biochar produced and the length of cooking time per fuel canister. This result was expected, considering that char oxidization begins when the pyrolytic flame front reaches the bottom of the fuel chamber. With an ash content of 24%, a burn time greater than 40 minutes resulted in a biochar yield consisting entirely of ash, which can not be used as a soil enhancer. From [16], emissions of carbon monoxide were found to significantly increase after 20-25 minutes for these tests. Therefore, extending the burn time is not only detrimental to the amount of soil enhancing biochar produced but also to the health of the stove user.

Table 1. Biochar yield versus burn time in a dung burning TLUD stove

Burn time [minutes]	Biochar and ash yield [% mass]
17.5	39.5
23	33
27	28
31	26
40	24

The cow dung biochar was found to have a carbon content of 45.0% and a nitrogen content of 5.3%. This gives the biochar a carbon to nitrogen ratio less than 15, indicating that it will mineralize shortly after being added to the soil, which will increase the availability of nitrogen to plant roots and benefit plant health. This can reduce the need for additional fertilizers (natural and synthetic).

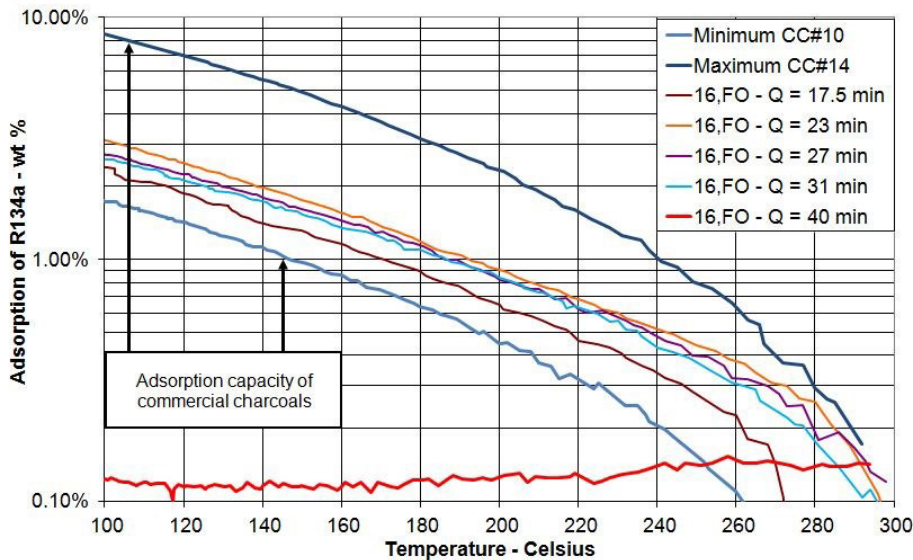


Fig. 3. A comparison of adsorption capacity of cow dung based biochar from a TLUD stove with varying burn rates and commercial charcoal.

The adsorption capacity of biochar is indicative of its ability to hold soil organic compounds which may be released to plant roots once added to the soil. Biochars with higher adsorption capacities retain higher levels of soil organic compounds and will be more beneficial as a soil enhancer. The adsorption capacity of each dung biochar from Table 1 is illustrated over a range of temperatures in Fig 3. The adsorption capacities of two commercially available charcoals are also plotted; these are a benchmark for the adsorption capacity of dung biochar. Biochars with similar adsorption capacity to charcoal are likely to be beneficial to plant health when added to soil.

All cow dung biochars produced in the dung burning TLUD stove have comparable adsorption capacities to that of commercial charcoal, except for the biochar that was used after 40 minutes of burn time. As stated previously, this biochar had completely oxidised to ash which has a very low adsorption capacity, and is less beneficial to soil health. These results show that the quality of the biochar produced in the dung burning TLUD stove, as measured by its adsorption capacity, is relatively independent of the burn time. However, the quantity of biochar produced decreases with increasing burn time, therefore, it is preferable to stop the TLUD stove after 20-25 minutes of operation.

6. Conclusion

A top-lit up-draft (TLUD) microgasifier stove designed to reduce harmful emissions has been tested to assess the quality and quantity of biochar produced from burning dung. Results show that burning various types of animal dungs results in sufficient burn times and power outputs for cooking applications. The relatively consistent constitution of animal dung implies that other types of dung that were not tested may be suitable for the dung burning TLUD stove. As a result dung burning TLUD stoves are expected to be applicable to regions of the developing world that use dung produced by animals other than buffalo for cooking fuel.

The yield of biochar is shown to have an inverse relationship to burn time; however the carbon and nitrogen content, as well as adsorption capacity are independent of burn time, assuming the biochar is not converted to ash. The overall quality of biochar produced from cow dung combustion is comparable to commercially available biochar, indicating that the TLUD design can be used to reduce harmful cookstove emissions, but also produce biochar suitable for soil enhancement.

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