Development of Agricultural Residue Biofuel Pellets and subsequent Design of a Green Cook Stove

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APPROVAL SHEET

Certified that the contents and form of the thesis entitled 'Development of Agricultural Residue Biofuel Pellets and subsequent Design of a Green Cook Stove' submitted by Ms. Nismah Rizwan, Ms. Sara Noor Ehsan, and Mr. Zahid Hussain have been found satisfactory for the requirement of the degree of Bachelor of Environmental Engineering.

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ABSTRACT

Large scale open biomass burning has resulted in inefficient utilization of available alternate resources along with increased emissions causing adverse health effects. This wasted energy is sufficient to abate the energy crisis currently faced by the world. Being an agrarian country, Pakistan holds the potential to bring its biomass resources in to use and contribute towards its development. However, the use of inefficient technology, in combination with biomass fuel, leads to an adverse environmental impact, particularly in the form of air pollution. So, executing the project in two phases, we aim to reach an optimum combination of biomass fuel and cook stove design. Utilization of the fuel in a cook stove has been chosen because cooking is a basic necessity and a significant contributor to deforestation and indoor air pollution, particularly in rural areas of Pakistan. The first phase of the project includes experimentation with cotton-gin by-product, wheat, and rice straws in combination with binding materials to yield biomass pellets, upon compression. These biomass resources have been chosen based upon their high availability, as they are the most cultivated crops of Pakistan. Once an optimum combination of biomass and binder has been determined, the formed pellets will be used in a rocket-type stove, optimized particularly for them. The design of the stove is based on careful consideration of air flow, fire power, loading height, material and insulation, such that thermal efficiency is maximized, and smoke and emissions of Carbon Monoxide are minimized. The stove is tested using the Water Boiling Test as it is a standardized and widely used method of testing cook stoves. The results reveal cotton-gin by-product pellets with paper pulp binder as the more efficient fuel. Using this fuel in co-combustion with wood in a combination of 60% wood and 40% pellets (by weight) results in an optimum trade-off between thermal efficiency (44%) and emission reduction, in comparison with both, conventional stoves (3-stone stoves) and improved stoves, with minimal cost.

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Chapter 1: Introduction

1.1 Background

Currently, the world, particularly Pakistan, faces a number of issues that are directly linked to deterioration of the environment. The most critical of these is indoor air pollution. On a global scale, around 4.3 Million premature deaths occur annually in association with indoor air pollution *(World Health Organization, 2016)*. In Pakistan, the major source of this pollution is sub-standard and unsafe cooking practices, particularly in the rural areas. These practices are commonly linked to the occurrence of eye and pulmonary illnesses. These stoves are mostly run on wood as fuel, which is a major reason for their high pollution potential.

Large scale deforestation is another direct result of the high consumption of fuel wood. Owing to the fact that around 70% of Pakistani households depend on fuel wood for energy *(Hamayun, Khan, & Khan, 2013)*, the already deficient forest cover (less than 4% currently) is depleting further. In addition to this, the instable economic situation of the country is increasing the difficulty in shifting from conventional to modern sources of fuel. So, since the use of traditional fuels cannot be ceased immediately, the exploration of alternatives is necessary.

Keeping in view the current situation of the country, the best possible alternative to fuel wood is agricultural residue biomass. Pakistan is an agrarian country, with vast areas of land being cultivated with a variety of crops. These crops produce approximately 114 Million tonnes of field-based residues, with an equivalent energy potential of about 1.6 MTJ every year *(The World Bank Biomass Atlas, 2016)*. More than 90% of these residues is burned in open fields. Globally, biomass fuel provides 11% of the energy demand, while more than 3 billion people use it for cooking. So, if the agricultural residues in Pakistan are brought in to use as well, they are sufficient to considerably alleviate the burden on current energy resources. This will simultaneously provide an efficient means of waste management, as otherwise these residues are burned in open fields leading to air pollution.

In Pakistan, three of the major crops are cotton, rice, and wheat. Around 10 Million tonnes of rice, and 25 Million tonnes each of cotton and wheat by-products are generated annually, and their combined equivalent energy potential is estimated at 3.4 MTJ/year *(The World Bank Biomass Atlas, 2016)*. These residues also provide the advantage of being inexpensive. Therefore, they can conveniently be used in domestic energy intensive activities, such as cooking. However, the adaptability of such fuel and technology is a major concern and needs to be addressed to ensure effectiveness.

1.2 Problem Statement

The limited supply of energy in relation with the ever increasing demand has resulted in an emerging energy crisis. In addition to this, large scale open biomass burning has resulted in inefficient utilization of available alternate resources, along with increased emissions which cause adverse health effects.

1.3 Objectives

The project aims to resolve the stated problem with two key objectives. The first objective involves processing and pelletization of agricultural residue to optimize its combustion characteristics and yield a low-cost, sustainable fuel. The second objective deals with the design of an improved cook stove, suited particularly to agricultural residue biomass, thereby reducing emissions and negative impact on the environment and health.

1.4 Scope

The project involves the use of agricultural residue in developing biomass pellets that may be used as an inexpensive fuel source. In order to do so, by-products of cotton, rice, and wheat have been used as they are most widely produced. These residues were combined with only readily available binding materials, such as paper pulp and starch. The pelletization process took place under ambient conditions of temperature and pressure, which are two of the most crucial process parameters. However, due to experimental difficulties they could not be varied and were kept constant within the ambient range. Also, the time of compression for each pellet was kept constant to allow standardization and better comparison.

The project also involves the design of a cost-effective, eco-friendly, and high-efficiency cook stove that is suited for the previously mentioned biomass fuel. The design of the stove was kept as simple and user-friendly as possible, without compromising on efficiency. The stove testing operation was carried out in an outdoor environment rather than in an indoor one due to lack of proper experimentation facilities. The effectiveness of the stove was tested based upon its thermal efficiency and pollutant emissions during operation. In order to measure thermal efficiency, only the water boiling test has been used as it is the most widely used of the standard methods. The controlled cooking and the kitchen performance tests have not been conducted. The emissions measured include those of Carbon Monoxide only. Particulate matter, which is the second most important pollutant emitted from solid biomass fuel, was not been measured due to lack of appropriate resources and technology. Also, the emissions were measured only for a fixed duration rather than throughout the water boiling test as should have been per protocol.

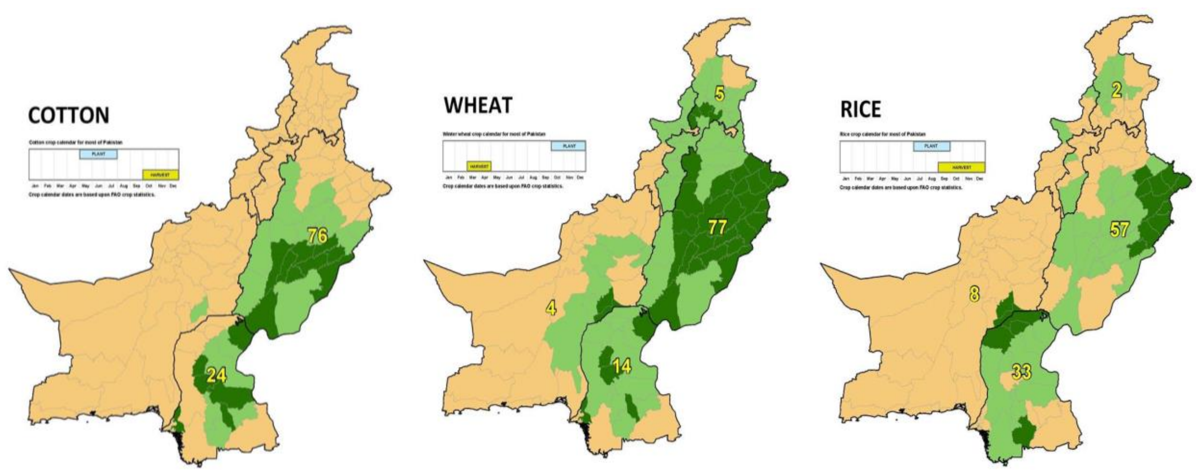
In order to ensure acceptability and easy adaptability of the product, the commonly practiced principle of co-combustion has been used rather than burning fuel pellets alone. Since wood is the most common fuel source among the rural population of Pakistan, which is the targeted audience, it was used for co-combustion along with the pellets. A number of combinations of the two have been tested to ultimately reach an optimum one.

Chapter 2: Literature Review

2.1 Overview of Crop Potential

2.1.1 Crop Production in Pakistan

Pakistan is an agrarian country with five major crops including: cotton, maize, rice, sugarcane, and wheat. It is among the World's top 10 producers of cotton, wheat, and sugarcane and holds the 13th position in rice production. Its major crops contribute to 6.5% of the country's GDP *(Food and Agriculture Organization (FAO), 2017)*. Cotton is considered to be the most important cash crop of Pakistan that is grown in the southern parts of Punjab and in Sindh along the banks of River Indus, while wheat is the most popular food crop of Pakistan. Being the staple diet of most of the population, wheat dominates all crops in acreage and production. It is cultivated in all four provinces of Pakistan. Punjab and Sindh provinces however rank at the top. The spatial distribution of cotton, wheat, and rice crops in Pakistan is illustrated in Figure 2.1.



*Yellow numbers indicate the percent each province contributed to the total national production. Provinces not numbered contribute less than 1%. Major areas combined account for 75% of the total national production. Major and minor areas combined account for 99% of the total national production.

Figure 2.1: Cultivation of Cotton, Wheat, and Rice Crops in Pakistan by major (dark green) and minor (light green) areas *(USDA, 2016)*

2.1.2 Crop Residue Potential in Pakistan

According to *World Biomass Atlas 2016*, the technical potential of crop harvesting residues was estimated at about 25.1 Million tonnes/year, with an equivalent energy potential of 342,236 TJ/year. Rice straw accounts for 30.4% of this energy potential, followed by wheat straw with 27.3%, cotton stalk with 26.4%, sugarcane trash with 12.9% and maize stalks with 3.0%. Tables 2.1 and 2.2 show the annual production of various crop residues and their corresponding energy potential, as reported in the World Biomass Atlas, 2016.

Table 2.1: Country level Annual Theoretical Potential of Crop Harvesting Residues

Type of Crop	Type of Residue	Annual Production of Residues (1000 tonnes)	Energy Potential of Residues	
			TJ/year	GWh/year
Cotton	Cotton stalk	49,405	741,075	205,854
Wheat	Wheat straw	34,581	497,966	138,324
Rice	Rice straw	16,754	209,425	58,174
Sugarcane	Sugarcane trash	7,831	98,671	27,409
Maize	Maize stalk	5,325	69,225	19,229
Total		**113,896**	**1,616,362**	**448,990**

Table 2.2: Technical Potential of crop harvesting residues based on existing uses

Type of Crop	Type of Residue	Annual Technical Potential of Residues (1000 tonnes)	Energy Potential of Residues	
			TJ/year	GWh/year
Cotton	Cotton stalk	5,039	75,585	20,996
Wheat	Wheat straw	5,689	81,922	22,756
Rice	Rice straw	6,534	81,675	22,688
Sugarcane	Sugarcane trash	2,552	32,155	8,932
Maize	Maize stalk	680	8,840	2,456

2.1.3 Potential use of Crop Residue

There are several conventional utilizations of the crop residues generated. The several key usages are described as follows:

- **Open Biomass burning:** Burning of agronomic residues is the most economical way to prepare available lands for the next crop round while quickly eliminating the residues. Field burning is regularly experienced in areas which have a short period of land preparation. *(Gadde, Bonnet, Menke, & Garivait, 2009)*
- **Cooking fuel:** Generally, people in rural areas burn loose crop residue directly in cook stoves. The use of agricultural residues as cooking fuel is not usually considered favourable because there are health and environmental risks involved due to smoke and incomplete combustion. *(Gadde et al., 2009); (Hoer et al., 2008)*
- **Animal feedstock**: Various kinds of residue are also used as animal feed and animal bedding. *(Hoer et al., 2008)*
- **Composting:** Combination of agricultural residue including rice straw with other agricultural residues and animal manure are utilized in composting. *(Hoer et al., 2008)*

2.2 Overview of Biomass Burning

2.2.1 Biomass burning and its types

Around 90% of biomass burning actions are initiated by humans. Over the years, humans have practiced various activities including deforestation, farming extension, wildflower control, residue burning and cultivation practices. It is further divided into 3 categories: agricultural, prescribed and wildfire burnings, as listed in Table 2.3:

Table 2.3: Categories of Open Biomass Burning *(USEPA, 1998)*

Type of Burning	Description
Agricultural	The planned burning of vegetative debris from agricultural operations.
	The use of fire as a method of clearing land for agricultural use or pastureland.
Prescribed	The pre-arranged burning of plants under controlled situations to achieve pre-determined regular resource managing objectives.
Wildfire	An unplanned wildland fire, unauthorized human-caused fires, or escaped prescribed burn projects.

2.2.2 Emissions from Open Biomass Burning

Biomass burning is an important cause of Particulate Matter (PM) and gaseous air pollution emissions. Emissions from biomass burning are known as a source of Greenhouse Gases (GHGs), for example CO_2, CH_4, and NO_x. Biomass burning mostly comprises of 2 stages: flaming and smouldering. Low temperature and incomplete combustion of biomass generates large amounts of toxic air pollutants, for example, $PM_{2.5}$, PM_{10}, NO_x, etc. *(Jittadejchaiyapath, 2016)*

2.2.3 Impacts of Emissions from Open Biomass Burning

Emissions from biomass burning have effects on atmospheric chemistry and air quality. It is reported that it meaningfully increases level of PM and gaseous pollutants (European Environment Agency (EEA), 2014). This ultimately influences the atmospheric quality and climate system. Some GHGs, such as CO_2 and CH_4 can also lead to the alteration of climate. Moreover, these gases are also responsible for the smoke and particulates emitted from large scale biomass burning, significantly reducing visibility. This can become a cause of disruption in daily human life.

Emissions from residues burned in open fields result in the community being exposed to higher air pollutant concentrations during the burning season. This leads to measurable health effects. The health impacts of trace gases causing air pollution can vary based on the types of pollutants, dose and time of exposure, and extent of interaction among pollutants *(World Health Organization, 1999)*.

2.3 Agricultural Residue as Fuel

It is very challenging to handle, transport, store and utilize loose form of agricultural residue as it comprises of irregular shapes and sizes, and has low bulk density *(Kaliyan & Vance Morey, 2009)*. By using techniques such as combustion and gasification, the residue can be converted to energy. Even though direct combustion can achieve high efficiency of energy conversion, it still faces difficulties in operation such as high ash content and sintering formation. However, chemical or biological pre-treatment can help reduce these problems. *(Saeed et al., 2015)*

Solid biomass for direct use as fuel may be processed using two slightly similar processes:

- **Briquetting**: Briquettes are a compressed block of combustible biomass material, which are biofuel substitutes to coal and charcoal. They are mostly used in areas where cooking fuel is not easily available.

Figure 2.2: Different types of biomass briquettes

  Briquettes are more advantageous as compared to the loose residue as they provide uniform particle size and quality, higher calorific value, feasible fuel transport and storage *(Chou, Lin, & Lu, 2009); (Jittabut, 2015)*. Chou et al. (2009) found that using rice bran as a binder shows better performance than 100% raw rice straw.

- **Pelletizing:** Biomass pellets are biofuel made from compressed organic matter. They can be used as fuel for power generation, commercial or residential heating or cooking purposes. They are very small in size, exceptionally dense and can be produced with lower moisture contents that enable higher combustion efficiency.

Figure 2.3: Different types of biomass pellets

For domestic cooking and industrial combustion purposes, the usage of pellets is preferred for combustion than other forms *(Maninder et al., 2012)*. For better combustion performance of pellets, it is advisable to combine a specific type of residue with suitable binder materials, such as starch or pulp *(Shyamalee, Amarasinghe, & Senanayaka, 2015)*. Moreover, the bulk density of biomass can be increased with the help of the pelletization process. The operating conditions have important effects on pellet properties, such as durability and bulk density. *(Saeed et al., 2015)*

2.4 Pelletization

2.4.1 Pelletization Process

Utilizing, the otherwise wasted, biomass by effectively converting it into useful commodities by the process of pelletization is an emerging trend. By utilizing various additives and processing techniques, residues, such as cotton-gin by-product, can be used to manufacture fuel pellets that have commercial potential. However, work needs to be done to minimize the ash content and determine optimal settings for maximum combustion *(Holt, Blodgett, & Nakayama, 2006)*. For the process of pelletization, pre-treatment and conditioning of raw material is of utmost importance. The different types of materials should be specifically handled to ensure desired conditions for easy processing. Before the pelletization process, the agricultural residue must be cut and sieved to reduce particle size and ensure particle size uniformity, and enhance the quality *(Ignacy et al., 2015)*. Moreover, according to research done on the pelletization of cotton-gin by-product, moisture content of the material entering the pelletization mill was found to be around 15-20% *(Holt et al., 2006)*. Another research by Daham Shyamalee (2015) also showed the effects of addition of various types of easily available binders that enhanced the pellet strength and combustion properties. These binders included dried cow dung, newspaper waste, and wheat flour. He also defined different categories of pressure ranges and their requirements, concluding that are necessary in low pressure requirements *(Shyamalee et al., 2015)*. Finally after the pre-processing, pellets are produced in a pellet mill that generally consists of a die with cylindrical press channels, and rollers that force the biomass through it. *(Stelte et al., 2012).*

2.4.2 Pellet Characteristics

Pelletization of biomass is energy and mass densification for materials that have low bulk density. Generally, the pellet quality depends on biomass type, moisture content and particle size *(Gilbert, Ryu, Sharifi, & Swithenbank, 2009)*. The effect of pelletization pressure and temperature are assessed in terms of density, mechanical strength and durability. The density of pellets is calculated after completion of the pelletization process and its mechanical strength is measured using a compressive strength machine *(Gilbert et al., 2009)*. Yan Huang (2017) discussed the co-relation of moisture content with temperature and pressure. He stated that at room temperature and differing pressures, the moisture content was not affected by pelletization, while increasing the temperature significantly reduced the moisture content. *(Huang et al., 2017)*

2.4.3 Pellet Testing

Quality of the pellets produced depends upon several parameters including: mechanical strength, durability, bulk density, and moisture content. To ensure viability of pellets as fuel that is to be transported in bulk quantity, their testing is required. The moisture content is tested according to the standard method of drying the biomass to achieve a stable mass and conducting replications for accurate results *(Niedziolka et al., 2015)*. The calorific value, according to the research, was calculated on the basis of combustion heat determined by the calorimetric method. Another research study concluded that pellet durability and strength depend on four key parameters that include: compression time and conditions, moisture content, and particle size distribution *(Kaliyan & Vance Morey, 2009)*. The mechanical strength of pellets is tested by crushing them between two flat plates to check for appearance of cracks at a standard strain rate of 1mm/min. *(Huang et al., 2017)*

2.5 Cook Stoves for Biomass Fuel

2.5.1 Improved Cook Stoves (ICS)

At present, around 2.7 billion of the world population still relies on biomass residues for cooking, heating, and agro-processing purposes which states approximately 90% of energy use in rural areas *(World Health Organization, 2016)*. In addition, rural populations regularly use traditional 3-stone cook stoves which emit high concentrations of air pollutants *(Urmee & Gyamfi, 2014)*. Hence, it is necessary to have a new version of biomass cook stoves which is appropriate for burning biomass residues, and reduces emissions. Improved cook stoves utilize modern construction to assist in better combustion and heat transfer for improving emissions and performance efficiency for turning biomass residues to energy. *(Kshirsagar & Kalamkar, 2014)*

2.5.2 Rocket Stoves

The goal of an ICS is to improve upon the shortcomings of the traditional stoves, while still ensuring low cost and ease of use. The most popular example of an improved cook stove is a rocket biomass stove that is able to reduce emissions by 40-75%, while increasing the fuel efficiency by almost 30% *(Kshirsagar & Kalamkar, 2014)*. Similarly, a rocket stove in generally is preferred as it is known to reduce energy consumption by one-third and CO emissions by at least half. *(MacCarty, Still, & Ogle, 2010)*

2.5.3 Cook Stove Testing

2.5.3.1 Water Boiling Test

The most basic lab-based test designed to explore the basic features of stove performance under controlled settings is the Water Boiling Test (WBT). The WBT protocol consists of three phases, namely: high power cold start, high power hot start, and low power simmering phases. Results from the high power phase help define the stove performance, while results of the hot start and simmering phases are useful to find the difference in stove performance between high and low power operations. Features like simplicity, ease of conduction, and quick-to-do procedures make WBT the most widely used testing protocol making it account for 73% of all tests performed on cook stoves *(Kshirsagar & Kalamkar, 2014)*. Moreover, the estimation of residual heat can be used to improve performance efficiency by understanding the energy flow and optimizing the design of the cook stove. Efficiency of the cook stove during simmering phase and turn down ratio are the key factors influencing the quantity of fuel saved during actual cooking conditions. *(Raman, Ram, & Murali, 2014)*

2.5.3.1 Emission Testing

Emission efficiency is an important part of stove testing that is included in the latest revised version of the Water Boiling Test. To effectively control harmful process emissions, an emission collection hood is used which involves a system to collect the emitted gases, along with providing a large amount of dilution (by adjusting air flow) to imitate actual cooking conditions. The gases and air are mixed and cooled after which the concentration of each pollutant (CO, PM, etc.) is measured in real time by a data acquisition system that requires calibration. *(MacCarty et al., 2010)*

The *Emission and Performance Testing Protocol (EPTP)* sets specific standards to classify stove as an improved cook stove. It sets limits for fuel use, and Carbon Monoxide and Particulate Matter emissions. According to the EPTP, for every 850g of fuel burned no more than 20g of Carbon Monoxide and 1500g of PM_{10} should be emitted. The emission analyzer must collect samples continuously throughout the test for CO using Non-Dispersive Infrared Spectrometry (NDIR). Similarly, data acquisition frequency must be adequate enough to detect fluctuations in performance.

Figure 2.4 demonstrates the process by which emissions are measured using the emission collection hood and the flue gas analyzer.

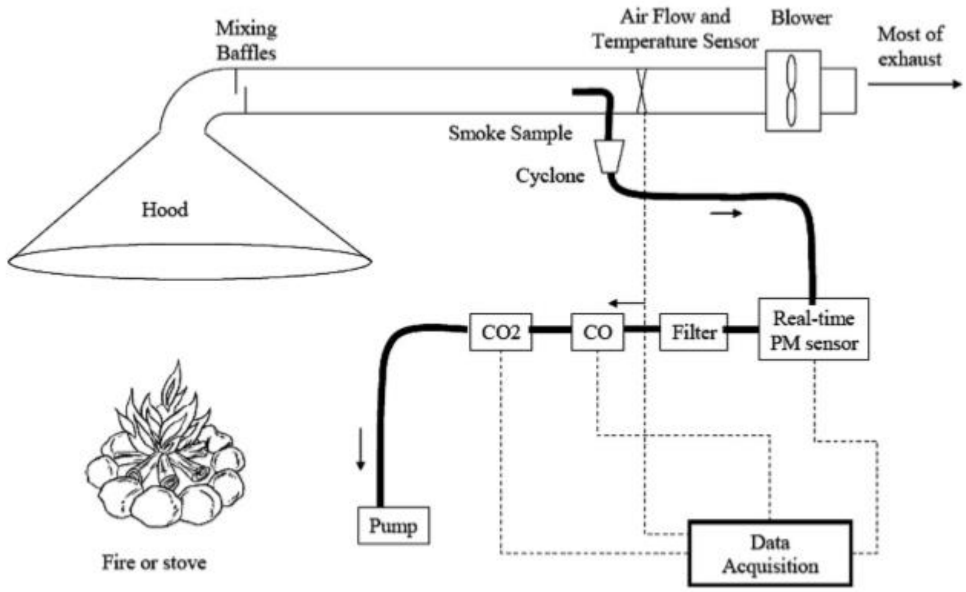


Figure 2.4: Emission Measurement schematic (Source: ETHOS Technical Committee, 2009).

Chapter 3: Methodology

The overview of the project methodology is as presented in the following flow chart:

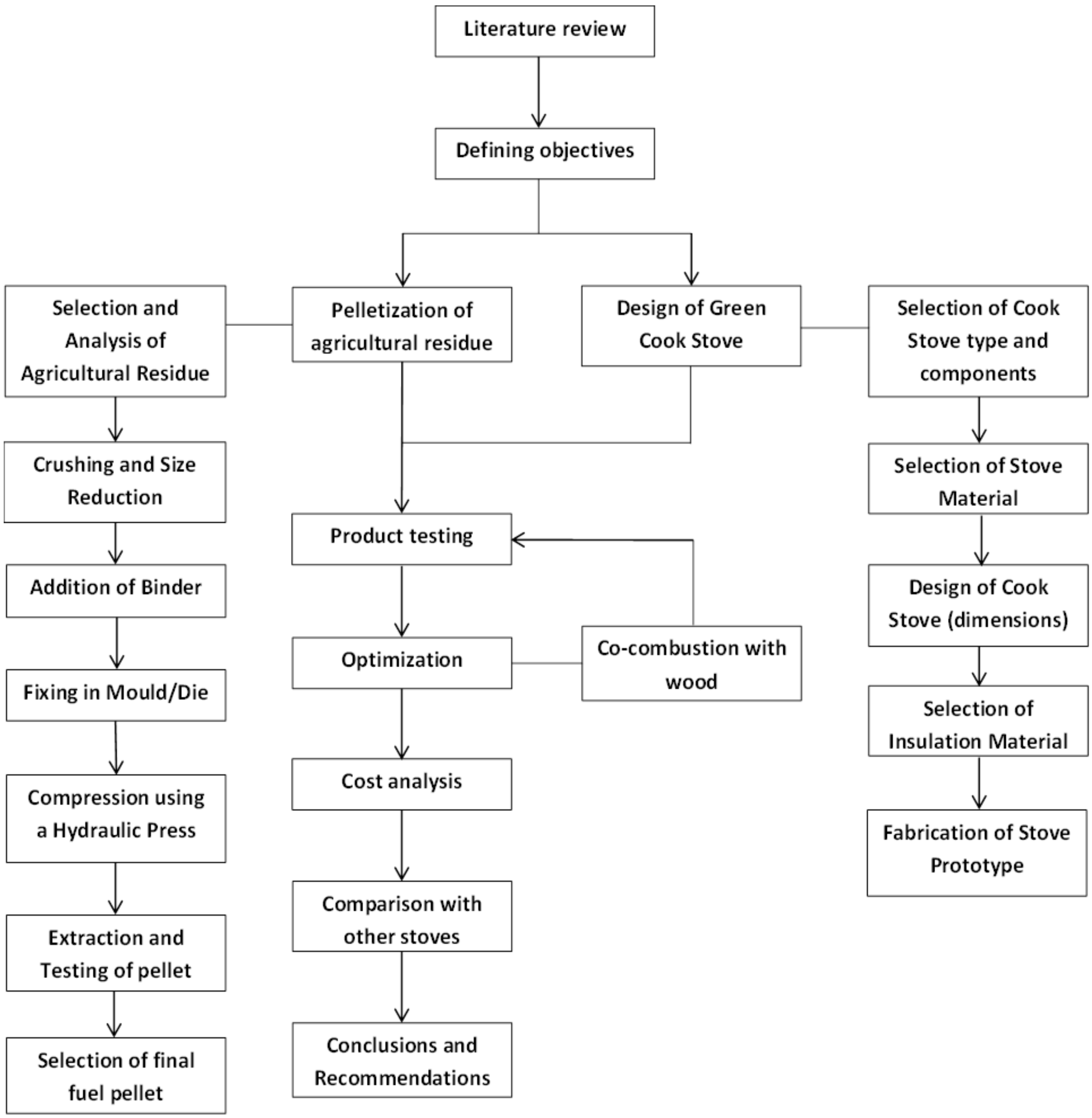


Figure 3.1: Framework of Methodology

3.1 Pelletization of Agricultural Residue

The pelletization of agricultural residue takes place in three major steps: pre-processing, pellet formation, and post-processing *(Stelte et al., 2012)*. Pre-processing includes: cleaning and removing contaminants, obtaining a manageable and uniform particle size, and optimizing moisture content of the residue. Pellet formation involves the combination of residue with a suitable binder, which is then placed inside a cylindrical die and compressed using a hydraulic press. Binding of the residue is achieved due to release of lignin present inside both, the residue and the binder, upon application of high pressure. Moisture in the raw materials helps reduce friction between the material and equipment, reducing energy and depreciation cost. Once the pellets are formed, they are sun-dried to reduce their moisture content, to less than 5%, to increase combustion efficiency and reduce smoke.

3.1.1 Analysis of raw material

3.1.1.1 Proximate Analysis

Proximate analysis of the agricultural residue was done in order to determine its chemical properties. The analysis involves heating the residues at various conditions to determine 4 components: moisture content, volatile matter, fixed carbon, and ash content.

For the analysis, a 2 gram sample of each residue was taken. First the moisture content was determined using the Standard Oven Drying method and heating the sample in an oven at 105°C for 1 hour. The difference in mass was recorded, to calculate moisture content as:

$$\boldsymbol{Moisture\ Content = \frac{M_w - M_d}{M_w} * 100}$$

Where,

M_w = Wet Weight of Residue (kg)

M_d = Dry Weight of Residue (kg)

The residue was then subjected to a temperature of 925°C, in a muffle furnace, under anaerobic conditions, for 7 minutes. The difference in mass was recorded to determine the mass that escapes/evaporates, i.e. the volatile matter. This residue was then heated at 550°C, in the presence of Oxygen, for 1 hour. The loss in mass was recorded as the amount of fixed carbon and the remaining residue was measured as ash content. The ASTMs for the analysis are listed in Table 1-A, in Appendix 1.

3.1.1.2 Calorific Value

Differential Scanning Calorimetry (DSC) was used to determine the energy content of agricultural residue. This technique measures the change in heat required to increase temperature of the sample in relation to a reference substance. It works on the principle that when a sample undergoes phase transformation, heat flows to or from it. This transfer of heat depends on the properties of the reference substance used, as the main goal is to maintain the two at the same temperature. A small sample, 0.5-100 mg in size, was heated under an inert Nitrogen atmosphere (to allow improved heat conductivity), and a thermocouple was used to detect the difference in temperature. The results were displayed as a curve of 'specific heat' against 'temperature', providing quantitative and qualitative data on endothermic and exothermic processes.

3.1.2 Pre-processing of Raw Material

Before pelletization, the size of agricultural residues was reduced in order to increase uniformity of particles. More uniform particles result in better pelletizability and relatively less energy consumption. A particle size in the range 600 – 850 µm was used for wheat and rice straw. This was achieved by first grinding the residues to reduce size for improved sieving output. They were then passed through a sieve set. The particles passing through sieve # 20 (850 µm opening) and settling on sieve # 30 (600 µm opening) were used for the pelletization process. Cotton-gin by-product cannot be passed through a sieve due to the agglomerating nature of its particles. So, it was only cleaned out to remove excess dirt and other contaminants.

3.1.3 Binding Agent

The choice of additive was based on a number of considerations, which include: accessibility, binding characteristics, cost, environmental impacts, and effect on calorific value. Water was added to each of the binding agents before use in order to attain moisture in the desired range, and to enhance their lubricating abilities and reduce energy consumption during processing. The analysis is as shown in the Table 3.1:

Table 3.1: Comparison and Analysis of different Binding Agents

Evaluating Parameters	Paper Pulp	Starch	Waste Engine Oil
Accessibility	Easily accessible	Varies with region	Varies with region
Cost	12 Rs/kg	235 Rs/kg	35 Rs/litre
Binding Characteristics	Improves mechanical strength	Improves mechanical strength	Reduces mechanical strength
Environmental Impacts	Low Sulphur Content Low NO_x emissions	High CO emissions	High CO emissions
Effect on Calorific Value of fuel	Enhancement	Reduction	Minimal Enhancement

Upon comparison between the three as binding agents in the pelletization of the agricultural residues, paper pulp was chosen as the most effective and feasible one. Old and used newspapers, otherwise wasted, represent a valuable source of energy mainly due easy separation from the waste stream. It is relatively homogeneous and mostly free from non-combustible and toxic contaminants. Moreover, the pulp formation process is relatively simple and quick. It is easily combustible and has a calorific value of 17,538.05 kJ/kg. So, it plays a role in enhancing the calorific value and flammability of the fuel pellet, as a whole. In addition to this, paper pulp has high lignin content; therefore it acts as an effective binding agent for the pellets. From the various moisture contents of paper pulp tested, the optimum value was agreed upon at 74%, for cotton-gin by-product and wheat straw. This moisture content allowed good binding without compromising the quality of the pellet. Rice, however, could not be pelletized with paper pulp, or even with the other binder choices.so, it was eventually negated from the experimentation process.

3.1.3.1 Pulp Making Process

Paper pulp, used in the pelletization process, was made using the process depicted in the following flow chart *(Shyamalee et al., 2015)*:

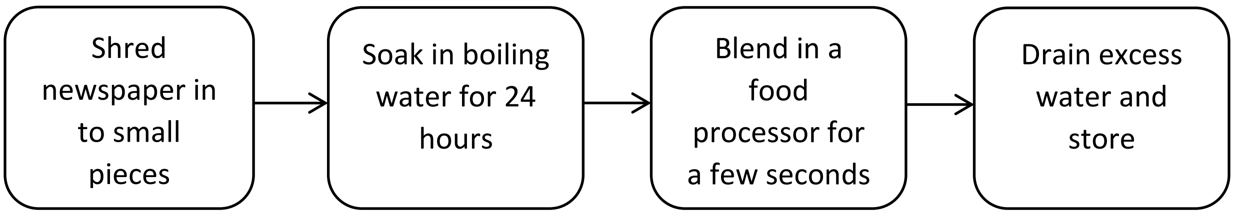


Figure 3.2: Schematic of Pulp Making Process

3.1.4 Compression Assembly and Equipment

For the pelletization assembly, a piston-type compression mechanism, made of mild steel, was fabricated *(Shyamalee et al., 2015)*. The assembly included a hollow cylindrical die, with an inner diameter and height of 3 cm, along with a solid-filled cylindrical rammer with a height of 8 cm. The material to be compressed was filled in to the die and the rammer placed on top. This assembly was then pressed between the plates of a hydraulic press to compress the waste in to a pellet.

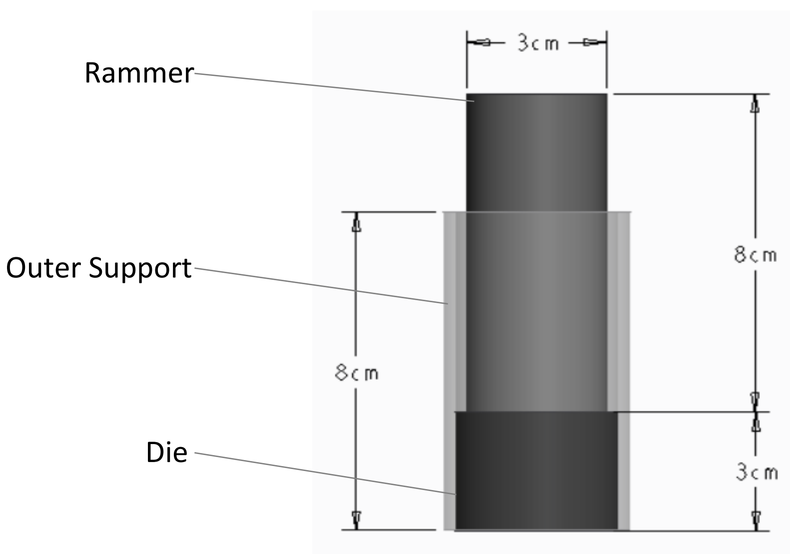


Figure 3.3: CAD Drawing of Pellet Compression Equipment

3.1.5 Experimental Matrix

The pelletizability of the biomass pellets was assessed in two stages: first by varying moisture content of the binding agent and then by varying binder concentration in the pellets. Deductions on the optimum conditions from each stage were based on the mechanical strength of the pellets. The compression pressure and time were kept constant at 21 bars and 3 minutes, respectively, for each stage.

For the first stage, the moisture of the paper pulp was manually adjusted to obtain pulp of two consistencies, one dry and the other wet. The moisture contents of these were determined by the standard oven drying method (Table A-1). The pelletization process was then carried out with both the pulps, while keeping the binder concentration constant at 50%. The pellets were tested for mechanical strength to determine the optimum binder moisture content.

For the second stage, the binder concentration was varied while keeping the binder moisture content constant at the value determined in the first stage. The concentrations were varied at 30% and 50% by weight. These pellets were also tested for mechanical strength to determine the optimum concentration.

3.1.6 Pellet Testing

In order to determine pellet quality, a number of parameters were tested, which are as discussed below:

3.1.6.1 Density

Pellet density indicates effectiveness of the pelletization process, and hence the pellet quality. The density for each individual pellet was calculated using the following formula:

$$\boldsymbol{Density}\ \left(\frac{\boldsymbol{kg}}{\boldsymbol{m^3}}\right) = \frac{\boldsymbol{Mass}}{\boldsymbol{Volume}} = \frac{\boldsymbol{M_p}}{\boldsymbol{\pi r^2 h}}$$

Where,

M_p = Mass of pellet (kg)

r = Radius of pellet (m)

h = Height of pellet (m)

3.1.6.2 Mechanical Strength

Hardness is used as a measure of a material's resistance to permanent deformation. It is an important parameter in determining a pellet's handling and transport properties. Hardness of the pellets was tested in terms of its compressive, or mechanical, strength, and a Universal Testing Machine was used for the purpose. During the test, the maximum load a pellet was able to sustain before cracking was measured in relation to the change in its length (strain). This was achieved by pressing the pellet between two flat plates and gradually increasing the applied load. The load applied per unit deformation was measured and displayed as a stress-strain curve. The Universal Testing Machine had a load capacity of 20 kN and a strain rate of 1 mm/min was used. *(Huang et al., 2017)*

Mechanical strength of the pellets was also used as an indicator of the optimum parameter in each phase of the experimental matrix. For each phase, the pellets were tested for their mechanical strength. The binder moisture content and concentration for which the strength was greatest was taken as the optimum value for that parameter.

3.1.6.3 Proximate Analysis

After going through all stages of the experimental matrix, and deciding the optimum pellet parameters, the produced pellets were tested for their chemical properties using proximate analysis. The procedure of the analysis was similar to the one used in Section 3.1.1.1.

3.1.6.4 Calorific Value

Calorific values for the produced pellets could not be determined using DSC analysis, due to a limitation of sample size. So, the values were interpolated based on the amount of each material present and its individual energy content.

3.2 Design of Cook Stove

The second phase of the project included the design of a cook stove; one that was optimized for the biomass pellets produced during the first phase but could also be used effectively for other biomass fuels. To achieve this objective, a rocket-type stove that works on a natural draft was chosen. This prevented the use of any mechanical parts, such as a fan, thus reducing capital and maintenance costs. The stove provides relatively cleaner combustion than the conventional stoves, reducing emissions by 60% and increasing fuel efficiency by 30% *(Kshirsagar & Kalamkar, 2014)*. It can easily be constructed with low cost and light-weight materials providing ease of utility. The stove design can easily be improvised to suit the required needs.

3.2.1 Cook Stove Material

For the cook stove material, a comparison was made between cast iron and mild steel. A comparison of their physico-chemical properties is shown in Table 3.2:

Table 3.2: Comparison of Materials for Cook Stove

Property	Cast Iron	Mild Steel
Composition	Alloy of Iron and Carbon (>2%)	Low Carbon Steel
Flammability	Non-flammable	Non-flammable
Melting Point	1150-1200°C	1426-1538°C
Specific Heat Capacity	460.5 J/kg·K	510 J/kg·K
Density	6800-7800 kg/m^3	7850 kg/m^3
Ultimate Tensile Strength	200 MPa	440 MPa

In addition to its high melting point, specific heat capacity, and strength, mild steel provided relatively easier machinability and weldability. It was also less costly, more easily available, and more flexible in terms of gauge and size. It provided an appropriate balance between ductility, strength, and toughness, making it convenient to process. Cast iron, on the other hand, was more expensive and less easily available. It was prone to corrosion and difficult to process, due to its non-malleable nature. Also, it had a greater capacity to absorb and contain a greater amount of heat within its structure, making it less practical to use for a cook stove.

Based on this comparison, mild steel (gauge = 16) was chosen for fabrication of the designed cook stove.

3.2.2 Design Simulation Software

An Excel Spreadsheet (Appendix 2) developed by Milind, et.al. (2015) was used to simulate the design of the cook stove. The spreadsheet has been developed based on several rocket biomass stoves and provides comprehensive and simple means of correlating stove design and performance. The software allows the variation of 20 input design and operational parameters to observe their effect on 31 output parameters that determine the fuel and thermal efficiency of the stove, mass and energy balance of the system, and flue gas properties. Dimensions of the cook stove were adjusted to cater to the fuel properties, such as moisture content and calorific value, and the stove performance desired. ***(Kshirsagar & Kalamkar, 2015)***

3.2.3 Cook Stove Components

The designed cook stove, illustrated in Figure3.4, has the following components:

- **Combustion chimney and elbow:** It is a vertical t-shaped cylindrical pipe, with a diameter of 10cm, in which the combustion of fuel takes place. Fuel is placed at the junction and air enters the combustion chamber through the elbow. The chimney ensures complete combustion of the fuel before the flame reaches the top surface (or pot). The hot combustion gases travel to the top, thus allowing a natural draft due to convection. Cooking is done on top of this chimney, which allows better containment of the flame and less loss of heat from the combustion chamber. This results in higher temperatures and combustion and fuel efficiency.
- **Fuel tray:** It is a flat circular plate placed at the junction of the elbow and chimney, on which the fuel is placed for combustion. The plate is grated to ensure that air reaches the fuel from the bottom and ash falls to the bottom without causing any blockage.
- **Insulation layer:** The combustion chimney is surrounded by a 3cm thick layer of insulation on all sides to minimize heat loss from the combustion chamber. The insulation layer is enclosed within a steel pipe that has a diameter of 16cm.
- **Ash collection plate:** A detachable plate is attached to the bottom of the stove that collects ash during operation. The plate’s latch may be opened to remove ash when necessary.

- **Auxiliary features:** Support features added to the stove include: fixtures at the top to hold the pot, and wooden handles on the sides to allow easier handling and avoiding contact with the hot stove surface.

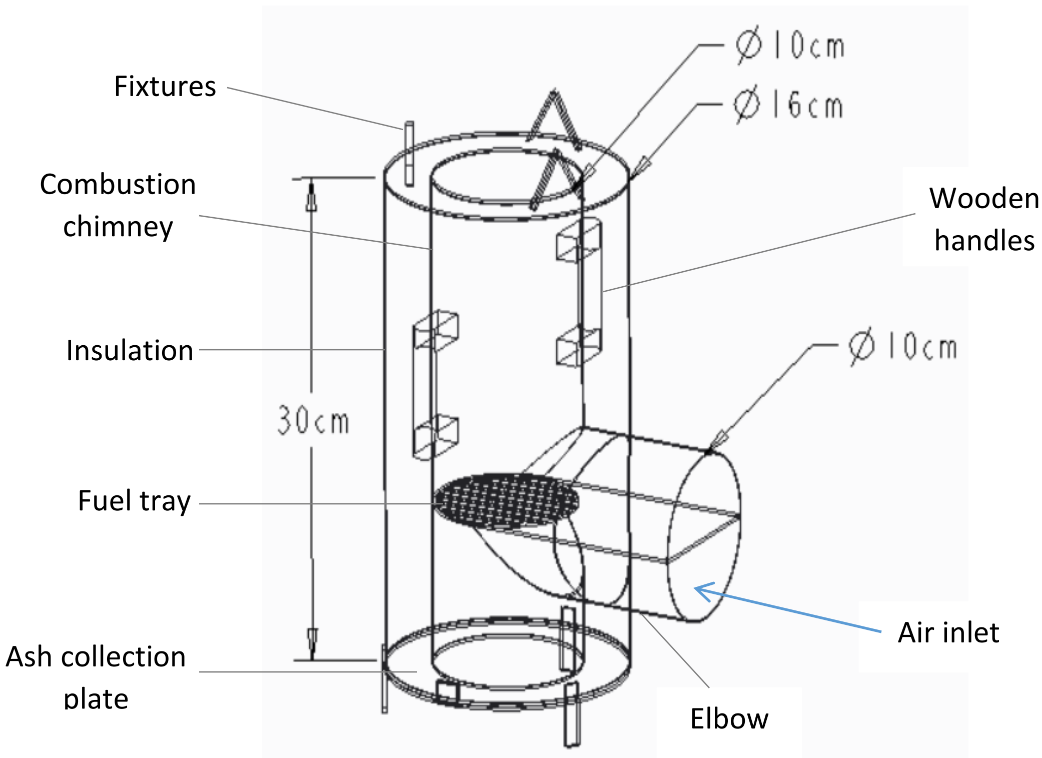


Figure 3.4: CAD Drawing of Cook Stove Design

3.2.4 Insulation Material

The insulation material should be such that losses from the combustion chamber are minimized and surface temperature does not become very high during operation. For this purpose, mineral wool is most commonly used. It also provides the advantage of being inflammable in nature. It may be one of the three types: glass, rock and ceramic wool. For the designed cook stove, rock wool was used as insulation as it offers thermal performance in the required operating temperature range (>750°C) and was locally available. Also, the pockets of air in the structure, formed when the wool fibres are pressed into sheets, enhance the insulative properties. Rock wool provides the additional advantage of being bio-soluble, rather than being soluble in water, reducing its potential to cause pollution. Important properties of the material are listed in Table 3.3:

Table 3.3: Properties of Rock Wool Insulation

Composition	Basalt or Diabase
Melting Point	> 750°C
Flammability	Non-flammable
Corrosivity	Irritates skin upon touching (Gloves required for use)
Stability	Chemically stable
R-Value	2.8 – 3.5

3.2.5 Cook Stove Testing

3.2.5.1 Efficiency Testing

To test thermal efficiency of the designed cook stove, the standard Water Boiling Test was used. As per the WBT 4.2.3 protocol *(EPA, PCIA, 2013)*, the test consisted of three successive phases:

- **Cold start high power phase:** This phase initiated the test by heating 2.5 litres of water using the cold stove. The water was heated till it reached boiling temperature, i.e. 100 ±2°C. At the end, the flame was extinguished, char was removed from the stove, and water in the pot was discarded.
- **Hot start high power phase:** This phase took off immediately from the first phase and involved heating 2.5 litres of water till boiling temperature, in a hot cook stove, i.e. a recently used one. At the end, the flame was extinguished however, the char was not removed and the water in the pot was used for the next phase rather than being discarded.
- **Low power simmering phase:** This phase involved keeping the temperature of the water, remaining after the hot start phase, close to 3°C below boiling for 45 minutes. The temperature was not allowed to go more than 6°C below the boiling temperature at

any time during this phase. At the end, the flame was extinguished, char was removed from the stove, and water in the pot was discarded.

At each phase of the test, a number of measurements were made, which include: mass of water evaporated, mass of fuel consumed, mass of char left when combustion was complete, initial and final temperatures of water, and the time to complete each phase. These variables were then used to calculate the thermal efficiency of each phase using the following formula *(Quist, Jones, & Lewis, 2016)*:

$$\eta = \frac{\textit{Sensible heat} + \textit{Latent heat}}{\textit{Energy available in dry fuel} - \textit{Energy required to remove moisture} - \textit{Energy remaining in chacoal}}$$

$$\eta = \frac{\left(Cp_w * m_w * \left(T_f - T_i\right)\right) + (\Delta h_w * \Delta m_w)}{\left(m_f * (1 - MC) * LHV_f\right) - \left(m_f * MC * y * LHV_f\right) - (LHV_c * m_c)}$$

Where,

Cp_w = Heat capacity of water at 100°C = 4.219 kJ/kg·K

m_w = Initial mass of water = 2.5kg

T_f = Final temperature of water (K)

T_i = Initial temperature of water (K)

Δh_w = Latent heat of vapourization of water at 1atm = 2259.36 kJ/kg

Δm_w = Mass of water evaporated during the test (kg)

m_f = Mass of fuel consumed (kg)

MC = Moisture content of fuel (%)

LHV_f = Calorific value of fuel (kJ/kg)

LHV_c = Calorific value of char (kJ/kg)

m_c = Mass of char produced (kg)

The value of ‘y’, which is a factor to account for the energy lost to removal of moisture from the fuel, may be calculated as:

$$y = \frac{\left(Cp_w * (T_{boil} - T_{amb})\right) + \Delta h_w}{LHV_f}$$

For each phase, the fire power was also calculated. Firepower is a measure of the amount of energy released per unit time, and is calculated using the following formula:

$$Fire\ Power\ (W) = \frac{Mass\ of\ fuel\ consumed}{Time\ to\ complete\ the\ phase}$$

The fire power for the boiling phase was calculated as the average of the first two phases, whereas for the simmering phase, it was calculated as the power for the low power phase. Ideally, the fire power for the boiling phase should be greater than that for the simmering phase.

3.2.5.2 Emission Testing

The designed prototype was tested for the amount of gaseous emissions using an emission collection hood and a flue gas analyzer. The stove was placed and operated inside the emission collection hood, which concentrated the emitted flue gases using its conical shape. The concentrated flue gases were then analyzed by the flue gas analyzer whose probe had been placed inside the hood outlet. The flue gas analyzer gave continuous measurements of flue gas temperature and pressure drop. It also measured concentrations of Oxygen, Carbon Monoxide, and oxides of Nitrogen in the flue gas.

From these measurements, the concentrations of Carbon Monoxide were quantified and compared with emissions from conventional and improved cook stoves from literature. The concentration of CO in the flue gas was first determined (at atmospheric pressure and temperature) using:

$$Concentration\ \left(\frac{mg}{m^3}\right) = \frac{Concentration\ (ppm) * MW_{CO}}{24.4}$$

Where,

MW_{CO} = Molecular Weight of Carbon Monoxide

The volume of flue gas was then determined using the area of orifice opening of the emission collection hood and the velocity of flue gas, at standard conditions of pressure and temperature, as *(Jittadejchaiyapath, 2016)*:

$$\boldsymbol{V_{std} = (A * v * t) * \frac{P_a}{P_s} * \frac{T_s}{T_a}}$$

Where,

V_{std} = Volume of flue gas at standard conditions (m^3)

A = Area of orifice = 0.0040 m^2

v = Velocity of flue gas (m/s) determined via interpolation

t = Sampling time (s)

P_a = Actual pressure (atm)

P_s = Atmospheric pressure = 1 atm

T_s = Ambient temperature = 25°C

T_a = Actual temperature of flue gas (°C)

The amount of Carbon Monoxide produced per unit mass of fuel burned was then calculated using the following formula *(Jittadejchaiyapath, 2016)*:

$$\boldsymbol{Emission\ Factor = \frac{Concentration\ of\ pollutant\ (\frac{mg}{m^3}) * V_{std}}{m_f}}$$

Where,

Emission Factor = Mass of CO produced per unit mass of fuel burned (mg/kg)

m_f = mass of fuel burned (kg)

The Carbon Monoxide emissions were determined for two phases of the combustion process, which are: flaming and smouldering. Both the phases were tested for in the designed prototype and compared with the conventional 3-stone stove. Also, the analysis was conducted for combustion when using 75% wood in combination with 25% pellets, in comparison with using 100% wood as fuel.

3.2.6 Co-combustion

In order to increase adaptability, the cook stove was tested using the common concept of co-combustion. The pellet fuel was burned with wood in various combinations (percentage by weight) to ultimately determine the optimum combination, i.e. one that uses minimum amount of wood while achieving high efficiency. The tested combinations include:

- Combustion using 100% wood.
- Combustion using 75% wood and 25% pellets
- Combustion using 60% wood and 40% pellets

For all the tests, fuel wood with properties listed in Table 3.4 was used:

Table 3.4: Properties of Fuel Wood

Moisture Content	18.15%
Volatile Matter	77%
Fixed Carbon	22.40%
Ash Content	0.60%
Net Calorific Value (LHV)	18.92 MJ/kg

3.2.7 Comparison with other cook stoves

The results of the efficiency and emission analysis of the cook stove were compared for the various co-combustion combinations used. In order to increase validity, the results were also compared to the operation of a conventional 3-stone stove and two other improved cook stoves, taken from literature *(Kshirsagar & Kalamkar, 2014)*.

The improved cook stoves referred to include:

- Envirofit G-3300 stove, tested with 100% fuel wood.
- StoveTec Greenfire stove, tested with both, wood and biomass.

Chapter 4: Results and Discussions

As per the results of the experimental phase, both the project objectives were fulfilled. Cotton-gin by-product, with paper pulp as a binding agent, was chosen as the optimum biomass fuel. Appreciable pelletization was achieved for it even under ambient temperatures and with application of a minimal pressure of 21 bars. On average, the cylindrical pellets formed had a diameter of 3 cm and a height of 2 cm. A compression time of 3 minutes was sufficient to allow pelletization. For the green cook stove, mild steel was used as the main construction material and rock wool as the insulation. Several tests were carried out on first the individual pellets and then on the stove operated in combination with them. The results of these tests are discussed in this chapter.

4.1 Analysis of Raw Fuel

4.1.1 Proximate analysis

The proximate analysis of an individual 2 gram sample of the pre-processed residues of cotton, wheat, and rice revealed that moisture content was within the desirable limit of 5% for all three. The ash contents were also found to be quite low in case of cotton-gin and wheat straw. Similarly, the volatile matter for all three residues was found to be high, with the highest for wheat. The results indicate a greater suitability of cotton-gin by-product and wheat straw, as fuel sources, in comparison with rice straw.

Table 4.1: Proximate Analysis of Raw Agricultural Residue

Agricultural Residue	Moisture Content (%)	Volatile Matter (%)	Fixed Carbon (%)	Ash Content (%)
Cotton-gin By-product	5.33	52.64	32.13	9.90
Wheat Straw	6.11	55.71	29.39	8.79
Rice Straw	4.86	47.41	29.43	18.30

4.1.2 Calorific Value

Results of the differential scanning calorimetric analysis of the three pre-processed residues showed a mostly exothermic peak for cotton-gin by-product in comparison with relatively more endothermic peaks for wheat and rice straws. This indicates that wheat and rice straws require more energy to burn than they give off during combustion. On the other hand, cotton-gin by-product releases a significant amount of heat, while requiring much less activation energy. Comparing the specific heats at a fixed value of temperature revealed that the calorific values of cotton-gin by-product and wheat straw were higher than rice straw.

Table 4.2: DSC Results of Raw Agricultural Residue

Agricultural Residue	Nature of Peak	Calorific Value(kJ/kg)
Cotton-gin By-product	Exothermic	16323.18
Wheat Straw	More Endothermic	16950.00
Rice Straw	More Endothermic	15300.00

4.2 Analysis of Pelletized Fuel

4.2.1 Proximate Analysis

Proximate analysis of the residues after undergoing pelletization indicated a significant increase in volatile matter and a decrease in ash content, thus highlighting the success of the process in improving combustion characteristics of the fuel. The moisture content of the pellets was relatively high initially, as shown in Table 4.3, but it was reduced to less than 5% by sun drying before use. Since pelletization of rice straw could not be achieved, its proximate analysis was not conducted.

Table 4.3: Proximate Analysis of Pelletized Fuel

Agricultural Residue	Moisture Content (%)	Volatile Matter (%)	Fixed Carbon (%)	Ash Content (%)
Cotton-gin By-product	11.80	82.90	12.60	4.40
Wheat Straw	17.40	81.00	13.10	5.90
Rice Straw	Pelletization not achieved			

4.2.2 Calorific Value

The calorific value of the cotton-gin by-product showed a slight increase whereas that for wheat straw showed a decrease upon addition of the binder and pelletization, as shown in Table 4.4. This indicates a greater suitability of cotton-gin by-product for use as pelletized fuel in comparison with wheat straw. Again, rice straw could not be pelletized, so no results were obtained.

Table 4.4: Interpolated Calorific Values of Pelletized Fuel

Agricultural Residue	Calorific Value (kJ/pellet)
Cotton-gin By-product	165.21
Wheat Straw	117.19
Rice Straw	Pelletization not achieved

4.2.3 Mechanical Strength

Mechanical strength of the pellets was considered as the criteria upon which all other process parameters were tested. When using stress-strain curves, a higher mechanical strength is exhibited by the material that undergoes minimum change in length (strain) upon maximum applied stress. Therefore, the material for which the curve extends to a higher value of stress and breaks off at a lower value of strains has the higher mechanical strength, which is desired.

Rice straw could not be pelletized so, no results were obtained for it. For the first phase of the experimental matrix (stated previously), the highest mechanical strength was observed for the pellets formed using paper pulp with a moisture content of 74%. Generally, the mechanical strength was seen to increase with an increase in moisture content of the binder, after which it started to decrease. This may be attributed to increased lubrication due to excess water.

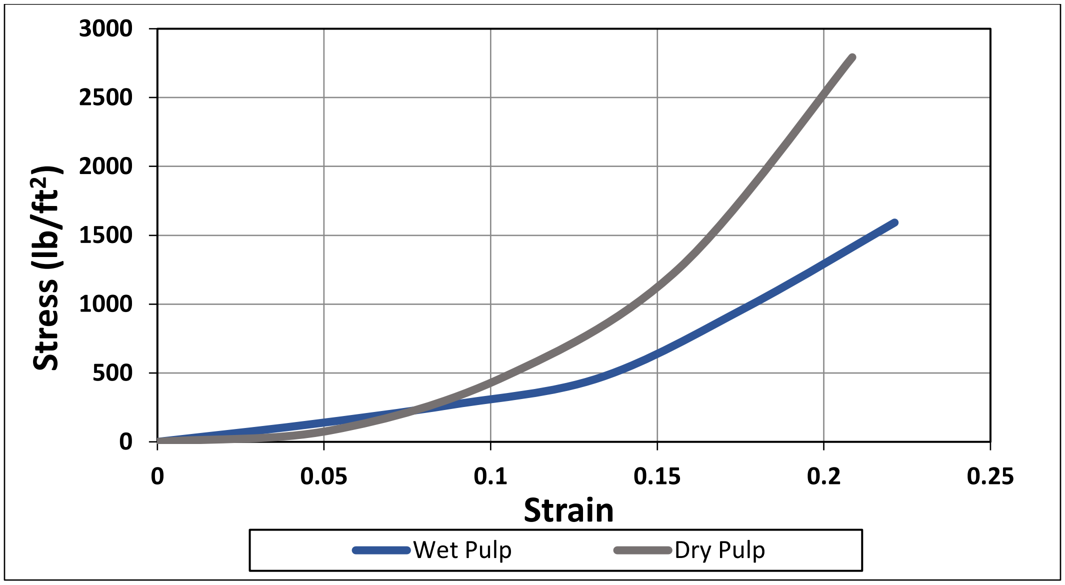


Figure 4.1: Stress-Strain Curves of Varying Moisture Contents of Paper Pulp

For the second phase of the matrix, binder concentration in the pellets was varied. The mechanical strength increased when the binder concentration was increased from 30% to 50% for cotton-gin by-product and wheat straw. This indicates that a higher binder concentration results in more efficient pelletization of the biomass.

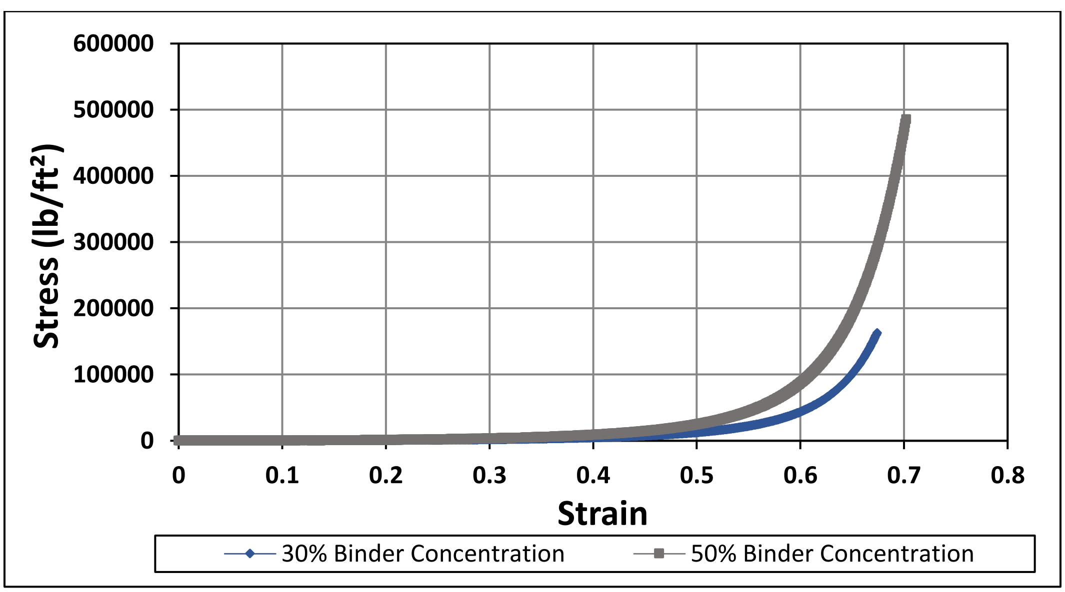


Figure 4.2: Stress-Strain Curves of Varying Binder Concentration in Wheat Pellets

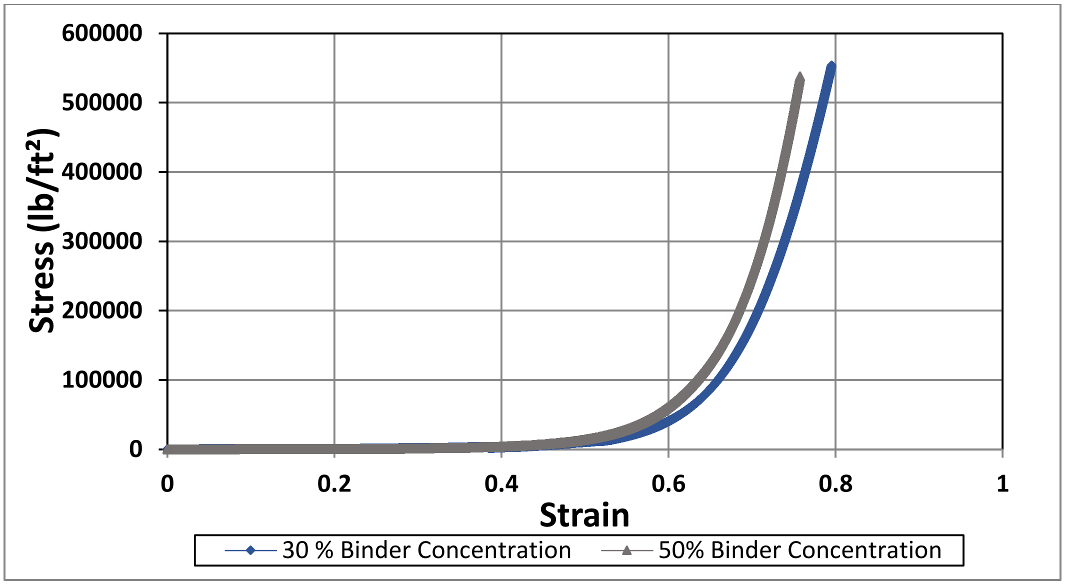


Figure 4.3: Stress-Strain Curves of Varying Binder Concentration in Cotton-gin by-product Pellets

Once the optimum pellets for both, cotton-gin by-product and wheat straw had been identified, mechanical strengths of the two were compared. The results showed a greater strength for pellets of cotton-gin by-product in comparison with wheat straw, as they had a higher density and better binding characteristics at ambient temperature.

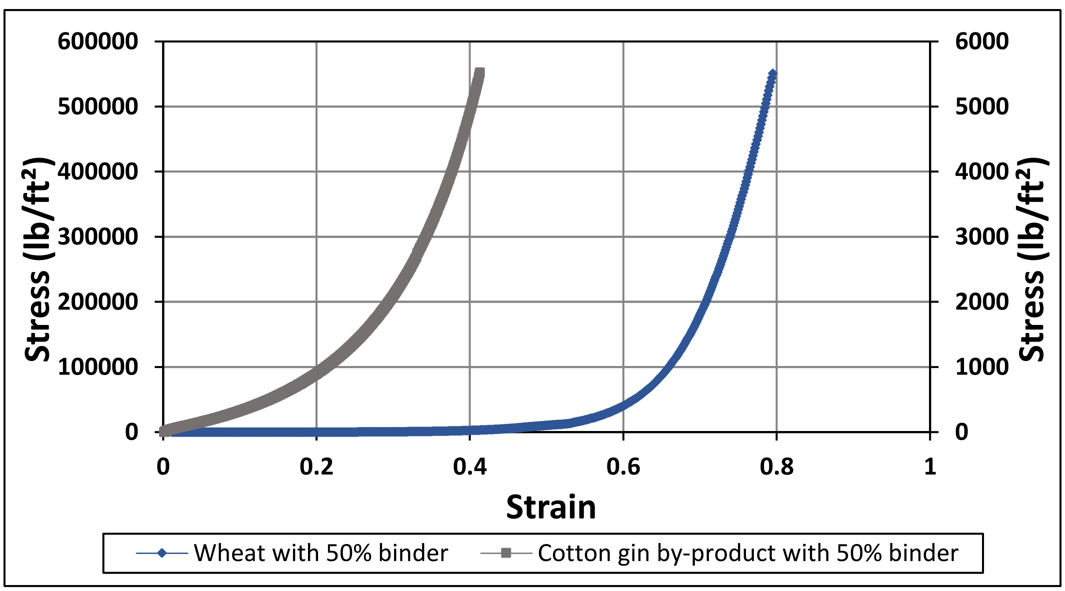


Figure 4.4: Comparison of Mechanical Strength of Optimum Cotton-gin by-product and Wheat Pellets

4.3 Cook Stove Efficiency

4.3.1 Thermal Efficiency

The cook stove was tested for combustion of 100% wood and co-combustion of wood and the selected fuel pellets. The results revealed a higher efficiency for the prototype for co-combustion in comparison with other widely used conventional and improved cook stoves. Among the co-combustion combinations tested, the thermal efficiency was higher for 40% pellets, in comparison with 25% pellets, at 44% and 41%, respectively. This validated the efficiency of the fuel pellets and their suitability to the designed prototype. The efficiency of the prototype was high even with 100% wood in comparison with a conventional stove, as shown in Figure 4.5.

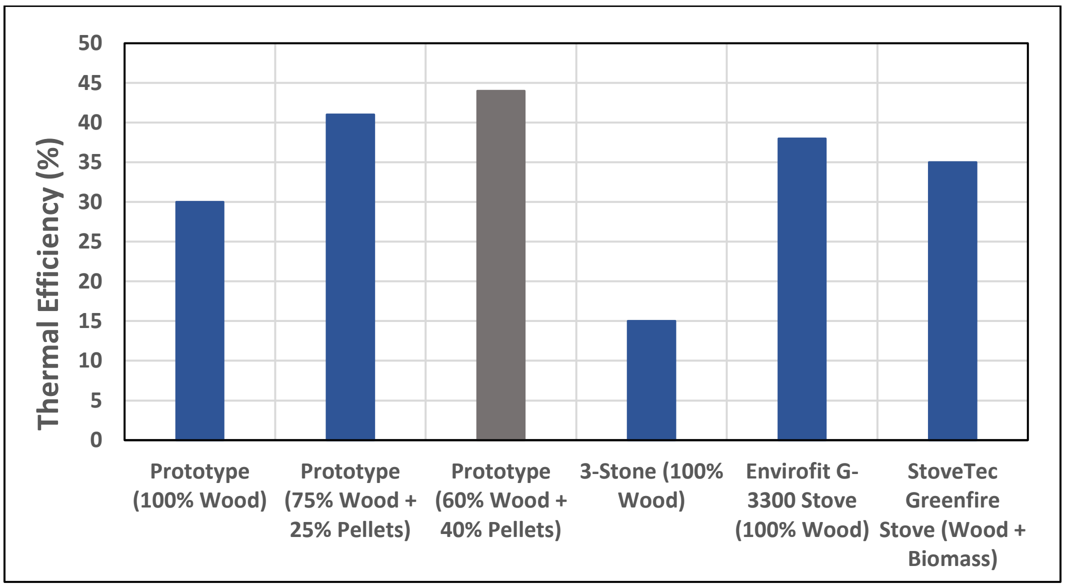


Figure 4.5: Comparison of Thermal Efficiency of the Prototype (using 3 different fuel combinations) with Conventional and 2 other Improved Cook Stoves

4.3.2 Fire Power

Higher power during the boiling phase and lower power during the simmering phase for all cook stoves validated the results of the water boiling test. Fire powers calculated for the prototype during both, the boiling and the simmering phases were found to be higher than the conventional 3-stone stove and two other types of improved cook stoves. Also, these results proved that the prototype was designed at higher fire power, as was the objective because smaller stoves have less consumer acceptability in Pakistan.

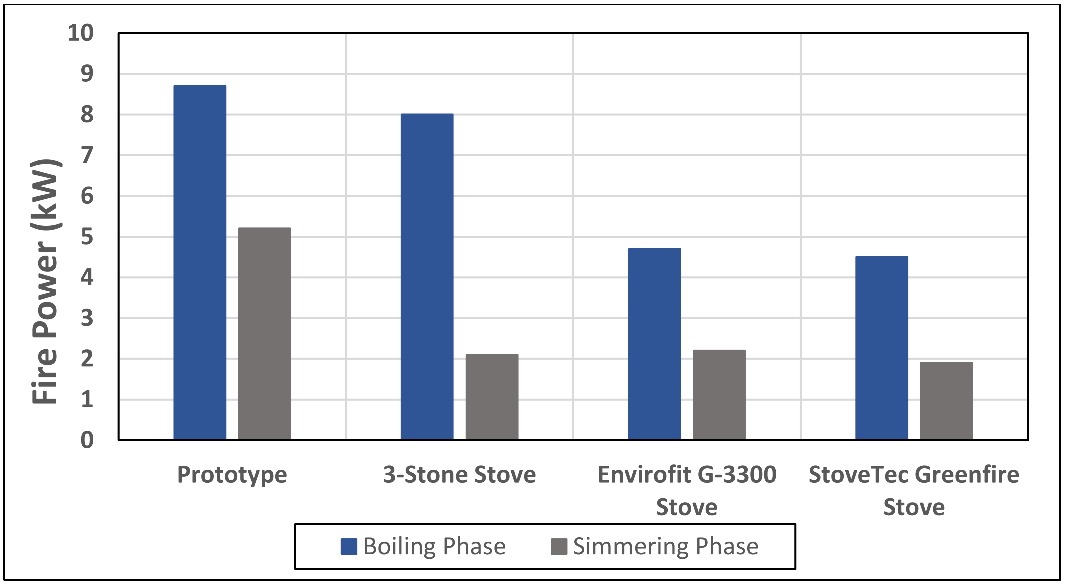


Figure 4.6: Comparison of Fire Power of the Prototype with Conventional and 2 other Improved Cook Stoves

4.3.3 Emissions

The emissions of Caron Monoxide, as measured using the flue gas analyzer, were considerably less for the designed prototype, when compared with both, a conventional 3-stone stove and two globally used improved cook stoves. A minimum concentration of 2.21 g/L of CO was observed when the fuel was burned in a combination of 25% pellets and 75% wood. Emissions for the prototype were significantly higher when 100% wood was burned in it. However, they were still low in comparison with the conventional 3-stone fire that burns 100% wood, which were at 12 g/L of CO. A significant reduction in smoke was also observed during operation of the stove, with an increasing percentage of pellets used. The analysis of Carbon Monoxide emissions indicates a considerably higher efficiency of design of the prototype, as shown by the bar chart in Figure 4.7.

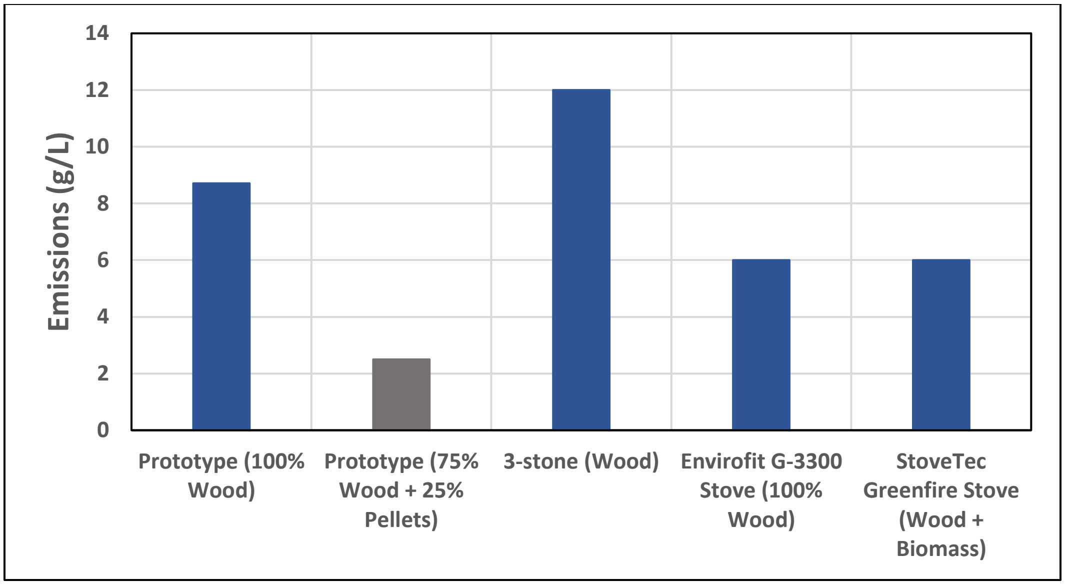


Figure 4.7: Comparison of CO Emissions of the Prototype (using 2 types of fuel) with Conventional and 2 other Improved Cook Stoves

Also, CO emissions during the flaming phase were higher than those during the smouldering phase. Since cotton-gin by-product has a higher smouldering phase in comparison with wood, the emissions were considerably lesser for co-combustion.

Chapter 5: Cost Analysis

Pellet production technology belongs to the category of alternate energy. In recent years, fuel pelletization has become a promising investment project. In terms of cost, pellet production is affected by a number of factors. These factors include: cost of local raw material including transportation, energy required for production, labour, machine use and depreciation. The breakdown, along with the total cost, of the product is discussed in this chapter.

5.1 Cost Analysis of Pellet Fuel

Generally, the conventional fuel used throughout the world is wood, which when burned openly causes a great amount of pollution. To replace that with a sustainable and environmental friendly fuel, cotton-gin by-product pellets have been developed. The total production cost of these pellets is described in Table 5.1 below:

Table 5.1: Production Cost of Cotton-gin by-product Pellets

Description		Cost (Rs/40kg)
Raw material	Newspaper	480
	Cotton-gin by-product	150
Total cost of pellet raw material		**315**
Depreciation cost of hydraulic press		10
Labour cost		12
Total cost		**347**

The calculated cost of pellets is clearly comparable with the cost of fuel wood, which is Rs. 530/40kg.

5.2 Cost Analysis of Cook Stove

A 3-stone fire is the most commonly used cook stove in the rural areas of Pakistan. There are no costs associated with its production, since it is constructed merely by placing three levelled stones in a triangular arrangement. So, no initial investment is involved. The only cost is of the fuel, which is mostly firewood.

Based on market discussions, cost of the cook stove has been estimated at 1500 Rs/piece as per bulk production of 100 pieces. This includes the cost of raw material and fabrication. The prototype demands initial investment in comparison with a 3-stone stove. However, it pays back in no time in combination with the cotton-gin by-product pellets, as it saves a considerable amount on fuel. Based on fuel efficiency of the designed stove, 35% less fuel may be consumed in comparison with a conventional 3-stone stove. This provides a more sustainable option in the long run.

5.3 Total Project Cost

From the cost analysis discussed above, a comparison of consumption costs of the two fuels, when used with the designed stove, is shown in the Table 5.2:

Table 5.2: Comparison of Fuel Costs

Fuel type	Consumption rate (kg/day)	Cost of fuel consumption (Rs/day)
Wood	5	66.25
Pellets	3.5	30.36

Based on this, every household will be able to save 35.89 Rs/day on fuel. For the consumers, this results in a payback period of approximately 42 days, for the cook stove.

5.4 Investment Potential and Projected Savings

Total cost of the project, from an investor's perspective, with a life of approximately 3 years is shown in Table 5.3. For the analysis, a single stove and its resultant fuel required for a year have been considered.

Table 5.3: Projected Cost of Product Development

	Initial Investment on Cook Stove (Rs/stove)	Initial Cost of Pellet (@ (3.5 kg/day)/month)	Labour Cost (@ Rs. 12/40 kg/month)	Total Development Cost (Rs/yr)
Year 1	1,500	879.3	31.5	2,410.8
Year 2	1,600	929.1	33.0	2,562.1
Year 3	1,700	982.2	34.5	2,716.7
Total	**4,800**	**2,790.6**	**99**	**7,689.6**

For comparison between conventional fuel and pellets, the costs saved when using pellets instead of fuel wood, for a period of 3 years, are calculated as shown in Table 5.4:

Table 5.4: Comparison of annual costs of Wood and Pellets

	Total Annual Cost of Fuel Wood (Rs/yr)	Total Annual Cost of Pellet Fuel (Rs/yr)	Annual Savings (Rs/yr)
Year 1	23,850	11,025	12,825
Year 2	25,000	11,545.2	13,454.8
Year 3	27,000	12,700.8	14,299.2
Total	**75,850**	**35,271**	**40,579**

The costs saved by the combination of the stove and pellets, is shown to increase each year during the three year period, as shown by the graph in Figure 5.1. The initial investment on the stove can be covered by the net savings gained in the first year of the project.

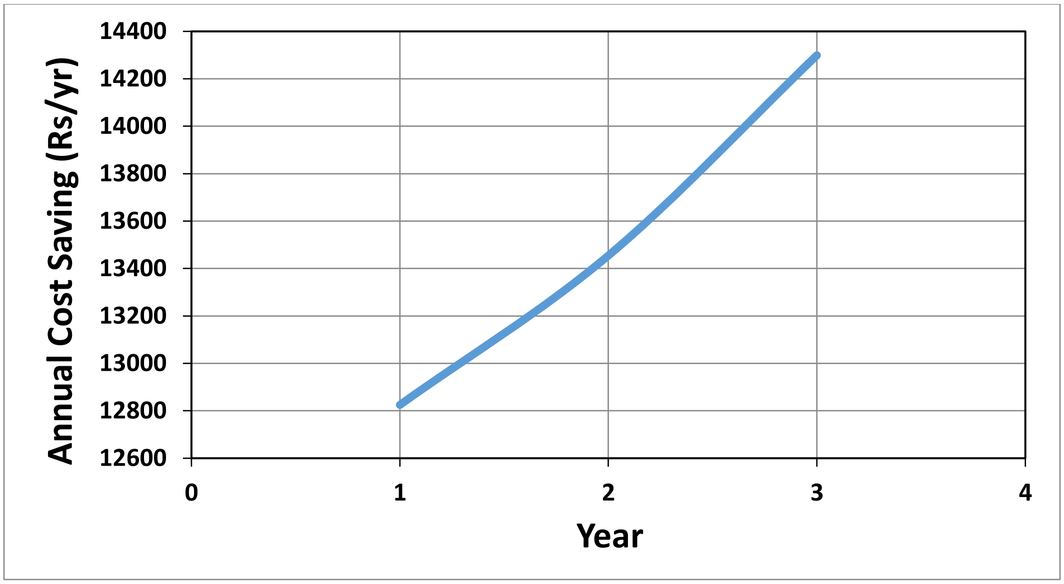


Figure 5.1: Annual Cost Savings for the Product

CONCLUSIONS

According to the objectives of obtaining a low cost sustainable fuel by pelletization of agricultural residue, and the design of an environment friendly cook stove specific to that residue, results of the research on the two products have led to the following conclusions:

- The agricultural residues were selected based on their availability and fuel potential. For selection of the additive to be used, the criteria observed include: accessibility, cost, binding characteristics, environmental impacts, and the effect on calorific value. Waste newspaper, used as raw material for pulp formation, is readily available throughout the country in contrast with starch or waste engine oil, which are accessible according to the region. Variation in cost of binders provided a comparison for feasibility analysis. The binding characteristics, as per literature review, show that paper pulp and starch improve mechanical durability of the pellets while the waste engine oil reduces it. Paper pulp has low sulphur content, and its use leads to fewer nitrogen oxides (NOx) emissions along with enhancing the calorific value. Furthermore, starch additives tend to reduce calorific value of the pellets while significantly increasing Carbon Monoxide emissions. Similar observations were made during the experimentation process, concluding paper pulp as the most feasible and suitable option to be used as a binder. However, paper pulp alone was not sufficient to yield high quality wheat and rice straw pellets, under ambient conditions.
- To compare the products of the complete process of pelletization for both cotton-gin by-product and wheat residue, their fuel characteristic analysis was done along with testing their mechanical strength.
- According to the experimental matrix set up to vary moisture content of the binder and its concentration for both the residues, the resultant of each variation was tested for mechanical strength to enable the next variation. The optimum moisture content of paper pulp (74%) in combination with the optimum binder concentration (50%) exhibited higher compressive strength for both residues. This is backed by the literature on pelletization as addition of binder enhances the calorific value of pellets while

simultaneously increasing the mechanical durability needed for their handling and transport.

- For the optimum choice of sustainable fuel, a comparison between both types of residues was made based on compressive strength. The results indicated a higher compressive strength for pellets composed of cotton-gin by-product with paper pulp as additive. This provided the requirements for mass production of the fuel.
- For the second phase of the project involving the design of a green cook stove, an Excel Spreadsheet software, developed by Milind and his co-workers, was utilized to adjust the dimensions of stove for optimum simulation. The primary focus was on the 10 physical parameters to enhance the design.
- After the prototype was fabricated, it was tested using the standard water boiling test to determine the working stove's important characteristics namely firepower, efficiency and Carbon Monoxide emissions when used with the designated fuel.
- Firepower of the prototype during boiling and simmering phases was comparatively higher than the conventional 3-stone and two other types of improved cook stoves from the literature. The results indicated the prototype to be at a higher firepower, as smaller fire powered stoves have less consumer acceptability in Pakistan.
- The emissions for Carbon Monoxide were tested for 100% wood and combinations of wood and pellets to provide a sufficient comparison. The results concluded lesser emissions for the fuel combinations, indicating the product's environmental friendliness in comparison with other reported stoves.
- The results for efficiency testing revealed a higher efficiency of the prototype for co-combustion in comparison with other widely used conventional and improved cook stoves. Since co-combustion is a widely accepted and used phenomenon, consuming the cotton-gin by-product fuel in such a manner would also increase its acceptability along with reducing the burden on other conventional fuels, such as wood. The conducted tests represent various combinations of pellets with wood. Increasing the percentage of pellets in the combination showed an increase in efficiency of the stove which validated the efficiency of the fuel. This indicated that the prototype was optimized for co-

combustion of pellets along with wood, as a fuel source, with the optimum combination at 60% wood and 40% pellets.

- The use of cotton-gin by-product biomass pellets for combustion in the designed prototype holds the potential to present a cost-effective solution to the previously stated issues of Pakistan. The stove, when used with the proposed fuel, has a payback period of less than 2 months, while consuming 35% less fuel wood. This ensures a much less operating cost in comparison with the conventional methods used. The lowered expenditure, coupled with the added advantages to health and the environment due to reduced CO emissions, significantly improve the product's prospects in terms of user acceptability and adaptability.

RECOMMENDATIONS

Throughout the course of the project, several observations were made that might help in improving efficiency of the stove and the quality of fuel produced. Based on these, we would like to make the following recommendations:

- Other types of additives, such as cow dung, for the pelletization of agricultural residue may be explored. Since we started out with three types of residues, but excluded rice straw because of difficulty in pelletization, due to lack of appropriate additive under given conditions, it is suggested that various binders be tried according to suitability with each residue. While paper pulp seemed to be a comfortable additive for cotton-gin by-product, it still represented a little difficulty for wheat straw. Other options for binders may be explored for optimum choice for each residue.
- Since pellet production was done using a manually operated hydraulic press, the process took a lot of time, as only a single pellet could be produced at a given time. However, the effectiveness of the pelletization process may be enhanced by the use of an appropriately designed pelletization mill. This will reduce the production time as multiple pellets can be produced simultaneously. This will also eliminate the errors that arise due to manual operation.
- There are two types of popular improved cook stoves namely rocket biomass and semi-gasifier cook stoves. We have worked on the rocket biomass stove keeping in mind our requirements and target audience. However, considering the fuel, the other type can be applied as well to enhance fuel consumption characteristics. Since cotton-gin by-product has a higher VOC content, it may be applied to a semi-gasifier cook stove for optimal utilization of its energy content.
- Experimentation with other insulation materials may further enhance thermal efficiency of the stove. We have only used rock wool insulation due to its easy availability and suitable characteristics according to conditions. Better insulation, such as ceramic wool, will prevent heat loss while simultaneously increasing efficiency of the whole process. Since rocket stoves are known for reaching high temperatures, up to 1000°C, the rock

wool may not be very effective, as it merely provides insulation up to 850°C. A change in insulation catering to higher temperatures will surely prevent heat losses and increase thermal efficiency.

- Since the stove is a prototype rocket biomass stove catering to pellets instead of traditional logs, the addition of fuel to the main combustion chamber (chimney) is an unsafe process. A safer mechanism to add fuel pellets to the cook stove needs to be explored. This may include the usage of tongs to add pellets one at a time or amending the design to add a larger volume of pellets, together, safely.

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APPENDIX 1

Table 1-A: ASTMs of the methods used in analysis

ASTM	Description
D3173	Standard test method for determining Moisture Content
D3174	Standard test method for Ash Analysis
D3175	Standard test method for Volatile Matter Analysis
D4179	Standard test method for Single Pellet Crush Strength
D5142	Standard test method for determining Fixed Carbon
E1269	Standard test method for determining Specific Heat Capacity by Differential Scanning Calorimetry

Table 1-B: Calorific Values of Various Materials

Material	Calorific Value (kJ/kg)
Cotton-gin by-product	16323.18
Char	29500.00
Newspaper	17,538.05
Rice Straw	15300.00
Wheat Straw	16950.00
Wood (Acacia)	18920.00

APPENDIX 2

Input Parameters (Operational)				
SN	Parameter	symbol	value	unit
1	Fire power	P	3.73	kW
2	Combustion efficiency	η_c	0.995	
3	Lower or net calorific value of fuel (Dry basis)	NCV	18280	kJ/kg
4	Moisture content of fuel (Wet basis)	M	7.0	%
5	Surface temperature of pot	Ts	373	K
6	Ambient temperature	Ta	300	K
7	Char Emissivity	εc	0.85	
8	Char temperature	Tchar	1100	K
9	Inlet area ratio	Ar	0.78	
Input Parameters (Physical)				
10	Chimney diameter	D	100	mm
11	Height of the chimney	H	300	mm
12	Stove outer diameter	Do	160	mm
13	Area factor for elbow length	Ae	1.67	
14	Feed area/Chimney area factor	Af	1	
15	Inner pot gap Width	Wi	18	mm
16	Outer pot gap width	Wo	18	mm
17	Pot diameter	Dp	225	mm
18	Pot height	Hp	162	mm
19	Height of water in pot	Hw	126	mm
20	Insulation thermal conductivity	k	0.24	W/mK
Intermediate parameters (Predicted)				
21	Insulation thickness	t	30.0	mm
22	Friction factor for Combustion Chamber	fc	0.070	
23	Gas Emissivity in Combustion Chamber	εg	0.106	
24	Gas Emissivity in pot gap	ε3	0.035	
25	Gas Emissivity in skirt gap	ε4	0.034	
26	Hydraulic diameter of elbow portion	D_h	0.083	m
27	C/S area of conmbustion chamber	A	0.007854	m^2
28	View factor between char bed and pot surface	$F_{char-pot}$	0.024	
29	View factor between char bed and feed door	$F_{char-door}$	0.200	
30	View factor between char bed and inner wall	$F_{char-wall}$	0.976	

Output Parameters				
SN	Parameter	symbol	value	unit
1	Fuel burn rate (dry)	mf	0.00020	kg of dry fuel/s
2	Fuel burn rate (wet)	mfw	0.00022	kg of dry fuel/s
3	Flame Temperature	Tg	1034	K
4	Entrance Temperature	Te	1022	K
5	Corner Temperature	Tc	958	K
6	Exit Temperature	Tex	716	K
7	Inner Wall Temperature	Ti	997	K
8	Outer Wall Temperature	To	572	K
9	Coefficient of discharge	Cd	0.306	
10	Flue produced per kg of dry fuel	mfg	15.50	kg/kg dry fuel
11	Mass flow rate of air	ma	14.42	kg/kg dry fuel
12	Excess air factor	λ	2.19	
13	% O2 in flue gas	% O2	11.40	%
14	Mass flow rate of flue	$\dot{m}_{exit}$	0.00316	kg/s
15	Density of flue	ρ	0.341	kg/m3
16	Velocity of impingement	V	1.1792	m/s
17	Reynolds No. In CC	Rec	946	
18	Grashof no for outer surface	Gr	180969184	
19	Rayleigh no for outer surface	Ra	123963891	
20	Inner heat transfer coefficient	hi	3.4	$w/m^2.K$
21	Radiative flame coefficient	hflme	22	$w/m^2.K$
22	Radiative char coefficient	hrad	223	$w/m^2.K$
23	Outer convective coefficient	hout	7.5	$w/m^2.K$
24	Outer radiative coefficient	hradout	19	$w/m^2.K$
25	Heat loss coefficient	Cl	0.416	0.575
26	Air/flue veocity in elbow	Ve	0.975	m/s
27	Reynolds no inside elbow	Ree	1329	
28	Velocity over the pot sides	Vs	0.59	m/s
29	Reynolds no over pot sides	Resg	240	
30	Nusselt no at the pot bottom	Nu	37	
31	Pot side convective heat transfer coefficient	hs	4	w/m2.K