COMPARISONS OF INFLUENCES OF MASS DENSITIES OF FUEL BRIQUETTES PRODUCED FROM EUCALYPTUS, OLIVE TREE, SORGHUM STALK AND KHAT WASTE RAW MATERIALS ON BURNING TIMES

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Comparisons of Influences of Mass Densities of Fuel Briquettes Produced from Eucalyptus, Olive Tree, Sorghum Stalk and Khat Waste Raw Materials On Burning Times

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As thesis advisors, we hereby certify that we have read and evaluated this thesis prepared, under our guidance, by **Wondwosen Kassahun** entitled: **“Comparisons of Influences of Mass Densities of Fuel Briquettes Produced from Eucalyptus, Olive Tree, Sorghum Stalk And Khat Waste Raw Materials On Burning Times”** We recommended as fulfilling the thesis requirement.

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As members of the board of examiners of the M.Sc. thesis open defense examination, we certify that we have read and evaluated the thesis prepared by Wondwosen Kassahun and examined the candidate. We recommended that the thesis be accepted as fulfilling the thesis requirement for the degree of Master of Science in Physics (Environmental Physics).

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DEDICATION

This work is dedicate to my family, especially to my wife for her continuous support .

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LIST OF ACRONYMS

CV	Calorific Value
FAO	Food and Agriculture Organization
FCC	Fixed carbon content
GHG	Green House Gas
MC	Moisture Content
MCB	Moisture Content of briquette
MCC	Moisture Content of charcoal
MCR	Moisture Content of raw material
VMB	Volatile mater of briquette
VM	Volatile mater
VMR	Volatile mater of raw material

BIOGRAPHICAL SKETCH

The author was born in 1986 G.C in Eastern Hararghe Zone Bedeno Woreda, Oromia Regional state, Ethiopia. He attended his primary education at Furda Primary School and at Bedeno Secondary and Preparatory School. He completed his College Diploma studies in 2007G.C. He joined Haramaya University in 2010 and graduated with Bachelor of Science in Physics in 2015 G.C. Then after serving for seven years at Secondary and Preparatory School in Bedeno, he joined Postgraduate Program Directorate of Haramaya University to pursue his Master of Science Degree in Physics (Environmental Physics).

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ABSTRACT

Global energy demand is rising, causing overexploitation of fossil fuels and environmental challenges. Renewable sources, especially biomass briquettes from residues, offer sustainable alternatives. Ethiopia relies heavily on unsustainable biomass, leading to deforestation and degradation. The rising demand for household energy in Ethiopia has intensified reliance on fuelwood and charcoal, contributing to deforestation and environmental degradation. This study investigates the potential of four locally available biomass raw materials Eucalyptus, Olive tree, Sorghum stalk, and Khat waste—for briquette production. Raw materials (20 kg each) were chopped, air-dried, and carbonized under limited oxygen to produce char powder. The resulting char was mixed with 10% clay binder and water, molded into cylindrical briquettes, and oven-dried. Performance tests were conducted using the water boiling method, measuring density, burning temperature, and effective cooking times. Results revealed significant differences in density and effective cooking time among the briquette types. Khat and Olive tree briquettes exhibited higher densities (0.442 and 0.476 g/cm³) and sustained heating, maintaining water temperatures above 75°C for 101 and 73 minutes, respectively. Sorghum briquettes showed the highest peak temperature (96°C) but had short endurance (40 minutes), while Eucalyptus briquettes demonstrated the lowest density and inconsistent burning behavior, averaging only 31 minutes above 75°C. ANOVA confirmed significant differences ($p < 0.05$) among treatments, indicating that raw material type strongly influences briquette performance. The findings suggest that Khat waste and Olive tree residues are the most promising biomass feed stocks for producing efficient and sustainable fuel briquettes in Ethiopia, offering a renewable alternative to fuel wood and charcoal while addressing waste management and deforestation concerns.

Key words**:** Biomass energy, Eucalyptus, Fuel briquettes, Khat waste, Olive tree, Sorghum stalk

1. INTRODUCTION

1.1. Background of the Study

Global energy demand is increasing rapidly due to increasing world population and economic growth. This increased energy use has led to various problems such as overexploitation of nonrenewable energy resources and other environmental problems such as deforestation, environmental degradation and climate change (EEA, 2008). In recent years, due to growing concerns of environment protection, energy security, over exploitation and rising price of fossil fuels, there is growing interest in renewable energy development such as hydro, wind, solar, geothermal and bio-energy (EEA, 2008).

The increasing global demand for energy, coupled with the environmental concerns associated with fossil fuels, has driven the search for sustainable and renewable energy alternatives. Biomass briquettes, produced from agricultural and forestry residues, have emerged as a promising solution due to their high energy density, ease of transportation, and potential to reduce waste (Kaliyan and Morey, 2009).

Energy is very essential to human livelihood and makes significant contributions to economic, social, and environmental features of human development. Renewable energy sources are important since they can be renewed and do not emit greenhouse gases. They can serve as alternative to non-renewable sources and sustainable.

Among the renewable energy sources, biomass fuels. Biomass fuels consist of firewood, forest waste, animal dung, vegetable matter, and other agricultural residues that are highly utilized by many rural and urban households for domestic use. However, the extensive and improper utilization of biomass fuel for household cooking results in deforestation, indoor air pollution, acute lower respiratory infections in women and children, and emission of greenhouse gases, which can be considered a great challenge to the world, particularly in developing countries.

In Ethiopia, fuel wood and charcoal are the primary sources of fuel for household cooking and heating. Proper management and effective conversion of biomass residues for biofuel production are crucial to reducing deforestation due to the cutting of trees for cooking and heating as a primary source of fuel and improving the energy utilization of households (Temesgen Kebede, 2022).

Ethiopia has huge renewable energy resource potential which includes biomass, hydropower, wind, solar, and geothermal energy. However, except the woody biomass (50%), agricultural residue (30%), hydropower (5%), wind (3%) and geothermal (1%) which are exploited, the available potential is not developed (Asresu, 2017**)**. Among various biomass sources, Eucalyptus, olive tree residues, sorghum stover, and khatwaste represent underutilized raw materials that culd be converted into efficient fuel briquettes.

Eucalyptus is known for its fast growth and high calorific value, making it a viable feedstock for briquette production (Jekayinfa and Omisakin, 2005). Olive tree pruning residues, abundant in Mediterranean regions, contain significant lignin content, contributing to better briquette durability (García-Maraver *et al*., 2012). Sorghum stover, an agricultural byproduct, offers an alternative biomass source, while khatwaste (from the stimulant plant *Catha edulis*) presents an opportunity to convert an otherwise discarded material into a valuable energy resource.

Fuel briquettes, compressed blocks of organic biomass, are a sustainable alternative to fossil fuels, offering efficient energy utilization and waste management. Material density (mass/volume) and energy density (energy/unit mass or volume) are critical metrics for evaluating briquette performance. This review compares these properties for briquettes derived from Eucalyptus, olive tree pruning residues, sorghum Stover, and khat waste, emphasizing their viability as fuel sources.

This study aims to compare the energy densities of fuel briquettes manufactured from four different raw materials: Eucalyptus, olive tree residues, sorghum stover, and Khat waste. These materials are abundant in various regions and represent a mix of woody and non-woody biomass. The found provided insights into the most efficient raw material for briquette production, contributing to sustainable energy solutions and waste management strategies, this research will support the optimization of biomass briquettes for household and industrial applications.

1.2. Statement of the Problem

As many papers showed briquettes are produced and use different binding materials like coffee husk, sawdust, and dry grass residues using paper pulp. The binder material is used to make the briquettes stronger. Then, it was found that the product did not burn well. However, Briquette produced from clay soil is easy to handle, transport, and store, and has a long burning time to save the consumption and dependency on fuel wood thereby Reducing fuel wood and deforestation. The utilization of clay soil by converting it into heat is economically justified.

Ethiopia heavily relies on biomass for its energy needs, with a significant portion coming from unsustainable sources, leading to deforestation and environmental degradation (EEA, 2021). Promoting the use of fuel briquettes made from locally available and sustainable biomass resources like agricultural and forestry waste offers a promising pathway towards achieving energy security, reducing environmental impacts, and improving livelihoods in Ethiopia. This research directly addresses the need for data on the suitability of specific locally abundant waste materials for briquette production. While there is existing literature on fuel briquettes made from various biomass materials, there is a noticeable gap in the direct comparative analysis of material and energy densities of briquettes manufactured specifically from Eucalyptus, Olive Tree waste, Sorghum Stover, and Khat Waste within the Ethiopian context. Furthermore, the utilization of Khat Waste for briquette production appears to be particularly under-explored.

The literature reviewed highlights the potential of fuel briquettes as a sustainable energy solution and underscores the importance of selecting appropriate raw materials. While studies exist (Roman and Grzegorzewska,2024) on briquettes made from Eucalyptus, Olive Tree waste, and Sorghum Stover, there is a lack of direct comparative data for these materials in Ethiopia, and the use of Khat Waste remains largely uninvestigated. This research aims to address these knowledge gaps by providing a comprehensive comparison of the material and energy densities of fuel briquettes produced from these four locally available raw materials, thereby contributing valuable information for promoting sustainable energy practices in Ethiopia.

1.3. Objectives of the Study

1.3.1. General objective

The general objective of this study is to prepare briquettes from eucalyptus, olive tree, sorghum Stover, and Khat residue and to determine correlations between the physical and energy densities (in terms of burning times) of the produced briquettes.

1.3.2. Specific objectives

- To prepare carbonized powders from Eucalyptus, Olive plant, Sorghum Stalk and Khat waste raw materials and to compare the physical densities of the carbonized powders.

- To measure and compare mass densities of fuel briquettes produced from Eucalyptus, Olive plant, Sorghum Stalk and Khat waste raw materials and to compare their energy outputs in terms of their burning temperatures and times.
- To correlate the physical densities of the carbonized powders with the burning times of the briquettes and to formulate relationships between the burning time and the physical densities.

1.4. Significant of the Study

This research was contributed to the growing body of knowledge on renewable energy sources by providing valuable insights into the properties of biomass briquettes made from different raw materials. The findings will help stakeholders in the energy sector make informed decisions about briquette production and utilization. Additionally, the study was promoted the use of agricultural and forestry waste as a sustainable energy source, reducing reliance on fossil fuels and mitigating environmental degradation. Fuel briquette produced from Eucalyptus, Olive Tree, Sorghum Stover, and Khat waste in Haramaya town has advantages for the population living in and around this town.

1.5. Scope of the Study

The study was limited to the materials available at the study location and therefore the results may vary depending on location, species of the plants and the geographical conditions under which the raw materials are grown.

2. LITERATURE REVIEW

This chapter provides an overview of existing scholarly work relevant to the production and characterization of fuel briquettes, with a specific focus on the four selected raw materials: Eucalyptus, Olive Tree waste, Sorghum Stover, and Khat Waste. It examines the established knowledge on fuel briquette technology, the properties of biomass relevant to briquetting, and the reported material and energy densities of briquettes made from similar and the target raw materials. Furthermore, it contextualizes the research within the energy landscape of Ethiopia.

2.1. Fuel Briquette Technology and Significance

Fuel briquetting is a well-established technology involving the densification of loose biomass into uniform, compact units, offering numerous advantages over raw biomass such as improved handling, storage efficiency, and enhanced combustion characteristics (Kaliyan and Vance, 2010). The process typically involves reducing the moisture content and particle size of the biomass, followed by compression under high pressure, often with or without the addition of binders (Bhattacharya *et al.*, 2002). The global interest in fuel briquettes stems from their potential to utilize waste biomass resources, reduce reliance on fossil fuels, and mitigate deforestation associated with traditional fuel wood consumption (IEA, 2017).

Briquettes offer several advantages over traditional biomass fuels such as increased energy density, reduced transportation and storage costs, more uniform combustion, and potentially lower emissions (Bhattacharya *et al*., 2002). The technology plays a crucial role in promoting the use of renewable energy sources and mitigating the environmental impacts associated with deforestation and the burning of unprocessed biomass (IEA, 2017).

2.2. Raw Materials for Briquette Production

A wide range of biomass materials can be used for briquette production, including agricultural residues (e.g., straws, stalks, and husks), forestry waste (e.g., sawdust, wood chips, and bark), energy crops, and industrial by-products (Demirbas, 2008). The suitability of a particular raw material depends on its availability, cost, chemical composition (e.g., lignin, cellulose, and hemicellulose content), moisture content, and particle size (Jenkins *et al*., 1998). The type of biomass significantly influences the quality and properties of the resulting briquettes (Olorunnisola, 2017).

2.2.1. Eucalyptus as a Briquette Raw Material

Eucalyptus is a fast-growing tree species widely cultivated in Ethiopia for various purposes, including timber, pulpwood, and fuel wood (Tadesse *et al*., 2018). Studies have explored the potential of using Eucalyptus wood and its residues (e.g., sawdust, bark) for briquette production. (e.g. Mani *et al*., 2006). These studies generally indicate that Eucalyptus biomass has favorable characteristics for briquetting due to its relatively high lignin content, which acts as a natural binder. Reported energy densities of Eucalyptus wood briquettes often fall within a specific range, highlighting its potential as a high-energy fuel source.

2.2.2. Olive Tree as a Briquette Raw Material

Olive tree cultivation is present in certain regions of Ethiopia, generating significant amounts of waste from pruning and olive oil extraction (pomace). Research has investigated the feasibility of utilizing olive tree waste for energy production, including briquetting (Miranda *et al.,* 2015). Studies have also shown that olive pomade and pruning residues can be successfully densified into briquettes, although their properties may vary depending on the specific type of waste and processing methods. The ash content of olive waste briquettes might be a consideration compared to woody biomass.

2.2.3. Sorghum Stover as a Briquette Raw Material

Sorghum is a major cereal crop in Ethiopia, and its Stover (the remaining stalks and leaves after harvesting) represents a substantial agricultural residue (CSA, 2023). Sorghum Stover has been explored as a potential feedstock and for fuel briquette production due to its abundance as well as relatively low cost (Manyuchi *et al.,* 2010). Studies-reported on the material and energy densities of briquettes made from sorghum Stover often highlight the need for proper pre-treatment (e.g., drying and size reduction) and potentially the use of binders to improve briquette quality and durability (Tumuluru *et al*., 2011). The energy density of sorghum Stover briquettes is generally lower than those of wood-based briquettes but still represents a valuable energy resource.

2.2.4. Khat Waste as a Briquette Raw Material

Khat (*Catha edulis*) is a widely cultivated and consumed stimulant plant in Ethiopia. The cultivation and consumption of Khat generate significant amounts of waste, primarily in the form of leaves and stems (Lemma *et al.*, 2016). While Khat is primarily known for its psychoactive properties, there is growing interest in exploring potential alternative uses for its waste, including energy production. Limited research exists (e.g. Wardi, 2025) on the utilization of Khat waste for fuel briquette production.

2.3. Density of Briquettes

Material density, typically expressed in kg/m^3, is a crucial property of fuel briquettes as it affects their handling, transportation, storage volume, and combustion rate (Grover & Mishra, 1996). Higher density generally leads to better combustion and increased energy content per unit volume. Energy density indicates the amount of heat released during the combustion of a unit mass of the fuel. It is a key indicator of the fuel's heating potential. Both material and energy densities are influenced by the type of raw material, particle size, moisture content, briquetting pressure, and the use of binders (Chen *et al.*, 2015).

2.4. Briquette Production

The production of briquettes has a number of steps which have to be carefully followed. Each step starting from fetching of the raw material and binding agents until getting the finished briquette requires time and careful preparation.

The first step in briquette production was selected the stem part of raw materials and the binding agent available locally. The raw material must be cut their stem to smaller sizes and air-dried for a number of days until the moisture content reduces to less than 15^{o}C. The dried material is combusted (carbonized) in a container with limited oxygen so that char powder which still has sufficient unbroken carbon bonds is formed. Next the char powder is mixed with a known quantity of binding agent and water in order to form a dough like structure. This dough like substance can be molded and pressed into a PVC pipe of known size and a cylindrical shaped mold of carbonized powder and binding agent mix comes out on the other side. This is cut into uniform lengths of 3cm spread on a flat surface and allowed to dry for a couple of days (the smaller the length the faster it dries), until the moisture reduces to nearly 10%. At this step the briquette is ready for burning.

The next step is burning the briquette and testing the energy contents based on the time it can burn and maintain water temperature above 75^{o}C. This is achieved using water boiling test.

3. MATERIALS AND METHODS

3.1. Sample Preparation

The production of briquettes has a number of steps which have to be carefully followed. Each step starting from fetching of the raw material and binding agents until getting the finished briquette requires time and careful preparation. The flow chart shown in Figure 2.1 illustrates the steps that need to be taken.

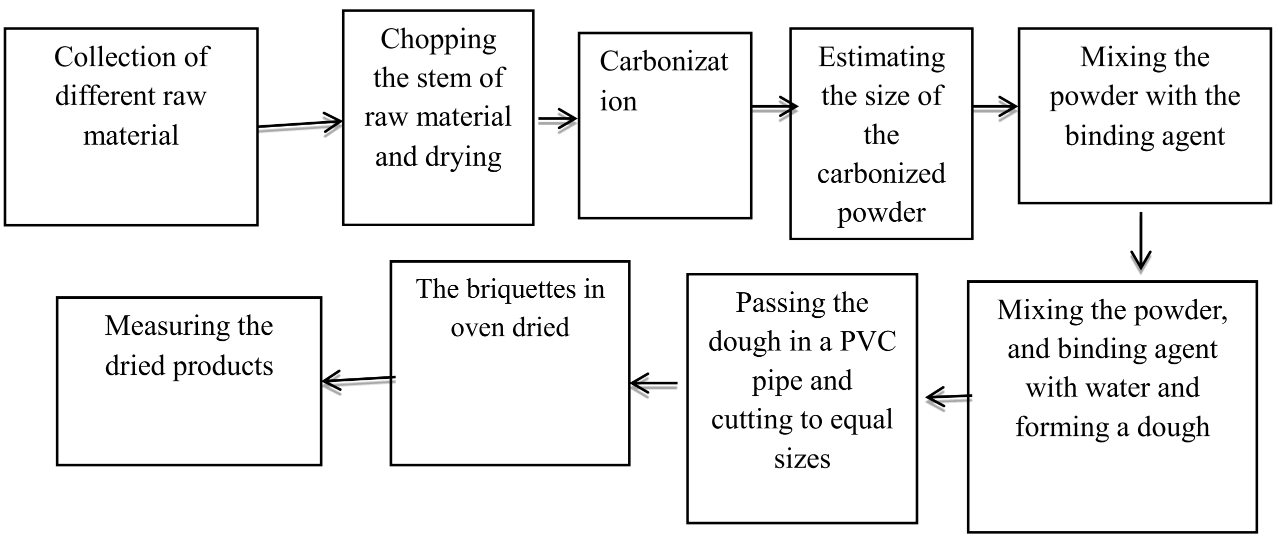

Figure 2.1. Briquette production flow chart

3.2. Sample Preparation and briquette production

The sample required for the experiment were first chopped and sun- dried. 20 kg samples were used from each treatment for the carbonization process.

The carbonization was done by placing the 20 kg in a metallic barrel. The samples were ignited and small waiting time 3-5 minutes allowed in until the samples catch fire properly. The time variations were done since some of the raw materials (e.g Sorghum stalk) burn very easily whereas sample like Eucalyptus would take longer to ignite. After the sample catch fire properly the metal barrel was closed to limit air entry for carbonization. Following the method of wardi (2025) each sample was allowed to remain between the barrel for 6 hours to complete the carbonization processes. After the 6 hours the samples were taken out and the powder part was separated from the coarse materials, since the fine materials are the once used for briquetting. For materials that could not produce sufficient fine powder, the coarse materials were broken into pieces and the powder were manually broken down to produce additional usable powder.

3.3. Briquette production

To produce briquettes, char powder was blended with 10% clay binder, ensuring thorough mixing of both components. Small amounts of water were gradually added until the mixture reached a doughy consistency. The dough was forced through a PVC pipe with a 3 cm inner diameter, resulting in cylindrical forms. These cylinders were then cut into 3 cm discs. The discs were placed in an oven and dried at 105°C for 24 hours to eliminate moisture.

3.4. Preparation and characterization

The raw materials used for briquette production are Eucalyptus, Olive Tree, Sorghum Stover, and Khat waste. The metallic barrel was used for carbonization. Clay soil was used as a binding agent. Additional instruments used like digital balance, thermometers, 4biomasses identical cook stoves, 4 identical pots, meter stick, mobile clock, a lighter, water, and kerosene.

The raw materials used for briquette production were purchased from the local markets in Haramaya town. Similarly, clay binding agent was obtained from Bedeno Woreda.

3.4. Volume and mass determination of the char powder

After carbonization, the mass of the resulting char powder from each biomass type was measured using a calibrated digital balance. Volume determination was performed using a cylindrical container of known cross-sectional area. The char powder was carefully added until it reached a uniform level, after which the height of the powder was taken. The volume was obtained by multiplying the powder height by the container’s cross-sectional area.

3.5. Briquette Combustion characterization

Before conducting the burning characterization tests, all prepared briquettes were weighed to ensure that 250 g of fuel and the standard amount for a single burning cycle was used in each cook stove. For the water-boiling test, 1 liter of water was added to each pot.

A 250 g sample of each briquette type was placed in four separate cook stoves and all briquettes were ignited simultaneously. Once ignition was achieved, the pots containing water. Each equipped with a thermometer inserted through the lid, were placed on the cook stoves. The initial water temperature, ambient temperature, and starting time were recorded immediately.

Water temperature readings were then taken at 5-minute intervals until the temperature in each pot dropped below 60 °C. The ambient temperature was measured again at the end of the experiment. The entire procedure was repeated four times to obtain replicate data.

3.6. Data Analysis

Determination of mass density of the carbonized product was done by measuring the mass of the char powder (M_{cp}) and the volume of the powder (V_{cp}). The mass density of the carbonized powder (ρ_{cp}) calculated as

$$\rho_{cp} = \frac{M_{cp}}{V_{cp}} \tag{3.1}$$

The other thing is determination of the mass fraction (F_{cm}) of the carbonized powder (M_{cp}) to the initial mass of the raw material (M_{rm}). This is evaluated as

$$F_{cm} = \frac{M_{cp}}{M_{cm}} \tag{3.2}$$

To determine how much char is produced from each raw material of the char produced (including the charcoal that has not been converted into powder) for each raw material were measured. Then they were packed it into a cylindrical or rectangular container to determine its volume. Finally, the mass was divided by the volume.

Mass percent of char (m_{char}%) is obtained from

$$m_{char}\% = \frac{m_{char}}{m_{raw\ mtr}} \times 100\% \tag{3.3}$$

Density of char (D_{char}) is obtained from

$$D_{char} = \frac{m_{char}}{V_{char}} \tag{3.4}$$

For the second specific objective, first temperature and time plots was done for each treatment separately. From the plots the time the temperature of water stayed above 75ºC (Δt) was evaluated for each replication of each treatment. The data was tabulated after which one-way anova was used for comparison among the treatments.

For the third specific objective, plots of mass densities of the four treatments was determined and correlated with effective cooking times.

4. RESULTS AND DISCUSSION

4.1. Volumes of Raw Materials Estimated from the Average Densities

Under this section, first the volumes of the raw materials used were estimated using literature data of the average densities of the raw materials used for briquette production. Next the char obtained from the raw materials are used to estimate char density and percent of mass converted to char. Table 4.1 shows the estimated values of volumes of the raw materials used. Table 4.1 shows the density of the char and mass percent of mass converted to char.

Table 4. 1. Volumes of raw materials estimated from the average densities

Type of raw material	Average density (kg/m^3)	Weight (kg)	Volume estimated (m^3)
Eucalyptus	800	20	0.025
Olive	985	20	0.02
Khat	892.5	20	0.05
Sorghum stalk	350	20	0.057

In addition to finding the densities of the raw materials, the amounts of chars produced from each raw material was also determined and the results are shown in Table 4.2.

Table 4.2. Density of the char and char production efficiency of raw materials.

Type of raw material	Measured mass of char (kg)	Measured volume of char (m^3)	Density of char (kg/m^3)	Char production efficiency
Eucalyptus	1.224	0.0415	29.5	6.12
Olive	1.292	0.038	34	6.46
Khat	2.620	0.0748	35	13.1
Sorghum stalk	1.146	0.0955	12	5.73

The percent mass converted to char shows the fraction of the raw material that materializes to char.

As observed in the table, raw materials densities of the raw materials did not show correlation with the amount of char produced. The quantity of char produced seems to be correlated to the burnability of the material, which is dependent on the sizes of the material. A material of smaller size generally burns faster and results in production of large quantities of char. Khat residues are of smaller sizes and they showed higher char yields. Sorghum stalk was totally converted to char , but on account of its low density, the char weight was also low.

4.2. Comparisons of Densities of Raw Materials with the Densities of the Briquettes

The burning time of briquettes is assumed to be correlated with the densities of the briquettes. It is important to know how the densities of briquettes is correlated with the densities of the raw materials. Table 4.3 shows the average mass and char densities of the four materials. The plot between the two is shown in Fig. 4.5.

Table 4.3.Correlations between char density and mass density

Type of raw material	Average mass density (kg/m^3)	Density of char (kg/m^3)
Eucalyptus	800	29.5
Olive	985	34
Khat	892.5	35
Sorghum stalk	350	12

As seen in the table and the plots, there is a positive correlation between the two densities. The correlation coefficient ($R^2 = 0.62$) of indicates a moderate positive linear relationship between the average density of the raw materials and the final density of the char. However, the slope shows weak correlation. This means in general, raw materials with a higher average density tend to produce char with a higher density.

4.2. Energy Outputs in Terms of Burning Temperatures and Times of the Briquettes

In order to compare the four types of briquettes, first plots were done for each replication of each treatment to estimate the time during which the temperature stayed above 75^{o}C. Next, the mean values, standard deviations and coefficient of variations (CVs) were determined as shown in Table 4.4. In the third step ANOVA comparisons were made.

4.2.1. Treatment-averaged times

The treatment-averaged times during which the temperature stayed above 75ºC are shown in Table 4.4.

Table 4.4. Treatment averages

Treatment	R1	R2	R3	R4	Average	Stdev	CV (%)
Khat	90	110	85	118	**101**	**16**	**48**
Olive	95	55	77	65	**73**	**17**	**66**
Eucalyptus	0	30	63	30	**31**	**26**	**156**
Sorghum stalk	48	30	53	30	**40**	**12**	**119**

The result in Table 4.4 shows that Khat and Olive tree briquettes outperformed others in maintaining cooking temperature, making them more efficient energy sources than the other two. However, the coefficient of variation (CV) values indicate large variations among the replications that indicates error in the carbonization processes or at the stage of energy characterization. The error is also manifested in the value obtained for eucalyptus, which happens to be lower than that of sorghum-stalk.

4.2.2. ANOVA results

In order to check whether there are significant differences, it is necessary to carryout statistical test as shown in Table 4.5.

Table 4.5. ANOVA table

ANOVA Table

Source	SS	df	MS	F	Prob>F
Groups	12278.2	3	4092.73	12.11	0.0006
Error	4054.2	12	337.85		
Total	16332.4	15			

As indicated in the table 4.5, the treatments are significantly different at $p < 0.05$ level. Variability among replications of treatments is shown in box plots of Figure. 4.1.

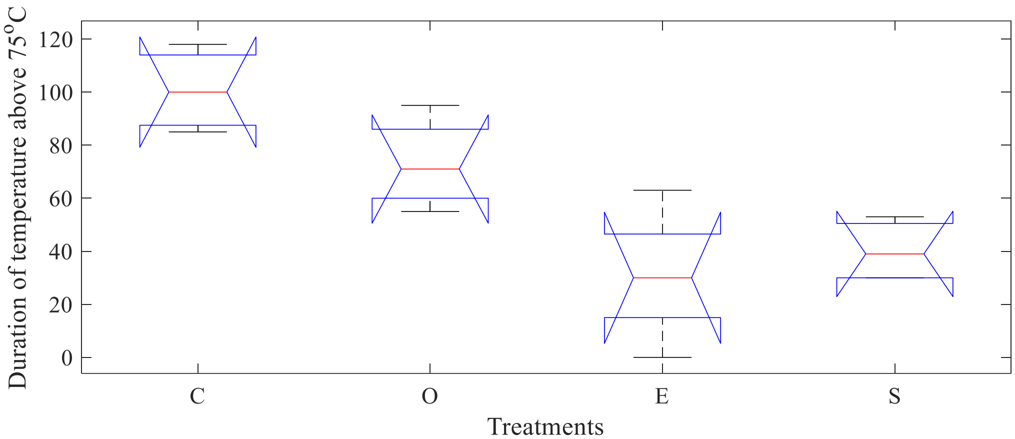

Figure 4.1. Box plots of the four treatments; C = khat, O = olive tree, E = eucalyptus, and S = sorghum stalk

As shown in Figure. 4.6 the box plot shows high **v**ariability across all treatments, with Eucalyptus showing the greatest variability**.** This result indicates inconsistent burning behavior in Eucalyptus briquettes, possibly due to irregularities in carbonization or density variation during the production of briquettes. The next step is to carry out pair comparisons, which is shown in Fig. 4.2.

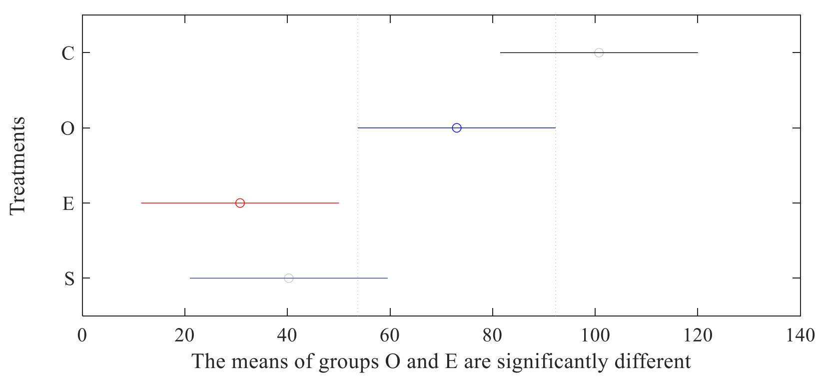

Figure 4.2. Pair comparisons of the four treatments; C = khat, O = olive tree, E = eucalyptus, and S = sorghum stalk

Treatments O and C are not significantly different from each other and also E and S. E is significantly different from C and O. S is significantly different from C. The result indicates higher values for the raw materials with high briquette densities (Table 4.3)

4.2.3. Graphical comparisons

Graphical comparisons are significant since they indicate the times at which initial the 75^{o}C is reached that indicates the *onset of cooking* in the actual cooking process and the final time at which the temperature drops below the same temperature. The two times are important in the actual cooking process. Small onset of cooking is important since it indicates how fast the cooking process starts. The final 75°C intersection with the plots is important since the longer this time is indicative of long time of cooking. Figure 4.3 shows the graphical comparisons of the four treatments.

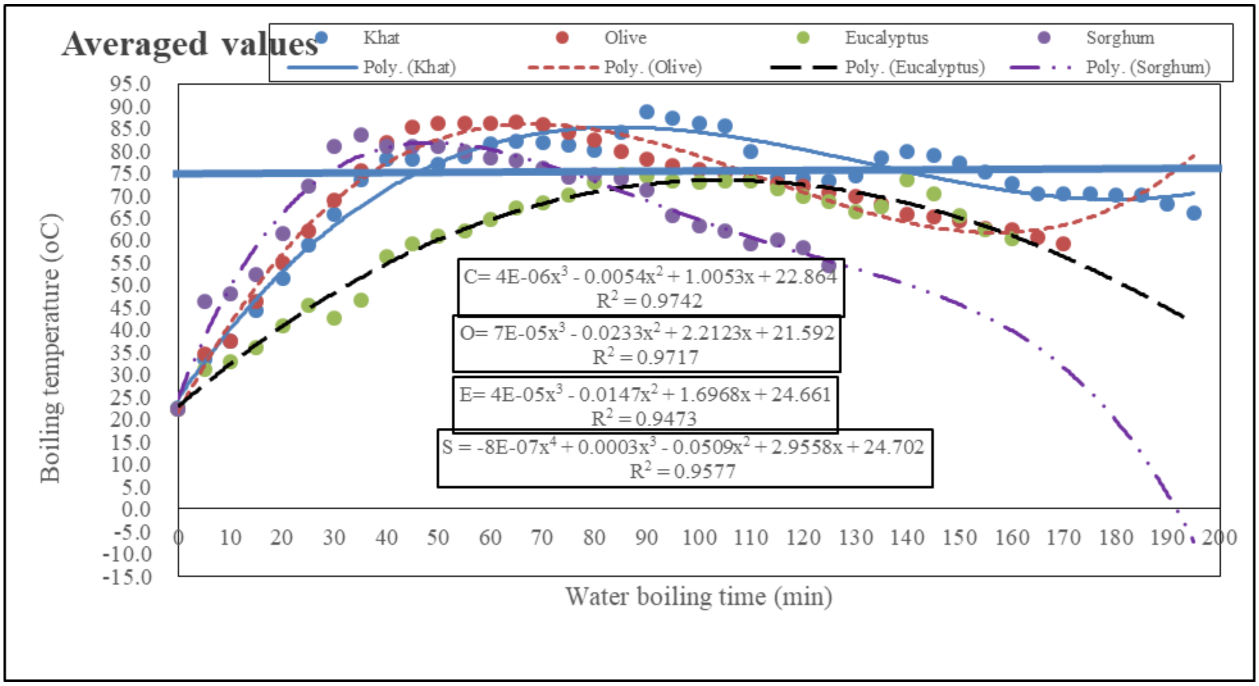

Figure 4.3. Graphical comparisons of the four treatments

As far as onset of cooking time is concerned, sorghum stalk exhibited the lowest time. This indicates briquettes with lower density burn faster and release energy before the ones with high density. The temperature of the same briquette is also the one that drops below 75°C faster. This indicates raw materials that result in low density briquettes are good for fast cooking but not suitable for foods that require long time of cooking. On the other hand, briquettes from olive tree and Khat residue reached 75°C late but relatively stayed longer. Such high density briquettes are not suitable for fast cooking but rather good for elongated cooking.

Eucalyptus briquette was the least performer in this experiment. In the average calculation of Table 4.1 a time of 31 minutes was obtained. However, in Fig. 4.3, this briquette did not manage to reach a temperature of 75°C at all. The difference is in the time the temperatures above 75°C were reached at each replication. In the average calculation of Table 4.1 time is not taken into consideration. In the graphical method the times must be within a given range or otherwise the positive value (> 75°C) are cancelled with the negative values (< 75ºC) as shown in Fig. 4.4.

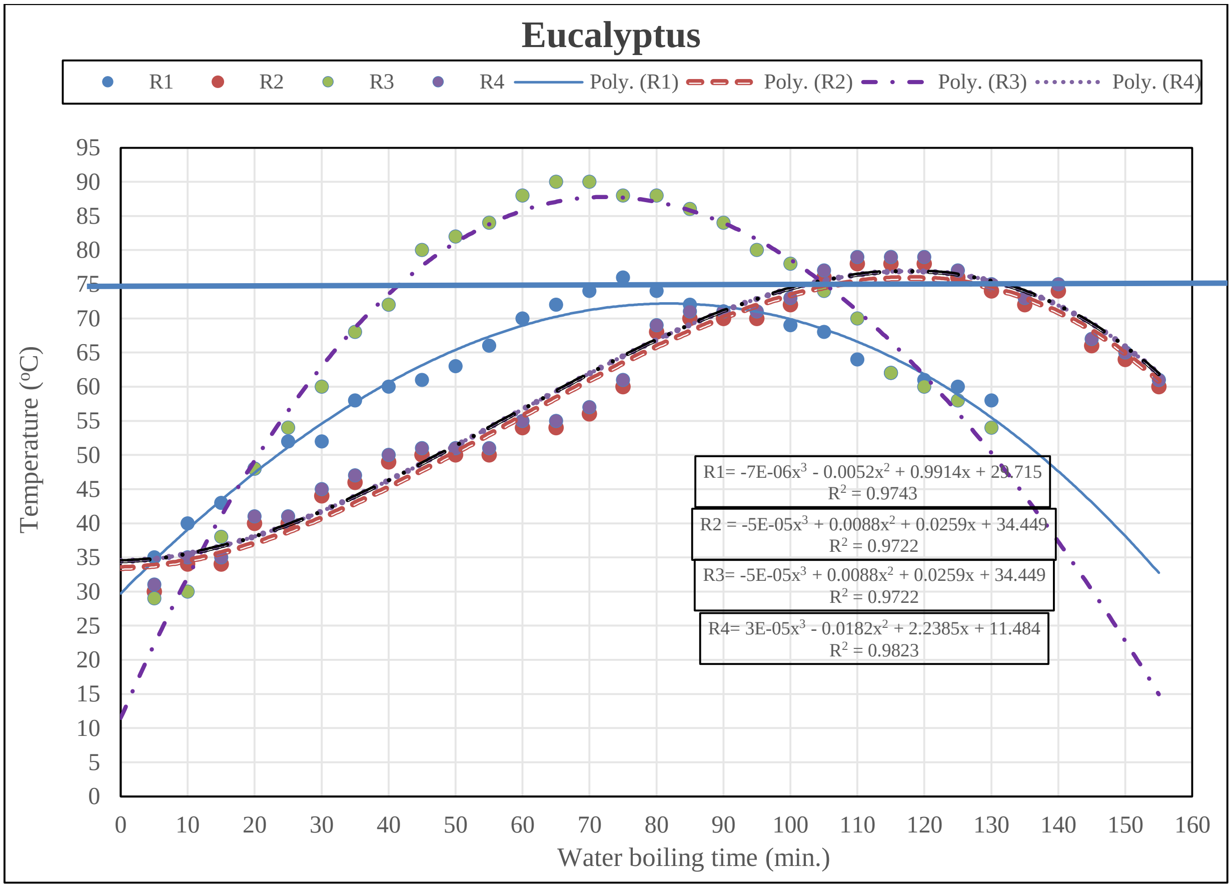

Figure 4.4. Temperature versus time plots of replications of heating with eucalyptus briquettes

As shown in Fig. 4.4, the temperature did not even reach 75ºC for replication 1 (R1). For replications 2 and 4, the 75ºC mark is barely exceeded between 105 and 130 minutes. Only replication 3 (R3) showed a relatively acceptable result with time range between 42 and 105 minutes. The result of this treatment indicates the need of appropriate care required during the carbonization process. Appropriate timing of drum closing time is essential since late closing time results in more oxidation (i.e., reduction in the quantity of burnable material) and early closing time results in production of less powdered char and more of unburned materials.

The other consideration is the uniformity of briquette density. Less dense briquettes burn faster, but cannot sustain longer burning time. Denser briquettes start burning late, but sustain burning longer. The other consideration is the mixing of the binding agent with the powdered char. Uneven mixing can result in lower or higher fractions of the burnable materials in the briquette. Lower fraction of burnable material implies more binding agent, which means lower heat energy since the binding agent does not contribute to the heating.

4.3. Correlation of the Mass Density, Briquette Density and the Burning Times

In order to find correlations between briquette densities to raw material mass density, the mass density of Khat was approximated based on the mass densities of briquettes of olive tree (476 kg/m^3) and eucalyptus (408 kg/m^3). The briquette density of Khat is 442 kg/m^3 and has a difference of 34 from both. Assumption was made that the mass density of Khat must be between the mass densities of the two raw materials and estimated as

$$d_k = \frac{d_o + d_e}{2} = \frac{985 + 800}{2} = 892.5\frac{kg}{m^3} \qquad (4.3)$$

Where d_k is the mass density of khat, d_o is that of olive tree and d_e is that of eucalyptus. In addition, since averaged cooking time of eucalyptus was very low, instead of taking the averaged value the value of the third replication which is more realistic was considered.

Fig. 4.5 was plotted based on the two considerations.

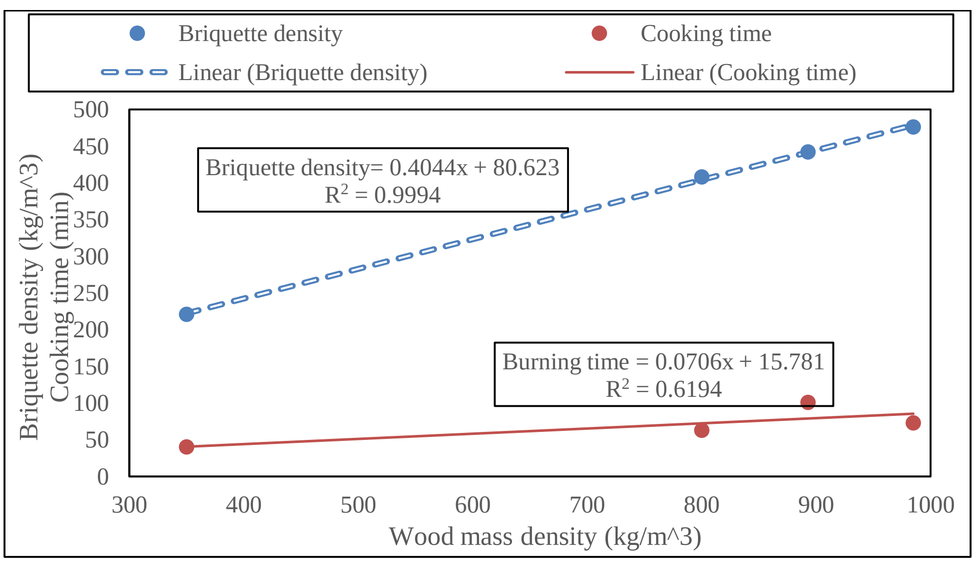

Figure 4.5. Plots of briquette density and cooking time against the mass density of the raw material

As observed in the figure, briquette density has strong correlation with the raw material mass density. Cooking time is also shows good correlation with the mass density of the raw materials. This confirms why briquettes produced from olive tree and khat outperformed the other two briquettes in terms of cooking times. Khat exhibited the highest cooking time of 101 minutes, not because of it is of a higher density, rather perhaps due to the smaller sizes that is convenient for drying and carbonization. Given many assumptions and the values of the average mass densities obtained from literature instead of actual measurement, the correlations obtained are considered to be very good.

The next step is to check existence of correlations between briquette density and cooking time. The plot of the two is given in Fig. 4.6.

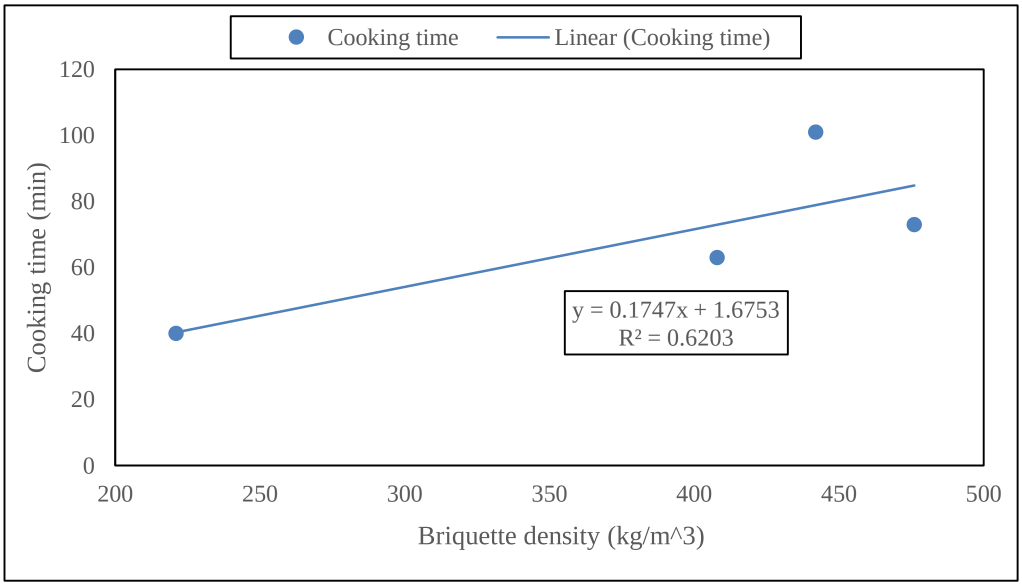

Figure 4.6. Cooking time versus briquette density

Cooking time showed good correlation (R^2 = 0.62) with briquette density as observed in Fig. 4.6. Briquette density depends on the packing and the amount of binding material in the briquette besides the density of the raw material used. Since the same quantity of binding materials is used in the four types of briquettes, if there is error it must be in the packing.

Overall, the onset of cooking and the burning times of briquettes is dependent on the density of the raw material and the density of the briquettes. Low density materials result in fast burning briquettes, while denser raw materials result in denser briquettes that in turn burn for longer times. Selection of materials may be limited, but the user can manipulate the burning time by the method of compaction of the briquettes. Carbonization is another factor that determines the burning time, but that requires further study on its own.

5. SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1. Summary

This study investigated the comparative physical and energy characteristics of briquettes produced from four biomass raw materials—Eucalyptus, Olive tree residues, Sorghum stover, and Khat waste—with the primary goal of identifying sustainable alternatives to traditional fuelwood and charcoal, which remain dominant household energy sources in Ethiopia and are major contributors to deforestation, greenhouse gas emissions, and environmental degradation. To achieve this, the selected raw materials were carbonized to produce char powder, which was then mixed with clay soil as a binding agent and molded into cylindrical briquettes that were subsequently air-dried prior to testing. The manufactured briquettes were analyzed using key performance indicators, including the density of the carbonized powder, the density of the finished briquettes, combustion temperature behavior over time, and effective cooking duration as measured by the water boiling test. In addition, statistical analysis was applied to assess whether variations in performance across the different raw materials were statistically significant, thereby providing reliable evidence on the influence of biomass type on briquette quality and energy efficiency.

5.2. Conclusion

This study focused on comparisons of energy densities of fuel briquettes manufactured from eucalyptus, olive tree, sorghum Stover and khat waste raw materials. The result shows that the type of biomass raw material strongly determines the quality and performance of fuel briquettes. Khat waste briquettes demonstrated the best overall performance, with long cooking duration (101 minutes above 75°C) and good density (0.442 g/cm³). Olive tree briquettes also performed well, sustaining 73 minutes of cooking with the highest density (0.476 g/cm³). These two residues produced durable briquettes with stable combustion, making them the most suitable alternatives to charcoal and firewood. Sorghum Stover briquettes, although capable of rapidly reaching high temperatures (96°C), showed weak endurance (40 minutes), making them better suited for fast cooking but less useful for meals requiring long heating. Eucalyptus briquettes performed poorest, with the lowest density and unstable combustion, averaging only 31 minutes of sustained cooking.

ANOVA confirmed that these performance differences were statistically significant ($p < 0.05$). The correlation analysis confirmed that denser briquettes generally sustain burning longer, while low-density briquettes ignite quickly but burn out faster. Thus, improving compaction or blending low-density residues with denser feed stocks could enhance performance.

Overall, the findings highlight Khat waste and Olive tree residues as the most promising raw materials for briquette production in Ethiopia, while Sorghum Stover and Eucalyptus may still be utilized if blended with higher-performing materials or subjected to further processing. The large-scale adoption of briquettes made from these agricultural and forestry residues could reduce reliance on traditional fuels, enhance renewable energy supply, and mitigate deforestation and environmental degradation in the country.

5.3. Recommendations

This study recommends further exploration of blending low-performing biomass (like Sorghum and Eucalyptus) with higher-density feed stocks to improve quality. Support renewable energy initiatives that utilize agricultural and forestry residues to reduce dependency on non-renewable fuels and mitigate deforestation. The study recommends to investigate alternative binders, combinations of raw materials, and advanced briquetting technologies to enhance briquette durability, calorific value, and combustion stability.

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7. APPENDICES

Appendix I:When materials were carbonized

Appendix II: Measured Char powder of materials.

Appendix III: Mixture of Char powder and Binding Agent

Appendix Iv: Process of Briquette production



Appendix V: Experimental work and Data Collection.


Appendix VI: Experimental work and Data Collection