

**EXPERIMENTAL INVESTIGATION ON THE
PHYSICAL AND COMBUSTION PROPERTIES OF
BRIQUETTES FROM VARIOUS AGRO -AQUATIC
WASTES**

A PROJECT REPORT

submitted by

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to

the APJ Abdul Kalam Technological University

in partial fulfilment of the requirements for the award of the Degree

of

Master of Technology

In

Computer Integrated Manufacturing



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SEPTEMBER 2022

DECLARATION

I, Sonu S, hereby declare that, this seminar report entitled ‘Experimental Investigation on the Physical and Combustion Properties of Briquettes from Various Agro - Aquatic Wastes’ is the bonafide work of mine carried out under the supervision of Dr. K A SHAFI Professor in the department of mechanical engineering, TKM College of Engineering, Kollam. This submission represents my ideas in my own words and where ideas or words of others have been included; I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to the ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. The content of this report is not being presented by any other student to this or any other University for the award of a degree.

Place: Kollam

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Date: 16/09/2022

**DEPARTMENT OF MECHANICAL ENGINEERING
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CERTIFICATE

Certified that this report entitled '**Experimental Investigation on the Physical and Combustion Properties of Briquettes from Various Agro - Aquatic Wastes**' submitted by '**Sonu S, (TKM20MECI13)**' to the APJ Abdul Kalam Technological University in partial fulfilment of the requirements for the award of the Degree of Master of Technology in Computer Integrated Manufacturing, Department of Mechanical Engineering is a bonafide record of the project presented by him, under my guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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ACKNOWLEDGEMENT

First of all, I am indebted to the **God Almighty** for giving me an opportunity to excel in my efforts to complete this project on time.

I am extremely grateful to **Dr. T.A. Shahul Hameed**, Principal, TKM college of Engineering and **Dr. Dileep P.N**, Head of the Department, Department of Mechanical Engineering, for providing all required resources for successful completion of my project.

I am greatly obliged to my internal supervisor **Dr. K.A. Shafi** Assistant professor, Department of Mechanical Engineering, for his encouragement, guidance and support.

My heartfelt gratitude to **Prof. Kannan S.**, PG coordinator, Department of CIM & **Prof. Faizal N.S.**, Assistant professor, Department of CIM for their valuable suggestions and guidance in the preparation of the project presentation and report.

I express my thanks to all Faculties and Technical staffs, Department of Mechanical Engineering, and all staff members and friends for all help and coordination extended in bringing out this project successfully in time.

I will be failing in duty if I do not acknowledge with grateful thanks to the authors of the references and other literatures referred to in this project.

Last but not the least; I am very much thankful to my parents who guided me in every step which I took.

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ABSTRACT

The constant increase in environmental pollution and depletion of renewable resources leads to a focus on bio briquette. Therefore, several issues arise relating to reusing or recycling such materials. Many of the bio-wastes are the main reason for the environmental issues. Yet, another major issue of concern in India is the aquatic weed infestation in water bodies. Invasive weeds such as water hyacinth (WH) pose severe environmental and economic issues. A potential remedy for this waste disposal and high dependence on non-renewable materials is the conversion of these aquatic weeds into sustainable biomass briquette. The primary objective of this work is to explore the potential of various biomasses for the production of bio briquette using natural rubber latex as a binder. Biomass briquettes were produced with biomass that passed through a sieve of 2.36 mm. An experimental investigation was carried out on the bio briquette to determine bulk density, proximate parameters, water absorption, shatter index, compressive strength, and calorific value. From the characterization of the raw material, it is clear that rice husk and banana peel have higher ash content (above 20 %). Hence, they are not suitable for biomass briquette production. Moreover, Sugar cane bagasse, dry leaves, water hyacinth leaves, oil palm fruit bunch, sawdust, vegetable market waste, and spent tea waste have excellent fuel properties and are good candidates for biomass briquette production. The density calculation shows that briquettes made from spent tea waste have the highest dimensional stability. The water performances of briquettes made from sawdust, rice husk, vegetable market waste, water hyacinth, and oil palm fruit bunch are excellent. Furthermore, all the developed briquettes have superior compressive strength except for spent tea waste. Also, the durability characteristics of all the produced briquettes were excellent; hence, the chances of collapse during transportation will be minimal. Higher heating values were obtained for briquettes made from sawdust, vegetable market waste, grass waste, oil palm fruit bunch, spent tea waste, and water hyacinth leaves from the characterization of biomass briquettes.

Keywords: Biomass; bio briquette; density; water absorption; calorific value; proximate parameters

CONTENTS

ACKNOWLEDGEMENT	i
ABSTRACT	ii
LIST OF TABLES	v
LIST OF FIGURES	vi
ABBREVIATIONS	viii
NOTATIONS	ix
CHAPTER 1: INTRODUCTION	1
1.1: General Background	1
1.1.1: Issues caused by water hyacinth	3
1.2: Problem Statement	4
1.3: Objectives	4
1.4 Scope of work	4
1.5: Thesis Outline	4
CHAPTER 2: LITERATURE REVIEW	4
2.1: Literature Review on Biomass Briquette	6
CHAPTER 3: METHODOLOGY	14
3.1: Materials	14
3.1.1: Raw materials	14
3.2: Mould Preparation	20
3.3: Briquette Production	21
3.4: Experimental Work	25
3.4.1: Physical properties	25
3.4.2: Durability	28
3.4.3: Mechanical Properties	29
3.4.4: Proximate analysis	30
3.4.5: Elemental analysis	32
3.4.6: Calorific value	32
CHAPTER 4: RESULTS AND DISCUSSION	33
4.1: Characteristics of raw material	33
4.1.1 Physical properties	33
4.1.2 Proximate analysis	34
4.1.3 Elemental composition	36

4.1.4 Calorific Value	37
4.2: Characterization of briquettes	38
4.2.1 Physical properties	38
4.2.2 Mechanical properties	42
4.2.3 Durability	42
4.2.4 Proximate analysis	44
4.2.5 Elemental composition	47
4.2.6 Calorific value	49
CHAPTER 5: CONCLUSION	50
5.1 SUMMARY	50
5.2 SCOPE FOR FURTHER WORK	51
REFERENCES	52

LIST OF TABLES

No.	Title	Page No
Table 4.1	Density of raw materials	33
Table 4.2	Proximate analysis of raw materials	34
Table 4.3	Physical properties of briquettes	38
Table 4.4	Compressive strength and shatter index of the briquettes	43
Table 4.5	Proximate analysis of the briquettes	44
Table 4.6	Elemental composition of briquettes	48

LIST OF FIGURES

No.	Title	Page No.
Fig 1.1	Energy reserves in billion tonnes of oil equivalent	1
Fig 1.2	India's total primary energy consumption by fuel type	2
Fig 1.3	Water hyacinth	3
Fig 3.1	Flow chart of the methodology	13
Fig 3.2	(a) Water hyacinth on river; (b) Water hyacinth; (c) Leaves and petioles are sun-dried separately	14
Fig 3.3	Empty fruit bunch	15
Fig 3.4	Sawdust	16
Fig 3.5	Grass waste (a) raw form (b) dried form	16
Fig 3.6	Dry leaves	17
Fig 3.7	Banana tree waste	17
Fig 3.8	Rice straw	18
Fig 3.9	Vegetable waste before drying (b) vegetable waste after drying	18
Fig 3.10	Spent tea leaves	19
Fig 3.11	Food waste	19
Fig 3.12	Banana peels	20
Fig 3.13	Mould for briquetting	20
Fig 3.14	Mould fabrication process – boring , welding, and shaping	21
Fig 3.15	Mould components -cylindrical die , piston, and a base plate	21
Fig 3.16	Locking arrangement in mould	22
Fig 3.17	Pre-treated raw materials kept in containers	22
Fig 3.18	Natural rubber latex	23
Fig 3.19	Briquette production with Universal testing machine	23
Fig 3.20	Biomass Briquettes samples made of various raw materials	25
Fig 3.21	Measuring dimensions using vernier callipers	26
Fig 3.22	Raw material filled in 100 ml test tube	26

Fig 3.23	Briquette measured in measuring jar	27
Fig 3.24	Water absorption test	28
Fig 3.25	Shatter index test	29
Fig 3.26	Compressive strength test of briquette sample in UTM	30
Fig 3.27	Briquette sample after compressive strength test	30
Fig 3.28	(a) Weighing of sample; (b) Samples kept in the furnace; (c) Heated samples	31
Fig 4.1	Moisture content of the raw materials	35
Fig 4.2	Volatile matter of raw material	35
Fig 4.3	Ash content of the raw material	36
Fig 4.4	Fixed carbon of the raw material	36
Fig 4.5	Elemental composition of the raw material	37
Fig 4.6	Calorific value of the raw materials	37
Fig 4.7	Density comparison of the raw material and briquettes	39
Fig 4.8	True density of briquette	40
Fig 4.9	Porosity of the briquettes	40
Fig 4.10	Water absorption of briquette	41
Fig 4.11	Relaxation ratio of the briquettes	41
Fig 4.12	Compressive strength of the briquette	42
Fig 4.13	Shatter index of briquettes	43
Fig 4.14	Moisture content of the briquettes	45
Fig 4.15	Volatile matter of the briquette	46
Fig 4.16	Ash content of the briquette	46
Fig 4.17	Fixed carbon of the briquette	47
Fig 4.18	Elemental composition of the briquettes	48
Fig 4.19	Calorific value of the briquette	49

ABBREVIATIONS

AC	Ash content
MC	Moisture content
VM	Volatile matter
FC	Fixed Carbon
CV	Calorific value
WL	Water hyacinth leaf
OF	Oil palm fruit bunch
RH	Rice husk
SD	Saw dust
GW	Grass waste
DL	Dry leaf
BW	Banana tree waste
RS	Rice straw
VW	Vegetable market waste
SW	Sawdust
POMS	Palm oil mill sludge

NOTATIONS

M	Mass (gm.)
V	Volume (m ³)

CHAPTER 1

INTRODUCTION

1.1 GENERAL BACKGROUND

The world's primary energy sources, fossil fuels, are non-renewable and have finite supplies. Fossil fuels emit massive amounts of greenhouse gases into the environment, and utilizing them to meet thermal energy demands puts a strain on growing economies like India's economy [1]. People are looking for alternative energy supplies due to the loss of forest resources due to the increased usage of wood and fuel. The rise in life-threatening environmental concerns in the years since has demonstrated the importance of renewable energy. Renewable energy is also economically beneficial and has prompted countries to engage in this industry [2].

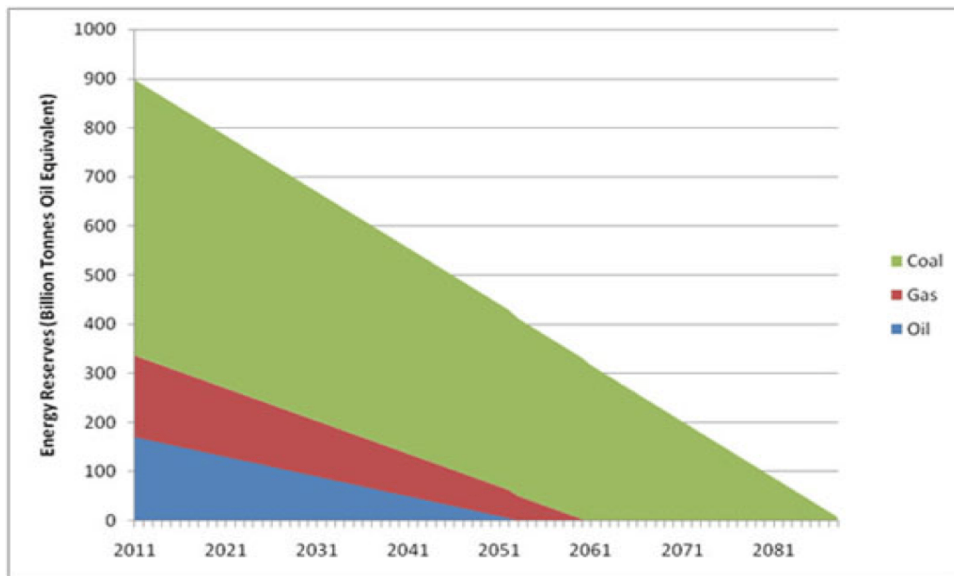


Fig 1.1 Energy reserves in billion tonnes of oil equivalent

(Source: <https://mahb.stanford.edu/library-item/fossil-fuels-run>)

Human survival has always relied heavily on biomass energy. After coal, oil, and natural gas, it ranks fourth in total global energy consumption and plays a critical role in the energy system. It has gotten much attention lately because of its benefits of being readily available, renewable, and environmentally beneficial [3]. Biomass fuel is energy from organic matter, such as plant materials, agricultural wastes, and forest residues. The leading biomass energy technologies include combustion, gasification, and pyrolysis.

Because of its low cost and excellent reliability, combustion has been the most developed and commonly used technique. Burning loose biomass and animal dung is inefficient since it produces smoke and pollutants [4,5]. Regarding land usage, air, and water quality, soil and biodiversity conservation, and carbon stock preservation, biomass briquette manufacturing and consumption are deemed environmentally sustainable [6]. For the urban and peri-urban residents of developing economies, briquetting technology produces safe and clean energy [7].

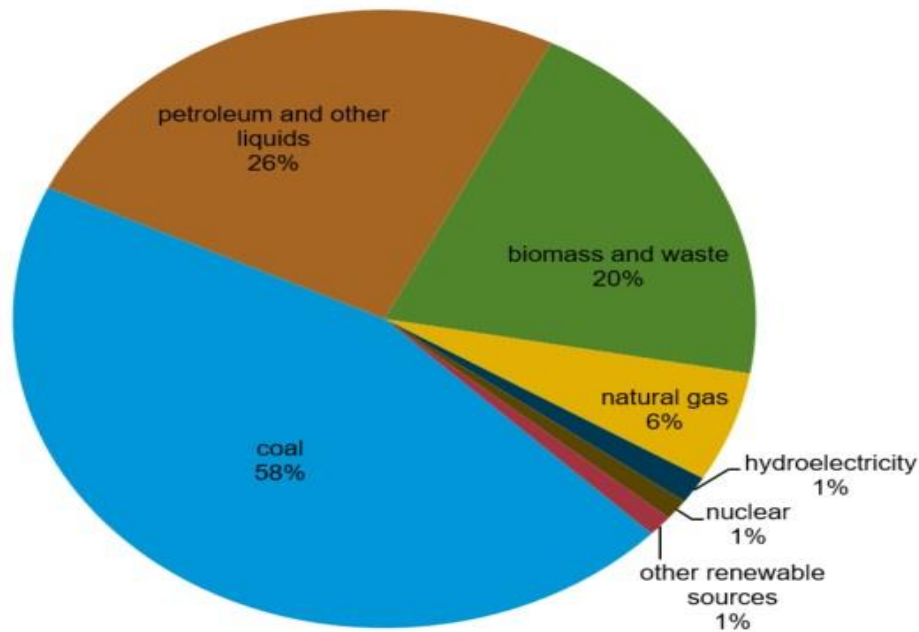


Fig 1.2 India's total primary energy consumption by fuel type, 2019

(Source: International Energy Agency, World Energy Outlook, 2019)

Briquetting is a densification process involving applying pressure to a loose precursor with or without a binder to produce a compact, long-lasting, and high-quality solid fuel. By increasing the bulk density and reducing moisture content, briquetting lowers handling, transportation, and storage costs while boosting volumetric calorific values [8].

Optimizing the briquetting parameters is also one of the essential steps. For that, there are several optimization techniques available. Box – Behnken Design methodology is used to find the optimum conditions for the compaction pressure, charcoal dust-molasses ratio, and drying temperature.[9]

The typical water hyacinth (*Eichhornia crassipes*) is a Pontederiaceae (Pickerelweed) aquatic weed found on nearly every continent. *Eichhornia crassipes* contain a high amount of cellulose and hemicellulose, quickly converted to simple sugars, making them ideal for biofuel briquettes [4].



Fig 1.3 Water Hyacinth

1.1.1 Issues caused by the water hyacinth

Water hyacinth is a fast-growing aquatic weed. Aquatic vegetation is replaced with water hyacinth, which grows into floating mats of interconnected plants. This can reduce the flow of the water bodies, which leads to floods. It can prevent transportation in the river, affect fishing, damage bridges and clog dams. Fish fatalities and oxygen deprivation can result from the water hyacinth's thick mats that block light from reaching underwater plants [4].

1.2 PROBLEM STATEMENT

Depleting non-renewable fuels are one of the main reasons to think about bio-briquettes. Especially coal is on the verge of extinction. To replace coal, we should move on to new biomass fuels. Aquatic weeds and agricultural wastes are the two predominant issues in the agricultural sector. It affects the agricultural sector in many ways, especially fish farming. Extensive agricultural waste is produced in Kerala, like rice straw, coir pith, vegetable market wastes, coffee stalks, etc. A large portion of crop residues is burnt. The smoke of these residues causes enormous air pollution in the environment. Invasive

aquatic weeds like water hyacinth (WH) pose severe economic and environmental issues in Kerala. In addition to climate factors, increasing market prices of traditional fossil fuels have driven consumer preference toward alternative fuels.

1.3 OBJECTIVES

The primary objectives of this work are:

- To characterise the agro-aquatic residues and assessment of their potential for bio briquette production
- To develop biomass briquettes from water hyacinth and other agricultural wastes using natural rubber latex as a binder
- To investigate the physical, mechanical, durability, and combustion properties of the developed briquettes
- To compare the properties of the developed briquettes with conventional sawdust briquettes and other fuels

1.4 SCOPE OF WORK

Current research centered on using renewable raw material resources, particularly agro-aquatic waste, as a component in bio-briquettes. Most of the conventional briquettes of sawdust which is costly. In Kerala, a substantial amount of agricultural waste, such as rice straw, coir pith, vegetable market wastes, coffee stalks, etc., is generated, and many crop residues are burned. The smoke from these residues causes significant environmental air pollution. Invasive aquatic weeds like water hyacinth (WH) pose severe economic and environmental issues in Kerala. In addition to climate factors, increasing market prices of traditional fossil fuels have driven consumer preference toward alternative fuels. The physical, mechanical, and combustion properties of raw material and briquette samples are investigated under relevant literature and standards. The literature study shows that briquettes made from agro or aquatic waste are much cheaper than conventional sawdust briquettes and have comparable overall properties. Using water hyacinth for the production of the bio-briquette may significantly reduce the problems caused by these aquatic weeds.

1.5 THESIS OUTLINE

Chapter bifurcation, in brief, is as follows. Chapter 1 deals with background information on the approaches and studies related to experimental investigations on the physical and combustion properties of briquettes from various agro-aquatic wastes. Chapter 2 involves a detailed literature review of the past and recent studies associated with the various biomass briquettes. Chapter 3 discusses the elaborated methodology for the development and performance evaluation of biomass wastes from various agro aquatic wastes. This chapter briefs on the calculation of bulk density, proximate analysis, ultimate analysis, emission characteristics, and handling properties of the biomass briquette thus developed. In chapter 4, the test results of the experimental work are discussed. A comparative study with biomass briquettes conventionally using sawdust briquettes is also included in this chapter. In chapter 5, the report concludes by highlighting the main contributions of this thesis work and future works that can be applied to this area, and chapter 6 portrays the references used for this thesis work.

CHAPTER 2

LITERATURE REVIEW

The purpose of this chapter is to provide a literature survey of past research efforts, such as journals or articles related to the development and performance evaluation of biomass briquettes from aquatic and agricultural wastes. Moreover, a review of the properties, such as bulk density, water resistance, durability index, ash content, moisture content, volatile matter, and various thermal properties, are also included in this chapter. The literature review discusses current and previous research on biomass briquettes from aquatic and agricultural wastes.

2.1 LITERATURE REVIEW ON BIOMASS BRIQUETTE

Deshannavar et al. [1] conducted a study to characterise briquettes made with rice husk and carbonised rice husk with starch and bentonite clay as a binder. Regression analysis is used to estimate the calorific value. Rice husk and carbonised rice husk were analysed with scanning electron microscopy then they found that the microstructure was highly heterogeneous and the low melting oxides fused with silica on the surface of the rice husk char. After proximate analysis and calorific value test, it is clear that the presence of carbonised rice husk decreases the volatile matter and increases the fixed carbon content. The calorific value of the briquette increases with an increase in fixed carbon and decreases with an increase in the volatile matter, moisture content, and ash content. A mathematical model was created using regression analysis to predict the calorific value. Then the calorific value obtained from the model was compared with the experimental value. The value of R^2 was found to be 0.94, and the RSDM of 0.0659. Relative percentage error was also calculated. The compressive strength of the briquette increases with increases in binder up to 6%, and it decreases after 8% of binder.

Ullah et al. [2] evaluated the thermal and handling properties of the briquette made from forest waste that consists of tree leaves and branches. They studied the effect of mould temperature and biomass particle size on these properties. Cow dung is used as the binder. A screw extruder was used for the preparation of the briquettes. The briquette production process involves five steps ie cleaning and sorting, feedstock drying, feedstock size reduction, feedstock mixing, and feedstock densification. They analysed physical characteristics as well as thermal characteristics. Physical characteristics include

feedstock and briquette moisture, density, durability, shatter resistance, moisture resistance and compression resistance. Thermal characteristic includes calorific value, ash content and flue gas emission values. Briquettes with 2 - 4 mm particle size and 225 -275 °C have the highest water resistance of 95 % and above. The highest calorific value of 4339 kcal/kg was obtained with a particle size of 4 mm and a mould temperature of 275 °C. Ash content ranges from 5.37 – 7.23%. The flue gas emission rate was found to be lower as compared to the emission rate of wood fuels. Finally, it is clear that mould temperature has an insignificant effect on the briquette fracture resistance, and particle size has no effect on the durability and compressive resistance. Mould temperature and particle size have a significant effect on the other properties.

Wu et al. [3] studied the effect of different carbonisation conditions on various briquettes' properties and compared emission factors for nitrogen and sulfur. Biomass used in this study was wheat, maize, and rice straw. Binder used in this experiment was the modified starch. Ultimate and proximate analysis of the raw biomass was conducted, and the values were recorded. The carbonisation temperature of 6000C and holding time of 180 min show the maximum fixed carbon content. Fixed carbon content increases with an increase in temperature. Charcoal yield decreases with an increase in temperature and holding time. Moulding pressure of 25 Mpa shows the peak value of drop and compressive strength. They found that the smaller particle size of less than 1 mm shows the maximum compressive and drop strength. Wheat straw shows the most significant values of emission factors of SO₂, NO, and NO₂. Rice straw has the minimum value of emission factors of SO₂, NO, and NO₂. Finally, they concluded that carbonisation temperature of 450 - 5000C, holding time of 180 min, and 50C/min heating rate are better for producing the briquette. The optimum values of briquetting pressure, particle size, and modified starch would be 25 Mpa, less than 1 mm, and 4.32wt%, respectively.

Onyango et al. [4] analysed the potential of water hyacinth for making biofuel briquettes with various binders such as Eucalypts globulus leaves powder, molasses and phytoplankton scum in the ratios of 10%, 20%, 30%. There are mainly three mixing ratios of water hyacinth and the binders, such as 90:10, 80:20, and 70:30. The particle size of water hyacinth is less than 5 mm. They evaluated compressed density, relaxed density, water resistance, durability, and calorific value to determine the best briquette. The obtained values were compared to charcoal briquettes that already exist on the market. Briquettes made up of Eucalyptus globulus show the lowest compressed and relaxed

densities. The durability varies from 66.34% - 95% (approx.). Durability increases with an increase in binding ratios. The lowest calorific value of 898.37 KJ/kg was recorded for the briquette with 10% of phytoplankton scum, and the highest value of 1148.35 KJ/kg was recorded for 20% of molasses binder. The calorific value of charcoal purchased from the market was 1422.97 KJ/kg. This study shows that the briquette with 30% binder shows better handling properties. Still, lower calorific values and the briquette with 20% binder (molasses) show better handling properties and calorific values.

Zanetti et al. [5] conducted a study to determine the quality of the pellets and briquettes made from glued wood waste. Materials used are cross-laminated timber (CLT) for pellets and wood shavings and lamellar processing waste for briquettes. A particle size of 4mm is used. The briquetting process is done with the help of a mechanical press which can exert a pressure of about 2000kg/cm². Characterization of both pellets and briquettes is carried out. The physical-mechanical and elemental analysis show almost better properties when compared with the standard values of the pellet. But it showed a value of 95.8 % of mechanical durability which does not meet the minimum value stated for a B quality class which has a value of 96.5%. The bulk density of the pellet was found to be 650 kg/m³ which was within the safe limit mentioned in standards. It showed a net calorific value of 16.5 MJ/kg. All the elementary contents such as nitrogen, sulfur, chlorine, copper, mercury, etc are also within the limit. Similar tests were carried out for the briquette samples. It showed a high durability value of 99%. It showed a calorific value of 17.1 MJ/kg. All the elemental contents were within the specified standard values. This shows that the briquettes fall in the category of A1 quality.

Balraj et al. [6] studied the sustainability of the briquette made up of biomass and coal-fine waste. The biomass includes bagasse, groundnut shell, and woodchips. This briquette is made without adding any binders. The conducted proximate analysis, scanning electron/elemental (SEM/EDX), and thermogravimetric analysis to analyse the properties of the briquette. The biomass particle size is 50, 143.3, and 199.7 μm . The biomass to coal ratio (B: C) is 7:1, 6:2, 4:4, 2:6. Moisture content varies from 4 – 14%, increasing with decreasing size. The volatile matter ranges from 42 – 69%. Volatile matter decreases with a decrease in particle size. Carbon content varies from 4 to 19 %. After proximate analysis, the briquette of ratio 7:1 with a 50 μm particle size shows better quality, and hence the briquette is used for further experiments. From SEM analysis, the

change in colour from brown to black can be observed from the obtained SEM images of the briquette. From those images, it is visible that the surface contains many cracks, cavities, and much damage. With a magnification of x 5000, the sample looks like a non-porous (amorphous) structure. With the help of EDX analysis, the percentage of elements such as carbon, oxygen, magnesium, aluminium, chlorine, and potassium in the briquette is found. It is found that it contains 54% of carbon, 40 % of oxygen, and 4% of potassium. From TGA analysis results show that 9.25 % of mass loss occurs at 218 °C and 39% of mass loss occurs at 337.6 °C, which is due to moisture removal, and 7.4 % of the residue is found at 1000 °C.

Gwenzi et al [7] analyzed high fuel energy briquettes which are made up of coal dust (C), bio waste which is the sawdust (S) and post-consumer plastics (P) in the form of polyethylene terephthalate (PET). PET bottles were crushed into flakes of dimension 12x12. Coal dust and sawdust were sieved through a 2mm sieve. Five different waste mix ratios are selected for the analysis purpose in the order of C:P: S. The mix ratios are 80:20:0, 80:0:20, 70:20:10, 60:30:10, 50:40:10. Water absorption, compressive strength, shatter index and density were evaluated to determine the handling properties of the briquettes. For thermal analysis, calorific values are also determined. Briquettes of mix ratios 70:20:10 and 80:0:20 showed a higher value of shatter indices. 50:40:10 briquette shows the maximum calorific value of 33.8 MJ/kg, which is higher than the value of high-energy coal. Moreover, 70:20:10 and 80:20:0 briquettes show values of 26.5 and 27.9 respectively which is greater than low-energy coal. Finally, the briquettes with mix ratios of 50:40:10 show better energy value, considerably good water absorption properties, and compressive strength. Hence it is considered the best briquette.

Tanui et al. [8] investigated the effects of the binder and processing conditions on the properties of briquettes. Briquette is made up of charcoal dust and molasses as a binder. The quantity of molasses varies from 0% to 10% to analyse its effects on the briquette properties. Box – Behnken Design methodology is used to find the optimum conditions concerning the compaction pressure, charcoal dust-molasses ratio, and drying temperature. So, the number of experiments conducted was reduced to 17 in each set. There are five sets of experiments, and each set contains a moisture content test, ash content test, gross calorific value, relaxed density, and shatter index. Briquettes are having a high amount of molasses and a lower drying temperature shows maximum relaxed density. The shatter index values range from 22.6 and 94.1 %. The gross calorific

value of 29.031 MJ/kg and the shatter index of 80.038% with a compaction pressure of 50 Mpa, 29.512 °C drying temperature, and 10% molasses ratio is considered the optimum value.

Ajimotokan et al. [9] reported on the physical-mechanical properties of briquettes made of corncob and rice husk. The particle sizes used in the study are 0.25, 1.00, and 1.75 mm. 5% of starch is used as a binder on a weight percentage basis. Finely powdered corncob and rice husk are blended in the mixing ratio of (corncob: rice husk) 80:20, 70:30, 60:40, 50:50 with a compaction pressure of 25, 50, and 65 kPa. The physical-mechanical property comprises compressive strength, density, relaxation ratio, durability, and water resistance capacity of dry briquettes. Moreover, a comparison study of these properties concerning the various particle size and compaction pressure was also conducted to find the best values for briquette production. Briquette having a mixing ratio of 50:50 mixing ratio, 0.25 mm particle size, and 65 kPa of compaction pressure, has a peak value of relaxed density and water resistance capacity of 972 sec. Lowering the relaxation ratio would produce briquettes with better stability. The briquette with an 80:20 mix ratio, 0.25 mm particle size, and 25 kPa of compacting pressure gave a lower relaxation ratio of 2.21. The durability of the briquettes ranged from 32.22% to 99.31%. Briquettes having a 50:50 ratio, 1.75 mm particle size, and 25 kPa have the highest durability. It was observed that the durability of the briquettes increases with decreased particle size.

Velusamy & subbaiyan [10] evaluated the utilization of agricultural waste and reduce the usage of fossil fuels. They made briquettes of sorghum panicle and pearl millet of various proportions (100:0, 10:90, 20:80, 30:70, 40:60, 50:50, 60:40, 70:30, 80:20, 90:10 and 0:100) using cassava starch as a binder. The hydraulic compression method is used for compacting with a pressure level of 200 KN. They conducted compressive strength analysis to find the maximum load value, elongation, breaking time, and pressure. The maximum withstand load of the sample was found to be 20.74 kN, and the corresponding elongation and pressure, and time were found to be 21.92mm, 17.29 N/mm² and 16.58s respectively. The maximum and minimum elongations of the briquettes were found to be 37.09 mm and 21.92 mm respectively. Wood biomass showed a maximum volatile matter content of 89.92%. The maximum carbon content of 34.16% was found in pineapple leaf and a minimum of 11.01% was found in the banana plant mixture. As a result of the TGA-DSC analyses, weight loss from the sample with 80:20 proportions was found as 26.07% at a temperature of 547.9 °C with a high heating

value of 26.87 MJ/kg. According to the studies and various tests, suitable briquettes could be selected that were efficient for domestic and industrial fuel production.

Kapen et al. [11] conducted a study to compare the properties of firewood charcoal to the three types of briquettes made with banana peel, corn husk, and a mixture of both biowastes. The binder used is cassava starch. Proximate analysis was conducted to determine fixed carbon, volatile matter, and ash content. Volatile matter ranges from 18.56% - 24.7%, ash content ranges from 11.28 – 36.89%, fixed carbon ranges from 44.46 – 67.8%. Elemental composition was also determined. The higher heating value of the banana peel ranges from 16.42 – 16.64 MJ/kg, for corn husk from 16.80 to 16.92 MJ/kg, and for a mixture of both materials, it ranges from 16.87 to 17.24 MJ/kg.

Mandal & Jena et al. [12] analysed the physical, handling and combustion properties of briquettes made from pine needles to identify the optimum parameters for the compression process. The studies were carried out utilizing an orthogonal array test with 16 trials for four levels of three independent characteristics: pine needle size, densification pressure, and temperature. They employed grey relational analysis to discover the optimum values of independent parameters that lowered briquettes per cent change in volume and density while boosting their durability and compressive strength. The optimum alternative was determined using grey relational grading, which assigned equal weight to all dependant attributes. The briquette quality was most significantly impacted by densification pressure, which impacted pine needle particle size less than 2 mm, a pressure of 9 MPa, and a temperature of 150 °C. There was 17.56 MJ/ kg of calorific value in the briquettes, 1228 kg m³ of density, and 7.05 MPa of compressive strength.

Bot et al. [13] analyzed the characteristic of the briquette made from sugarcane bagasse, ratan waste, coconut shell, and banana peels. The binder used is cassava starch. The briquette samples were made by drying the raw material, then carbonizing, crushing, and mixing it with a binder; finally, the briquette was produced. They analyzed the wet mass reduction, and that rattan waste showed an 81.67 % of loss in weight, and that of coconut shell is 80.15%. Briquette made of coconut shell showed the highest density 0.851 g/cm³. Banana peel has the highest moisture content of 7.64%, and the lowest value is for coconut shell of 4.33%. The least volatile matter was obtained from banana peels of 60.92 % and the highest value of 70.50% from coconut shells. Banana

peel briquette showed the highest ash content, and rattan waste showed the lowest ash content. The highest calorific value of 32.16 MJ/Kg was recorded for coconut shells.

Obi and Okongwu [14] conducted study on the characterization on the briquettes made of rice husk and palm oil mill sludge. They studied about the physical and combustion properties of the briquettes produced. 1:10, 1:5, 3:10, 2:5, 1:2, 3:5, 7:10, 4:5, 9:10, and 1:1 are the ratio of rice husk and palm oil sludge used in the production of the briquettes. The oil palm is the main material which makes an impact in the physical and combustion properties of the briquettes. The 1:1 ratio showed the better compressed density of 1044.93 Kg/m³. It has a relaxation ratio of 2.10. It shows calorific value of 21.68 MJ/Kg.

Karimibavani et al. [15] conducted a study on the properties of the briquettes made of orange peel and banana peel. They produced briquettes in different compaction pressure and later they carbonised the briquettes at 600⁰C for 60 min. The physical and combustion properties of those briquettes were compared. They used 2, 3, 5 tons/cm² as the compaction pressure. For orange peel the maximum value of compressive strength is 2.03 Mpa and for banana peels 2.45 Mpa.

CHAPTER 3

METHODOLOGY

The purpose of this chapter is to introduce the research methodology for the development of biomass briquette from agro-aquatic waste. This chapter gives a deeper understanding of the various physical, mechanical and thermal properties of the developed biomass briquettes. The research plan, including the methodology, materials, mold preparation, and testing methodology of the developed biomass briquettes are the primary components of this chapter.

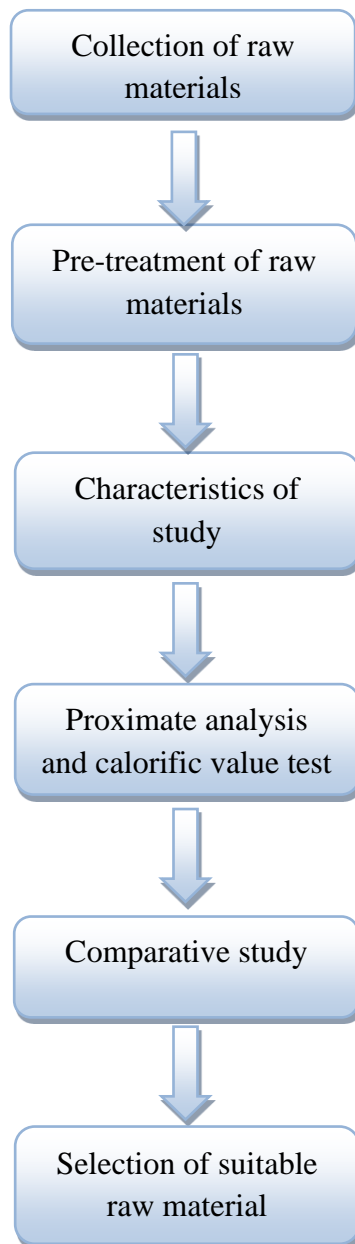


Fig 3.1 Flow chart of the methodology

3.1 MATERIALS

3.1.1 Raw materials

(i) Water Hyacinth

The aquatic plant that is thought to cause the most severe issues are frequently considered to be the water hyacinth; a common freshwater weed found in most of the world's frost-free areas. It causes the development of thick, impenetrable mats that block water bodies and complicate boating, fishing, and nearly all other water-related activities. Native plants are displaced below and above the water's surface, reducing biodiversity. Water hyacinth is harvested in the Kollam area from a river. The root of the water hyacinth has been taken out. Petiole and leaves of the water hyacinth have been separated and handled separately. Then sieved, it after sun drying, milling, and sieving with a 2.36 mm ISO standard sieve. It is then rigorously containerized after that.

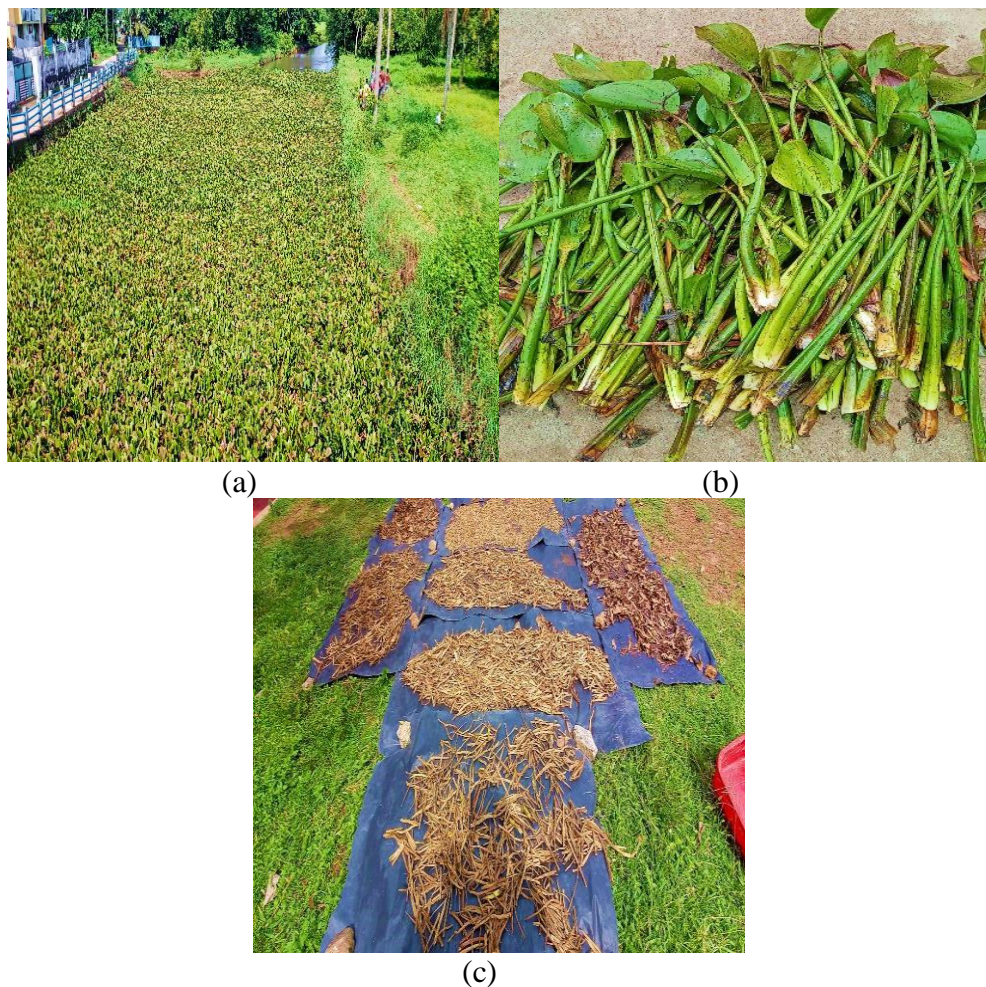


Fig 3.2 (a) Water hyacinth on river; (b) Water hyacinth; (c) Leaves and petioles are sun-dried separately; (d)

(ii) Oil palm fruit bunch

Kerala is one of India's major oil palm growers. An empty fruit bunch's potential was undiscovered. Due to their abundance, empty fruit bunches can be used as biofuel. Oil palm fruit bunch is one of the lignocellulose feedstocks containing cellulose, hemicellulose, and lignocellulose. The presence of the lignocellulose ensures the fuel property of the oil palm fruit bunch. The oil palm fruit bunch was gathered from the Kollam oil palm plantation. It was also sun-dried before being milled to reduce particle size. An ISO standard sieve with a diameter of 2.36 mm was used to guarantee a particle size of 2.36 mm. It is then placed in a container to avoid contact with moisture.



Fig 3.3 Empty fruit bunch

(iii) Rice husk

Rice husk is the protective outer covering of the rice. Rice husk can be used as a building material, insulation material, fuel, etc. Rice husk contains opaline silica and lignin. Direct combustion of the rice husk produces a large amount of smoke. Rice husk gas from the gasification process can produce blue flame during combustion. India, one of the largest producers of rice in the world, utilizes the rice husk as a direct-burning fuel in boilers to process paddy. Rice husk was collected from the Kollam flour mill. The collected materials are stored in the container after drying.

(iv) Sawdust

Sawdust is a by-product of wood from sawing, milling, planing, sanding, etc. When sawdust enters water bodies unprocessed, it can cause environmental problems, because it contains lignin and fatty acids. Saw dust can create air pollution when it burns in its

raw form. Sawdust could be obtained readily from carpentry workshops and wood mills. Sawdust is also widely available. Sawdust is now employed as a biofuel due to its reasonable calorific value. Sawdust was gathered from the Kollam wood mill for our purposes. It was dried under sunlight to remove any excess moisture.



Fig 3.4 Sawdust

(v) Grass Waste (*Cymbopogon Citratus*)

This type of grass spreads quickly. Once it begins to spread, it may eventually engulf the entire region. It can be used as a biofuel due to its abundance. Here, grass that had grown on the campus was collected. It takes a few weeks for it to remove moisture. Once it was cut into small pieces, then it was milled. Finally, it was sieved through a 2.36 mm ISO sieve. After that, it is kept in an air-tight container.



(a)

(b)

Fig 3.5 Grass Waste (*Cymbopogon Citratus*): (a) Raw grass waste; (b) Dried grass waste

(vi) Dry Leaves

One of the best biomasses for burning in its raw state is dry leaves. Furthermore, it has a higher calorific value. It can thus also be used as a biofuel. To get rid of the initial dampness, dry leaves collected from the college grounds are dried. It is then decreased in size and sieved using an ISO 2.36 mm sieve before being placed in the container.



Fig 3.6 Dry Leaves

(vii) Banana Tree waste

Banana tree waste includes the banana trunk and banana stem. It is possible to find these wastes in large quantities in Kerala. Consequently, this may be turned into a biofuel. Banana tree waste is collected from our homes, milled into small pieces, and then dried in the sun for a few days before being kept in a container.



Fig 3.7 Banana Tree waste

(viii) Rice straw

Rice straw is nothing but a leftover from the rice plant. Since India is famed for its rice cultivation, rice straw is widely available here. In its raw state, rice straw makes an excellent biofuel. If it transforms into briquettes, the characteristics may improve. We obtained rice straw from local farmers close to the campus for our use. It is milled before being packaged after being dried in the sun.



Fig 3.8 Rice straw

(ix) Vegetable Market Waste

A large number of vegetable waste from the markets are not being disposed of properly and is dumped in the open areas and waterbodies, which causes environmental issues. When contemplating its disposal, vegetable market waste is one of the main concerns. It is among the best biofuels available when appropriately treated. Untreated vegetable market trash can cause various kinds of pollution. Market waste from the neighbouring market is collected. The garbage is left to dry for a few days before being cut into small pieces. It is then allowed to dry until its moisture content has significantly decreased. After that, it is ground and put into the containers.



(a)

(b)

Fig 3.9 (a) Vegetable waste before drying (b) vegetable waste after drying

(x) Spent Tea Leaves

If utilized effectively, used tea leaves make excellent biomass. In India, there is a tea store on every corner, making it simple to gather used tea leaves. Spent tea leaves were from the campus cafeteria. Then it is exposed to the sun to dry, and a 2.36 mm ISO standard sieve is used to separate it. It is then kept within the container.



Fig 3.10 Spent tea leaves

(xi) Food waste

Food waste is deposited in landfills, decomposing and releasing methane, a greenhouse gas 28 times more potent than carbon dioxide. This can cause environmental issues. It can contaminate waterbodies and can cause disease-causing mosquitoes. Processing this can eliminate most environmental problems and be converted into biofuel. We collected food waste from the college canteen. Then it is dried under sunlight, milled, sieved, and kept in the container.



Fig 3.11 Drying of food waste

(xii) Banana peels

Banana peel is one of the waste material that is obtained from the plantain. This can be easily collected from the tea shops, hotels, canteen, etc. Banana peels contains low moisture content. Banana peel can be collected in a large scale, so it can be considered for the briquette production. Here the material is collected from the college canteen and is dried, milled, sieved using standard ISO sieve and is stored in the container.



Fig 3.12 Banana peels

3.2 MOULD PREPARATION

To carry out the briquette production for the experimentation, a cylindrical mould of the required dimensions has been fabricated as shown in Fig. 3.12 for the biomass densification process. It was made from scrap materials such as G.I pipe, gear, rods etc. and the workshop activities involved in fabrication are shown in Fig. 3.13. The mould is 430 mm in height and 70 mm inner diameter.



Fig. 3.13 Mould for briquetting.



Fig. 3.14 Mould fabrication processes -boring welding and shaping

A locking arrangement, with the assistance of nuts, bolts and washers, was fabricated as shown in Fig. 3.15.



Fig. 3.15 Mould components- cylindrical die, piston and a base plate

The locking facility was provided to prevent slippage between the base plate and cylindrical die during the compaction process.



Fig 3.16 Locking arrangement in mold

3.3 BRIQUETTE PRODUCTION

Pre-treated raw materials were stored in a container for characterisation and production of the briquettes.



Fig 13.17 Pre-treated raw materials kept in containers



Fig 13.18 Natural rubber latex

The proportion of the raw material and the binder is in the ratio of 70: 30. A total of 300 g of mixture is used for the production of the briquettes. The 210 grams of raw material and 90 grams of natural rubber latex for each briquette preparation are measured in a basin using a weighing machine. Then it is mixed thoroughly using a mechanical mixer. A total of 300 grams of the mixture is then filled in the mould and compacted intermittently using the piston to ensure the uniform distribution of the material around the mould. The upper portion of the mould and base plate are tightened using a nut and bolt. Then the piston is inserted into the mould and is placed between the two jaws of the Universal testing machine, as shown in the figure.



Fig 3.19 Briquette production with Universal testing machine



(a)

(b)



(c)

(d)



(e)

(f)



(g)

(h)



(i)

(j)

Fig 3.20 Biomass Briquettes samples made of various raw materials: (a) dry leaves; (b) grass waste; (c) banana tree waste; (d) rice straw; (e) sawdust; (f) rice husk; (g) water hyacinth leaves; (h) oil palm fruit bunch; (i) vegetable market waste; (j) spent tea leaves;

A load of 200 KN is then applied to compact the mixture inside the mould. After the dwell time, the load is released. Then the base plate is removed, and the others are kept at a certain height for demoulding the briquette. Then the mass and the dimensions are measured next using a weighing machine and vernier callipers, respectively. The briquette is kept for 21 days for drying. The dried briquettes are then kept in a tight container to avoid contact with the moisture for testing purposes. A total of 5 samples were produced for each proportion.

3.4 EXPERIMENTAL WORK

To analyze the different properties of bio-briquettes, the following tests were conducted.

3.4.1 Physical properties

(i) Density (Compressed density and relaxed density)

Bulk density is calculated by measuring the mass of the briquette in grams and the dimensions of the briquette. The length and diameter of the briquette are measured using a vernier calliper. For each sample, length and diameter are measured at three different positions. Then the average value is taken for the calculation of the volume.

$$\text{Volume of the briquette} = (\pi \div 4) \times D_{\text{avg}}^2 \times L_{\text{avg}} \quad (1)$$

Where D_{avg} is the average diameter of the briquette and L_{avg} is the average length of the briquette.

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} \quad (2)$$

There are two types of briquette density compressed density and relaxed density. Compressed density is calculated with the parameters measured after the briquette is demoulded from the mold. Relaxed density is calculated with the briquette after 21 days of drying.



Fig 3.21 Measuring dimensions using vernier callipers

Density of raw material is calculated by filling the raw material in a test tube of 100 ml capacity. The raw material is filled up to 100 ml and it is then converted to mm^3 . Then the mass of the raw material in the test tube is measured. Then density is calculated using equation [2].



Fig 3.22 Raw material filled in 100 ml test tube

(ii) True density

True density can be calculated using the Archimedes principle, which states that “The upward buoyant force that is exerted on a body immersed in a fluid, whether partially or fully submerged, is equal to the weight of the fluid that the body displaces and acts in the upward direction at the center of mass of the displaced fluid.” This test uses 2000 ml measuring jars. Then it is filled with water at a level of 500 ml. The briquette is immersed in water and is left for 15 min. The rise in water is noted in ml and is converted to mm³.



Fig 3.23 Briquette immersed in measuring jar

(iii) Porosity

For a fuel, porosity is one of the main factors that affect the combustion properties. Ignitability of a fuel is the ability of a fuel to ignite faster. If the porosity of fuel decreases, then its ignitability also decreases. Porosity can be found by using the following equation:

$$\text{Porosity} = 1 - \frac{\text{Apparent density}}{\text{True density}} \quad (3)$$

(iv) Water absorption

Water absorption of the fuel must always be lower to have better combustion properties. Increased water absorption may decrease ignitability and calorific value. For this test, the initial mass of the briquette before the test is measured. The briquette is fully immersed in the water for 2 minutes. Then measure the mass of the sample after 2 minutes. Following is a formula for calculating briquette water absorption:

$$\text{Water absorption \%} = \frac{W_1 - W_2}{W_1} \times 100 \quad (4)$$

Where W_1 is the initial mass and W_2 is the final mass of the briquette sample. Water resistance can be found by using the following equation:

$$\text{Water resistance \%} = 1 - \text{water absorption} \quad (5)$$



Fig 3.24 Water absorption test

(v) Relaxation ratio

The relaxation ratio is the ratio of the compressed density to the relaxed density. Compressed density is the density that is calculated after the briquette is ejected from the briquetting mold. Relaxed density is the density calculated after 21 days of drying. The relaxation ratio is a property that influences a briquette's dimensional stability and strength. A higher relaxation ratio indicates a more stable briquette, and a lower relaxation ratio indicates unstable bio-briquettes. The relaxation ratio should always be approaching one for a good quality briquette.

$$\text{Relaxation ratio} = \frac{\text{Compressed density}}{\text{Relaxed density}} \quad (6)$$

3.4.2 Durability

(i) Shatter index

A shatter index test of the briquette is essential to conduct to ensure the durability of the briquette. First, the briquette is placed in a closed container and dropped from a height of

2 m to a hard surface. Briquette sample in the container is sieved through a 2.36 mm ISO standard sieve. The mass left in the sieve is measured. Then the shatter index is calculated using the following relation:

$$\text{Shatter index \%} = \frac{W_2}{W_1} \times 100 \quad (7)$$

Where W_1 is the initial mass and W_2 is the final mass left in the sieve.



Fig 3.25 Shatter index test

3.4.3 Mechanical properties

(i) Compressive strength

Compressive strength is one of the mechanical properties of the briquette and an essential property when considering the handling property during transportation. Compressive strength is carried out using the universal testing machine. Before the test, the initial length of the briquette is measured using vernier callipers and is noted as L_0 . Diameter is measured to calculate the initial area of the briquette. The briquette sample was then placed in the UTM, as shown in the figure. Then the load is applied till the crack occurs. Load at the time of failure is noted as peak load (P). When the crack occurs, the load automatically drops to zero. The sample is then taken from the UTM, and the final length is measured and noted as L to calculate axial strain using equation (7). The diameter is measured to calculate the corrected area using the equation (8). Compressive strength is calculated using equation (9).

$$\text{Axial Strain} = \frac{L_0 - L}{L_0} \quad (8)$$

Where L_0 is the initial length in mm and L is the final length in mm.

$$\text{Corrected area} = \frac{\text{Initial area}}{1 - \text{Axial strain} \times \text{Final length}} \quad (9)$$

$$\text{Compressive strength (Mpa)} = \frac{\text{Peak load}}{\text{Corrected area}} \times 1000 \quad (10)$$



Fig 3.26 Compressive strength test of briquette sample in UTM



Fig 3.27 Briquette sample after compressive strength test

3.4.4 Proximate analysis

Combustion characteristics are determined by conducting proximate analysis, which includes the determination of moisture content, volatile matter, ash content, and fixed carbon.

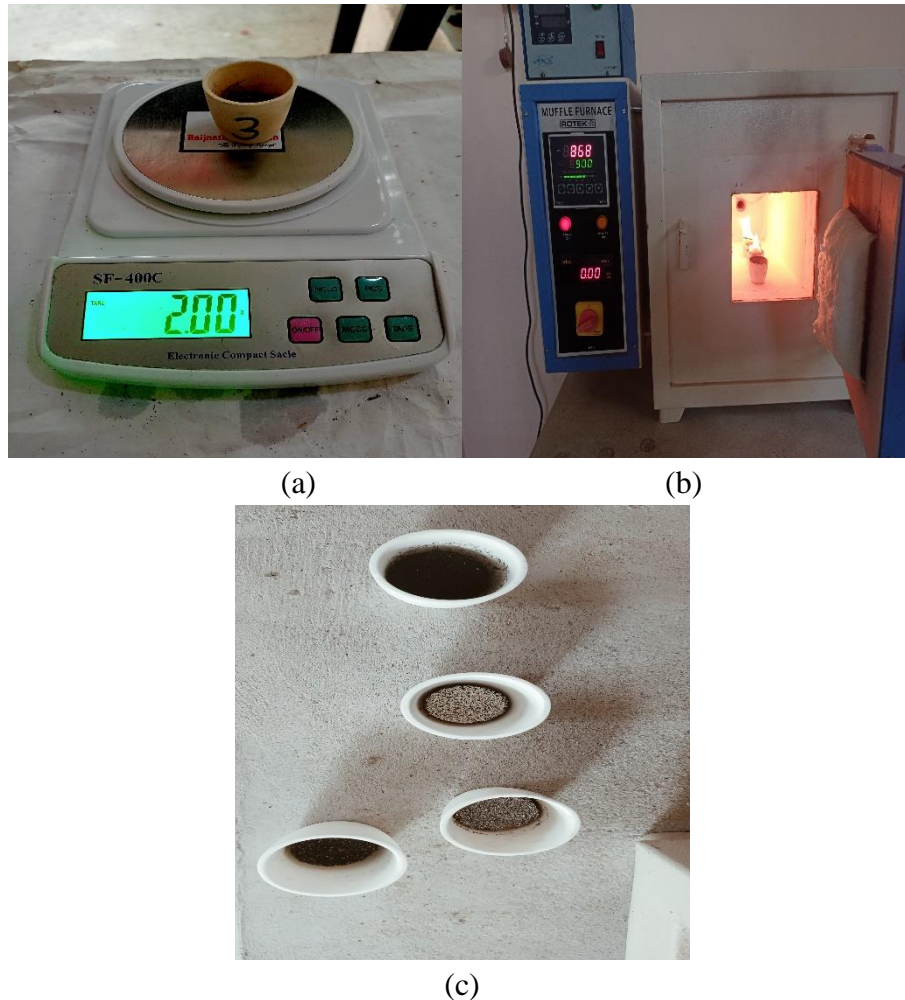


Fig 3.28 (a) Weighing of sample ;(b) Samples kept in the furnace; (c) Heated samples

(i) Moisture content

This test was conducted according to the ISO 18134-2:2017. Two grams of sample are taken in the crucible and placed in the furnace at 105 °C for 24 hours according to the standard. The mass of the crucible with the sample is measured before and after heating. Moisture content can be found by using the following equation:

$$MC \% = (W_2 - W_3) / (W_2 - W_1) \quad (11)$$

Where W_1 is the weight of the empty crucible, W_2 is the weight of the crucible with the sample and W_3 denotes W_2 after drying.

(ii) Volatile matter

Volatile matter was found according to ISO 18123:2015. After the moisture content test, the samples are kept in the same crucible to determine the volatile matter. Crucibles with samples are placed in the furnace at 550 °C for 1 hour. The final mass of the crucible is measured, and the volatile matter is calculated with the following formula:

$$VM \% = (W_3 - W_4) / (W_3 - W_1) \quad (12)$$

Where W_1 is the mass of the crucible, W_3 is the mass of the crucible and the sample after the moisture content test, and W_4 is the mass of the crucible with the heated sample after the volatile test.

(iii) Ash content

ISO 18122:2015 is the standard used to determine ash content. For the ash test, the sample is first heated in the furnace for 1 hour at 105 °C; two grams of sample are measured from it. Then the crucible with 2 grams of heated sample is placed in the furnace for 1 hour at 550 °C. Ash content is calculated by using the following formula.

$$AC \% = (W_6 - W_1) / (W_5 - W_1) \quad (13)$$

Where W_1 is the mass of the crucible, W_5 is the mass of the crucible with 2 grams of heated sample and W_6 is the mass of the crucible and sample that was left after the ash test.

(iv) Fixed carbon

Fixed carbon can be found by the following formula:

$$FC \% = 100 - (VM \% + AC \%) \quad (14)$$

3.4.5 Elemental analysis

With the following empirical relations, proximate parameters were used to determine the elemental composition of the raw material and briquette, including carbon, oxygen, and hydrogen. With a 95% confidence level, these were evaluated.

$$\text{For C element:} \quad 0.637 \times F.C + 0.455 \times VM \quad (15)$$

$$\text{For H element:} \quad 0.052 \times FC + 0.062 \times VM \quad (16)$$

$$\text{For O element:} \quad 0.304 \times F.C + 0.476 \times VM \quad (17)$$

3.4.6 Calorific value

With the following empirical relation, proximate parameters were used to determine the calorific value of the briquette and raw materials. With a 95% confidence level, these were evaluated.

$$CV = 0.1846 \times VM + 0.0352 \times FC \quad (18)$$

CHAPTER 4

RESULTS AND DISCUSSION

The initial stage of the work is the characterization of the raw materials, and it consists of proximate analysis, ultimate analysis, calorific value test, and density. From this value, we can select the better material for briquette production. But to study the properties of the briquette, we converted every raw material into a briquette and conducted several tests to analyze its physical, mechanical, durability, and combustion properties. The results are discussed below:

4.1 CHARACTERISATION OF RAW MATERIALS

4.1.1 Physical properties

i. Bulk density

Table 4.1 Density of various raw materials

Source Material	Density (kg/m ³)
Water Hyacinth leaves	204.40
Oil Palm Fruit Bunch	228.80
Rice husk	264.30
Saw Dust	241.40
Grass Waste	210.40
Dry Leaves	330.50
Banana tree Waste	220.20
Rice straw	196.80
Vegetable Market Waste	700.10
Spent tea Waste	515.20
Sugarcane bagasse	117.20
Water Hyacinth petiole	143.60
Banana Peels	603.20
Canteen Food Waste	679.40

From the table it is evident that vegetable market waste has the highest density of 700 kg/m³ and water hyacinth has the lowest density because of the porous nature of the petiole.

4.1.2 Proximate analysis

The proximate analysis consists of moisture content tests, volatile tests, ash content tests, and fixed carbon. The values obtained from these tests for various raw materials are listed below.

Table 4.2 Proximate analysis of raw materials

Source Material	MC %	VMC %	AC %	FC %
Water Hyacinth leaves (WL)	11.17	82.75	10.33	6.92
Oil Palm Fruit Bunch (OF)	9.17	83.48	14.33	2.18
Rice husk (RH)	13.50	71.33	24.50	4.17
Saw Dust (SD)	12.83	88.20	6.17	5.64
Grass Waste (GW)	9.17	83.88	11.50	4.62
Dry Leaves (DL)	10.17	79.43	10.50	10.07
Banana tree Waste (BW)	10.17	78.74	16.17	5.09
Rice straw (RS)	12.17	76.22	18.83	4.95
Vegetable Market Waste (VW)	5.83	83.74	11.50	4.76
Spent tea waste (SW)	5.33	83.22	6.67	10.11
Sugarcane bagasse (SB)	10.33	91.12	3.17	5.71
Water Hyacinth petiole (WP)	8.50	80.66	17.50	1.84
Banana Peels (BP)	3.17	75.17	22.17	2.66
Canteen Food Waste (CW)	3.17	77.68	16.00	6.32

(i) Moisture content

The moisture content of the above-mentioned raw materials ranges from 3.17 to 13.50 %. Lowest moisture content recorded for banana peels and canteen food waste and the highest moisture content for rice husk. if moisture content of the material is very high then it affects the combustion properties. that does not mean that moisture content should always be a smaller value. If it is so small then it can affects its binding property.

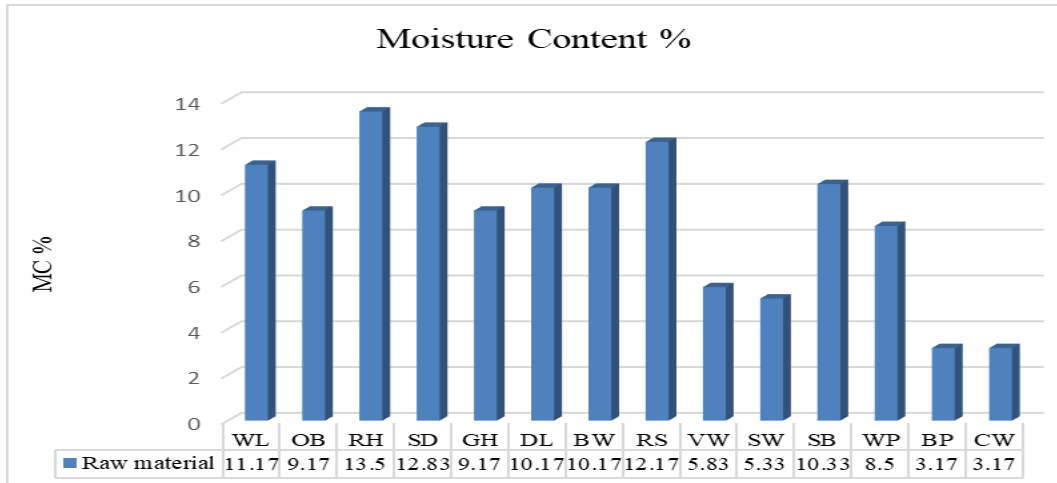


Fig 4.1 Moisture content of the raw materials

(ii) Volatile mater

For fuel volatile matter should always be higher to ignite the fuel faster.

The values of the volatile matter ranges from 71.33 – 91.12. Sugarcane bagasse showed the highest value of volatile matter of 91.12 and rice husk showed the lowest value of volatile matter of 71.33 % for good fuels values should be greater than 70. And here all the raw materials showed value greater than 70%.

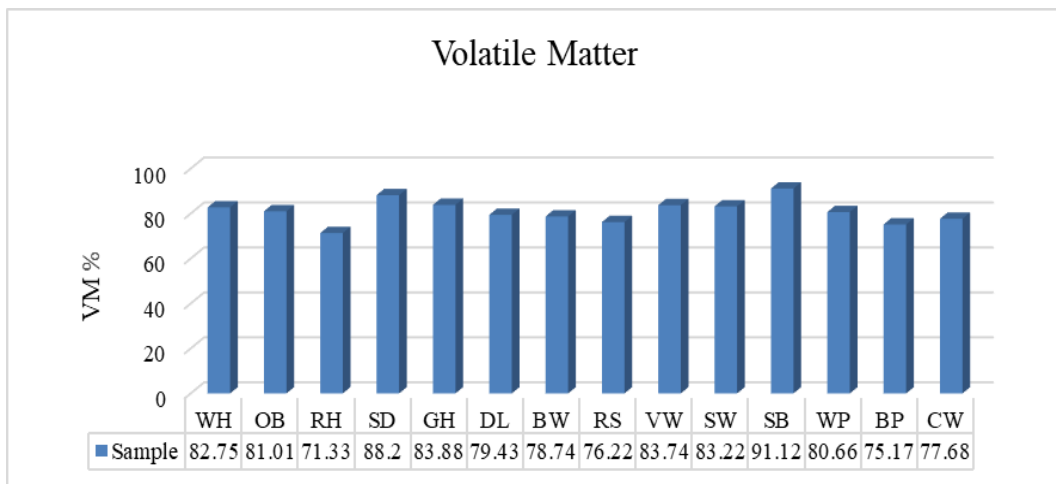


Fig 4.2 Volatile matter of the raw material

(iii) Ash content

Ash content is the non-combustible content in a fuel. Ash content is one of the concern in many of the industries. A lesser ash content fuels are always preferred. An ash content greater than 20% is considered as polluting. An ash value of less than 4% is always

preferred. Here the ash content ranges from 3.17 to 24.5. Lowest value is for sugarcane bagasse and largest value is for rice husk.

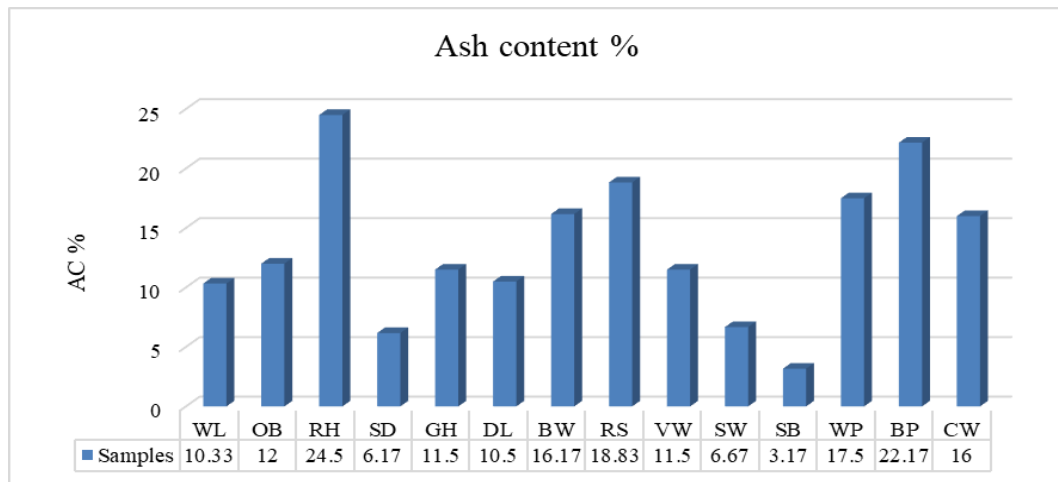


Fig 4.3 Ash content of the raw materials.

(iv) Fixed carbon

Fixed carbon is the element which influences the calorific value of the material. Fixed carbon of the raw material ranges from 1.84 to 10.11%. the largest value is obtained by spent tea leaves. The smallest value is obtained by water hyacinth petiole of 1.84%.

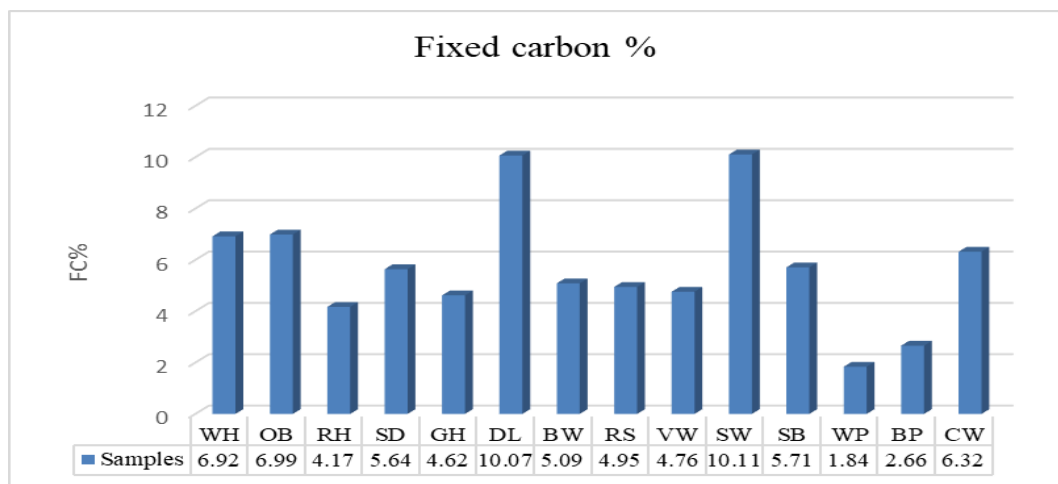


Fig 4.4 Fixed carbon of the raw material

4.1.3 Elemental composition

Three elements, C, O, and H, have been checked to ensure combustion properties. The previously mentioned equations calculate elemental compositions. For fuel, the combustion properties are influenced by C and H. as the level of C and H increases; the combustion property may increase. O should always be a lesser value. Here the content

of C varies from 35.11 to 45.1 %. The largest value is for sugarcane bagasse, and the rice husk shows the lowest value. The value of hydrogen ranges from 4.64 % to 5.95%. The largest and smallest values are for sugarcane bagasse and rice husk. The value of O ranges from 35,22 to 45.11. As earlier lowest and the highest value is for rice husk and sugarcane, respectively.

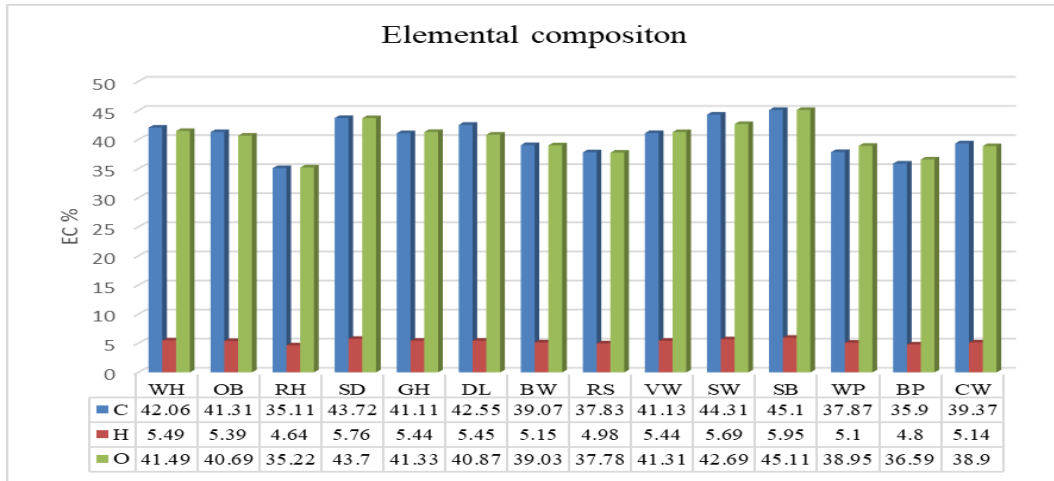


Fig 4.5 Elemental composition of the raw material.

4.1.4 Calorific value

Calorific value is the main property of fuel it determines how much heat the material can generate. So that value must be a higher value. Generally, for biomass the value ranges from 12 – 20MJ/kg. here the calorific value ranges from 13.76 to 17. 08%. Rice husk and sugarcane bagasse showed the minimum and maximum values of calorific value. The maximum value of calorific value is due to the presence of C and H in the sugarcane bagasse as you can see that the rice husk has the minimum value of C and H hence the lowest value of calorific value.

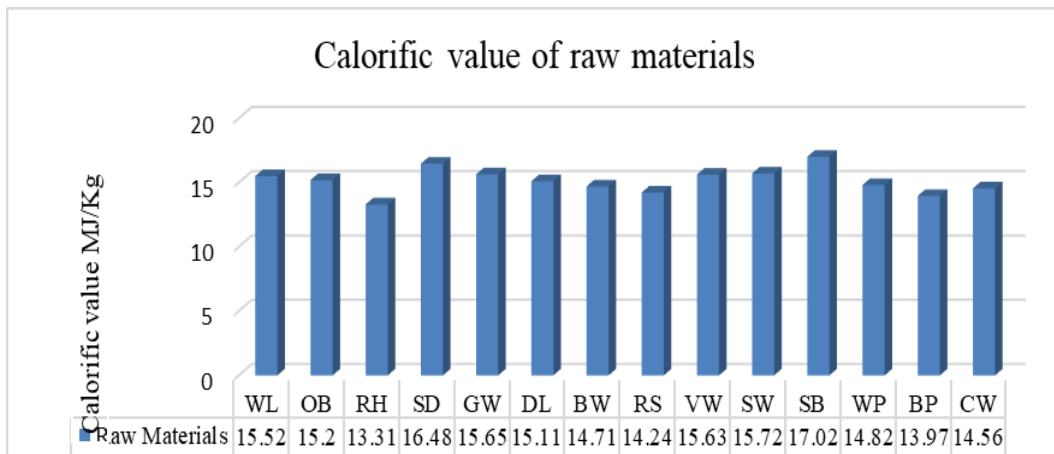


Fig 4.6 Calorific value of the raw materials

4.2 CHARACTERIZATION OF BRIQUETTES

4.2.1 Physical properties

Physical properties consist of bulk density (compressed and relaxed density), true density, porosity and water absorption. The values that are obtained from the experiments are listed in the table below.

Table 4.3 Physical properties of briquettes

Material	Physical properties						Ref.
	Compressed density	Relaxed density	Relaxation ratio	True density	Porosity	Water absorption %	
Water Hyacinth leaves (WL)	732.36	625.90	1.30	795.00	0.08	21.92	[Present work]
Oil Palm Fruit Bunch (OF)	674.15	739.40	1.38	737.67	0.09	15.96	[Present work]
Rice husk (RH)	590.11	582.68	1.47	690.67	0.15	6.57	[Present work]
Saw Dust (SD)	551.00	579.90	1.42	565.27	0.03	3.87	[Present work]
Grass Waste (GW)	528.30	540.51	1.66	801.46	0.34	49.38	[Present work]
Dry Leaves (DL)	591.48	603.90	1.51	865.89	0.32	31.14	[Present work]
Banana tree Waste (BW)	552.60	557.58	0.991	979.25	0.44	145.25	[Present work]
Rice straw (RS)	475.66	493.77	1.86	953.50	0.50	86.21	[Present work]
Vegetable Market Waste (VW)	1038.53	1046.19	1.16	1159.62	0.10	11.21	[Present work]
Spent tea waste (SW)	824.53	795.24	1.02	1014.40	0.19	48.97	[Present work]
Banana peels	678	-	-	-	-	-	[13]
Rattan waste	793	-	-	-	-	-	[13]
Coconut shell	1120	-	-	-	-	-	[13]
Sugarcane bagasse	845	-	-	-	-	-	[13]
Orange peel	1100	-	-	-	-	-	[15]
Palm oil mill sludge + rice husk. 1:10	799.89	333.46	2.40	-	-	93.77	[14]
POMS to rice husk 1:5	856.65	343.08	2.50	-	-	91.77	[14]
POMS to rice husk 3:10	903.53	397.51	2.27	-	-	89.36	[14]
POMS to rice husk 2:5	942.71	432.68	2.18	-	-	86.58	[14]
POMS to rice husk 1:2	947.93	451.09	2.10	-	-	83.59	[14]
POMS to rice husk 3:5	964.52	485.18	1.99	-	-	80.76	[14]
POMS to rice husk 7:10	1009.45	465.84	2.17	-	-	76.99	[14]
POMS to rice husk 4:5	1015.88	487.95	2.08	-	-	75.95	[14]
POMS to rice husk 9:10	986.54	494.05	2.00	-	-	75.23	[14]
POMS to rice husk 1:1	1044.93	498.55	2.10	-	-	74.73	[14]

(i) Bulk density

Bulk density is a concern while considering the combustion and handling properties of the briquettes. Bulk density can reduce the ignitability of the briquette if its value is far greater than an optimal value. It can also affect the burning time if the bulk density is much lower the briquette can be burned more faster which is not the desired property. In the chart it is can be seen that vegetable market waste has the highest bulk density of 1038 Kg/m³ and rice has the minimum calorific value. In the previous papers banana peels [13] shows a compressed density of 678 Kg/m³, rattan waste [13] shows 793 Kg/m³, coconut shell [13] shows 1120 Kg/m³, sugarcane bagasse [13] has 845 Kg/m³, orange peel [15] briquettes exhibits 1100 Kg/m³. Another type of briquette made from palm oil and rice husk exhibits compressed density ranges from 799.89 – 1044.93 Kg/m³.

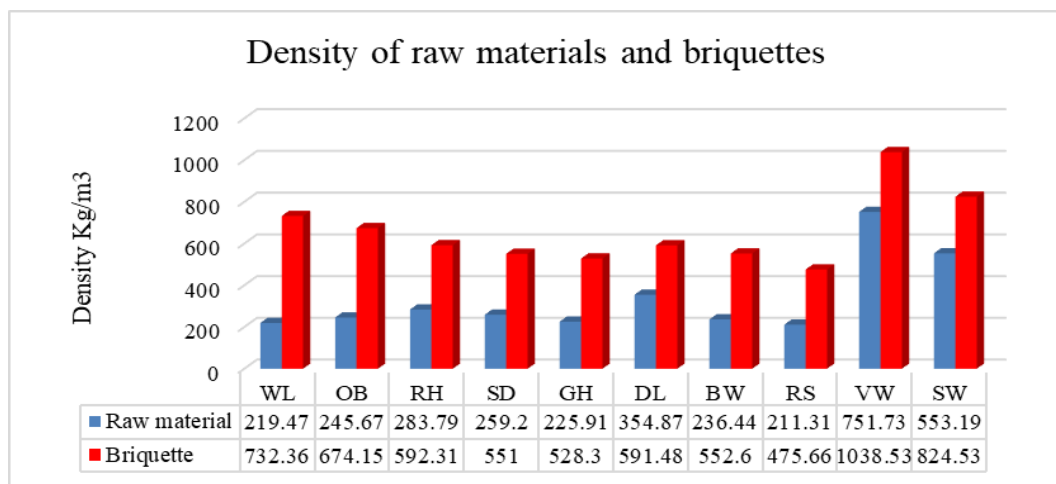


Fig 4.7 Density comparison of the raw material and briquettes.

(ii) True density

True density is nothing but the actual density of the material. This is found by using Archimedes principle. True density has an effect in the porosity of a briquette. As true density increases the porosity of the material decreases. Vegetable market waste has the largest value of true density of 1159.6 Kg/m³ and sawdust has the lowest value of true density of 565.27 Kg/m³. For finer particle size material, the true density also be a higher value. The lower value of the true density is due to larger particle size, the maximum particle size of the raw material is 2.36 mm that of the standard ISO sieve. The true density can also be a factor while considering the water absorption of the briquette.

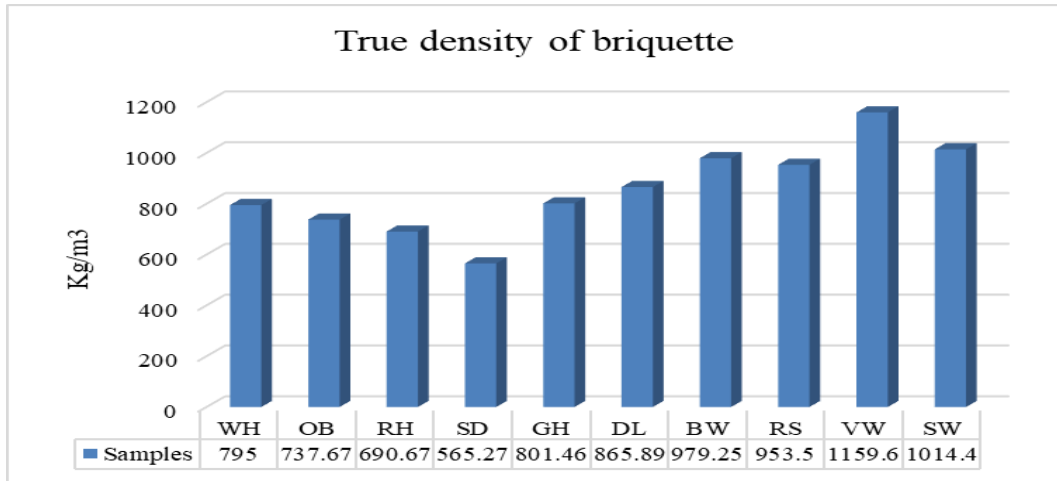


Fig 4.8 True density of briquette

(iii) Porosity

Porosity is the factor which determines the ignitability of the briquettes. As the porosity decreases the ignitability of the briquette also decreases. The rice straw briquettes show the maximum porosity of 0.5 and sawdust shows the minimum value of 0.03. The rice straw briquettes exhibit maximum ignitability or rice straw briquette is easy to ignite than other briquettes.

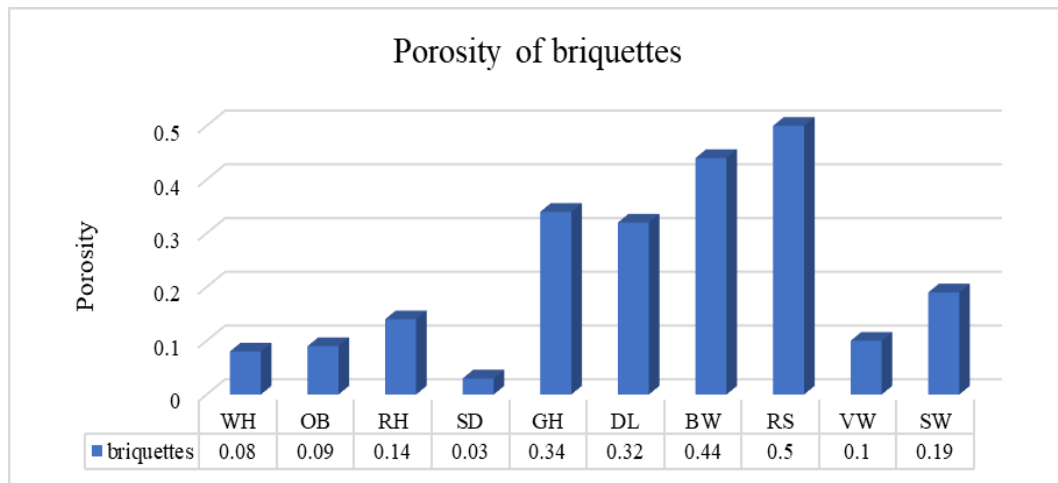


Fig 4.9 Porosity of the briquettes

(iv) Water absorption

This is one of the properties that briquette should have. The water absorption property should always be a lower value. Banana tree waste shows the largest water absorption of 145.25 % and saw dust shows the lowest water absorption value of 3.87 %. Water absorption is a factor that depends upon true density and porosity. Highly porous

briquettes can absorb more water than other briquettes. Here we can see the banana tree waste and the rice straw have the larger values of porosity and those briquettes have the largest water absorption property. The sawdust has a smaller porosity value, hence its minimum water absorption value. The acceptable limit of water absorption limit is below 30%.

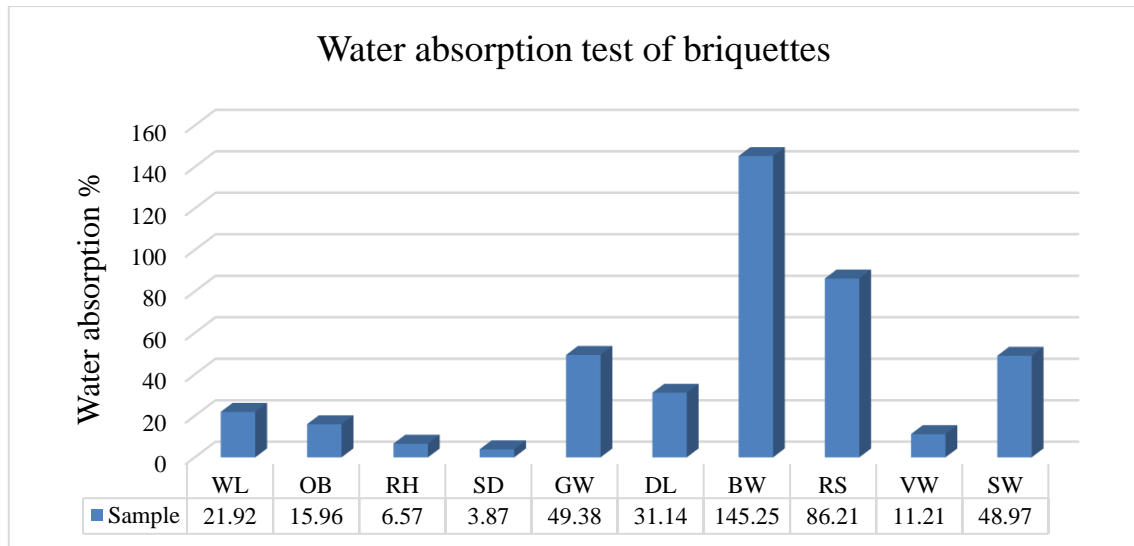


Fig 4.10 Water absorption of briquette

(v) Relaxation ratio

Relaxation ratio is a parameter that defines the dimensional stability of the briquettes. It is the ratio of the compressed density to the relaxed density. For better dimensional stability the relaxation ratio should be nearer to 1. From the table 4.3 it is evident that all the values are nearer to one. Rice straw shows the maximum relaxation ratio of 1.86 and saw dust show the minimum relaxation ratio of 1.02. from the table 4.3 the relaxation ratio of [14] rice husk and palm oil mill sludge show a value greater than 2.

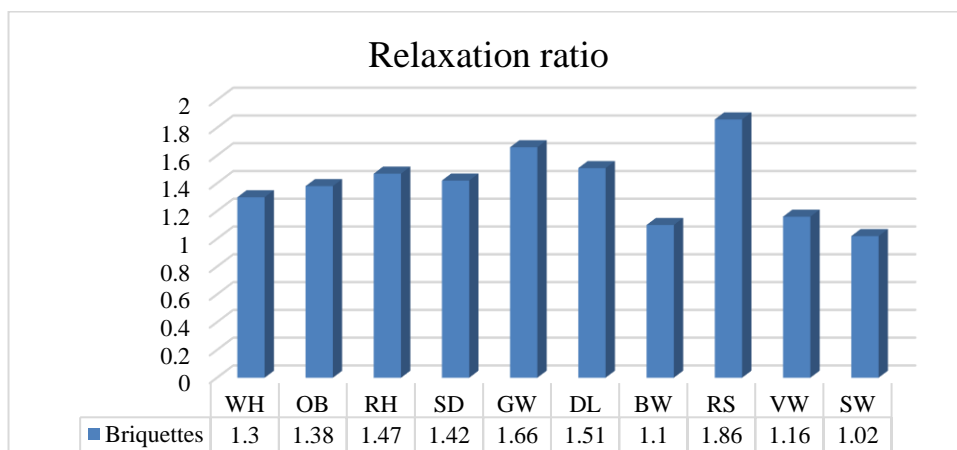


Fig 4.11 Relaxation ratio of the briquettes

4.2.2 Mechanical properties

(i) Compressive strength

While considering the handling properties compressive strength is one of the properties in which a briquette must have. Otherwise transportation of the briquettes might be a problem. From the chart it is clear that rice straw, banana tree waste and grass waste showed a better compressive strength of 26.65 Mpa, 22.65 Mpa and 26.37 Mpa respectively. Minimum acceptable value of the compressive strength is 1 Mpa. The lowest value of compressive strength is obtained for spent tea waste. From table 4.4 the briquette made from sorghum panicle and pearl millet showed a compressive strength range from 65.90 – 66.361 Mpa.

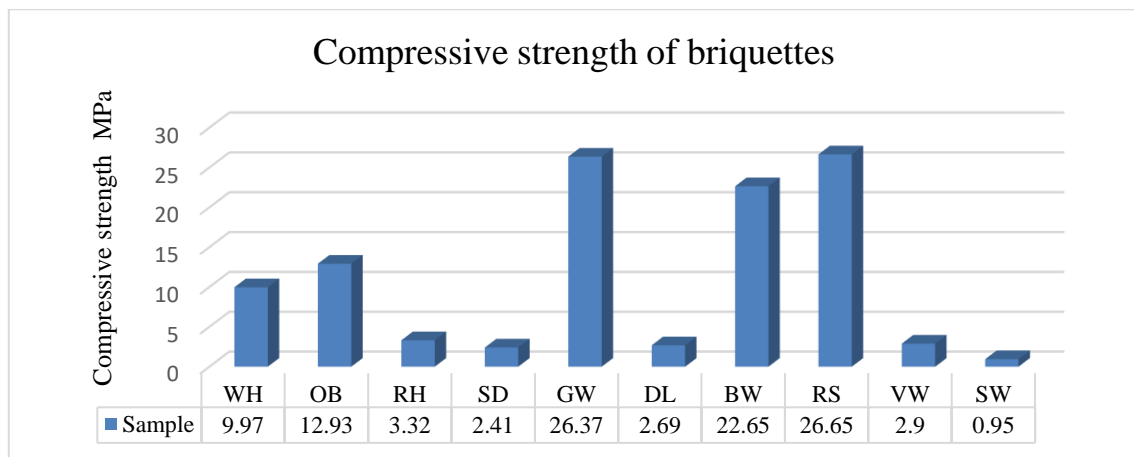


Fig 4.12 Compressive strength of the briquette

4.2.3 Durability

(i) Shatter Index

Shatter index is another handling property that shows how much impact the briquette can holds. The minimum value of shatter index that a briquette must have is any values greater than 90 %. Here all the values are between 99% and 100 % which shows that the briquette owns a better shatter index. From table 4.4 it is clear that the shatter index of other briquette made of rice husk and palm oil mill sludge [14] has values greater than 90 other than one of the combination.

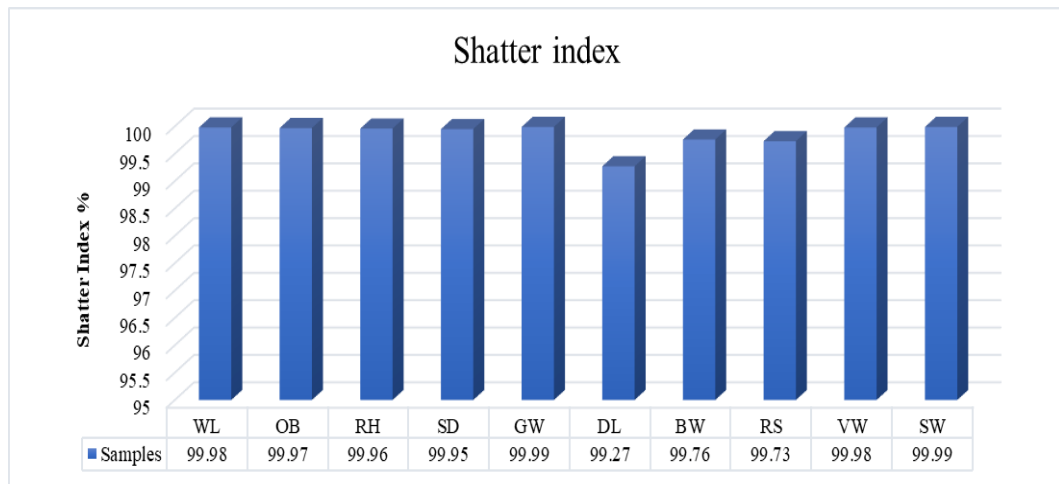


Fig 4.13 Shatter index of briquettes

Table 4.4 Compressive strength and shatter index of the briquettes

Materials	Compressive Strength (Mpa)	Shatter Index (%)	Reference
Water Hyacinth leaves (WL)	9.97	99.98	[Present work]
Oil Palm Fruit Bunch (OF)	12.93	99.97	[Present work]
Rice husk (RH)	3.32	99.96	[Present work]
Saw Dust (SD)	2.41	99.95	[Present work]
Grass Waste (GW)	26.37	99.99	[Present work]
Dry Leaves (DL)	2.69	99.27	[Present work]
Banana tree Waste (BW)	22.65	99.76	[Present work]
Rice straw (RS)	26.65	99.73	[Present work]
Vegetable Market Waste (VW)	2.90	99.98	[Present work]
Spent tea waste (SW)	0.95	99.99	[Present work]
Sorghum Panicle – Pearl millet (100:0)	65.90	-	[10]
Sorghum Panicle – Pearl millet (30:70)	66.262	-	[10]
Sorghum Panicle – Pearl millet (0:100)	66.361	-	[10]
Palm oil mill sludge to rice husk. 1:10	-	76.19	[14]
POMS to rice husk 1:5	-	91.18	[14]
POMS to rice husk 3:10	-	93.54	[14]
POMS to rice husk 2:5	-	94.21	[14]
POMS to rice husk 1:2	-	95.61	[14]
POMS to rice husk 3:5	-	98.61	[14]
POMS to rice husk 7:10	-	99.16	[14]
POMS to rice husk 4:5	-	99.17	[14]
POMS to rice husk 9:10	-	99.22	[14]
POMS to rice husk 1:1	-	99.61	[14]

4.2.4 Proximate analysis

Proximate analysis consists of moisture content, volatile matter, ash content and fixed carbon. The results obtained from the proximate analysis are listed in the table below.

Table 4.5 Proximate analysis of the briquettes

Material	Moisture content (%)	Volatile matter (%)	Ash content (%)	Fixed carbon (%)	Calorific value (MJ/Kg)	Reference
Water Hyacinth leaves (WL)	8.75	82.43	11.88	5.70	15.42	[Present work]
Oil Palm Fruit Bunch (OF)	4.25	82.40	8.25	9.35	15.54	[Present work]
Rice husk (RH)	5.12	74.29	16.25	9.46	14.05	[Present work]
Saw Dust (SD)	4.25	86.68	4.12	9.19	16.33	[Present work]
Grass Waste (GW)	6.75	85.05	9.75	5.20	15.88	[Present work]
Dry Leaves (DL)	9.87	80.86	12.00	7.14	15.18	[Present work]
Banana tree Waste (BW)	6.25	80.47	14.13	5.40	15.05	[Present work]
Rice straw (RS)	6.25	74.58	18.00	7.42	14.03	[Present work]
Vegetable Market Waste (VW)	7.12	84.81	8.88	6.31	15.88	[Present work]
Spent tea waste (SW)	6.87	85.24	5.62	9.13	16.06	[Present work]
Banana peels	7.64	60.92	11.95	19.49	16.983	[13]
Rattan waste	5.57	68.12	7.44	18.87	30.077	[13]
Coconut shell	4.33	70.50	10.02	15.15	32.169	[13]
Sugarcane bagasse	5.97	63.54	11.511	18.98	25.551	[13]
Palm oil mill sludge + rice husk. 1:10	6.21	68.66	19.39	11.95	13.45	[14]
POMS to rice husk 1:5	6.66	69.11	19.17	11.73	14.36	[14]
POMS to rice husk 3:10	7.17	71.45	18.86	9.69	15.94	[14]
POMS to rice husk 2:5	9.25	72.25	19.43	8.32	16.42	[14]
POMS to rice husk 1:2	9.54	72.40	16.10	11.49	17.41	[14]
POMS to rice husk 3:5	8.44	72.86	17.08	10.07	18.10	[14]
POMS to rice husk 7:10	9.77	73.75	16.78	9.47	19.48	[14]
POMS to rice husk 4:5	8.56	74.84	16.67	8.49	20.30	[14]
POMS to rice husk 9:10	9.34	75.75	16.10	8.15	20.60	[14]
POMS to rice husk 1:1	10.42	76.23	15.13	8.64	21.68	[14]

(i) Moisture content

Moisture content is an important factor while considering the fuel properties of the briquettes. If the moisture content of the briquette is larger than 20% then it may create smokes. Due to higher moisture content the ignitability of the briquette may increase because at the initial stage the heat may use to vaporise the moisture content. Here the moisture content ranges from 4.25% - 7.58%. Minimum value of 4.25 % is for oil palm fruit bunch and saw dust. The maximum value is for dry leaves of 7.58%. The ISO standard values range from 2.2 – 15.9 %. From table 4.5 it is evident that the briquette samples are in this range. From the table it is clear that the materials such as banana peels, rattan waste, coconut shell, sugarcane bagasse [13] and the briquette made of palm oil mill and rice husk [15] shows moisture content ranges between 4% and 11%.

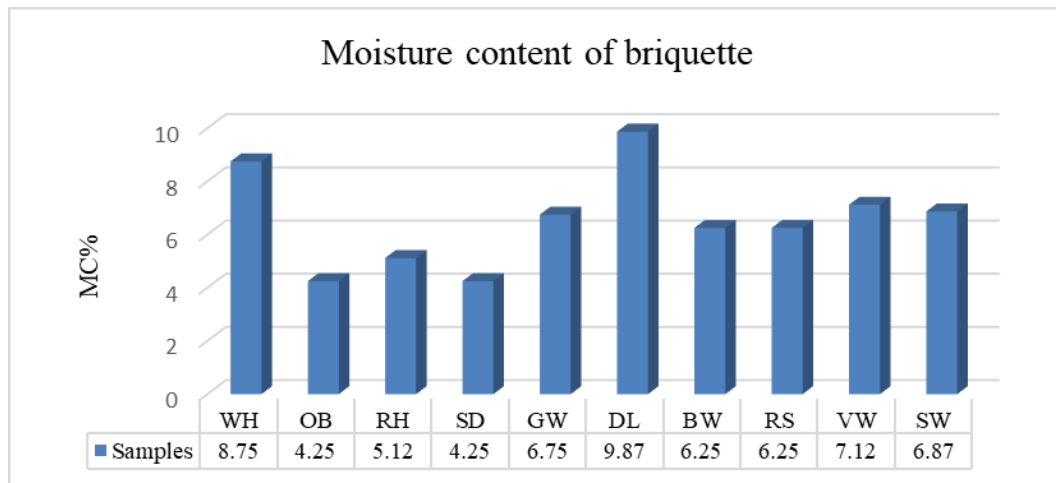


Fig 4.14 Moisture content of the briquettes

(ii) Volatile matter

Volatile matter is the content which can be vapourised from the biomass other than water content. Volatile matter can help the briquette to ignite faster. The volatile matter of the briquette ranges from 74.29% to 85.24%. Spent tea waste showed maximum volatile matter of 85.24 and rice husk showed minimum value of 74.29 %. The ISO values of the volatile matter ranges from 75.8 – 94.7 %. Except rice husk (74.29%) all other briquettes shows a value between that range. From table 4.5 it is clear that the materials such as banana peels, rattan waste, coconut shell, sugarcane bagasse [13] and the briquette made of palm oil mill and rice husk shows volatile matter content ranges from 60 – 78%.

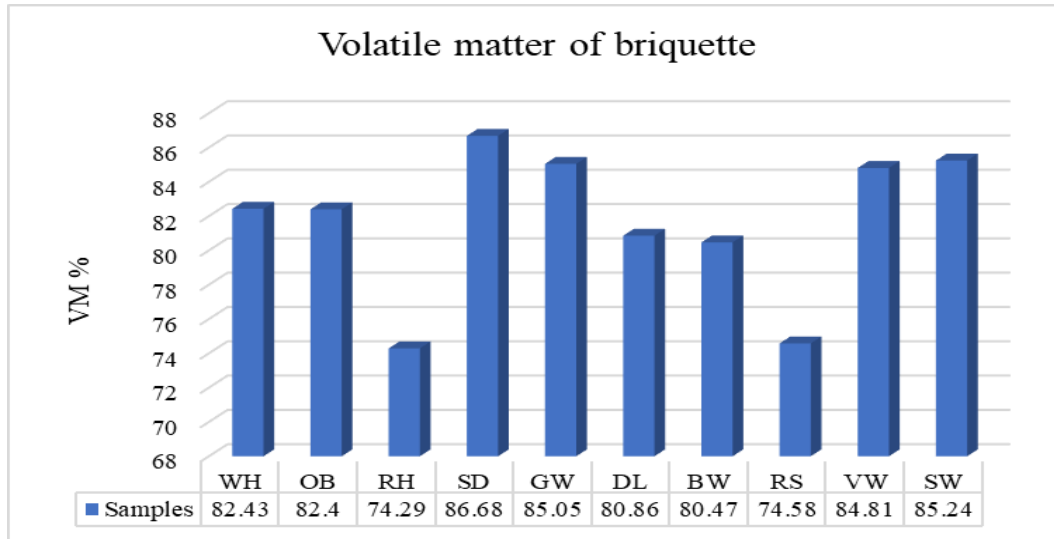


Fig 4.15 Volatile matter of the briquette

(iii) Ash content

Ash content of the fuels represent the incombustible content in the fuel. Greater value of ash content may cause some problems in the boilers. Ash content ranges from 4.12 to 18.00 %. Rice straw has the highest value of ash content and saw dust shows the lowest value of ash content of 18 and 4.12 % respectively. The ISO standard values for the briquette are in between 3.3 -11.7 %. Rice straw has a value of 18% which is very much beyond this range. From table 4.5 it is clear that the materials such as banana peels, rattan waste, coconut shell, sugarcane bagasse [13] and the briquette made of palm oil mill and rice husk [14] shows ash content ranges between 7% and 20%.

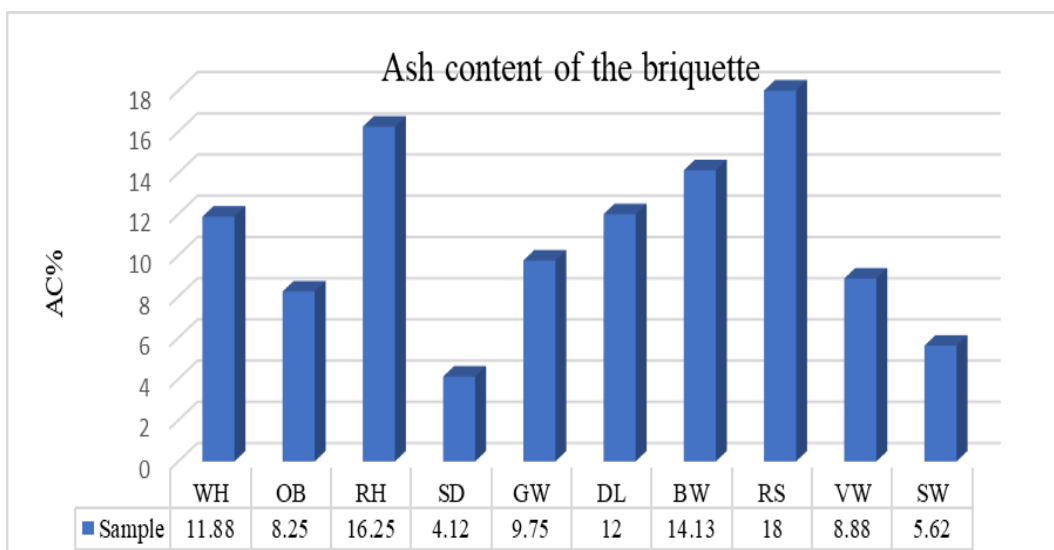


Fig 4.16 Ash content of the briquette

(iv) Fixed carbon

Fixed carbon is the parameter which is related to the calorific value of the fuel. So larger the fixed carbon larger the calorific value. Fixed carbon of the briquette varies from 5.70 to 10.46 %. Water hyacinth leaves has the lowest fixed carbon and rice husk has the highest fixed carbon.

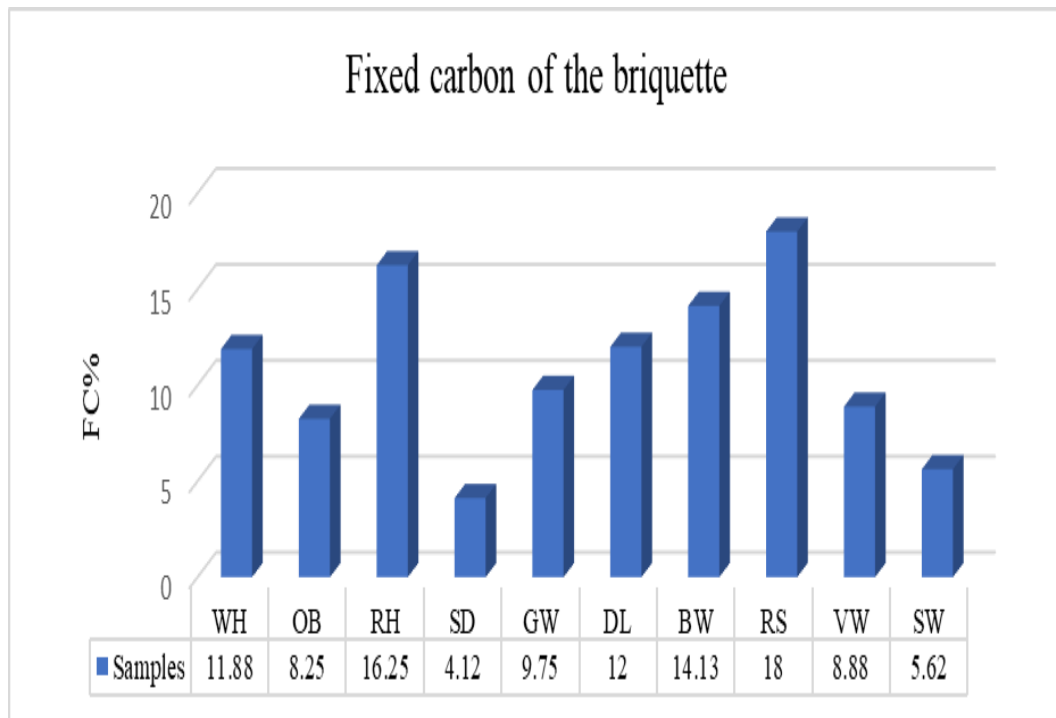


Fig 4.17 Fixed carbon of the briquette

4.2.5 Elemental composition

The values of elemental composition briquette that obtained from the calculations are given in the table 4.6. Three elements, C, O, and H, have been checked to ensure combustion properties. The previously mentioned equations are used to calculate elemental compositions. For fuel, the combustion properties are influenced by C and H. As the level of C and H increase, the combustion property may increase. O should always be a lesser value. Here the content of C varies from 37.76% to 44.06%. The largest value is for sawdust, and the rice straw shows the lowest value. The value of hydrogen ranges from 5.01 % to 5.85%. The largest and smallest values are for sawdust and rice straw. The value of O ranges from 37.76 to 45.11. As earlier lowest and the highest value is for rice straw and sawdust, respectively.

Table 4.6 Elemental composition of briquettes

Material	Carbon (C)	Hydrogen (H)	Oxygen (O)	Reference
Water Hyacinth leaves (WL)	41.13	5.41	40.97	[Present work]
Oil Palm Fruit Bunch (OF)	43.45	5.60	42.07	[Present work]
Rice husk (RH)	39.83	5.10	38.24	[Present work]
Saw Dust (SD)	45.30	5.85	44.06	[Present work]
Grass Waste (GW)	42.01	5.54	42.06	[Present work]
Dry Leaves (DL)	41.34	5.38	40.66	[Present work]
Banana tree Waste (BW)	40.06	5.27	39.95	[Present work]
Rice straw (RS)	38.66	5.01	37.76	[Present work]
Vegetable Market Waste (VW)	42.61	5.59	42.29	[Present work]
Spent tea waste (SW)	44.60	5.76	43.35	[Present work]
POMS (Palm oil mill sludge) to rice husk. 1:10	38.85	4.88	36.31	[14]
POMS to rice husk 1:5	38.91	4.89	36.46	[14]
POMS to rice husk 3:10	38.68	4.93	36.96	[14]
POMS to rice husk 2:5	38.18	4.91	36.92	[14]
POMS to rice husk 1:2	40.26	5.09	37.96	[14]
POMS to rice husk 3:5	39.56	5.04	37.74	[14]
POMS to rice husk 7:10	39.59	5.06	37.98	[14]
POMS to rice husk 4:5	39.46	5.08	38.21	[14]
POMS to rice husk 9:10	39.66	5.12	38.53	[14]
POMS to rice husk 1:1	40.19	5.18	38.91	[14]

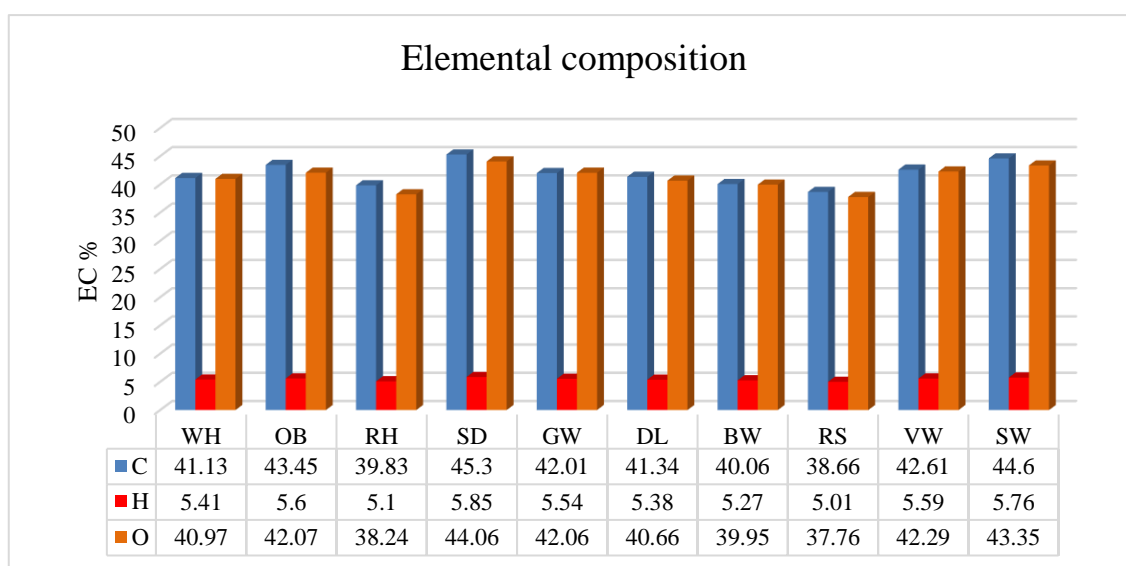


Fig 4.18 Elemental composition of the briquettes

4.2.6 Calorific value

Calorific value is the main property of fuel, it determines how much heat the material can generate. So that value must be a higher value. Generally, for biomass the value ranges from 12 – 20 MJ/kg. Here the calorific value ranges from 14.03% to 16.33%. Rice straw and saw dust showed the minimum and maximum values of calorific value. The maximum value of calorific value is due to the presence of C and H in the sugarcane bagasse as you can see that the rice husk has the minimum value of C and H hence the lowest value of calorific value. From table 4.5 briquettes from rattan waste and coconut shell shows a calorific value of 30.077 and 32.169 MJ/kg.

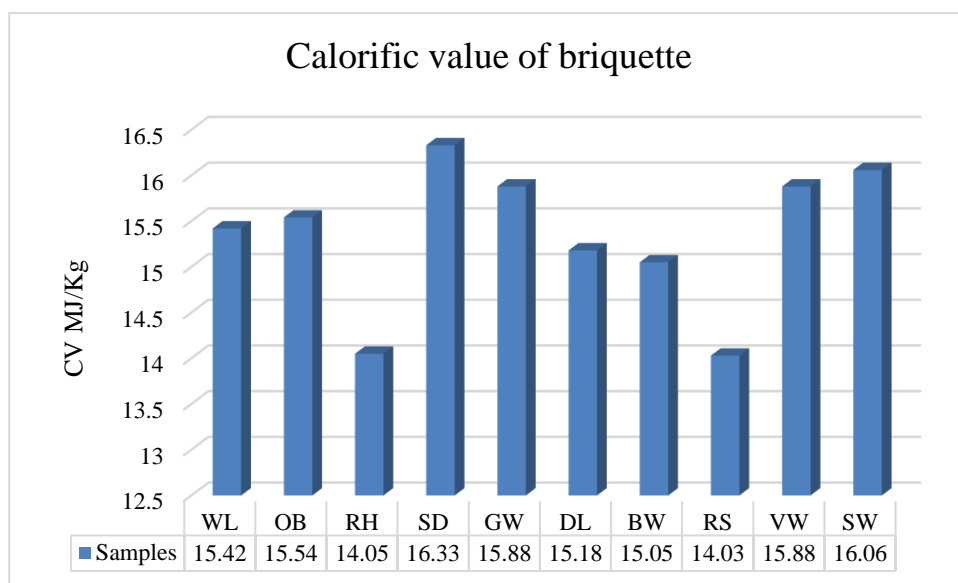


Fig 4.19 Calorific value of the briquette

CHAPTER 5

CONCLUSION

5.1 SUMMARY

Depleting non-renewable fuels are one of the main reasons to think about bio-briquettes. Especially coal is on the verge of extinction. To replace coal, we should move on to new biomass fuels. Aquatic weeds and agricultural wastes are the two predominant issues in the agricultural sector. It affects the agricultural sector in many ways, especially fish farming. Extensive agricultural waste is produced in Kerala, like rice straw, coir pith, vegetable market wastes, coffee stalks, etc. A large portion of crop residues is burnt. The smoke of these residues causes enormous air pollution in the environment. Invasive aquatic weeds like water hyacinth (WH) pose severe economic and environmental issues in Kerala. In addition to climate factors, increasing market prices of traditional fossil fuels have driven consumer preference toward alternative fuels. In this work, biomass briquettes were developed using agricultural and aquatic feedstock materials using natural rubber latex as the binder. The characterization of the raw material is conducted. Experimental works to determine the mechanical, physical, durability and combustion properties were performed and compared properties. Accordingly, the results can be summarized as follows:

- From the characterization of the raw material, it is clear that rice husk and banana peel have higher ash content (above 20 %). Hence, they are not suitable for biomass briquette production.
- Even though water hyacinth petioles and sugarcane bagasse have comparatively better fuel properties, their binding characteristics with natural rubber latex are poor. Hence it is not recommended for briquette production with natural rubber latex.
- Sugar cane bagasse, dry leaves, water hyacinth leaves, oil palm fruit bunch, sawdust, vegetable market waste, and spent tea waste have excellent fuel properties and are good candidates for biomass briquette production.
- The density calculation shows that the relaxation ratio was highest for rice straw and lowest for spent tea waste. The lower the relaxation ratio value, the higher the

dimensional stability. Therefore, briquettes made from spent tea waste have the highest dimensional stability.

- The porosity values were higher for briquettes made from rice straw and banana tree waste; hence, their water penetration resistance is much lower than other biomass briquettes. Therefore, the water performance of these briquettes is very low. Moreover, the water performances of briquettes made from saw dust, rice husk, vegetable market waste, water hyacinth, and oil palm fruit bunch are excellent.
- From the compressive strength characteristics, all the developed briquettes have superior compressive strength except for spent tea waste.
- The durability characteristics of all the produced briquettes were excellent; hence, the chances of collapse during transportation will be minimal.
- Higher heating values were obtained for briquettes made from sawdust, vegetable market waste, grass waste, oil palm fruit bunch, spent tea waste and water hyacinth leaves from the characterization of biomass briquettes.

5.2 SCOPE FOR FURTHER WORK

The current work concludes by comprehensively listing the properties of biomass briquettes made from different agricultural and aquatic residues and the key findings of this study will be helpful to the researchers in this area. The current work can be extended into the following areas.

- Experimental works can be performed to determine the mechanical, physical and fuel properties of briquettes with different binders to investigate the effect of binders on the briquette characteristics.
- Also, a detailed comparative study on the effect of particle size and compaction on the properties of the briquettes can be investigated.
- Moreover, compositing of water hyacinth with other feedstock materials is yet another future scope of this research.
- Further investigation into fuel briquettes combustion and emission characteristics is also recommended.

REFERENCES

1. **Umesh B. Deshannavar, Prasad G. Hegde, Zeba Dhalayat, Vyjayanti Patil, Suchit Gavvas**, (2018), Production and characterization of agro-based briquettes and estimation of calorific value by regression analysis: An energy application, <https://doi.org/10.1016/j.mset.2018.07.003>
2. **Saif Ullah, Rana Shahzad Noor, Sanaullah & Tian Gang**, (2020), Analysis of biofuel (briquette) production from forest biomass: a socioeconomic incentive towards deforestation., *Biomass Conversion and Biorefinery*, <https://doi.org/10.1007/s13399-021-01311-5>
3. **Zhenkun Guo, Jianjun Wu, Yixin Zhang, Feng Wang, Yang Guo, Kening Chen, Hu Liu**, (2020), Characteristics of biomass charcoal briquettes and pollutant emission reduction for sulfur and nitrogen during combustion, *Fuel*, <https://doi.org/10.1016/j.fuel.2020.117632>
4. **Janet Onyango, Kelvin Babu, Samwel Njuguna, Wyclife Wanzala, Xue Yan**, (2020), Harnessing the potential of common water hyacinth as an industrial raw material for the production of quality biofuel briquettes .*SN Applied Sciences*, <https://doi.org/10.1007/s42452-020-3109-1>
5. **Emanuele Cesprini, Rosa Greco, Valerio Causin, Tiziana Urso, Raffaele Cavalli, Michela Zanetti**, (2021), Quality assessment of pellets and briquettes made from glued wood waste, *European Journal of Wood and Wood Products* 79:1153–1162, <https://doi.org/10.1007/s00107-021-01695-1>
6. **Ambedkar Balraj, Jagannathan Krishnan, Keerthana Selvarajan, Keertthana Sukumar**, (2020) Potential use of biomass and coal-fine waste for making briquette for sustainable energy and environment. *Environmental Science and Pollution Research*, <https://doi.org/10.1007/s11356-020-10312-2>
7. **Willis Gwenzi, Rumbidzai S. Ncube, Tungamirai Rukuni**, (2021), Development, properties and potential applications of high-energy fuel briquettes incorporating coal dust, biowastes and post-consumer plastics, *European Journal of Wood and Wood Products* ,79:1153–116, <https://doi.org/10.1007/s00107-021-01695-1>
8. **Josephat Kipyegon Tanui, Paul Ndirangu Kioni, Peter Ngugi Kariuki, John Mburu Ngugi**, (2018), Influence of processing conditions on the quality of briquettes produced

- by recycling charcoal dust, *International Journal of Energy and Environmental Engineering*, <https://doi.org/10.1007/s40095-018-0275-7>
9. **H A Ajimotokan, S E Ibitoye, J K Odusote, O A Adesoye, P O Omoniyi**, (2019), Physico-mechanical Properties of Composite Briquettes from Corncob and Rice Husk (2019), *Journal of Bioresources and Bioproducts*, 159–165, <https://doi.org/10.12162/jbb.v4i3.004>
 10. **Sampathkumar Velusamy, Anandakumar Subbaiyan, Ramesh Srikrishnaperumal Thangam**, (2021), Combustion characteristics of briquette fuels from sorghum panicle–pearl millets using cassava starch binder, *Environmental Science and Pollution Research* 28:21471–21485, <https://doi.org/10.1007/s11356-020-11790-0>
 11. **P.Tiam Kapen, M.Nandou Tenkeu, E. Yadjie, G. Tchuen**, (2021), Production and characterization of environmentally friendly charcoal briquettes obtained from agriculture waste: case of Cameroon ,*International Journal of Environmental Science and Technology*, <https://doi.org/10.1007/s13762-021-03497-7>
 12. **Sandip Mandal, G. V. Prasanna Kumar, T. K. Bhattacharya, H. R. Tanna, P. C. Jena**, (2017), Briquetting of Pine Needles (*Pinus roxburgii*) and Their Physical, Handling and Combustion Properties, *Waste and Biomass Valorization* <https://doi.org/10.1007/s12649-018-0239-4>
 13. **Bill Vaneck Bot, Olivier Thierry Sosso, Jean Gaston Tamba, Eugénie Lekane, Jacques Bikai, Max Keller Ndame**, (2021), Preparation and characterization of biomass briquettes made from banana peels, sugarcane bagasse, coconut shells and rattan waste, *Biomass Conversion and Biorefinery*, <https://doi.org/10.1007/s13399-021-01762-w>
 14. **Okey Francis Obi & Kingsley Chukwudi Okongwu**, (2016), Characterization of fuel briquettes made from a blend of rice husk and palm oil mill sludge, *Biomass Conv. Bioref.* DOI 10.1007/s13399-016-0206-x.
 15. **Bahareh Karimibavani, Ayse Busra Sengul, Eylem Asmatulu**, (2019), Converting briquettes of orange and banana peels into carbonaceous materials for activated sustainable carbon and fuel sources, *Energ. Ecol. Environ.* <https://doi.org/10.1007/s40974-020-00148-4>