Viability of Waste-Based Cooking Fuels for Developing Countries: Combustion Emissions and Field Feasibility

by

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Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Mechanical Engineering at the

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Abstract

Biomass-derived cooking fuels are used by three billion people worldwide. The drawbacks of such fuels, typically wood or wood-derived charcoal, include health hazards, negative environmental effects, and perpetuation of poverty. Briquettes made from various waste materials have been proposed as an alternative to address these issues. The purpose of this work is to understand whether such fuels are viable as compared to wood charcoal considering toxicity, usability, and economic criteria.

Briquettes made from carbonized agricultural waste (AWC) using a process developed by MIT’s D-Lab were investigated. These briquettes were comparable to wood charcoal in terms of energy density, carbon monoxide, and polycyclic aromatic hydrocarbon emissions. Particulate matter emissions from these briquettes were 3-5 times higher but the emissions were only dominant during the initial stages of the fire. Methods for mitigating these emissions are proposed. Ultra-fine particles from wood charcoal and AWC were characterized, offering a novel understanding of these emissions. The effect of variations in raw material inputs on combustion emissions was documented and manure was found to be a promising binder material.

Field studies were conducted on AWC, assessing cooking fuel emissions in households in Nicaragua, ascertaining end user perception of the fuel, piloting production with a women’s cooperative, and conducting an economic analysis of the viability of this production model. Emissions were found to be comparable to wood, user perception was cautiously positive, and production was hypothetically profitable if systems are introduced effectively.

Briquettes produced in Haiti from paper waste and fabric scraps were also studied and found to be highly problematic from the perspective of emissions and cooking performance. Most concerning from a health perspective is the increased particulate emissions, as compared to wood charcoal, by a factor of up to 45. These types of briquettes are being disseminated and no prior art on their emissions has been identified.

In summary, AWC has promise as an alternative fuel but care must be taken in terms of particulate matter exposure and minimizing deviation from the studied
briquette formula. Any alternative fuels should not be introduced until the emissions hazards and cooking performance limitations are addressed.

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Charcoal schematic. Image reproduced with permission from Eli T. Banzaert.
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Chapter 1

Introduction

The purpose of this research is to define the viability of solid cooking fuels made from wastes for use in developing countries. A technical investigation of the combustion emissions of these fuels, including applying measurement techniques novel to the field of indoor air pollution in developing countries, has been integrated with a more qualitative inquiry into the cultural context in which the proposed cooking fuels might be used. By studying both the scientific and societal aspects of waste-based cooking fuels, a more robust understanding of this proposed solution to the problem of cooking fuel is provided.

1.1 Motivation

Nearly 40% of the world’s population — 2.7 billion people — use biomass and conventional methods for cooking [48]. Traditional biomass-based fuels include wood, charcoal made from wood, agricultural waste, and dung. Regions where at least 50% of the population use traditional biomass include sub-Saharan Africa, almost all of Asia, and much of Latin America. In certain countries, including Haiti, Nicaragua, Myanmar, Nepal, Sri Lanka, and the majority of Sub-Saharan Africa, at least 90% of the population relies on biomass [46]. Most people who cook primarily with biomass live in rural regions while 500 million live in urban areas. The International Energy Agency predicts that by 2030, the number of people cooking with biomass will in-
crease to 2.8 billion [47]. The drawbacks of using biomass in a traditional manner are numerous, affecting human health, the environment at the local and atmospheric level, and poverty.

1.1.1 Health impacts

The World Health Organization has documented 1.3 million deaths each year from exposure to indoor air pollution caused by solid fuels [104]. Children under the age of five, being more susceptible to disease, comprise half of these deaths. Women are also disproportionately affected, as both they and their children typically spend large periods of time near the cooking area. To put this rate of death into context, the common causes of death in developing countries are shown in Figure [1-1]. In countries with a gross national income per capita (GNI) of US$825 or less, indoor air pollution from solid fuels is the sixth leading cause of death. In countries with a GNI between US$825 – $10,066, this source is the ninth leading cause of death; worldwide, it is the tenth leading cause of death. The International Energy Agency predicts that by 2030, annual deaths from exposure to biomass will increase to 1.5 million, while deaths associated with unsafe sex, malaria, and tuberculosis will all decrease by at least a factor of two [47].

Apart from the death toll, indoor air pollution detracts from quality of life: exacerbating existing conditions, causing asthma, and triggering many other respiratory ailments. The annual, worldwide burden of disease from indoor air pollution is documented as 41 million disability-adjusted life years (DALYs) lost [1]; for reference, 64 million DALYs are related to unsafe water, sanitation, and hygiene [104, 46].

The reason that biomass-based cooking generates health hazards is primarily due to the process being non-stoichiometric: the combustion process is oxygen-starved and, therefore, a large number of products of incomplete combustion (PIC) are pro-

---

1“One DALY can be thought of as one lost year of ‘healthy’ life. The sum of these DALYs across the population, or the burden of disease, can be thought of as a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability” [106].
Figure 1-1: Annual deaths from leading causes in countries with gross national income per capita of US$825 or less [104]
duced during cooking, as seen in Equation 1.1

\[(CH_2O) + O_2 \rightarrow CO_2 + CO + CH_4 + NMHC + PM + H_2O + \ldots\]  \hspace{1cm} (1.1)

The \((CH_2O)\) term represents a generalized form of the composition of organic matter, which combines with oxygen, \(O_2\), during combustion. The resultant combustion products include carbon monoxide \((CO)\) carbon dioxide \((CO_2)\), methane \((CH_4)\), non-methane hydrocarbons \((NMHC)\), particulate matter that is carbon-based \((PM)\), and water \((H_2O)\). The ellipsis represents the numerous other PIC emitted, which vary depending on factors such as the organic matter composition and temperature of combustion. It has been documented that carbon monoxide and carbon dioxide comprise 95% of biomass combustion emissions [58].

The combustion emissions of most concern for human health and most associated with combustion, as documented by the World Heath Organization, include carbon monoxide \((CO)\), particulate matter \((PM)\), and polycyclic aromatic hydrocarbons \((PAH)\), a type of NMHC. The other toxins noted to be most prevalent in indoor air are benzene, formaldehyde, naphthalene, nitrogen dioxide, radon, trichloroethylene and tetrachloroethylene [105].

The research presented here focuses on CO and PM, compounds that are comparatively easy to measure, are known risks to health [103], and are produced in large quantities when cooking with biomass. PAH were also studied for certain portions of the investigation.

Both acute and chronic exposure to carbon monoxide is hazardous. At concentrations exceeding 100 \(mg/m^3\) averaged over 15 minutes, carbon monoxide limits maximum exercise capacity, increases symptoms of heart disease, and reduces brain function. As blood concentrations (COHb) exceed 25%, consciousness is lost; at approximately 60% death is probable. Chronic exposure above 7 \(mg/m^3\) is associated with cardiovascular problems and may be associated with respiratory illnesses including asthma and pneumonia, neurological and psychiatric effects, and negative effects on fetuses [105].
Particulate matter is categorized into a range of sizes all of which may present hazards to human health. The total suspended particles in the air (TSP) are divided into coarse particles, those exceeding a cut point diameter of 2.5 $\mu m$; fine particles, less than or equal to a cut point diameter of 2.5 $\mu m$ ($PM_{2.5}$); and ultra-fine particles with a diameter below 0.1 $\mu m$. Fine particles are believed to have the greatest effect on human health, causing harm to the respiratory and cardiovascular systems \cite{77, 103}. However, there is growing evidence that ultra-fine particles may in fact be quite hazardous, as particles of this size are more likely to move from the respiratory system to other parts of the body including the central nervous system and lymph nodes \cite{74, 21, 77}.

Polycyclic aromatic hydrocarbons are well-understood to be directly linked to lung cancer and, in homes using biomass for cooking, are typically found in indoor air in levels exceeding the WHO recommended exposure level by more than a factor of 10 \cite{103, 84}. Trichloroethylene exposure is associated with carcinogenic effects as well as harming the central nervous system. Tetrachloroethylene exposure is believed to harm kidneys and the central nervous system. While the latter two toxins are rarely found in concentrations that would be hazardous related to combustion products, they may be present in certain non-agricultural wastes and are therefore a concern for aspects of this research \cite{105}.

1.1.2 Environment

Traditional cooking with biomass can degrade the environment locally and globally. Wood fuel is generally understood to be harvested sustainably at present, although unsustainable wood harvest has been noted in parts of Africa and regions of countries worldwide. Much of the supply of wood fuel currently used is related to forest clearing for agriculture and therefore the resultant deforestation is identified as being associated with agriculture; if sufficient land is cleared for agriculture, it is likely that wood fuel will be considered the cause of deforestation. As road infrastructure expands, improved access to forests results, increasing deforestation \cite{6}. In regions where large quantities of charcoal are made from wood with little regulation of either
charcoal trade or forestry, cooking fuel can be the primary cause of deforestation \[73\]. Overall, nearly half of legally harvested wood worldwide is used for wood fuel \[37\]. As informal and illegal wood removal is not well-documented and thought to be the majority of wood felled, the actual quantity of wood used for fuel is believed to be much larger.

The emissions from biomass cooking associated with global warming are also of concern, including methane, black carbon (BC), and particulate matter \[86, 92, 50\]. In particular, combustion of biomass for cooking has been shown to contribute 20\% of the world’s atmospheric BC \[14\]. BC emissions are believed to disrupt monsoon rainfall and contribute to glacial melting \[40\].

### 1.1.3 Economics

The economic impact of fuel on families in poverty in developing countries is consequential. Families who collect fuel may spend up to four hours a day doing so \[92\]. For example, in Tanzania, travel up to 7 miles per day was identified, with collectors typically carrying 20 kg of fuel, but as much as 38 kg has been documented \[46\]. Women and children are primarily responsible for collection of fuel, driving a number of burdens. For children, time spent on fuel collection prevents them from receiving an education. Women risk injury from excessive strenuous labor and assault associated with traveling long distances to collect fuel \[47\]. For families purchasing fuel, the cost can require 10-20\% of the household budget \[45\].

### 1.1.4 Biomass cooking context and barriers to change

Although the economic, environmental, and health drawbacks of biomass cooking fuel are large, introduction of alternatives is challenging due to a variety of barriers to change.

Exposure to indoor air pollution and the use of biomass is strongly correlated to poverty, particularly in regions where per capita income is less than US$1 per day \[31\]. Therefore, any solutions must be appropriate for families with severe resource
limitations. In addition, use of biomass for cooking persists even as households and countries gain wealth and access to additional fuel options. It is typical that more modern (and often more expensive) fuels are used for specific needs such as television or heating beverages, while biomass usage prevails for primary cooking and heating needs. Many households that use modern fuels extensively still maintain a biomass-based cooking option for cooking traditional staples such as bread and tortillas [46]. An awareness of food preferences and associated cooking habits is thus critical for implementing alternative cooking options.

While the health impacts of indoor air pollution are severe, one cannot extrapolate that end users are either aware of these health effects or willing to spend the resources required to address the situation [70, 26, 50, 28, 81]. Further, certain households express a preference for smoky fires, as these are perceived to keep away insects [39]; a common belief in Peru is that smoke feeds guinea pigs, a staple in the Peruvian diet [71]. Similarly, the environmental costs associated with biomass usage are not well reflected in the price of the fuel. This reality is exacerbated by the fact that the wood used for cooking and for making wood charcoal is rarely harvested legally [37].

1.2 Existing alternatives and proposed solutions

Many approaches have been tried to begin to address the challenges outlined in the previous section. The solution space can be considered in two realms: household changes and fuel changes. Household changes include improving airflow within the kitchen, adding chimneys to stoves, separating all living areas from the kitchen to reduce smoke exposure, changing cooking behaviors, and introducing cookstoves that burn more cleanly and/or more efficiently [92]. Fuel changes include expansion of the electric grid [67], introduction and subsidization of liquid propane gas [76, 35], introduction of biogas [110], and direct alternatives to traditional biomass. This work is focused on the last solution: development of fuels that can directly replace existing biomass-based cooking fuels without additional behavior or infrastructure changes; certain behavioral changes are also proposed.
The majority of related solutions documented in the literature are briquettes made from uncarbonized agricultural waste, sawdust, and paper. A comprehensive overview of these densified biomass approaches is provided by Bhattacharya [11]. Examples of densified biomass briquettes include use of coffee husks in Cuba [87], sugarcane bagasse in the Dominican Republic [44, 88], and rice husks and sawdust in Thailand [12]. Investigations were conducted into the viability of biomass-lignite blends [107], waste paper and wheat straw mixtures [22], sawdust and wheat-straw [97], and rice straw and rice bran [18].

Carbonized agricultural waste briquettes have also been explored [13, 66], including carbonized brown seaweed [43] and sugarcane bagasse [10].

1.3 Agricultural waste charcoal

The Fuel from the Fields (FftF) project developed a method for making charcoal briquettes from agricultural waste. The process of making agricultural waste charcoal (AWC) was developed by Amy Smith, founder and director of MIT’s D-Lab, with numerous colleagues and students including the author [10, 85, 95, 34, 3, 79, 53]. D-Lab is a program at the Massachusetts Institute of Technology focusing on developing appropriate, sustainable technologies for impoverished people in developing countries. The FftF process and required equipment, shown in Figure 1-2, have been designed to be as simple and inexpensive as possible. The expectation is that the approach is appropriate for individuals, families, or small cooperatives in developing regions where there is good access to biomass waste, underemployment, and widespread use of solid fuels. Producers could both make AWC for their own use and sell it in the marketplace as an income-generating activity. The equipment required for production costs on the order of US$30, a modest investment when compared to larger kilns and automated briquetting machinery.

The process for making AWC, shown in Figure 1-2, is as follows. Raw agricultural waste – such as corn cobs and stalks, sugarcane bagasse, and coconut husks – is dried and then loaded into a simple kiln. This kiln is made from a 55-gallon oil drum, with
**D-Lab: Fuel from the Fields** Charcoal-Making Process

- **Dry agricultural waste** (sugarcane bagasse, corn cobs & husks, coconut husks, etc.)
- Fill modified 55-gallon drum with waste.
- Raise up on bricks & light on fire.
- Smoke dissipates; volatiles have burned off: cover completely with lid, put drum on ground, use wet sand to fill any gaps and make airtight.
- In ~2 hours, charcoal fines (nearly pure carbon) remain.
- Crush fines into powder.
- Mix powder & binder.
- Bake briquettes in next fire to solidify.
- Completed briquette.
- Use $2 briquette press to make briquettes.
- Briquettes are ready for use.

Create binder from grated yucca, using waste heat from carbonization to boil yucca & water mixture.
a large hole cut into the top for waste loading and about eight 10-15 cm diameter holes in the bottom for promoting airflow through the drum. The drum is raised off the ground about 10 cm by bricks or stones to permit airflow. The waste is lit on fire. Much of the volatile organic matter in the raw waste burns off at this time. Once the smoke dissipates, the drum is lowered to the ground, a cover is placed on the top, and the drum is “sealed” with water and sand or mud around all edges. In about two hours time, the material has cooled and the charcoal fines in the drum can be removed, crushed, and mixed with a binder. The binder is typically made from grated yucca boiled in water. The ratio of fines to binder by weight is generally 10:1. The briquettes are then formed with a simple press and dried. To further harden the briquettes, they can be placed inside a mesh basket which is dropped into the oil drum kiln during another burn just before the kiln is covered.

To put this process into context, wood charcoal is traditionally made using the pit method [27, 36]. Felled trees are placed into an earthen pit, covered, and then lit on fire. This method is difficult to control and uneven carbonization is common. A pit in Nicaragua is shown in Figure 1-3.

The intent of the D-Lab charcoal is to provide a cooking fuel that addresses the economic, environmental, and health issues of most solid fuels, while being easy to adopt both from an end user and a producer standpoint. Initial internal analyses predict that AWC can be produced at or below the cost of wood charcoal in many regions; that using plant waste like corn cobs and husks, sugarcane bagasse, and coconut husks should have less of a carbon impact than making charcoal from wood; and that this fuel should be as clean-burning as wood charcoal, a measurable improvement over non-carbonized solid fuels used in unimproved cookstoves. Carbonized fuel is generally understood to be cleaner-burning than uncarbonized fuel in terms of CO and PM emissions [29, 66, 33, 25]. However, from an environmental perspective, carbonized wood fuel is problematic. The carbonization process itself requires about 66% of the embodied energy in the raw material [36], driving unsustainable deforestation. The use of non-woody, renewable biomass offers a compelling alternative in this regard. Further, AWC was expected to replace wood charcoal directly without requiring any
Figure 1-3: Charcoal pit in Nicaragua
changes to the cookstove or cooking habits, improving the likelihood of adoption.

A number of open questions about AWC and solid fuel inspired aspects of this work: is AWC, in fact, as clean-burning and energy dense as wood charcoal? Are combustion emissions affected when the raw materials used are varied? Is AWC viable from an economic standpoint? Are end users willing to switch to this fuel? The majority of the work is focused on addressing these questions, with an emphasis on combustion emissions.

1.4 Prior art

There are numerous studies focused on the combustion performance of various cookstoves, the combustion of biomass that has not been densified, and combustion of traditional fuels like wood and wood charcoal [92, 68, 33, 112, 94, 80, 108, 58]. However, there is very little published on the combustion emissions of alternative biomass briquettes. By far, the most comprehensive study was performed by Jetter et al., documenting a wide variety of emissions from 22 cookstoves and six affiliated fuels [51]. Apart from this study, for the vast majority of fuel examples listed in Section 1.2, the prior art only ascertained the mechanical properties and energy density of the fuels. These characteristics are important from the perspective of needing to store and transport briquettes without damage, and ensuring that the briquettes’ heating value is sufficient for user acceptance. However, the lack of investigation into the combustion emissions associated with these briquettes, given the potential health consequences outlined in Section 1.1.1, is a notable oversight. Wei et al. mentioned this gap in their study of CO and CO$_2$ emissions from pelletized biomass in comparison to wood and uncompressed biomass. They found that the two pelletized biomass fuels had lower CO/MJ emissions by a factor of thirty [99]. Ehrlich et al. found pelletized biomass to emit far less particulate matter than other fuels studied, although the cookstoves tested were generally more refined than those typically found in developing countries [24]. Sheesley et al. investigated emissions of various uncompressed biomass and one compressed biomass briquette comprehensively, including particulate matter and
bulk chemical composition \[83\], although the stove and control methods used were not representative of cooking in developing countries. One investigation of the health impacts of non-traditional briquettes focused on comparing combustion of briquettes made from biomass and coal as compared to coal \[17\]. Rather than study combustion emissions directly, Cheng et al. investigated the effect of combustion on rabbits exposed to smoke over a period of time. Given the work to introduce raw waste briquettes in developing regions as an alternative fuel by organizations including the Clinton Foundation and the Legacy Foundation \[19, 90\], it is troubling that combustion emissions have not been considered fully prior to implementation. The intent of this work is to begin to address this need.

### 1.5 Summary of work

This dissertation describes the work accomplished to understand the viability of waste-based cooking fuels for use in developing countries. The second chapter provides an overview of the materials and methods used to conduct the majority of the combustion emissions studies, including a demonstration that the laboratory environment is a reasonable proxy for field conditions. The third chapter explores the emissions performance of solid fuels made from agricultural waste in the laboratory. The energy density and combustion emissions of AWC are characterized, showing that the fuel is an acceptable alternative to wood charcoal. Ultra-fine particle emissions are characterized for both AWC and WC. A brief window when PM emissions are most problematic — during the lighting of the fire — is identified and proposed as an area of focus for technological and behavioral intervention. The fourth chapter explores AWC effectiveness in the field, determining that AWC has promising combustion emissions in kitchens in Nicaragua and modest success in terms of end user interest and production economics. Other AWC formulations are tested and manure is found to be a viable binder. The fifth chapter documents the severe potential health hazards of solid fuels — both uncarbonized and carbonized — made from paper, wood, and/or fabric waste. The dissertation concludes in Chapter 6 with a
summary of contributions and recommendations for future investigations.
Chapter 2

Fuel testing materials & methods

2.1 Overview

The methodology for testing the cooking emissions and energy density of waste-based fuels is described in this chapter. The purpose of this investigation was to understand whether the experimental fuels studied have merit from the perspective of health risks and usability (in the form of energy density). An additional goal was to characterize the ultra-fine particle emissions of wood charcoal and agricultural waste charcoal, as more awareness of the health hazards of ultra-fine particles develops, described in Section 1.1.1. The specific questions investigated were:

1. Are the emissions of the alternative fuels in question comparable to wood charcoal?

2. Are the energy densities of the alternative fuels in question comparable to wood charcoal?

3. What sizes and concentrations of ultra-fine particles are emitted when cooking with charcoal and how do ultra-fine and coarse particle emissions vary over the duration of a cooking test?
2.2 Fuels tested

The disadvantages of cooking with traditional biomass are numerous and there are no simple solutions to the problem. Use of agricultural waste, which will be explored in the subsequent chapters, has been proposed and has started to be adopted in particular communities in a variety of regions [15, 19, 59, 23, 44]. However, there is insufficient volume of non-woody biomass worldwide to meet the needs of the 2.7 billion people who rely on solid fuel currently. A recent estimate is that 20% of the needs could be served by available non-woody biomass [19, 90, 10, 85]. More efficient stoves can reduce the total amount of fuel required but will not solve this disparity entirely. Given this gap and a growing awareness of the drawbacks of landfills — particularly unregulated ones — there has been growing interest in making fuel briquettes from certain household and industrial wastes.

For example, the Clinton Global Initiative has sponsored a program in Haiti to make briquettes from waste paper, cardboard, and sawdust [15, 19]. The CODEVI apparel manufacturers, in conjunction with the Inter-American Development Bank, are investigating briquettes made from various combinations of scrap t-shirt fabric, denim, rice bran, rice straw, coffee husks, sugarcane bagasse, and corn stalks. Takachar, a group started at MIT in collaboration with colleagues in Kenya, and mentored by the author, is working to organize youth groups to create charcoal briquettes from household organic waste in Kenya [59]. Technologies for Renewable and Efficient Energies (TREE) in Tanzania has produced biomass fuel pellets and an associated stove from rice husk and Jatropha seed cake [23].

There is little documented information about the health safety of any of these fuels in terms of emissions, leading to the desire to perform some initial testing on certain briquette samples. It seems conceivable that waste from more processed sources such as paper and fabric could create additional health risks because of the chemicals used to produce these materials. For example, tetrachloroethylene (PCE) is used in textile making and trichloroethylene (TCE) is used in inks that can be found on paper and textiles. Both of these chemicals are well-understood to be major indoor air pollution...
hazards. While study of these particular toxins was beyond the scope of this investigation, their use in these products points to the potential additional hazards in household and industrial waste that are unlikely to be found in biomass.

### 2.2.1 Raw versus carbonized fuels

It is well-quantified that wood charcoal (a carbonized fuel) is significantly cleaner-burning than wood when considering unimproved cookstoves. For example, a study in Kenya found that the frequency of acute respiratory infections, which are correlated to indoor air pollution, were halved when switching from cooking with wood or dung to wood charcoal. When considering cookstoves that have been carefully designed to improve combustion efficiency and emissions, the comparative risks of wood can be mitigated. However, improved cookstoves are still poorly disseminated on a worldwide level and for the most impoverished there are many barriers to making that change. A severe drawback of wood charcoal is the environmental devastation associated with its production.

The improved cleanliness of wood charcoal in typical usage scenarios is clear and a reasonable hypothesis is that the act of carbonizing any raw fuel could improve the end product’s cleanliness from the very nature of pyrolysis. During that process, much of the volatile matter is burned off, so that more of the material remaining is carbon.

The majority of cooking fuels made from non-traditional biomass, household, and industrial are uncarbonized (raw). These raw fuels are likely to be quite concerning from an emissions standpoint. One aspect of this work was to investigate whether carbonizing such waste-based fuels would reduce their hazardous combustion emissions.

### 2.2.2 Details of fuels tested

The six fuels investigated for this research are summarized in Table. American-made lump wood charcoal (WC) was used as the benchmark to which all experimental
fuels were compared. This WC can be considered a high-quality proxy for WC made in developing countries. WC made in the US is readily available and is produced at large volumes, whereas WC produced in developing countries is generally made by a few individuals in a far less controlled environment and therefore varies in quality greatly. Therefore, in terms of comparing the experimental fuels to WC, knowing that the American made WC is of the highest quality and superior to many of the charcoals available in developing countries, moderate reductions in identified quality between WC and the experimental charcoal were considered acceptable. The WC used as the control was acquired through a single bulk purchase from a single American manufacturer in order to minimize variability [100].

Agricultural waste charcoal (AWC), made from corn stalk waste using yucca as the binder, was created using the D-Lab Fuel from the Fields process shown in Figure 1-2. The effect of using other raw materials on the emissions output of the briquettes was also studied and is discussed in Section 4.5.

Paper waste briquettes (PWB) were imported from Haiti, where they are being produced in Carrefour Feuilles [15, 19]. These briquettes are made from a mixture of sawdust, paper, and cardboard — all household wastes — and processed by saturating the waste in water and then compressing the material into briquettes. Carbonized paper waste briquettes (PWC) were made by taking PWB and carbonizing them in a furnace using the process described in Section 2.2.3.

Fabric waste briquettes (FWB) were also imported from Haiti, where they were being produced experimentally by CODEVI (Companie Development Industriel), an industrial plant on the outskirts of Ouanaminthe. Apparel manufacturers associated with CODEVI generate a great deal of fabric waste from t-shirt and denim materials; a variety of paper, cardboard, and agricultural wastes — including rice bran, rice straw, coffee husks, sugarcane bagasse, and corn stalks — are also readily available in the region. The intent of producing these briquettes was to displace wood charcoal usage in Ouanaminthe; the Inter-American Development Bank approached D-Lab to determine the viability of these briquettes. The manufacture of the briquettes is quite similar to the manufacture of PWB, described in the previous paragraph. In addition,
Table 2.1: Summary of fuels tested. For WC and AWC, the + sign next to the number in the “n” column represents that certain types of tests had additional repetitions.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Waste</th>
<th>Binder</th>
<th>Carbonized?</th>
<th>n</th>
<th>Process</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC</td>
<td>wood</td>
<td>N/A</td>
<td>yes</td>
<td>6+</td>
<td>industrial carbonization</td>
<td></td>
</tr>
<tr>
<td>AWC</td>
<td>corn stalks</td>
<td>yucca</td>
<td>yes</td>
<td>6+</td>
<td>D-Lab FftF</td>
<td></td>
</tr>
<tr>
<td>PWB</td>
<td>sawdust, paper, cardboard</td>
<td>paper</td>
<td>no</td>
<td>2</td>
<td>saturation &amp; compression</td>
<td></td>
</tr>
<tr>
<td>PWC</td>
<td>sawdust, paper, cardboard</td>
<td>paper</td>
<td>yes</td>
<td>2</td>
<td>saturation &amp; compression then furnace carbonization</td>
<td></td>
</tr>
<tr>
<td>FWB</td>
<td>t-shirt cotton, denim, rice bran</td>
<td>rice bran</td>
<td>yes</td>
<td>2</td>
<td>saturation &amp; compression then furnace carbonization</td>
<td></td>
</tr>
<tr>
<td>FWC</td>
<td>t-shirt cotton, denim</td>
<td>yucca</td>
<td>yes</td>
<td>3</td>
<td>furnace carbonization then D-Lab FftF briquetting</td>
<td></td>
</tr>
</tbody>
</table>
t-shirt and denim fabric from CODEVI was imported so that other formulations of briquettes could be produced within D-Lab facilities to speed development.

There were a number of concerns about the potential toxicity of the fabric, given what is known of the chemicals used in fabric production [16]. Therefore, only carbonized forms of fabric briquettes were considered. The provided FWB were carbonized in a furnace as described in Section 2.2.3. In similar fashion the raw fabrics were carbonized as well. These fabrics were then crushed, mixed with a binder made from yucca, and briquetted into fabric waste briquettes carbonized before briquetting (FWC), using the D-Lab Fuel from the Fields briquetting process (Figure 1-2).

For all types of briquettes other than WC and AWC, the number of tests was severely limited by the availability of raw material. Given that it is recommended that any cooking emissions test be repeated at least four times [8] and in light of the known variability of emissions testing [56], all results should be considered preliminary with repetition required to strengthen confidence in results. The least number of tests performed on a given fuel is shown in Table 2.1.

All fuels were stored in a laboratory with moderate temperature and humidity controls, which were held constant throughout the testing time period (20°C and “dry” setting). By minimizing temperature and humidity variation, the moisture content of the briquettes was controlled, as moisture is a known factor affecting combustion emissions [58, 27, 101].

2.2.3 Briquette carbonization

To carbonize raw, pre-made briquettes most easily and in a controlled fashion, the retort method of carbonization was used: external heat is applied to the material, which is kept in a near-anaerobic environment [27]. The briquettes were placed into a cast aluminum covered pot with an eighth-inch diameter hole drilled in the top (to allow for the release of pyrolitic gases). The pot was placed into a furnace that was programmed to ramp from room temperature to 450°C in 1 hour, hold at that temperature for 3 hours, and then cool to room temperature in approximately 24 hours (the slow temperature decline was due to the kiln insulation).
2.3 Experimental setup

The vast majority of tests were conducted in a combustion chamber — built by the author for fuel and stove testing — that was largely modeled after the field-implementable test hood developed by The Engines and Energy Conversion Lab in the Department of Mechanical Engineering at Colorado State University Fort Collins [63]. Schematics of the author’s chamber and apparati in two configurations are shown in Figure 2-1; a panoramic view of the laboratory with all apparati installed (as in schematic b.) is shown in Figure 2-2.

The chamber is connected to a general ventilation suction blower that provides 0.03 m$^3$/s flow out of the chamber through 4" diameter ductwork. All CO measurements were taken from a port about one meter downstream from the curve in the ductwork. This curve was a limitation of the laboratory facility used. The CO measurements were made with a Bacharach ECA450 Combustion Efficiency and Environmental Analyzer that uses active sampling and an electrochemical sensor to measure carbon monoxide concentrations [7].

For all studies, a TSI DustTrak II Aerosol Monitor 8530 was used to measure total suspended particles (TSP) emitted. This device uses a light-scattering laser photometer to provide real-time aerosol mass readings as well as in-line gravimetric sampling, which was used for reference calibration [93].

A LI-COR LI-840A CO$_2$/H$_2$O Analyzer was used for carbon dioxide measurements. This device uses active sampling for non-dispersive infrared (NDIR) analysis [65].

For the measurements addressing paper waste briquettes, fabric waste briquettes, and how the variation of raw materials in AWC affect emissions, the aerosol monitor and CO$_2$ analyzer sampled from the flue about 6 inches upstream from the port for the combustion analyzer. A Fox mini-eductor (611210-015-SS), driven by a motive flow of 60 psi of gaseous nitrogen, was used to draw samples into a dilution chamber, to which the aerosol monitor was connected [38]. The use of the dilution chamber is explained in the next subsection.
Figure 2-1: Combustion chamber schematics. a. used for tests involving CO, CO$_2$, and TSP measurements. b. used for tests involving all apparatus. a. the stove is inside the chamber, centered below the vent duct, which has a volumetric flow rate of 0.03 m$^3$/s. A thermocouple measures water temperature inside the pot on the stove. From the vent duct, CO is measured. In the set-up shown in schematic a., all other sampling occurs from this duct. The CO$_2$ sensor is connected to a valve that allows for sampling directly or through a dilution chamber. Nitrogen provides the motive flow for a mini-eductor, from which samples flow into the dilution chamber. The device measuring TSP samples from the dilution chamber. The set-up shown in schematic b. has a few key differences. The nitrogen source is connected both to the mini-eductor and to a critical orifice that provides additional nitrogen in the dilution chamber when needed. Two additional devices are connected to the dilution chamber: the SP-AMS and the SMPS.
Figure 2-2: Combustion chamber panorama. On the top row, from left to right, the dilution plenum, or chamber, can be seen, as well as the combustion chamber. On the bottom row, from left to right, the following apparati can be seen: the aerosol monitor that measures total suspended particles (TSP), the soot-particle aerosol mass spectrometer that was used to measure polycyclic aromatic hydrocarbons (PAH), the location of the carbon dioxide analyzer (CO$_2$), the scanning mobility particle sizer that measured ultra-fine particles, the thermocouple that measured water temperature ($T_{water}$), and the location of the combustion gas analyzer that was used to measure carbon dioxide (CO).
For the measurements directly comparing wood charcoal to agricultural waste charcoal and for all experimental results including PAH and ultra-fine particles, the dilution chamber and associated mini-eductor sampled from a tube placed 40 cm above the top of the stove. In this case these two devices connected to the dilution chamber in addition to the aerosol monitor and CO$_2$ meter.

Ultra-fine particle measurements were made using a TSI Scanning Mobility Particle Sizer Spectrometer 3080 Electrostatic Classifier with Condensation Particle Counter 3775 (SMPS), whose operation is described by Wang and Flagan [98]. McMurry offers a useful overview of different particle measurement technologies [69]. PAH measurements were made using an Aerodyne Soot Particle Aerosol Mass Spectrometer (SP-AMS) [75].

A K-type thermocouple attached to a Lascar EL-USB-TC-LCD data logger measured the temperature of the water in the pot that was placed on the stove for each study [62].

2.3.1 Dilution chamber

A dilution chamber was integrated into the experiments because most of the devices used had maximum exposure thresholds well below the level of particles produced by the fuels tested. As stated above, a mini-eductor driven by gaseous nitrogen was used to draw the sample into the chamber. The dilution factor was determined empirically, using the CO$_2$ measurement as a reference. The CO$_2$ meter was connected to a three-way valve. One port led to the flue where the CO measurements were made by the Bacharach combustion analyzer. The other port was connected to the dilution chamber. By periodically sampling from the flue, the dilution ratio could be ascertained.

For the tests that included the SP-AMS, an additional dilution option was employed, as this device is highly sensitive to excessive particulate. The flow out of the nitrogen dewar was split, with one line providing motive flow to the mini-eductor, and the other line feeding into the dilution chamber. That secondary line also had a valve on it, so that extra nitrogen could flow into the dilution chamber as needed, as well
as a critical orifice to maintain a constant flow rate. In cases where the particulate count still exceeded the operating range of the SP-AMS despite the dilution, the inlet to that device was turned off until particle levels dropped to allowable concentrations.

2.4 Experimental procedure

A modified version of the Water Boiling Test (WBT) was used for all experiments [8]. In this test, the fire is lit and a pot with a fixed quantity of water is placed on the fire in order to heat and then simmer the water. The weight of the water evaporated and the mass of the fuel used are documented in order to estimate the energy consumed to heat the water. The deviations from the standard testing procedure were:

- The hot-start test was not used, instituted for time efficiency.

- 300g of fuel were used: all of the fuel was placed in the stove before lighting, none was added, and care was taken not to interact with the fuel throughout the test, to minimize fuel demand and to minimize fuel movement, which could add variability to the findings, and to minimize opening the door to the chamber, which could also add variability and increases smoke release into the laboratory.

- One liter of water was boiled, instituted for time efficiency and to minimize fuel demand and disruption.

- Water was boiled for thirty minutes, instituted for time efficiency.

- A lid was used with the pot, to minimize steam interactions with the combustion emissions. As noted in the WBT literature, using a lid can add variability as fluctuations in steam pressure can change the amount of water vapor released [8]. To minimize that effect, the same pot with a loose-fitting lid was used for every test.

- For the “simmering” stage, the water was kept at boiling, to minimize variability associated with moving the fuel and pot in order to maintain a lower water temperature, and to minimize opening the door to the chamber.
The stove used is a simple metal charcoal stove made in Ghana, shown in Figure 2-3. It was used for all tests, as stove variations are well-understood to significantly change fuel emissions [9, 33]. This stove offers no thermal insulation or air flow control and features a grate that supports a cooking pot, separating it slightly from the fuel, and a slotted base for supporting the fuel, so that ash can fall below the combustion area. This type of stove is typical of basic charcoal stoves worldwide, although exact designs and features vary widely; a number of charcoal stoves found worldwide are shown in Figure 2-4.

A 3.4 liter pot with lid used for all tests was outfitted with a K-type thermocouple that was fixed in place to ensure that the thermocouple was in the water but not touching the bottom of the pot at all times. One liter of water (1000±0.5 grams) and a consistent amount of fuel — 300±5 grams — was used for each test. For tests involving larger briquettes made from fabric or paper waste, it was not possible to maintain that tolerance without breaking the briquette. In these cases a greater deviation was permitted to avoid changing the surface characteristics of the fuel, which can affect burning dynamics [78].

To start the fire, two methods were employed. In the vast majority of cases, three firelighting mini briquettes made of compressed sawdust and vegetable oil, produced
Figure 2-4: Charcoal stoves from a variety of locations worldwide. All stoves but the top two in the right-hand column are from Nicaragua. These remaining stoves were purchased in Africa.
by the *If You Care* company, were placed on top of the fuel and lit [109]. In the case of raw fuel, the mini-briquettes were placed under the fuel, as indicated by the directions for this product. These briquettes were used as a proxy for pine-sap impregnated wood, which is often used in Haiti and Nicaragua for firelighting. For two AWC and two WC burns, 15-30 ml of kerosene was used instead of firelighting briquettes, due to insufficient availability of the firelighting briquettes. No detectable difference between the firelighting methods was noticed in terms of time to light, CO, TSP, or ultra-fine particulate emissions.

The procedure for running the tests is as follows.

1. Weigh 300g of fuel and 1000g of water.

2. Light fire using a butane lighter and the lighting fuel (explained in the previous paragraph).

3. Wait until lighting fuel extinguishes naturally, approximately ten minutes.

4. Open combustion chamber door, place pot on stove, close door.

5. Wait until water boils, approximately fifteen minutes, using thermocouple data logger to determine when boiling occurs.

6. Wait 30 minutes while water boils.

7. Conclude test:

   (a) Weigh remaining water.

   (b) Weigh any remaining unburnt fuel.

   (c) Weigh any ash from the fire.

### 2.5 Analysis methodology

The following analyses were used to understand the data. In all cases it should be noted that the results allow for comparisons between tests, not values that can be
compared directly to experiments conducted in other investigations, since features of
the test set-up (including sampling location, choice of equipment, and hood exhaust
flow rate) can influence results.

2.5.1 Energy density

To determine the relative energy density of each fuel, the energy emitted by the
fuel, calculated based on the amount of water vapor released, was divided by the
grams of fuel consumed. This calculation is shown in Equation 2.1 where WT is the
total weight of water boiled in grams, $\Delta T$ is the change in water temperature from
initial temperature to boiling, 4.186 J/gK is the heat capacity of water at standard
temperature and pressure, WF is the final weight of water, and 2257 J/g is the heat
of vaporization of water at standard temperature and pressure.

$$\text{Energy Density (MJ/kg)} = \frac{WT \times \Delta T \times 4.186 + (WT - WF) \times 2257 \times 1000}{2} \tag{2.1}$$

This calculation is an underestimate of total calorific value of the fuels tested, as
only a portion of the energy is transferred to the water and some of the water vapor
that evaporates condenses on the lid of the pot and remains in it. The findings are a
good representation of the total usable energy for the type of stove tested.

2.5.2 Toxins emitted

To determine the average toxin concentration, measurements were integrated over
the time period studied, as shown in Equation 2.2 where T is the total time period
studied, n is the number of data points collected, $X_n$ is the measured toxin for the
given time period, and $t_n$ is the time period over which $X_n$ was measured.

$$\text{Average Toxin Concentration (g/m}^3\text{)} = \frac{1}{T} \sum_{i=1}^{n} X_n \Delta t_n \tag{2.2}$$
2.6 Correlation of laboratory testing to field behavior

The emissions tests performed in the combustion chamber would be of much greater utility if the fire behavior in the chamber is comparable to fire behavior in kitchens, given the differences in volume and airflow between the two environments.

To gain a rough understanding of whether the combustion behavior differed, the emissions ratio (ER) of carbon monoxide to carbon dioxide was studied, to understand whether the two conditions were comparably fuel-rich \[58\]. The ambient (background) level of the gas was subtracted from the measurement of the smoke plume prior to calculating the ratio. This ratio is given in Equation 2.3

\[
ER = \frac{CO_{\text{plume}} - CO_{\text{background}}}{CO_{2\text{plume}} - CO_{2\text{background}}} \tag{2.3}
\]

Measurements of CO and CO\(_2\) were taken in the laboratory as outlined in Section 2.3. To measure the emissions ratio in field conditions, a mock kitchen was created in the alley between buildings E34 and E33 at MIT, using the underside of a stairwell as a kitchen space, with plastic contractor bags as makeshift walls. The set-up is shown in Figure 2-5. The entrance ports for the CO\(_2\) and CO monitors were placed on a stand 40 cm above the top of the stove. All other aspects of the fuel burn were consistent with the protocols previously described in this chapter.

As can be seen in Figure 2-6, the “field” and laboratory measurements were comparable. In the laboratory, the average emissions ratio with standard deviation was 0.110±0.016. The average emission ratio in the field test was 0.114±0.030. The field measurements were twice as variable due to the changing wind speed in the outdoor environment. The measured emissions ratios show good agreement to ratios in the literature \[58\], and these results suggest that the oxygenation levels for laboratory and field tests are consistent.
Figure 2-5: Set-up of outdoor emissions ratio test. An overhead close-up view of the set-up is shown in the left photograph. The stove with charcoal can be seen in the center of the photograph. At the top right, the probes for the carbon monoxide and carbon dioxide measurements can be seen. In the right-hand photograph, the overall testing location can be seen. A mock kitchen was constructed beneath a stairwell in an alley. Black plastic bags were used to reduce airflow into and out of the kitchen. The setup shown in the left-hand photo is behind the plastic bags underneath the stairwell to the right of the wooden box on the ground.
Figure 2-6: Combustion emissions ratios for field and laboratory conditions, in red and blue respectively. The agreement between both sets of conditions is strong. The emissions ratio for field conditions shows more variation than in the laboratory, due to gusts of wind outside.
Chapter 3

Agricultural waste charcoal
laboratory performance

In this chapter, results from the laboratory emissions tests of agricultural waste charcoal (AWC) are presented. This novel charcoal is compared to wood charcoal (WC) in terms of energy density, PM, CO, TSP, and PAH emissions. Particular documentation is provided for ultra-fine particles emitted and the way in which PM emissions vary over the course of the combustion test. Recommendations are presented based on these findings. For these results, it is important to recall that all values are only comparative in nature and do not represent hard numbers that could be compared to other tests not performed using the exact methodology described in Chapter 2, given the impact that set-up can have on the resultant emission concentration measurements.

Due to the challenging nature of acquiring the raw materials required for testing, a relatively small number of sample briquettes were tested; given the low sample size, all results must be considered preliminary. Descriptive statistics are used to present the data in the form of a box plot, shown in Figure 3-1 [57].
Figure 3-1: Representative boxplot. The central line is the median; the lower and upper edges of the box surrounding that line represent the first and third quartile of the data, respectively. The first or third quartile is taken by finding the median of the data below or above the overall median. The maximum and minimum values are a non-parametric form of a standard deviation, calculated by subtracting 1.5 times the inter-quartile range (the first quartile subtracted from the third quartile) from the quartile value of interest.
3.1 Energy density

The comparative energy density of the fuels is shown in Figure 3-2. AWC has 73% the energy density of WC. As noted in Chapter 2, the WC tested is of the highest quality and therefore the lower energy density for AWC in fact reflects performance comparable to many wood charcoals used in developing countries, based on field testing.

Figure 3-2: Comparative energy density for agricultural waste charcoal (AWC) and wood charcoal (WC). Given the high quality of the WC tested, as compared to WC typically used in developing countries, this result is promising in terms of AWC’s viability.
3.2 Carbon Monoxide emissions

A comparison of the carbon monoxide emitted by the briquettes, normalized to the energy released by the briquettes over the course of the test, is shown in Figure 3-3. The normalization is introduced because of the direct relationship between energy released and carbon monoxide produced. AWC and WC CO emissions are comparable.

![Carbon Monoxide Emissions Graph]

Figure 3-3: Comparative normalized carbon monoxide emissions for AWC and WC

3.3 PAH emissions

The average and maximum levels of PAH emitted for AWC and WC are shown in Figure 3-4. AWC produces PAH emissions comparable to WC.
3.4 Particulate matter emissions

The overall particulate matter findings are presented in Figure 3-5, showing results for both total suspended particles (TSP) and ultra-fine particles (UFP) in terms of mass density. On average, AWC produces 5 times the TSP emissions of WC, and 2.7 times the UFP. This difference warranted closer investigation of this aspect of emissions.

The evolution over time of TSP and UFP for AWC and WC is shown in Figure 3-6. The same form of image plots in this figure are shown in Figure 3-7 for six test iterations of each fuel type.

Early on in the course of a burn, there is generally a spike of relatively large particles at the start of the fire that tails off as the burn progresses. There is variation
in particle mass density and concentration but the trend is consistent. In two of the WC burns, in the right-most column, the spike is not evident, because the concentrations are below the color scale resolution. Generally, this spike is much greater for AWC than for WC and is what drives the additional particulate produced by AWC on average. Following the spike, both the average particulate diameter and density drop, although the time required for the drop to occur varies. At this stage in the burning process, AWC has a lower particulate concentration than WC; the ultra-fine particles persist for much longer, generally, for WC than for AWC.

The average ultra-fine particulate emissions are shown in Table 3.1. AWC emits a greater concentration and density of ultra-fine particles, which have a slightly larger diameter.

### 3.4.1 Time-based consideration of exposure

The evolution of particles over time, as seen in Figure 3-6, leads to an important possible opportunity for reducing health hazards for people who cook with biomass. The period of time when particulate emissions are the most substantial for AWC is during the fire-lighting stage, which occurs for 10–20 minutes 1–3 times per day.
Figure 3-6: Evolution of particulate matter emissions over the course of a 50-minute burn for AWC and WC. The graphs on the top half of the image display particle density (ultra-fine in blue, total suspended in green) and concentration (in red) over the course of a burn. The image plots in the bottom half of the graph show particle diameter on the logarithmic y-axis. Particle density is shown through color, where purple and blue represent a high density of particles, and red represents negligible particle concentrations.
Figure 3-7: Ultra-fine particle emission image plots for WC and AWC. Each subplot shows the evolution of the particulate matter over time in terms of particulate diameter and concentration. The x-axes are time in two-minute increments; the y-axis is the diameter of the particle measured on a logarithmic scale. The color distribution shows the density of particles for each diameter at a given time.
Table 3.1: Average ultra-fine particulate emissions

<table>
<thead>
<tr>
<th></th>
<th>AWC</th>
<th>WC</th>
</tr>
</thead>
<tbody>
<tr>
<td>concentration (p/cc)</td>
<td>14x10^5</td>
<td>9.5x10^5</td>
</tr>
<tr>
<td>diameter (nm)</td>
<td>396</td>
<td>343</td>
</tr>
<tr>
<td>density (μg/m³)</td>
<td>1288</td>
<td>481</td>
</tr>
</tbody>
</table>

Conversely, very few particulate emissions are released during the cooking phase of the burn, which can last 2–4 hours 1–3 times per day. If a technological or behavioral change can be made that would prevent users from being in the kitchen environment during the fire-lighting stage of AWC, 88% of TSP and 70% of UFP emissions would be avoided, as shown in Table 3.2. The impact would be less significant for WC, but still important: 33% of TSP and 50% of UFP.

Table 3.2: Relative particulate matter exposure for different burn stages. For AWC, the exposure is dominated by the ignition stage for both TSP and UFP.
3.5 Discussion of findings

The results presented in this chapter offer insight into the potential emissions hazards from a variety of waste-based fuels. AWC seems generally comparable to WC for energy density, carbon monoxide, and polycyclic aromatic hydrocarbons; for particulate emissions, the initial spike in particulate emissions that AWC briquettes generate is concerning and further research is warranted. Possible reasons for the difference between these fuels include the difference in mass density between the fuels and the difference in the ratio of elements in the fuels including: carbon, hydrogen, oxygen, nitrogen, sulfur, potassium, and phosphorus [13, 52, 101].

The ultra-fine particulate emissions of WC and AWC have not previously been studied, apart from some investigation of WC by Jetter et al. [51] and represent a contribution to the field of cookstove-related indoor air pollution. As understanding of the health risks of ultra-fine particles increases, interest in these size diameters will likely increase as well.

Finally, the awareness that 33-88% of particles are released during the time when the fire is starting, as compared to the time when the fire is actively burning, may offer an opportunity to introduce low-cost technological or behavioral changes to biomass users to reduce the health risks they experience when cooking. A possible technological change might be the introduction of bellows or a chimney can for firelighting to minimize human interaction; a behavioral one could be encouraging all family members not involved in the fire-lighting process to leave the kitchen for the first 20 minutes following the start of the fire and for the person lighting the fire to leave the kitchen for about ten minutes as soon as the fire is lit.
Chapter 4

Design and use of agricultural waste charcoal

In the previous chapter the viability of AWC was assessed from a laboratory-based emissions and cooking performance standpoint. This assessment would be incomplete if it were not performed with an understanding of the circumstances associated with the creation and use of this fuel in real-world situations. Therefore, a variety of investigations were undertaken to integrate the technical understanding of the fuel with the cultural context in which it is used. Combustion emissions from wood, wood charcoal, and AWC were studied in a number of homes; prospective end users were interviewed about their perceptions of cooking and AWC; trainings were conducted on making AWC; and the AWC-making cooperative that formed as a result of those trainings was studied. These studies were approved by MIT’s Institutional Review Board, COUHES, under protocol number 1106004526. An additional laboratory investigation was performed to document how changes to the recipe used to make AWC affect the emissions of the fuels.

4.1 Study location

AWC has the potential to be viable anywhere in the world where people currently cook with biomass and have agricultural waste products available for use. The ideal
locale for understanding the product initially would be one that minimizes barriers
to entry through the following qualities:

1. End users cook with charcoal.

2. The community, or a subsection within it, is open to trying novel fuels and
   providing feedback.

3. There is agricultural waste in the area that is not being repurposed in any way
   but is currently rotting or being burned without use of the resultant energy.

The site chosen for this project’s field research was a community called Sabana
Grande, which is located within Totogalpa, south of Ocotal, in Nicaragua. The bene-
fit of this site is that it met the second and third criteria well: there is regular farming
in the area with unused waste available and the community is generally open to inno-
vations and working with outside groups. Grupo Fenix, an organization that has been
operating for more than two decades in the region, focuses on the development and
implementation of renewable energy technologies. It has strong ties to the community
and supports Mujeres Solares de Totogalpa (Solar Women of Totogalpa), a local co-
operative interested in alternative energy [42, 72]. Grupo Fenix welcomed this project
and facilitated access to the Mujeres Solares, who were willing to consider the idea.
This region is also one of the poorest in Nicaragua, the second poorest country in the
western hemisphere. From a purely logistical standpoint, the time and cost required
for travel were also important criteria and Nicaragua is easier from that standpoint
than many other locales considered. The limitation of this location is that people in
the region use wood for cooking, rather than wood charcoal, almost exclusively. Some
families cook with charcoal occasionally for a special barbecue but that practice is
infrequent and many families never do so. Therefore, the openness to using charcoal
and comfort with charcoal cooking are likely lower than in a community that uses
charcoal regularly. However, this location offers an opportunity to test the technology
in a region where fuel switching would be required, which is of great interest because
of the widespread use of fuel wood in developing countries.
In Sabana Grande, all of the households that were studied (emissions testing, interviews, or both) had a family member involved in the Mujeres Solares. Fieldwork was conducted in August of 2010 and 2011 by the author. Training in the making of AWC was provided in the following three stages. In January of 2010, the author gave a presentation on charcoal-making to the Mujeres Solares, who expressed great interest in the project and started collecting agricultural waste for use. In March of 2010, students taught by the author provided a first hands-on training in charcoal-making. Subsequently, those trained tried making AWC a few times, but found the process challenging and their yields were extremely low. In March of 2011, additional students taught by the author provided an in-depth training and further support via phone following the trip. After this training, the women felt much more comfortable with the process and created a cooperative of four women to start making and selling AWC, pictured in Figure 4-1.

Figure 4-1: Women’s charcoal cooperative
4.2 Emissions in kitchens

As discussed in Section 2.6, the need for correlating the laboratory testing to real-world cooking conditions was recognized as crucial to this work and the agreement of the ratio of carbon monoxide to carbon dioxide in laboratory and approximated field conditions was presented.

Additional emissions tests were performed in kitchens in Nicaragua to further document the combustion emissions associated with cooking fuels, particularly the fuel most commonly used in Nicaragua — wood — as compared to Nicaraguan wood charcoal and agricultural waste charcoal. Kitchen emissions testing was conducted using a convenience sampling method of seven kitchens in Sabana Grande. All kitchens had an adobe wood stove as the primary cooking appliance; a representative example of this type of stove is shown in Figure 4-2. An improved version of this stove, which was introduced to the community in 2010 by a Grupo Fenix volunteer, has been slowly gaining acceptance; it is shown in Figure 4-3. This stove replaces the open-hole burners with a flat steel plate as the cooking surface and includes a chimney, in an attempt to limit smoke emissions in the kitchen. For cooking with charcoal, all test subjects used their own rudimentary charcoal stove that they had constructed specifically for cooking with AWC. This project was an offshoot of a project in D-Lab Energy in 2010, an MIT class that was created and taught by the author. The optimization of this charcoal stove design and training of the community in its construction was conducted by MIT undergraduate Amelia Servi as part of a summer fellowship associated with the class [82]. A picture of this stove, which was placed on an unused section of the adobe stove for use, is shown in Figure 4-4.

4.2.1 Experimental design

The design of experiments for cooking emissions testing in the field was highly constrained by logistics. Very few pieces of equipment were appropriate for use in the field: the devices needed to be robust to humidity, temperature, and combustion gas and particle extremes without dilution, capable of surviving modest shocks due to the
Figure 4-2: Typical adobe stove. Note the two holes on the top surface for cooking pots, the cracked chimney at the far end of the stove, and the front of the stove where logs of wood are loaded.
Figure 4-3: Improved adobe stove. Note the steel plate that replaces the open holes as a cooking surface, and the chimney. Loading of fuel is similar to a traditional stove although the opening is smaller to reduce smoke emissions from that part of the stove. Photo reproduced with permission from Elisha R. Goodman
Figure 4-4: Charcoal stove. Photo reproduced with permission from Elisha R. Goodman
rigors of travel in remote regions and the accidental falls that typically occur during testing, operate without access to electricity during testing, have minimal power requirements for battery charging when electricity is available, log data for at least eight hours continuously, and be small and light enough that one person could transport them along with modest personal effects over a two mile walk on rocky paths.

With these limitations in mind, the three devices used for field testing were the TSI DustTrak II Aerosol Monitor 8530 previously described in Section 2.3, a Lascar EL-USB-CO Carbon Monoxide (CO) Data Logger [61], and a Lascar EL-USB-2-LCD Temperature and Humidity Data Logger [60]. The two Lascar data loggers and the end of the length of conductive tubing connected to the inlet of the DustTrak were affixed to a stand that held the sensor inlets approximately 1.5 meters above the ground and 1 meter from the cookstove horizontally, as shown in Figure 4-5.

A second limitation of the experimental design was the constraint on the choice of kitchens. Only certain women were available and/or willing to allow testing to occur in their homes. The time in the field was limited, preventing repeated measures. There was also notable house to house variation in terms of the stove itself and its household environment. The features of the kitchens that are likely associated with emissions — cooking area, number of windows and doorways, chimney or lack thereof, and whether the kitchen was connected to the other room(s) of the house — are shown in Table 4.1.

Given the variations in cooking area, use of chimneys, etc., a large variation between houses was anticipated. It should also be noted that certain features of the homes that one might expect to improve emissions were quite limited. In the cases of detached rooms, the smoke associated with firelighting was quite noticeable over a broad radius around the kitchen at times. For example, during all three visits to this community, the author slept in bedrooms detached from the kitchen by at least 15 meters and the rooms had no open doors or windows facing the kitchen. Nevertheless, the smoke from the initial firelighting of the day (before dawn) was noticeable enough from that distance to wake the author consistently.

Second, all windows were somewhat blocked for privacy and security reasons, as
Figure 4-5: Representation of the field emissions test setup. The inlets of all devices were located at the red sampling point shown in the figure, 1.5 meters above the ground, and 1 meter from the cookstove horizontally.
Table 4.1: Features of kitchens tested. *The chimney in household d. is 180 cm high and does not reach the roof, which is 267 cm tall.

<table>
<thead>
<tr>
<th>household</th>
<th>cooking area ((m^2))</th>
<th>chimneys</th>
<th>windows</th>
<th>doors</th>
<th>attached / detached</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>5.67</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>detached</td>
</tr>
<tr>
<td>b</td>
<td>12.00</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>bedroom &amp; living room</td>
</tr>
<tr>
<td>c</td>
<td>20.39</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>detached</td>
</tr>
<tr>
<td>d</td>
<td>13.21</td>
<td>1*</td>
<td>3</td>
<td>1</td>
<td>detached</td>
</tr>
<tr>
<td>e</td>
<td>7.80</td>
<td>?</td>
<td>3</td>
<td>1</td>
<td>detached</td>
</tr>
<tr>
<td>f</td>
<td>approx. 8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>detached</td>
</tr>
<tr>
<td>g</td>
<td>outside</td>
<td>0</td>
<td>under awning outside house</td>
<td>under awning outside house</td>
<td>adjacent to living room</td>
</tr>
</tbody>
</table>

shown in Figure 4-6. Thus, the airflow was reduced from what might be expected. Further, in times of poor weather, many homes had the ability to close off all windows and doors to prevent driving rain from entering the room.

Conversely, in all homes, there was a gap of at about 10 cm between the top of the walls and the ceiling (apart from supporting posts), that allowed for rising smoke to escape more easily than if the rooms had sealed joints between the walls and ceilings.

The other limitations of this work due to the use convenience sampling are primarily that the end users studied were somewhat educated about the health hazards associated with the emissions of cooking, which is not necessarily the case in other communities in Nicaragua. Hence, these users were expected to be more likely to adopt practices to limit their exposure to cooking smoke: for example, by modifying their stove to include a chimney, using a modified stove design that incorporates a metal plate as the cooking surface rather than the traditional openings, or placing covers on any open hole of the cooking surface that is not covered by a pot. These users were also all familiar with agricultural waste charcoal and had all constructed their own charcoal stoves to use with AWC and wood charcoal.
Figure 4-6: Window with privacy and security feature that limits airflow
4.2.2 Results and discussion

The aggregate results for emissions in all households for carbon monoxide and TSP are shown in Figures 4-7 and 4-8, respectively. The specific results for each household test are shown in Figure 4-9. Based on the literature — and the variation in the ventilation, stoves, and user behaviors — it was expected that the variation between certain houses would be up to a factor of 20 for a given fuel type [56]. This level of variation was seen: a factor of 20 at most — for wood PM — and a factor of 2–10 for other fuel/emissions combinations. Finally, as discussed in Chapter 3, lighting the fire seems to be the primary source of particulate. When arranging to conduct particular test runs, it was difficult to ensure arrival prior to the start of lighting the fire; certain test runs did not include the firelighting stage. This incomplete data capture is indicated by an open, rather than solid, marker.

Given the limitations described above, firm conclusions cannot be drawn from the data. However, some initial trends stand out. First, cooking with AWC in an unimproved cookstove appears comparable to cooking with wood on a stove with some improvements, such as a chimney. As it would be expected that charcoal fuel have fewer emissions than wood, as described in Section 2.2.1, the similar emissions are likely due to the fact that the charcoal stove used had no chimney, while many of the wood stoves tested did. Second, the results may indicate that AWC has similar particulate emissions to Nicaraguan WC, a finding that is distinct from the laboratory results, discussed in Section 3.4, where AWC had higher PM emissions than WC. This discrepancy is likely related to the fact that the WC acquired in Nicaragua for use in these tests was of noticeably poorer quality than the American WC used in laboratory tests in terms of density, ease of lighting, and quality of carbonation as assessed visually. American WC and Nicaraguan WC are shown side-by-side for comparison in Figure 4-10.

Household b. has the improved stove shown in Figure 4-3. This stove may have reduced CO and PM emissions compared to unimproved adobe stoves. The women interviewed who have used this stove report that it reduces smoke, takes a bit longer
Figure 4-7: Carbon monoxide emissions aggregated for all households

\[ \Delta t \approx 90 \text{m} \]
Figure 4-8: Total suspended particle emissions aggregated for all households
Figure 4-9: Specific emissions tests for all households. Aggregated data is shown in the rightmost column. Each household was assigned a letter; certain households had just one test performed in them, some had two, and some had three. Additionally, due to challenges of collecting data in extreme conditions, certain trials have only CO or PM measurements but not both. Data collected after the fire had started is shown with an open, rather than solid, marker.

Figure 4-10: Wood charcoal from America and Nicaragua. a. American-made WC is shown on the left. b. Nicaraguan-made WC on the right.
to heat up, and like cooking tortillas directly on the surface.

4.3 Interviews with end users

Eight interviews were conducted with women in the community in August 2011. The interviewees selected were all women because they are the family members who do the cooking. Each interview took about 30 minutes and was conducted with a translator familiar with both the interviewees and the purpose of the study. Additional informational interviews were conducted with a variety of people in Jinotega, a city in the north central region of Nicaragua, visited because wood charcoal is produced there. The most relevant findings from these interviews are presented here. Given that the interviews were conducted by the author, who is not native to the area, all feedback should be considered critically and somewhat skeptically, as it is probable that courtesy bias was a factor in the interactions [20].

4.3.1 Basic cooking and kitchen information

All women interviewed used adobe wood stoves that had one or two holes to hold pots and an additional hole meant for a chimney. Four of the women did not have chimneys attached to that hole. One explained that her family had a chimney previously but the chimney was too hard to clean and got blocked regularly so they dismantled it. When discussing making improvements to a stove, one women explained that a stove is like your child: you look after it and don’t change it.

In addition to the wood stoves, two women had gas stoves and four had solar ovens (that they built cooperatively through a program with Grupo Fenix). One of the gas stoves was not being used because the family lacked money for propane. The women with gas stoves used them to make rice and coffee; they preferred the wood stove for making beans and tortillas. Only one woman reported using her solar oven frequently.

The women all cooked three meals per day. The median number of people cooked for was six, the maximum was ten, and the minimum was two. They reported spend-
Five of the women’s families also gathered some wood, representing 10–75% of their family’s fuel use.

The way in which the women used their stoves also varied. Two women preferred to keep their stove hot all day, adding fuel as needed. The remaining six preferred to let the fire go out after cooking and relight the stove when it was time to prepare the next meal. All women believed that their particular behavior was the most efficient use of fuel.

An interviewee who studies cooking behavior in Nicaragua professionally explained that, in the town of Jinotega, 40% of people cook with wood exclusively. She estimated that 97% of that wood was collected illegally and then sold. She reported that most people who use gas still use wood for cooking beans and tortillas. One interviewee, who had both gas and wood stoves, reported that she was told to avoid smoke at all costs by a physician. She still cooked on her wood stove on a daily basis for tortillas and beans, although she tried to use gas as much as she could.

### 4.3.2 Charcoal and other alternative fuels

All but one of the women interviewed had tried cooking with wood charcoal. They reported a range of experiences with the charcoal. If more than one person gave the same feedback, the number of responses is shown in parentheses.

What they liked about charcoal:

- less smoky (6)
- easier to light than wood (4)
- gets hot fast (2)
- cooking was a lot faster (2)
- doesn’t go out as easily as wood (2)
- is handy to use when it rains (2)

---

1. At the time of the interview, the exchange rate between Nicaraguan Cordobas and U.S. Dollars was about 20:1.
• do not have to dry charcoal like you do wood

• less bulky

• good for grilling

• better for health

• better for the environment

• flavor is better; not smoky and bitter like wood.

What they disliked about charcoal:

• too expensive (2)

• does not last long enough (2)

• charcoal is harder to light than wood (2)

• need too much for cooking a meal

• cooking beans and corn is hard with charcoal

It is interesting that four women found charcoal easier to light than wood and two found it more difficult. The discrepancy may be a training issue or related to the difference in lighting ease for AWC and Nicaraguan wood charcoal (the latter is generally much harder to light than the former).

Additional comments about charcoal:

• it cooks the same as wood

• good charcoal can make tortillas; bad charcoal doesn’t last long

• I would cook rice and beans with charcoal but not tortillas because they would stick

• I can cook everything with charcoal ... but not tortillas
• I cooked rice and beans with charcoal, haven’t tried tortillas but am willing to try

• I would pay a 10% premium for charcoal (but not more)

• I would try charcoal if the price were the same as wood: I like to have options for cooking

• AWC lasts longer than WC

In these comments, it is notable that certain women were reluctant to cook with charcoal for tortillas. Two women were not willing to try making tortillas with the charcoal, although they were open to using it for other foods. Tortillas are a staple in Nicaragua and it was clear from informal conversations and observation that most women took great pride in the quality of their tortillas. Change aversion for particularly important foods is predictable but proves valuable in that self-reports of willingness to change fuels may be more reliable if investigators focus on particular staple foods with particular value to local cooks.

All women liked the idea of making their own charcoal from agricultural waste, although three felt they were too busy to do so. Some women reported access to agricultural waste; others said the waste was composted or fed to the cows.

In both Jinotega and Sabana Grande, interviewees were aware of a project in these regions to make briquettes from compressed sawdust. One interviewee said that she had seen the sawdust briquettes used, that they produced excessive smoke as compared to wood, and she would therefore be uninterested in using them.

4.4 Economic analysis with pilot program

A crucial consideration for the viability of AWC is its economics. Following the second training in making AWC in March 2011, the charcoal cooperative members were interested in making charcoal in earnest. They initially considered the economics with a volunteer visiting the community through Grupo Fenix, Scott Eaton, who was
investigating the D-Lab charcoal-making method for the purposes of making biochar for soil enrichment (rather than for cooking). The group then started making charcoal, which they used for their own cooking and saved a large quantity for a visit by the author in August 2011. At that time, the cooperative and author then reviewed and revised the economic analysis together. After that review and the acquisition of more barrels for combustion (five were acquired in total), the cooperative actively started to produce and sell charcoal locally.

A summary of the economic analysis is presented in Table 4.2. The proposed and actual work schedules are shown in Figure 4-11. The women participating in the charcoal-making pilot said that they were comfortable earning between C$10 – C$15 per hour. (The exchange rate at the time was approximately 20 Nicaraguan cordobas to 1 U.S. dollar.) In the plan developed together, they would have earned approximately C$11 per hour and said they were pleased by this prospect. They also planned to use a nominal amount of profit for rental of the land that they used for production, which was owned by one of the members of the cooperative. They decided to save a small amount of income from each burn for the cooperative itself, so that the oil drums, which degrade over time, and other similar fixed costs could be accounted for.

However, when the plan was put into place by the cooperative, a number of variables changed, appreciably reducing profits. The yucca used for binder cost C$14 rather than C$2 per burn. Additionally, the women opted to use a production schedule in which they all worked on each task together, rather than splitting up the work. Both of these changes reduced their earnings to C$7 per hour, as shown in the “reality” column. The women were frustrated to be earning less than minimum wage in Nicaragua (C$9.625 per hour at the time, according to the women), so they discontinued their charcoal-making efforts.

The “best case” column presents a scenario where costs might be cut even further. In this situation, the changed assumptions are:

- Waste heat from the burns is used to boil the water, rather than using purchased fuel.
Table 4.2: Balance sheet for AWC production. Inputs that varied from the original plan in a given scenario are highlighted in yellow.

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Plan</th>
<th>Reality</th>
<th>Best case</th>
<th>Four barrels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Briquette income</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>charcoal from each burn (lbs)</td>
<td>A</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>price of briquettes (C$/lb)</td>
<td>B</td>
<td>10.00</td>
<td>10.00</td>
<td>10.00</td>
</tr>
<tr>
<td>gross income per burn</td>
<td>C=A*B</td>
<td>75.00</td>
<td>75.00</td>
<td>75.00</td>
</tr>
<tr>
<td>Volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of barrels each day</td>
<td>D</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Variable costs (C$) / burn</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>raw material for each burn</td>
<td>E</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>wood for heating binder</td>
<td>F</td>
<td>5</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>binder raw material</td>
<td>G</td>
<td>2</td>
<td>14</td>
<td>2</td>
</tr>
<tr>
<td>cost of bags</td>
<td>H</td>
<td>0.35</td>
<td>0.35</td>
<td>0.35</td>
</tr>
<tr>
<td>cost of matches</td>
<td>I</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>cost to rent the land</td>
<td>J</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>co-op savings for supplies like barrels</td>
<td>K</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>total variable costs per burn</td>
<td>L=SUM(E:K)</td>
<td>15.36</td>
<td>27.36</td>
<td>10.36</td>
</tr>
<tr>
<td>total variable costs per day</td>
<td>M=D*L</td>
<td>76.8</td>
<td>136.8</td>
<td>51.8</td>
</tr>
<tr>
<td>Labor costs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>number of people</td>
<td></td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>total hours worked</td>
<td>N</td>
<td>19.5</td>
<td>27</td>
<td>19.5</td>
</tr>
<tr>
<td>hours to cut, carry, dry, sell the material</td>
<td>O</td>
<td>7</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>total work hours per day</td>
<td>P=N+O</td>
<td>26.5</td>
<td>34*</td>
<td>24.5</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gross income each day (C$)</td>
<td>Q=C*D</td>
<td>375.00</td>
<td>375.00</td>
<td>375.00</td>
</tr>
<tr>
<td>daily income less variable costs</td>
<td>R=Q-M</td>
<td>298.20</td>
<td>238.20</td>
<td>323.20</td>
</tr>
<tr>
<td>Hourly rate paid (C$)</td>
<td>S=R/P</td>
<td>11.25</td>
<td>7.01</td>
<td>13.19</td>
</tr>
</tbody>
</table>

* multiple days, see work schedule
Figure 4-11: Proposed and actual Nicaraguan production schedules. In the proposed schedule, tasks are distributed amongst the four women to maximize efficiency. In the actual production schedule, the four women worked together on all tasks, increasing the time spent to produce AWC by nearly 40%.
• Manure or cooperative-grown yucca is used as the binder raw material and can be acquired with minimal cost.

• Machinery is donated and sales are consolidated, allowing the women to spend much less time on these operations.

The last column is identical to the “plan” scenario, except that it assumes the use of four, rather than five, barrels. This column was included to demonstrate how labor costs do not scale with the number of barrels in the scenario where work is distributed to maximize efficiency.

Because all start-up materials were donated (oil drums, briquette presses, etc.), only variable costs were considered in this analysis. Were the cooperative to purchase all startup materials, assuming 5 drums at C$550 each, 3 briquette presses at C$200 each, and C$1000 in miscellaneous costs, the women would have to work without pay for 13-18 days before they would start to earn income, depending on the scenario considered. Alternatively, if the women received a no-interest loan for these startup costs, they would be able to pay back the costs after 175 days of production, assuming they saved C$5 per day as shown in line K of Table 4.2.

4.4.1 Producer viability interviews

A group interview was conducted with the women in the charcoal cooperative. There were two key findings from those interviews. First, the potential for this project seems promising in terms of waste availability. There were a variety of agricultural wastes in the community that they mentioned as good candidates for charcoal-making: millón (millet), maíz (corn stalks), and caña (sugarcane bagasse). The women also expressed interest in growing and using bamboo, a plant they knew to grow well in that region, although that plant was not growing in the immediate area. They also planned to grow yucca so that they would not have to purchase it.

Second, the women found the heat from the oil drum kiln, which they had to be near when covering up the drum to create an anaerobic environment, very challenging to manage. They explained that it is not considered safe from a health perspective
to shower when one is overheated but only when one is at a normal temperature. When they get overheated from the drum they cannot cool down. This concern was novel for all who have worked on AWC in a variety of regions and demonstrates the criticality of understanding the local context of any proposed intervention. Students in the 2011 D-Lab: Energy class, taught by the author, developed a different process for covering the drum that reduced heat exposure. When the women learned the method from the author in August of 2011, they much preferred it because of the decreased heat exposure.

4.4.2 Production outcomes in other regions

As the pilot production effort in Nicaragua was not successful, it is worthwhile to note profitable programs that have occurred in regions where charcoal is used more commonly. The following information was provided by the D-Lab Scale-Ups program, which is investigating the viability of disseminating AWC widely.

In Uganda, the Teso Women Development Initiatives (TEWDI) was taught to make AWC by a D-Lab representative and now produces approximately 130 tons/year from corn cobs and stalks, groundnut shells, charcoal dust, and grass. They have 40 farmers earning $600 per year for this rate of production. They price their briquettes 20% lower than wood charcoal, although the wood charcoal price is rising, so they expect to be 40% more affordable in the future. The organization reports that AWC is comparable to local WC but consumers need to make some adjustment to cooking style (not brushing away the ash because it retains heat and not dousing the briquettes after use to save the remainder, as they will disintegrate). They report the briquettes burn well, produce no smoke, and light easily.

In Tanzania, the Appropriate Rural Technology Institute-Tanzania (ARTI-TZ) currently produces about 2,000 tons/year of AWC, made from coconut and rice husks, corn stalks, shrubs and bushes, sawdust and wood shavings, and tree clippings [5]. To put these production rates into context, in Dar es Salaam 500,000 tons of charcoal are consumed per year and this number represents half of the total charcoal usage in the country [91]. They have 720 farmers earning about $275 per year for the feedstock.
They price their briquettes 20–40% lower than WC as well. This organization has found that their customers are more likely to adopt the briquettes if they are directly shown how to use them.

### 4.5 AWC composition optimization

Based on feedback from and production methods used by end users in the field, other formulations of AWC were tested in order to understand how variation in the fuel’s inputs would affect the emissions and performance of the briquettes. The test matrix is shown in Table 4.3. The two raw materials tested were corn stalks and sugarcane bagasse. Both of these raw materials have been identified in numerous locations worldwide as readily available and currently unused. There are regions where corn stalks are used as cattle feed or for composting back into the field, and where bagasse is used as fuel for powering sugarcane refineries, but there are many other locales where the waste rots or is burned, according to various D-Lab students and staff visits to locales worldwide.

#### 4.5.1 Methodology

Binder was varied in two ways. Briquettes made with 50% more yucca-based binder were studied to understand whether the additional raw material in the briquettes would adversely affect emissions. Manure was also studied as a possible binder, given that many end users have asked whether that waste could be used as a binder. The initial instinct was to avoid manure binder, given the well-documented toxicity of emissions from dung exclusively used as fuel [64, 96, 30]. However, since binder is typically only 10% of a briquette, and since yucca is a somewhat problematic binder given that it is generally not free and is a food, the value of testing manure seemed evident. The briquettes tested in this investigation are visually similar to the AWC briquettes shown in Table 2.1.
Table 4.3: AWC test matrix

<table>
<thead>
<tr>
<th>raw material</th>
<th>corn</th>
<th>bagasse</th>
</tr>
</thead>
<tbody>
<tr>
<td>yucca</td>
<td>AWC</td>
<td>AWCB</td>
</tr>
<tr>
<td>50% extra yucca</td>
<td>AWCX</td>
<td></td>
</tr>
<tr>
<td>manure</td>
<td>AWCM</td>
<td></td>
</tr>
</tbody>
</table>
4.5.2 Results

The comparative energy density of the fuels is shown in Figure 4-12. All formulations appear to be similar, apart from the sugarcane-based charcoal (AWCB). When sugarcane charcoal fines are crushed, the resulting particles are noticeably finer than that of corn stalk charcoal. As smaller particles allow for improved compression, an resultant increased energy density for these briquettes is unsurprising.

Figure 4-12: Comparative energy density emissions for AWC optimization: standard formulation of agricultural waste charcoal (AWC), AWC made from sugarcane bagasse rather than corn (AWCB), AWC made with extra binder (AWCX), AWC made with a manure binder (AWCM)

The comparative carbon monoxide emissions normalized to energy emitted are shown in Figure 4-13. The differences between the fuels here also align with the understanding of the different fuels, particularly the expectation that a denser briquette would produce less CO because of improved combustion characteristics of the denser fuel. While the fuel with extra binder (AWCX) is not statistically different
from the typical fuel (AWC) or from that made with manure (AWCM), with further repetitions it may be shown to emit more CO/MJ due to the extra binder, which is uncarbonized material in the briquette.

The comparative particulate matter emissions are shown in Figure 4-14. The extra particulate emissions associated with the briquette with extra binder are unsurprising, based on the argument presented in the results for carbon monoxide.
Figure 4-14: Comparative particulate matter emissions for AWC optimization.
4.6 Summary of findings

In summary, AWC was studied in a community in Nicaragua considering emissions in kitchens, end user interest, and economic viability. All results are highly preliminary given the limited time available to conduct fieldwork. Emissions of AWC appears to be similar to or less than wood and wood charcoal, although further research with chimney-based stoves is needed for better understanding. End user interest seems moderate, with some users open and interested in the use of charcoal, and others less interested. That some users expressed interest, given the lack of charcoal usage in the region, is a more positive outcome than one might otherwise expect. Finally, based on the outcomes of pilot production, it is clear that proper training in the manufacturing system proposed, which minimizes labor time, must be provided in order for the expected profits to be realized. Additionally, the costs of raw materials must be carefully understood in order to predict profits properly.

There are a few important outcomes from the AWC formulation analysis. First, using a manure binder does not seem to adversely affect emissions. The ability to use manure as a binder may allow many more people to produce charcoal, and others to do so more affordably. Second, using only the quantity of binder specified, and not adding additional binder, is important for combustion emissions. Third, the energy density and CO emissions of the corn-based briquettes may improve if it is possible to crush that material more fully and/or compress those briquettes with greater force.
Chapter 5

Fuels from household and industrial waste

In this chapter, findings from studies of fuels made from certain household and industrial wastes are presented. These experimental fuels are compared to wood charcoal in terms of energy density, carbon monoxide, and TSP emissions. For these tests, a very low number of repetitions was possible because importing these fuels in large quantities from Haiti was extremely difficult. Given the low sample size, all results must be considered preliminary.

The comparative energy density of the fuels is shown in Figure 5-1. Fabric waste briquettes with the fabric carbonized before briquetting (FWC) and carbonized paper waste briquettes (PWC) show comparable energy densities and comparable mass densities: about 75% of wood charcoal. Fabric waste briquettes carbonized after briquetting (FWB) had about 66% of the energy density of AWC and, given that it also has a lower mass density (about 50% of WC), the reduced energy density is expected. Similarly, raw biomass fuels generally have lower energy densities than carbonized ones, so the results for the uncarbonized paper waste briquettes (PWB) — about one third the energy density of AWC — are also as expected.

A comparison of the carbon monoxide emitted by the briquettes, normalized to the energy released by the briquettes over the course of the test, is shown in Figure 5-2. In this case the mean emission level for all briquettes made from fabric or paper
Figure 5-1: Comparative energy density for waste briquettes: paper waste briquettes (PWB), paper waste briquettes – carbonized (PWC), fabric waste briquettes with carbonization following briquetting (FWB), fabric waste briquettes with carbonization prior to briquetting (FWC), wood charcoal (WC)
Figure 5-2: Comparative normalized carbon monoxide emissions for waste briquettes: paper waste briquettes (PWB), paper waste briquettes – carbonized (PWC), fabric waste briquettes with carbonization following briquetting (FWB), fabric waste briquettes with carbonization prior to briquetting (FWC), wood charcoal (WC).

waste are worse than wood charcoal by at least a factor of two. Based on research conducted by Zhang et al., this increase represents exposure levels four times the level recommended by the World Health organization [111].

The particulate matter findings are presented in Figure 5-3. All briquettes made from fabric or paper waste release more particulate matter than wood charcoal by at least a factor that ranged between 9–45. Ezzati et al. demonstrated that an 18-fold increase in TSP doubled respiratory infections so these increases are significant from a health perspective and highly concerning [32].

The results presented in this chapter offer insight into the potential emissions hazards from certain of waste-based fuels. Important limitations of briquettes made from fabric or paper waste have been identified: these fuels have carbon monoxide
Figure 5-3: Comparative particulate matter emissions for waste briquettes: paper waste briquettes (PWB), paper waste briquettes – carbonized (PWC), fabric waste briquettes with carbonization following briquetting (FWB), fabric waste briquettes with carbonization prior to briquetting (FWC), wood charcoal (WC)

$\Delta t \approx 60 \text{min}$
and particulate emissions far in excess of wood charcoal and certain variations also have limited utility in terms of energy density. Given how much more CO and PM emissions these briquettes produce as compared to WC, it is strongly recommended that any briquette made from an untested waste or using an untested process be properly vetted in terms of emissions prior to dissemination to minimize creating greater health hazards in order to improve environmental outcomes.
In this dissertation, four primary contributions are presented in the area of the use of wastes as raw materials for cooking fuels in developing countries. First, agricultural waste charcoal (AWC) was studied in depth for the first time and found to be generally promising. From an emissions standpoint, the fuel is largely comparable to wood charcoal (WC) in laboratory tests. While AWC has 73% of the energy density of WC, this level compares with many wood charcoals found in developing countries [27]. AWC and WC had indistinguishable levels of carbon monoxide emissions when normalized to the energy released. AWC released four times the total suspended particulate matter of WC and further investigation is recommended to minimize these emissions, which may be related to the density of the fuel or the mineral content of the raw materials. AWC particulate levels drop more quickly than WC levels, however, and given the time spent cooking rather than lighting the fuel, this finding may make AWC more appealing for certain stages of cooking.

Second, the ultra-fine particulate emissions of AWC and WC were characterized. Ultra-fine particulate has only once previously been measured for indoor air pollution associated with cooking fuels in developing countries, likely due to both the cost of the apparatus for doing so and the fact that the understanding of the health hazards of this size of emissions is only recently gaining notice [51]. Characterization of ultra-fine particle emissions of AWC has not previously been conducted. Ultra-fine emissions are generated with an average concentration of $14 \times 10^5$ p/cc, an average mass density...
of 1288 µg/m³, and diameters centered at 396 nanometers. As awareness of the health risks of these sizes of particles grows, further research is warranted into this form of indoor air pollution from cooking.

The study of particulate emissions allowed identification of the spike in particulate emissions during the lighting phase of the burn for both AWC and WC. As the time required to light the fire is much shorter than the overall length of cooking (10-20 minutes versus 2-4 hours), technological and behavioral interventions that can minimize either this spike or people’s exposure to that spike could offer important health benefits. Focusing on one step of the cooking process, rather than the entirety, may be an easier endeavor from a cost and dissemination standpoint.

Third, AWC was studied in the field from an emissions, user, and economic standpoint. Further research is recommended into the emissions of the fuel while used in real conditions, including introducing a stove that includes a chimney, so that the smoke from wood and AWC cooking are vented more similarly. In a region of Nicaragua where people primarily cook with wood, users reported a surprising though not overwhelming level of interest in the alternative fuel. Finally, it was shown that care must be taken in disseminating the manufacturing operations methodology in order to ensure that production meets profit expectations. Pilot production in East Africa has been more promising, which is likely due to the greater use and cost of charcoal in that region.

An understanding of the effect of material inputs on emissions and energy density was developed. Manure was found to be a viable binder from an emissions standpoint, which is a surprising outcome given the known hazards of dung fuel, although less surprising when one considers the percentage of binder to carbonized waste in AWC briquettes. This outcome may be quite valuable to producers in developing countries, as it offers producers a binder alternative that is not a food source and is readily available in many locales.

Finally, a range of raw and carbonized briquettes made from paper and fabric wastes were studied. These types of briquettes are currently being tested or actively promoted in Haiti and similar briquettes are being disseminated at a small scale world-
wide. All waste briquettes incorporating paper and/or fabric were found to emit at least two times more carbon monoxide and 9-45 times more particulate emissions than wood charcoal. Carbonization of the material prior to or following briquetting did not improve the emissions results. Given the known health risks of carbon monoxide and particulate matter, these briquettes should no longer be disseminated and use should be terminated. Other briquettes made from waste should be properly tested prior to pilot testing, funding, and dissemination. Further, for wastes that are likely to contain added chemicals, it is recommended that additional tests be performed to ascertain if other harmful emissions are generated.

Based on these four contributions, a number of further investigations are recommended. First, more repetitions of these experiments in both the laboratory and field would help improve the statistical significance of these findings. Additional pilot tests of the fuel, including an understanding of the economics and user interest in the fuel, is also an important next step that is currently being undertaken by the MIT D-Lab Scale-Ups program.

One of the challenges of significant repeated measures is the required quantity of fuel and time required for a test. The quantity of fuel is particularly challenging in laboratory tests, as most fuels must be imported from the field at considerable expense. The development of a methodology that can reduce this volume and time by at least a factor of 2 while still maintaining relevance to field use of the fuel would be of great benefit to all those conducting these types of studies.

Further exploration of the types of wastes that are safe and unsafe to use for cooking fuel, and determining whether affordable steps can be taken to generate safe solid fuel from more complex wastes like paper and fabric scraps, would be of great interest to those looking for alternative sources of raw material for solid cooking fuel. Finally, exploration of how AWC and other novel fuels perform in improved stoves is warranted to determine whether these fuels are still comparable to WC in conjunction with an improved stove, as well-designed stoves can offer tremendous benefit from both an emissions and efficiency standpoint.
Bibliography


