Process development for the production of briquette using agro forest waste and taro binder for rural household applications

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by

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Dedicated to

my Parents and my husband

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CERTIFICATE

It is certified that the work contained in the thesis entitled **"Process development for production of briquette using agro forest waste and taro binder for rural household applications"** submitted by **Ms. Anjali Narzary** to the **Indian Institute of Technology Guwahati** for the award of the degree of **Doctor of Philosophy** has been carried out under my supervision in the **School of Agro and Rural Technology**. This work has not been submitted elsewhere for the award of any other degree or diploma.

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SELF DECLARATION

I declare that,

a. The work contained in this thesis is original and has been carried out by me under the supervision of **Prof. Amarendra Kumar Das**.

b. To the best of my knowledge, the work has not been submitted to any other institute for any degree or diploma.

c. I have followed all the guidelines provided by the institute in preparing the thesis.

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ABSTRACT

The potential use of agro forest waste (Rice straw, Eleusine indica grass, Polyalthia longifolia leaves) for briquette production using low-power screw press machines was studied in this research. A low-cost, abundant, and novel binder, Taro (Colocasia esculenta) was used for briquetting. The briquettes obtained were tested for physical, mechanical, physio-chemical, and thermal properties. As charcoal is reported to enhance the briquette properties, so bamboo charcoal was added to the same composition of raw materials at three percentages (0, 25, and 50) % and briquetted and analyzed for fuel properties. Taguchi-Grey analysis was employed to obtain the best briquette composition based on calorific value, shatter resistance, density, water resistance, and compressive strength. The best result was obtained for the straw and 25 % charcoal and 15 % binder. Cost analysis and specific energy consumption during briquetting were also done. Specific energy consumption shows that size reduction using a chaff cutter machine consumes 87 % of the total specific energy required for briquette production. Therefore, to omit the chaff cutter machine in order to reduce the specific energy, the rice straw was carbonized for the next step before briquetting. As carbonization effectively reduces the material's resilient properties and is effective in the reduction of pollution emissions, carbonization was the chosen pre-treatment method. The novel binder was compared with the two most widely used binders in the literature to validate its use as a binder. The result showed that the taro binder does not harm the briquette quality and is equally effective as starch and paper binder. For the last step, a low-cost manual press was fabricated at a local welding shop. The briquette obtained was compared with the same combination sample obtained using a screw press, and the best selection was obtained from Taguchi-Grey analysis. The result showed that the taro binder does not harm the briquette quality and is equally effective as starch and paper binder. A low-cost manual press was fabricated at a local welding shop to fulfill this objective. The machine was used for briquetting the best combination of straw at 15 % binder; the sample characteristics were compared with the same combination sample obtained using a screw press, and the best selection was obtained from Taguchi-Grey analysis. The samples were analyzed and compared based on physical, thermal, mechanical, and physio-chemical properties. Cost, specific energy consumption, and burning rate were also compared. The results show that as carbonization helps omit the chaff cutter from the briquetting process, the specific energy and cost of capital investment and production cost decreases. This technology is best for insitu briquette production, which will reduce the transportation cost, which is one factor that adds up to the cost of the raw materials used for briquetting.

Keywords: *Agro-forestry waste, Physiochemical properties, mechanical properties, TGA, gas emission, Taguchi-Grey analysis, cost analysis.*

CONTENTS

LIST OF NOMENCLATURE

A, B, C, D, E	Different factors under study
P	Electric power
3V	Linear voltage
I	Line current
CosΦ	Power factor
T	Time in seconds
E	Electrical Energy
Y_{ij}	Observed response value
H	S/N ratio co-efficient
x_i	Normalized value
$\Delta x_i(k)$	Derivation co-efficient
Ξ	Grey relation Co-efficient
Ψ	Distinguishing Co-efficient

LIST OF ACRONYMS

VM - Volatile matter

AC- Ash content

MC - Moisture content

FC- Fixed carbon

HHV- High heating value

CV- Calorific value

DL - Dry leaves

FESEM - Field Emission Scanning electron microscopy

TGA - Thermo Gravimetric Analysis

DSC - Differential Scanning Calorimetry

GRG - Grey Relational Grade

MS - Mean of squares

DOF - Degree of Freedom

SS - Sum of squares

ANOVA - Analysis of Variance

S/N - Signal to Noise ratio

BP - Binder Preparation

CS - Compressive Strength

WR - Water Resistance

SR - Shatter Resistance

BD - Bulk Density

C - Carbon

H - Hydrogen

N - Nitrogen

O - Oxygen

IUCN - International Union for Conservation of Nature

TEE - Total Energy Expenditure

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Chapter 1: Introduction

1.0 Introduction

In this chapter, various wastes produced in India and current methods of waste management are discussed. The densification method for energy generation as a process to tackle the waste generated and its advantages are also discussed.

1.1 Background

Agriculture waste is challenging nowadays, and vast amounts of agricultural waste are available in our surroundings every day. Recent trends in producing biofuels from agricultural wastes are an emerging field of research. Processes such as thermochemical, fermentation, gasification, liquefaction, distillation, combustion, and fast pyrolysis, could be investigated to produce biofuels from agricultural wastes such as rice straw, corn stover, wheat straw, cotton stalk, etc.[1]. Forest residue is also a promising raw material for producing biofuels. India is among the world's top ten countries rich in forest resources. According to the Food and Agriculture Organization of India 2022 report, a land area of 721,600 Sq. km is covered in forest [2].

India is an agro-based country, with around 70 % of its rural household still depending primarily on agriculture for their livelihood [3]. With all the agriculture products, many other by-products such as straw, rice husk, maize stalks, cotton, millets, pulse, sunflower & other stalks, groundnut shells, coconut trash, etc. are also produced. They are all biomass with great potential to meet the fuel requirement for cooking and other household purposes. Still, due to their low bulk density, production of an uncontrolled fire, and low heat production, while burning, they do not serve a good purpose as fuel for the people [4]. Gravalos et al. [5] stated that straw burning emits 7300 kg CO_2 -eq/ha year^{-1} of GHGs. Some of the Agricultural waste, along with their calorific value, are listed in **Table 1.1**. This biomass is mainly regarded as waste as it cannot be composted or transported to other places quickly, and they do not have any other use. Therefore, technology intervention in converting this biomass to some valuable products could be a great way to tackle the waste issues and provide clean fuel in rural areas, as improper disposal of agro-wastes will cause environmental pollution and waste many times valuable biomass resources.

Table 1.1: Calorific values of some agriculture residues (Tumuluru et al.[6])

Agricultural residue and waste species	Mean GCV ($MJ\cdot kg^{-1}$)
Rice husk with a moisture content of 8.30 %	15.972
Rice husk without moisture (dried at 105˚C for 24 h)	16.643
Rice straw with a moisture content t 12.19 %	15.092
Rice straw without moisture (dried at 105˚C for 24 h)	16.475
Sunflower husks	18.674
Sunflower seed cake with a moisture content of 12.72 %	21.231
Rapeseed cake with a moisture content of 11.17 %	21.569
Cotton (Gossypium hirsutum L.) plant root	17.707
Switchgrass (Panicum virgatum L.) rain-fed	17.308
Switchgrass (Panicum virgatum L.) irrigated	17.279
Switchgrass/rain-fed/ N-fertilization with 80 $kg\cdot ha^{-1}$	17.209
Switchgrass/rain-fed/ N-fertilization with 160 $kg\cdot ha^{-1}$	17.339
Switchgrass/rain-fed/ N-fertilization with 240 $kg\cdot ha^{-1}$	17.259
Switchgrass/rain-fed/dry stem	17.190
Switchgrass/rain-fed/dry leaves	16.768
Switchgrass/rain-fed/dry sheaths	16.840
Switchgrass/rain-fed/dry flowers	17.756
Common reed (Phragmites atralis) fresh leaves	17.494
Common reeddry leaves	18.274
Common reed fresh stem	16.943
Common reed dry stem	17.933
Cotton plant terminal bud	16.396
Cotton plant vegetative branches	17.376
Cotton plant fruiting branches	17.368
Cotton plant leaves	16.059
Cotton plant seeds	22.933

1.2 Motivation

Biomass briquetting is a process that can solve the problem related to waste management and, in the process, produce solid fuels, which can be an answer to the scarcity of energy. Briquetting is also one of the most straightforward biomass conversion techniques.

The bioenergy conversion process occurs mainly through four methods, i.e., thermal, thermochemical, and biochemical/biological, chemical technologies. Among many reported techniques, densification is a promising way to overcome all the obstacles to using biomass as fuel as it is a straightforward process. Densification occurs when biomass is mechanically compressed, increasing its density about ten times [5]. Therefore, the densification of biomass materials could be very effective in reducing the costs of transportation, handling, and storage. Because of their uniform shape and sizes, densified products can be easily handled using standard handling and storage equipment. Therefore, they can be quickly adopted in direct combustion or co-firing with coal, gasification, pyrolysis, and other biomass-based conversions. Commercially, biomass densification is performed using pellet mills, other extrusion processes, briquetting presses, or roller presses. Biomass densification is a technology for converting plant residues into usable energy fuel. These technologies are also known as briquetting, pelleting, or accumulation. It makes handling easier for transport, storage, etc. [7].

Many commercial briquette production technologies are available in the market. Some of them produce high-quality briquettes but are very costly, whereas some are low in cost but inefficient. Most of these machines target either large business organizations or wealthy farmers. There are hardly any machines made feasible for small farmers or for domestic use of small rural families. Hence, the author is motivated to adopt biomass briquetting of agro-waste and forest waste to find a solution to waste management and solid fuel production at a low cost.

1.3 Agriculture and forest residue

The waste generated after agricultural activities and forestry processes is known as agroforestry waste [8]. This waste can be waste from agricultural activities (e.g., paddy straw, rice husk, Ground nut shell, sugarcane bagasse, maize stalk, etc.) and forestry waste (leaves, tree barks, tree stumps, and foliage after wood extraction [9]. As this waste is not disposed of properly, it has become a leading environmental problem globally [10]. The traditional methods of waste disposal include thermal treatment, landfills, and compost pits; however, these waste dumping methods are accompanied by adverse consequences like emission of CO, CO_2, NO_x, SO_x, ashes, foul odours, and contamination of underground water [11]. Moreover, as the waste increases, the cost of disposal increases, pointing to the importance of sustainable methods for turning waste into valuable products.

The total amount of crop residues generated in the year (2017-18) was 516 million tonnes, whereas it was just 79 million tonnes in the year (1950–51) (**Table 1.2**) [12].

Table 1.2: Amount of crop residue produced, burnt, and gas emissions

Crop	Annual production (Gg)	Quantity of residue(Gg biomass)	Quantity of dry residues (Gg dry matter)	Total biomass burnt (Gg dry matter)	Total carbon released (Gg C)	Total N released (Gg N)
Rice	112,800	169,200	145,512	32,740.2	13,567.54	189.95
Wheat	99,900	169,830	149,450.4	33,626.34	16,318.86	195.83
C. Cereals	47,000	70,500	28,200	6,345	2,987.86	59.76
Pulses	25,400	38,100	27,051	6,066.475	2,866.12	57.32
Oilseeds	31,500	18,900	15,120	3,402	1701.00	85.05
Sugarcane	379,900	151,960	133,724.8	30,088.08	15,044.04	300.88
Cotton	5,576	16,728	13,382.4	3,011.04	1,505.52	30.11
Jute and Mesta	1800	5,400	4,320	972	486.00	9.72
Total	703,876	640,618	516,760.6	116,271.135	54,476.94	928.61

Abbreviation: Gg- Gigagram, C. Cereals- Coarse Cereals

The growth in population leads to an increase in food demand, which is attributed to the increase in cropping area and intensity. The increase in cropping intensity from 111.07 % to 139.56 % is seen between 1950-51 and 2010–11. The increase in total production of food grain from 50 million tonnes (1950–51) to 285 million tonnes (2017–18) is reported because of the increase in cropping intensity, total cropped area, and use of technology. Economic survey 2020 says crop residues generated from cereals are about 334 million tonnes (2017–18), followed by sugarcane (133 million tonnes) and fiber crops (17.7 million tonnes) (**Table**

2) [12]. The rice crop contributes about 145.5 million tonnes within the cereal crops category, and the wheat crop contributes 149 million tonnes of crop residue. These crop residues have little or no use to the farmers and are challenging to handle and transport.

Farmers burn straw in the field because they know that burning rice straw in the cultivated area will remove weeds, control crop diseases, and release required nutrients for the next crop [13]. However, burning in the open fields cause lots of pollution, thus influencing the air quality around the nearby areas [14]. Burning rice straw increases some nutrients such as phosphorus and potassium temporarily. Still, it reduces soil acidity, nutrients such as nitrogen and sulfur, and Organic matter [15]. In 2017-18, the total amount of crop residues generated was estimated at 516 million tonnes, out of which 116 million tonnes were burnt in the open fields (**Figure 1.1**) whereas, the rest are being used for different farming and housing activities such as roof taching, cover for crops, animal feed etc. This burning activity gave rise to the release of about 176.1 Tg of CO_2, 10 Tg of CO, 313.9 Gg of CH_4, 8.14 Gg of N_2O, 151.14 Gg of NH_3, 813.8 Gg of NMVOC, 453.4 Gg of $PM_{2.5}$, and 935.9 Gg of PM_{10} [16].

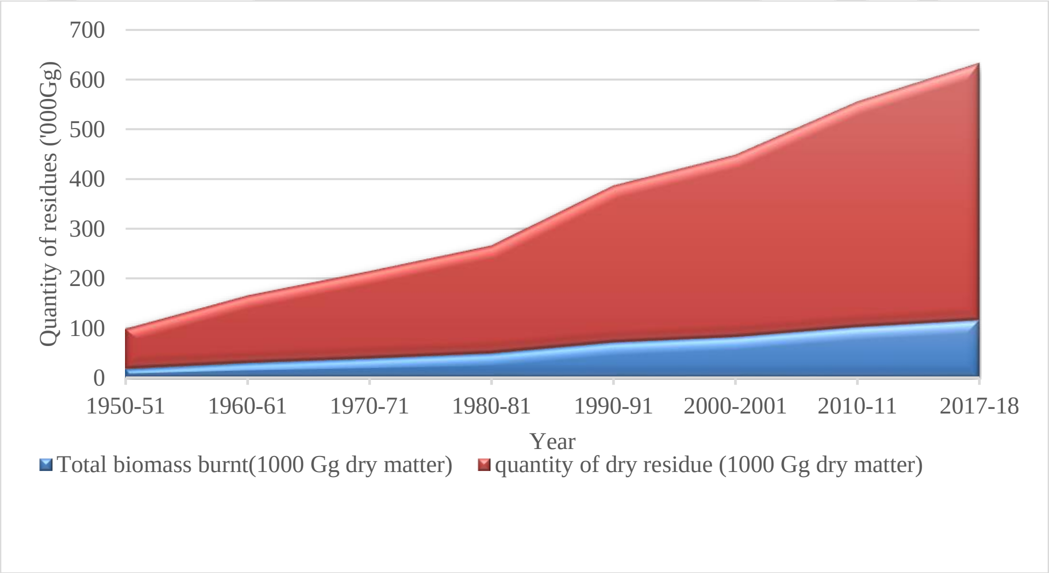


Figure 1.1: Crop residues generated versus crop residue burnt in India between 1950–51 and 2017–18. Source: Crop statistics of India were obtained from the ‘Agricultural Statistics at a glance 2018’ and ‘Economic Survey.019–-2020’ [12]

Burning of dry residues causes adverse effects on atmospheric, human and soil environment. The above figure (**Figure 1.2**) shows a schematic diagram of atmospheric environment, human environment and soil environment.

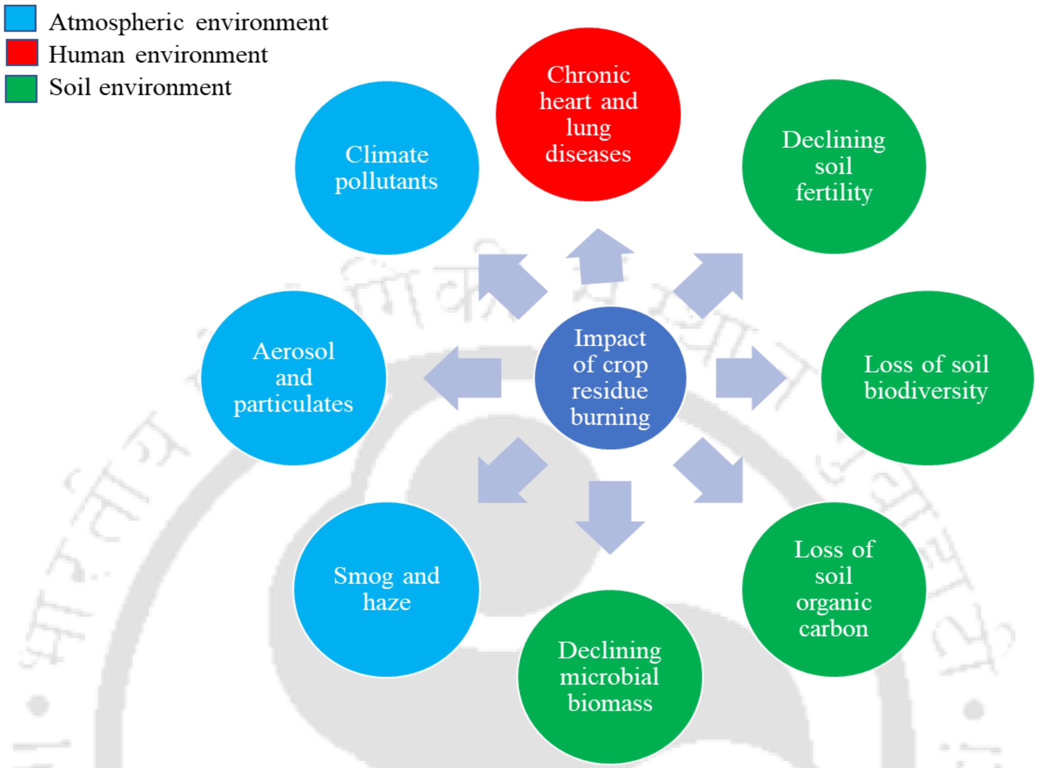


Figure 1.2: Impacts of crop residue burning [16].

It can be seen from **Figure 1.3** that the annual Rice production and availability of rice straw in Southeast Asia and the rest of Asia constitute more than 80 % of the rice product of the rest of the World.

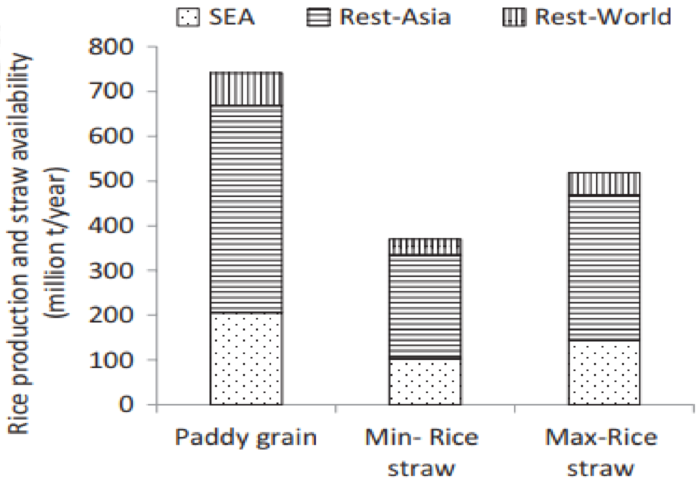


Figure 1.3: Annual Rice production and availability of rice straw in southeast Asia, the rest of Asia, and the rest of the World [17].

Similarly, India's total forest and tree cover area are 80.9 million hectares, 24.62 percent of the country's geographical location. With a large forest area, a considerable amount of leaf shedding occurs. Moreover, in rural areas, the leaves can be allowed to sit and degrade to increase soil fertility due to the wide availability of land areas. However, in urban areas, due to lack of open spaces there is little or no scope for enabling the leaves to sit for decomposition; hence, they must be disposed off or transferred to some other location [18].

1.4 Introduction to biomass briquetting

1.4.1 Densification process

The process of compaction of residues to higher bulk density is called densification. The briquetting process involves applying pressure with or without a binding material to convert the residue to a compact agro material. Agricultural residues can be briquetted by overcoming their elastic property through high pressure with or without heating. Loose biomass with a bulk density of 0.1 to 0.2 g/cm³ can be converted to briquettes with a bulk density of 1.2 g/cm³, which can be burnt to obtain controlled flame and also produce lesser smoke compared to open air burning of loose biomass [19].

1.4.2 Advantages and disadvantages of densification [5]

Converting residues into a densified form has the following advantages:

1. The net calorific value of raw material per unit volume increases
2. The end product is easy to handle, transport and store
3. The produced fuel is uniform in size and high quality
4. The process serves the purpose of solving problems related to residue disposal
5. The process helps reduce deforestation by providing a substitute for fuelwood.

Residue densification also has certain disadvantages, including:

1. High initial investment and energy input throughout the process
2. Undesirable combustion characteristics (e.g., poor ignitability)
3. The tendency of briquettes to loosen when exposed to water or even high humidity

1.4.3 Classification of Densification Processes

According to (Bhattacharya et al. [5]), densification can be classified into two categories based on the operating condition (A) Hot and high-pressure compaction and (B) Cold and low-pressure compaction. Based on the mode of operation, densification can be categorized as Continuous and Batch densification. Different operating conditions and operation methods can be used to produce briquettes. The most common variety is hot, high-pressure continuous densification.

Again based on the equipment, densification can be classified into four main types (A) piston press, (B) screw press, (C) roller press, and (D) pelletizer. The output of the first three methods is more prominent in size, called briquettes, and the latter produces small-size products called pellets.

1.4.3.1 Piston Press

Piston press technology is a comparatively older technology than other available technologies. A flywheel operates a piston, which presses the feedstock through a tapered die where the briquette is formed. The hydraulic piston press is one of the most widely used briquetting machines nowadays, unlike the mechanical piston press. Here the energy to the piston is transmitted from an electric motor using high pressure with a single- or double-way hydraulic oil system [20]. The piston of the press reciprocates and compresses the material supplied from the feed hopper. The material is taken into the conical die, compressed by the piston, and the briquetted part is extruded through the die opening. A lot of friction is involved during the compression process, so the material gets heated up to 150°C to 300°C [5]. A typical piston press machine is shown in **Figure 1.4.**

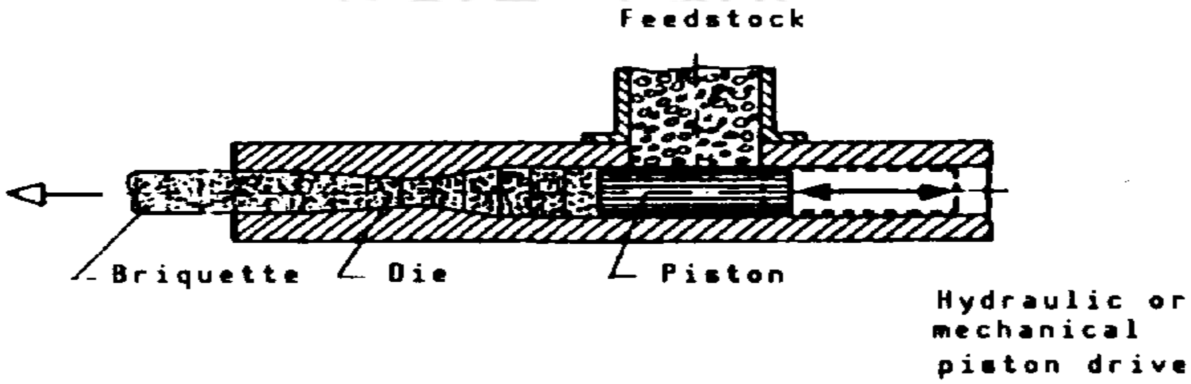


Figure 1.4: Piston press machine (Eriksson et al. [21]).

Piston press briquetting technology is the most common method used in India, Brazil, and Africa [22]

1.4.3.2 Screw Press

A screw press (**Figure 1.5**) consists of a rotating screw of the varying cross-section that compresses the raw material fed to the machine. A separate drive mechanism operates the screw rotation. The screw conveyor has a variable cross-section that helps push the material through the chamber's passage, thereby achieving compression. Finally, the briquetted material is expelled from the die [23].

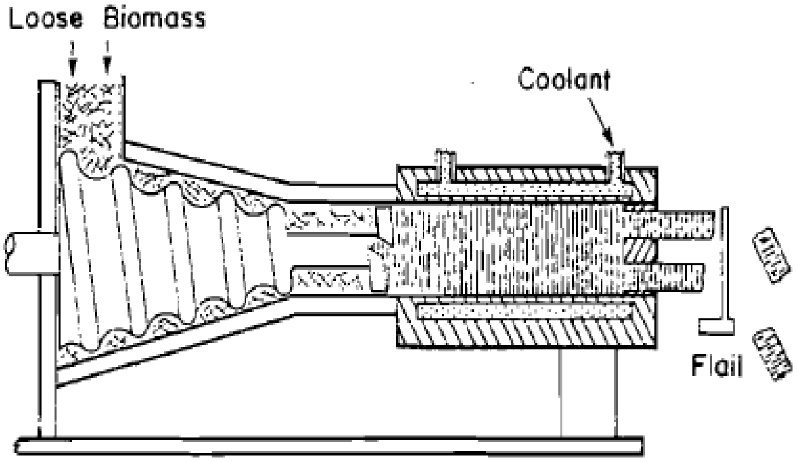


Figure 1.5: Conical screw press machine (Bhattacharya et.al.[5])

Briquettes produced by this method are strong and have good thermal properties. They do not fall apart during combustion [22].

1.4.3.3 Roller Press

In the roller press (**Figure 1.6**), the raw material is fed through the hopper, and a separate control mechanism controls its flow. A predetermined quantity is supplied to the screw mechanism, pre-compressed. The partially compressed feedstock is fed between the rollers and compressed further to a small size. The sizing of the stock is carried out effectively as it passes through the screw and roller [22]. Compared to the piston press, the force applied to the stock is less, and hence, a store with a smaller particle size is desirable here.

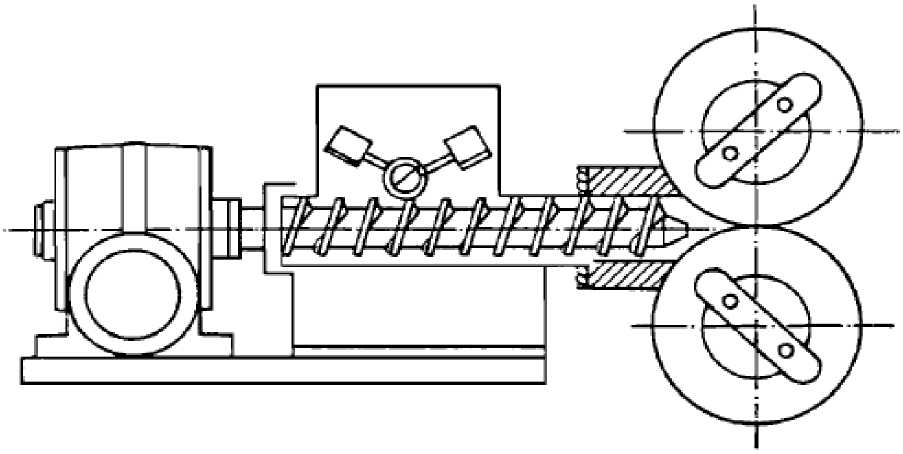


Figure 1.6: Roller press (Bhattacharya et.al.[5]).

1.4.3.4 Pellet Press

The pellet press (**Figure 1.7**) consists of an annular matrix and a roller. The residue to be palletized is compressed between the roller and the annular matrix, containing several perforations of pre-determined sizes. The feed is expelled out of these perforations in the form of pellets. A knife cuts the pellets to length, and the pellets are collected at the bottom of the equipment. These devices are more suitable for the mass production of pellets as the pellet press capacity is not bounded by the density of the raw material, as is the case of the piston or screw presses. Pelletizers are available in varying degrees that range from 0.2 tons/hr to 8 tons/hr. The power consumption of these pelletizers usually ranges from 15kWh/ton to 40 kWh/ton [19].

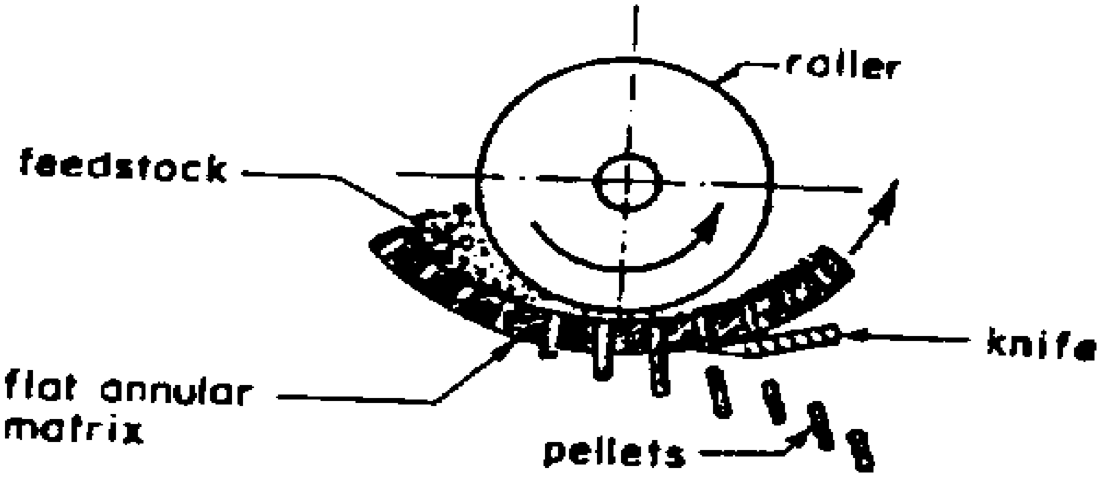


Figure 1.7: Pellet press [21]

1.4.4 Stages in the Densification process

Mani et al.[23] postulated three stages during the densification of biomass:

<u>First stage</u>**:** Particles rearrange to form a closely packed mass where most particles retain their properties. Next, the energy is released due to inter-particle and particle-to-wall friction.

<u>Second stage</u>**:** The particles are rubbed against each other and undergo plastic and elastic deformation, which increases the inter-particle contact significantly; particles become bonded through van der Waal's electrostatic forces.

<u>Third stage</u>: A significant reduction in volume at higher pressures results in the density of the pellet reaching the actual thickness of the component ingredients.

By the end of the third stage, the deformed and broken particles can no longer change positions due to fewer cavities and 70 % inter-particle conformity. Therefore, it is essential to understand the densification process and the variables that govern its performance, such as the combination of temperature, pressure, and equipment. Steps in briquetting are shown stepwise in **Figure 1.8**.

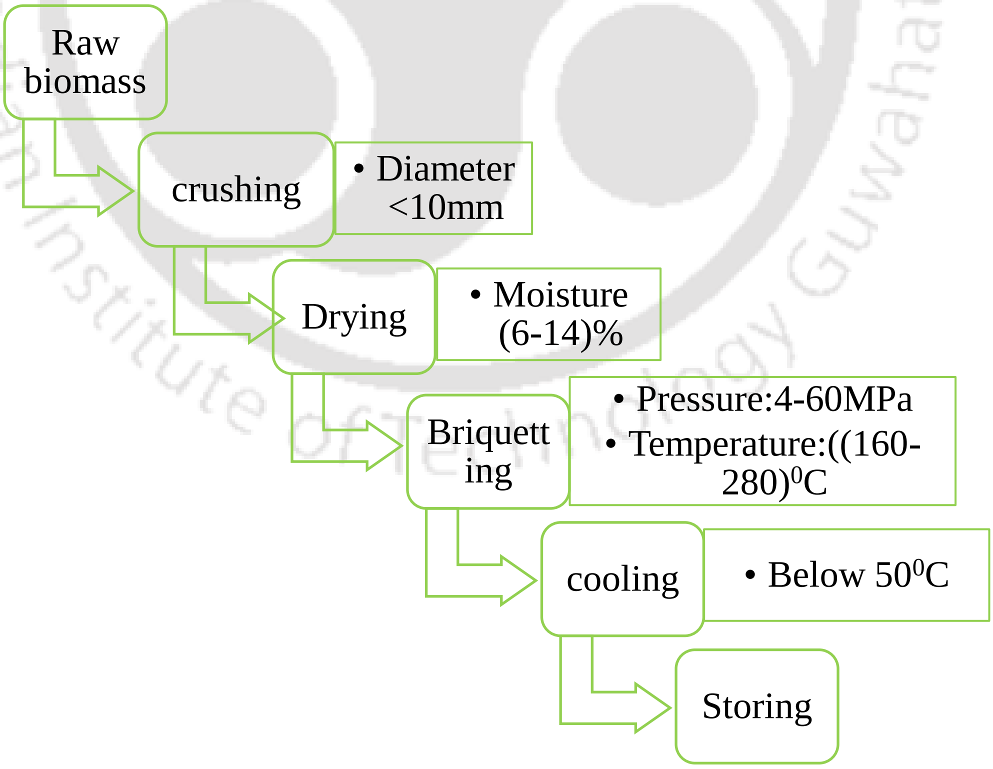


Figure 1.8: Existing biomass briquetting techniques (Adopted from Che Zhanbin [24]).

1.4.5 Role of chemical composition in binding

The chemical composition of the biomass, such as cellulose, hemicelluloses, protein, starch, lignin, crude fiber, fat, and ash, affects the densification process. During compression at high temperatures, the protein and starch present in the biomass plasticize and act as a binder, increasing the strength of the densified biomass. When high pressure is applied, the heat generated gelatinizes the starch in the presence of moisture, resulting in better binding. The softening temperature of the lignin present in the biomass mainly depends on its moisture content. It is around 90-100^0 C at 30% moisture (wet basis) and around 130^0 C at 10% (wet basis) moisture. So, Lignin cannot soften at room temperature [19] [25]. Likewise, protein acts as a binder that needs processing at high temperatures too. Therefore, in ambient temperature, binding agents need to be supplied externally. These binding agents can be made of different waste materials which are readily available for economic feasibility.

1.4.6 Role of external binder in densification

Biomass generally has a limited degree of elasticity. So whenever any physical pressure is applied to the biomass, the deformation caused may not be permanent as there is a tendency to spring back or even fall apart when the force is released. Binders or stabilizing agents may be introduced to reduce bounciness and maintain maximum bulk density. Binding materials strengthen the briquettes, enhance charcoal adhesion, and produce identical briquettes. Commercially available starch made from wheat, rice and cassava, rice powder, and clay soils, although they have their advantages and disadvantages, are used as a potential binder for briquetting. Binders are desirable that they are not from the human food chain, should not be costly, should not require complicated methods for preparation, should not interfere in the burning of the briquette, and should be readily available. The properties of binders are different from binder to binder.

For example, when used as a binder, clay increases the ash content of the briquette but has no contribution to the calorific value. On the other hand, binders including starch, gum, molasses, and tar/pitch contribute to heat value. Therefore, mixing the binder may require thermal treatment depending on the binders used. Binders can help improve the particle adhesion, compressive strength, abrasion resistance, and energy content of briquettes. They may also reduce the energy cost of producing such briquettes by reducing the compaction pressure, conditioning temperature, and wear on production equipment [26].

A binder plays a vital role in briquetting biomass materials; therefore, a binder should have essential properties such as easy availability and extraction. Furthermore, it should be outside the human food chain and have good adhesive properties, and the addition of such a binding agent should not degrade the thermal properties of the briquettes made [27]. Organic binders are agriculture waste, aquatic plants, forestry biomass, paper mill waste, lignin derivative, lignin, and starch [28], [29], [26]. Different natural binders found in the literature are cow dung, wheat flour and paper pulp [30], cactus plant [31], cassava starch and clay [32], molasses [33], sawdust [34], alkaline lignin, and starch [35].

Chin and Siddiqui [36] reported that the density of the briquettes decreases with an increase in the binder (starch and molasses) ratio for sawdust and coconut fiber, yet an increase in the relaxed density of briquettes was seen with an increased ratio of the same binder in the case of peanut shell and palm fiber.

1.5 Quality parameters involved in briquetting

The quality of the biomass briquette plays a significant role in end-user applications. Improving the quality of the densified biomass in terms of physical, chemical, and physiochemical composition can be done by taking care of all the variables that have a direct or indirect role in the densification process. For example, the quality of the briquettes depends upon the feedstock composition and on the moisture, particle size, conditioning, temperature/preheating of feed; added binders; and densification equipment variables, which significantly affect the physical properties of the densified products. In addition, the quality helps to evaluate the effectiveness of the densification process and determine whether the pellets or briquettes can withstand the compressive force and water during storage and transportation [5].

1.6 Factors affecting densification

Several variables affect densification and the properties of the densified product. These include the properties of the material being densified (e.g., particle size, moisture content, and bulk density) as well as the variables of the densification process (e.g., pressure, temperature, the addition of binder, and so forth) [5].

1.6.1 Effect of pressure and temperature

Maintaining a high temperature during the manufacturing process can enhance the quality of briquettes, reduce the briquette material's tendency to expand, and improve durability and bulk density. High temperature also helps to achieve better bonding of briquette components, which results in increased density [37], [38].

Orisaleye et al.[38] and Okot et al. [39] discovered that increasing the pressure, temperature, and particle size positively affected biomass briquettes' density and mechanical strength. Seco et al. [40] found that raw materials with lower moisture content required higher pressure and temperature.

Song et al. [41] found that increased briquetting temperature and pressure benefited the densification of Cotton stalk/Wood sawdust. Chou et al.[42] found that the hot-pressing temperature significantly helps the briquette in solidification and declines the expansion of the briquette.

1.6.2 Effect of Binder and its ratio

Binders can be added during the feedstock's mixing or after the feedstock's carbonization before briquetting. Some biomass materials will not stick together until the addition of a binder, mainly if compacted using a low-pressure technique. Adding Binder to biomass feedstock is a co-processing practice that aids in densification or increases the mechanical or thermal properties of the product [43]. Binder addition helps to reduce the wear and tear of the briquetting machine. Binders help to reduce the silica problem that leads to abrasion of the briquetting machine [5]. In addition, it helps form a bridge to enhance strong inter-particle bonding with biomass components [44]. The quantity of Binder required depends on the binding properties of the raw material and the binding agent. Binders used for briquette production can be classified as inorganic, organic, and compound binders [45]. However, adding some binders can have adverse effects on fuel briquettes during the densification and combustion stage, like a decrease in compaction of the briquettes, disadvantageous combustion properties, or air-borne emissions when used in large quantities [46]. Also, binders with higher cellulosic content, such as biosolids and microalgae, exhibit lower compaction effects on briquettes, reduced durability, and energy contents [26]. Hence, the choice of binders in briquette production is crucial and should be carefully considered. In addition, the correct quantity of binders needed to produce fuel briquettes to obtain better yield and performance must also be significant. Several factors could influence the performance of fuel briquettes, including the compaction pressure, the number of binders used, conditioning temperature, mix ratio, wear on production equipment, moisture content, type of feedstock, particle size, and environmental conditions [47],[48].

1.6.3 Effect of composition of the raw materials

Before taking any raw material for briquetting, its combustion properties must be known. It was found that the time duration for flaming combustion of raw material is directly proportional to the product of the inverse of the square of specific surface area and briquette density. The proportionality constants are correlated with the mass percentage of hemicellulose in the raw material. However, the time duration of char combustion for each raw material is directly proportional to the inverse square of the specific surface area multiplied by the fixed carbon content of the briquette. The proportionality constants correlate with the biomass's mass percentage of ash content [49]. Natural binders such as lignin and protein in the raw material play a crucial role in the bonding between the particles of briquettes [27]. Proximate analysis is one of the essential characterization methods when considering biomass thermal conversion. It determines raw biofuel's moisture, ash, volatile matter, and fixed carbon contents. These values are crucial to ascertain moisture, volatile matter and fixed carbon affect the combustion behavior and the plant design. In that way, high moisture values decrease the combustion yield, while high volatile matter/fixed carbon ratios are related to the fuel's reactivity. On the other hand, ash profoundly influences the process's transport, handling, and management costs. It is also influential in corrosion and slag formation [50].

1.6.4 Effect of particle size of the raw material

Size reduction is a critical process before biomass briquetting. Size reduction partially breaks down the lignin content of biomass and thereby increases the total surface area, leading to more excellent inter-particle bonding [7],[51]. The size reduction in biomass also increases bulk density, improving biomass flow during densification [44]. Particle size reduction also improves the flow of the binders among the mixture of raw material before briquetting [51]. Several size reduction methods include chopping, chipping, hammer milling, crushing, shredding, and grinding. Saptoadi [52] tested five different particle sizes, i.e., more than 100 mesh, between 70 and 80 mesh, between 60 and 70 mesh, between 50 and 60 mesh, and between 40 and 50 mesh. The investigations revealed that the smaller the particle size, the lesser the porosity; on the contrary, the higher the density. Briquettes made from coarser rice husks tend to expand more significantly shortly after being released from the briquetting machine. The combustion tests show that lower porosities hinder drying, devolatilization, and char-burning processes due to fewer free spaces for mass diffusion. Wang et al. [53] found that the briquetting energy consumption was higher for raw materials with larger particle sizes.

1.6.5 Effect of moisture content

High moisture creates problems while grinding and requires extra energy for drying, leading to microbial decay and spoilage of the product. High moisture content also leads to swelling and cracks in the briquettes. The optimum range suggested by Mani et al.[23] moisture content in the raw material is (6-15) %. This moisture was the reason behind the formation of cohesive forces amongst the particles. The liquid (water) spreads the binder through the space between the biomass particles. As a result, liquid bridges are formed. Viscous and capillary forces are responsible for the formation of liquid bridges. The drying kinetics of the briquettes was studied to find the optimum moisture content. The moisture removal was rapid, up to 4 days, after which the drying period gradually reduced. The drying kinetics followed a similar pattern reported by Chungcharoen and Srisang [54].

1.6.6 Effect of pre-treatment of the raw material

Pre-treatment plays an essential role in densification because it prepares lignocellulosic biomass for different densification systems. Any raw biomass has to undergo pre-treatment to be utilized thoroughly. The pre-treatment of biomass can be done mechanically, chemically, thermally, hydrothermally, or biologically. Though the most sought routes are thermal and biological, the natural course has some limitations due to their added advantages over others. Therefore, the thermal path can be the most effective while converting biomass into a utilizable product.

Torrefaction is a thermal pre-treatment method to increase energy density and decrease the grinding energy of biomass [55]. Pre-treatment helps reduce specific energy consumption and produce other high-quality, densified products for various end-use applications. Generally, pre-treatment improves the quality attributes (higher durability and bulk and energy densities), storage and handling characteristics, and transportation logistics. Some promising pre-treatment methods for bioenergy applications include (i) grinding, (ii) pre-heating/steam conditioning, (iii) steam explosion, (iv) torrefaction, and (v) AFEX. Integrating pre-treatment with a densification process can help address many storage, handling, and transportation logistics challenges [56].

Torrefaction is the slow heating of biomass in an inert environment to a maximum temperature of 300°C. Torrefaction removes most smoke-producing compounds and other volatiles, resulting in a final product with approximately 70 % of the initial weight and 80–90 % of the original energy content. In addition, the primary decomposition reactions affect the hemicelluloses and, to a lesser degree, the lignin and cellulose [57].

Torrefaction helps to develop a uniform feedstock and improves binding during pelletization by increasing the number of available lignin sites, breaking down the hemicellulose matrix, and forming unsaturated fatty structures. It results in bulk densities of 750–850 kg/m^3 and energy densities exceeding 20 GJ/m^3 [58]. **Table 1.3** lists out various benefits of torrefaction for briquette production.

Table 1.3: Benefits of torrefaction for briquette production

References	Benefit of torrefaction
Kiel et al. [59]	1. Torrefaction results in weakened biomass polymers (i.e., less fibrous and more plastic) and catalyzes chemical modifications that lead to more fatty structures, which act as binding agents during densification. 2. Lignin content typically increases 10–15 % as the devolatilization process during torrefaction leads to hemicellulose degradation. 3. Densification of torrefied biomass at 250°C indicated that the pressure and energy required for briquetting could be decreased by a factor of two, and the throughput increases by two times compared to raw biomass densification using a pellet mill.
Atan et al. [60] and Yang et al. [61]	The SEM image of rice husk and banana residue torrefaction at 300℃ for 30 minutes revealed that torrefaction led to shrinkage of fibres size increasing the thermal stability of the briquettes.

Song et al. [41]	1. Hydrothermal pre-treatment significantly improved the resulting biomass briquettes' physical properties. As the hydrothermal pre-treatment temperature increased, the resulting heating values increased, the content of fixed carbon increased, and the yields of volatiles decreased. 2. HT promoted combustion characteristics. The most cost-effective briquette produced from the cotton stalk and wood sawdust was obtained by hydrothermal pre-treated at 200 °C and 230 °C under 75 °C and 80 MPa pressure.
Waheed and Akogun [62]	ANOVA revealed that torrefaction and feedstock blending significantly influenced the characteristics of briquette at $p < 0.05$.
Kumar et al. [63]	1. Pure charcoalobtained from torrefaction possesses a higher calorific value than that binder and biomass. 2. Ash content and moisture ash content are lower for biomass briquettes than charcoal briquettes; volatile matter is low for charcoal briquettes.
Fehse et al. [64]	Briquetting of the pre-treated spent coffee ground by extraction leads to increased briquette quality since pre-treatment removed the oil fraction of 16.12 %.
Yuliah et al. [65]	The HHV of rice husk can be maximized by mixing it with wood charcoal. Therefore, secondary ingredients with a high heating value can be mixed to increase the fuel quality and value of biomass materials that have a low heating value but is sufficiently available throughout the year.

1.7 Cost of briquette production

The Economics of briquetting is site-specific and depends on the local conditions of regions with different outcomes. Therefore, this review restricts itself to the fundamental economic aspect of briquetting considered in general but applied to suit local needs. Production of biomass briquettes requires technology, which can be high energy-powered or low energy-powered. Raw materials for the briquetting process are a significant determinant of the equipment and machinery used and the briquette's varied quality and production costs [7]. Therefore, the price is crucial when proposing setting up a briquetting plant [48]. The briquette production cost depends on other expenses such as capital, installation, operation, and repair and maintenance costs. The costs of processing equipment, briquetting machines, land, and building are the capital cost of a biomass briquetting plant. The costs associated with mounting the kit and machinery on the production site are the installation cost. The operation cost includes the cost of labor, raw material, electric power, oil, and lubricant for machinery, transportation, and other related inputs that helps in the smooth running of the briquetting plant. Finally, the repair and maintenance costs comprise expenditure on the maintenance of the briquetting machinery or any other machinery in the briquetting plant daily, weekly, monthly, or when necessary [48].

Stolarski et al.[66] compared briquettes made from agricultural and forest biomass in north-eastern Poland using a small-scale production of briquettes. The raw material used was *S. viminalis; S.hemaphrodita*; rape straw; a mixture of *S. viminalis* and rape straw in a 50:50 ratio; a variety of rape straw and rapeseed oilcake in a 75:25 ratio; a mix of rape straw and rapeseed oilcake in 50:50 ratio; a combination of *S. viminalis* and *S. hemaphrodita* in 50:50 ratio and from pine sawdust for comparison. The briquette production cost ranged from 66.55 € t−1 to 137.87 € t−1 for rape straw briquettes and those made from a mixture of rape straw and rapeseed oilcake (50:50), respectively. Briquette production was profitable, except for the briquettes made from a straw and rapeseed oilcake mixture.

Tippayawong et al. [67] surveyed the cost analyses and economic feasibility to evaluate the potential benefits of biomass briquetting. Charcoal briquettes were prepared from biomass residues and thermally treated to produce smokeless charcoal briquettes. This study focused on the feasibility of demand, engineering, and financial concern. It was observed that the cost of the raw charcoal was a significant variable, critically affecting the company's profitability. Therefore, the price range of this raw material should be carefully monitored and controlled (between 5 to 11.5 THB/kg) to ensure acceptable inbound quality and prevent a negative return on investment.

1.8 Benefits of briquetting and carbonization

Due to the increasing adverse effect of global warming and energy demand, new sources have been investigated to satisfy this problem through an environmentally friendly route. The resolution of this problem is mainly related to renewable energy sources and plant biomass. Biomass, including tree leaves and grass trimmings, is inexpensive and widely available in all seasons, which makes it a suitable source that can be used for ethanol, biodiesel, and methane for direct use as fuel [68], and also as activated carbon for water treatment. The main problem with biomass is transportation and handling due to its loose structure. Briquetting is a cost-effective way to address this issue. In addition, biomass from different sources can be utilized for activated carbon, fuel generation, and various other fields. The current work will offer many benefits, including the following:

Biomass from grass trimmings and tree leaves and their activated carbons can be integrated into fuel production systems for many applications, such as heat/steam, sewer, refinery, cosmetic, and wastewater treatments [69].

Briquetting and carbonization processes can be tailored by changing the system and process parameters (e.g., humidity, temperature, pressure, particle size, loading rate, binding agents, blending concentrations, and other additives) for better production [69].

Briquetting and carbonization processes offer eco-friendly and economic benefits since they reduce the use of fossil fuels and also create local job opportunities.

Carbonized briquettes can also be used for household purposes such as barbequing, cooking, heating, and drinking water [70].

The briquetting process established here is low in cost, so it will reduce water treatment costs.

The briquetting process will substantially reduce landfills and the generation of methane produced from grass and tree leaves.

1.9 Organization of the thesis

This thesis comprises of six chapters. Chapter 1 gives the present energy scenario and introduces briquetting technology and parameters affecting briquettes. Chapter 2 gives the literature review of the work conducted to fulfill this study. Chapter 3 states the motivation and objectives of the present work. Chapter 4 provides the experimental setups, methods, and materials used while performing the study. The statistical tools Taguchi-Grey relational analysis used for optimization are also explained in this chapter. Chapter 5 reports the results and findings of the research with graphs, tables, and figures. The results include physio-chemical, thermal, mechanical, and physical properties of the briquette, emissions charts, burning rates, Specific energy consumption, and cost. Finally, Chapter 6 summarizes the research findings and discusses the future scopes.

Chapter 2: Literature Review

2.0 Introduction

This chapter deals with all the literature reviewed for the present study and the supporting references for methods used in this research. The literature review is arranged in tabular form to list the various aspects of biomass briquetting that will be focused on in my present work. The focused headings are as follows: The machine used, Raw material; Binder used, Pre-processing of raw materials for briquetting, physiochemical characteristics, calorific, physical, and handling properties of briquettes.

2.1 Biomass energy generation and conversion pathways

This section introduces different types of biomass and their various conversion pathways to obtain any specific form of energy. Different products can be obtained from biomass by following different conversion paths. Many products are versatile and can be adapted to compete with traditional fuels, using the existing energy and vehicle fuel infrastructure. Biomass in its natural form is not suitable for use as an energy product, to utilize biomass to its maximum potential, biomass materials have to be enhanced by following the conversion pathway. These primary conversion pathways can be classified into four categories: direct combustion, mechanical, thermochemical, and biochemical. **Figure 2.1** gives an overview of different biomass processing technologies and the form of energy generated through each conversion technique.

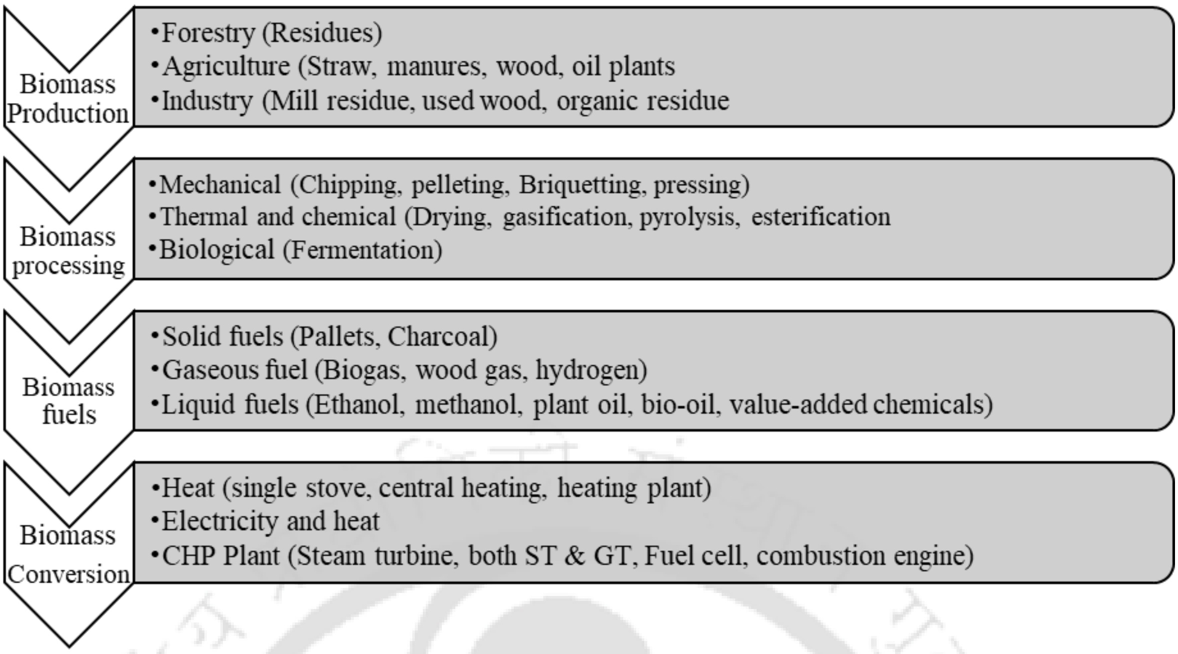


Figure 2.1: An overview of biomass production, processing, and conversion to energy (adopted from chum et al.[71])

2.1.1 Mechanical conversion process

Biomass densification is a mechanical technology for the conversion of biomass into solid fuel. The technology is known as briquetting, improving handling, transportation, and storing properties. With the help of densification, the use of biomass for energy production becomes more convenient since it improves the volumetric calorific value of fuel and reduces transportation costs. Briquetting is an agglomeration technique that is broadly characterized as a densification technology. Agglomeration of residues is done to make them denser for their use in energy production. Raw materials for briquetting can be wood industry wastes, loose biomass, and other combustible waste products. Based on compaction pressure, the briquetting technologies can be divided into a) High-pressure compaction, b) Medium pressure compaction with a heating device c) Low-pressure compaction with binders [5].

2.2 Waste materials used for briquetting

The current availability of crop biomass in India is estimated at more than 500 MMT (million metric tons) per year, including forest and agricultural residues, which have a potential of about 18,000 MW (megawatts) [72]. The current global energy supply of approximately 119502.86 MT per year is mostly obtained from fossil fuels, while biomass contributes approximately 11950.28 MT, which makes it one of the most important renewable energy sources. Around 70–80% of these biomass is used for traditional non-commercial use. Modern bio-energy—that is, large-scale commercial use of biomass for powergeneration, industrial applications and transportation fuels—is still growing [73]. An excess of 7000 MW of energy could be obtained by bagasse-based cogeneration of biomass energy [74]. India has 159.7 million hectares of arable land area, the second largest in the world. The gross irrigated crop area of the country was found to be 82.6 million hectares (215.6 million acres), the most prominent in the world. With all the agriculture products, many other by-products include straw, rice husk, maize stalks, cotton, millets, pulse, sunflower & other stalks, and groundnut. MNRE initiated several programs and policies to promote efficient biomass potential conversion in various sectors. **Table 2.1** list some raw materials used for briquette making under various conditions and gives a brief about the highest calorific value, density, compressive strength and some other important properties obtained by the researchers using various raw material to obtain briquettes.

Table 2.1: Raw materials used for briquette making under various conditions and their properties

Raw materials used	**Properties of briquettes obtained**	**References**
Dried and milled forest waste	Density=1092 kgm^{-3} Durability $\geq$ 95 % C.V=18.166 MJ/kg	Ullah et al. [75]
Perennial energy plants (*Salix viminalis)* clone UWM 006 and *Sida hemaphrodita* Raspy, rape straw and rapeseed oilcake, and pine sawdust	Highest C.V =18.144 MJ/kg (Pine sawdust)	Stolarski et al.[66]
Cow dung, cactus plant, peanut shell, Mopani leaves, yellow thatching grass	Highest density = 0.446 Kg/m^3at (Peanut shell briquette at pressure of 19MPa)	Shuma and Madyira [31]
Banana Culture Waste	Compressive strength = 15 MPa - 5.3 Mpa C.V = 17.10 MJ/kg	Sellin et al. [76]

Maize residues, wood wastes, dried fallen leaves, branches, roots, and barks from garden and forest trimming	Briquette obtained were smokeless during combustion	Tippayawong et al. [67]
Solid waste from various leather operation units in Unique Leather Finishing Company.	Highest C.V = 24.101 MJ/kg Highest compressive strength = 0.00217 MPa	Onukak et al. [77]
Agricultural wastes (groundnut shells and corn cobs), wood residues (Anogeissus leiocarpus)	Highest density = 530 kg/m^3 (Groundnut shells) Highest C.V = 34.42 MJ/kg (*A. leiocarpus)*	Falemara et al. [78]
Maize cob	Highest density = 710 Kg/m³ (briquettes obtained at 4.39 MPa pressure)	Sunardi et al.[79]
Sawdust, ground nut shell, sugarcane bagasse, Jatropha shell, rice straw, wheat straw, cotton stalk, and rice husk	No significant difference in Equilibrium moisture content was noticed at relative humidity values up to 70 %	Vyas et al. [80]
Mixed forest waste	The low pressure was found to be most suitable for *Pinus* sp. forest biomass briquettes. CV = 19.97 MJ/kg, Density = 1220 kg/m^3, and Compressive strength = 16.37 MPa.	Furtado et al. [81]
Coconut husks, sawdust, rice husks, and coffee husks	Highest C.V = 18.635 MJ/kg (coconut husks)	Suryaningsih et al.[82]

2.3 Binders used in the works of literature

The briquette binder plays a crucial role in the process of briquette production. The quality and performance of the briquette also depend on the quality of the briquette binder. Different types of briquettes need other binders. Binder used in the briquetting process can be divided into an inorganic, organic, and compound binder. Inorganic binders have advantages, such as abundant resources, low cost, excellent thermostability, and good hydrophilicity. However, a significant problem arising from inorganic binders is increased ash content.

Organic binders have many advantages, such as good bonding, good combustion characteristics, and low ash content. But organic binders are easy to decompose, so the mechanical strength and thermal stability of organic binder briquette are lower, and their price is high [83].

Zhang et al. [83] reported that organic binders generally have good binding properties, high impact and abrasion strength, and increased water resistivity. However, they fail to show thermal stability and mechanical strength at high temperatures [84]. They are characterized mainly by wide availability, cheap, high calorific value, and low ignition temperature. Organic binders are especially of four types:

1. Biomass (agricultural residues, forest biomass, etc.)
2. Petroleum bitumen (coal tar pitch, tar residues, etc.)
3. Lignosulphonate
4. Polymer (starch, resins, and polyvinyl)

Miao et al. [85] stated that organic binders could be further classified as hydrophobic (e.g., coal tar) and hydrophilic (e.g., biomass) based on how they react with water. However, organic binders have limited commercial application in biomass briquetting as they have poor thermal stability [86].

Inorganic binders are low cost, have strong adhesion and good hydrophilicity, and are also non-polluting with sulfur capturing characteristics. However, they have limited calorific value and high ash content, decreasing their combustion efficiency [87]. Examples are clay, ammonium nitrate, bentonite, etc. Inorganic binders are mainly classified into three types 1) Industrial (bentonite clay, cement, sodium silicate, magnesium chloride) 2), civilian (clay and limestone), and 3) environmental protection (desulfurization agents, e.g., calcium oxide, iron oxide, and magnesium oxide) [83].

Compound binders comprise two or more binders intending to take advantage of the multiple binding properties offered by the different binders, thus yielding briquettes with high mechanical strength and thermal stability. Examples are starch, bentonite, molasses, and carbide lime [88], [89]. Zhang et al.[83] describe the various classifications of briquette binders in detail. The selection of binders in biomass briquetting is often influenced by several factors, including availability, cost, moisture content of the mix, the working pressure, and the briquet's desired energy content [47]. In most developing communities, the price and availability of the binders are the most critical factors that are considered in selecting binders. The type and ratio of binders used in biomass briquetting strongly influence the properties of briquettes, like combustion and mechanical properties [90]. Different binders have different degrees of influence. Aransiola et al. [90] studied the effect of binders on carbonized corn cobs. They found that briquettes produced with corn starch displayed lower moisture content, higher relaxed density, and better compressive strength than those with corn starch and gelatin. The increased concentration of African Elemi resin as a binder resulted in increased strength and density of charcoal briquettes [91]. Lubwama and Yiga [92] used cassava starch and clay as a binder to produce briquettes from rice and coffee husk. They found that cassava starch made briquettes with better physical and calorific properties than clay binder.

Muazu and Stegemann [26] stated that the type of binder used for briquetting influences the pressure and temperature required. It also reduces the wear on the production equipment, thus reducing the overall cost of the briquetting process.

Gill et al. [93] observed that when 30 % cotton stalk was added as a binder while briquetting chopped rice straw, the power requirement for briquetting significantly reduced from 40.4 kW to 36.6 kW while making briquette using 2 tons of maize stalk in a briquetting machine of capacity 1200Kg/h using an electric motor of 59 hp. However, adding some binders in the densification of loose biomass could negatively affect some briquette properties such as reduction in density, deposit formation, emissions, etc.) and some binders could also be compromised for its other uses, including food and industrial uses [94]. Therefore, more recent studies have focused on cheaper binders, improved briquette qualities, sustainability in their use, and optimized biomass–binder ratio, which is all-important in the long-term commercial production of biomass briquettes [93], [95].

2.4 Binder and their influence on briquette properties

As stated earlier, binders are added to biomass in the densification process to improve the mechanical properties and abrasion resistance, to prevent wear of the machine, and, in some cases, to improve the calorific value of the raw materials [26]. Various biomass materials require different types of binder due to their underlying material bonding mechanisms [83].

Many biomass materials exhibit natural binding agents [96], [97]. Still, the critical power can be further strengthened and enhanced during briquette production by including additional binders in the mixture. However, some problems are often encountered with some binders during the combustion of fuel briquettes, such as high ash content, disadvantageous combustion properties, or a decrease in compaction of the briquettes [46] [98]. Hence, an environmentally friendly and easily accessible binder must be used. Binders frequently used in briquette production include cow dung, molasses, starch, microalgae, sawdust, and resin [34] [99] [100] [91], [101].

Madiedo et al. [102] studied the influence of binder type on greenhouse gases and PAHs from the pyrolysis of biomass briquettes and found that molasses and paraffin produced lower amounts of PAHs than coal.

Olugbade et al. [47] reported the influence of binders on the Combustion Properties of biomass briquettes. They found that binders mixed with phosphorus-based additives such as $Ca(H_2PO_4)_2$ and $NH_4H_2PO_4$ enhance the combustion rate of fuel briquettes and reduce pollutant emissions. In addition, they also observed that higher compacting pressure of the binder and processing temperature produces higher density and higher energy content per unit volume of fuel briquettes.

Wakchukre and Mani [101] studied biomass briquettes' thermal and storage characteristics with organic binders. They found that the calorific values were higher for briquettes prepared using a press mud binder than those prepared using a distiller's dry grain and molasses binder. Bulk density and calorific values of all types of biomass briquette decrease when stored for an extended period. A total reduction of 49 % in bulk density and about 9 % in calorific value was found during the storage period of 180 days. Espuelas et al. [103] studied on coffee ground briquettes with an organic binder found that Xanthan and guar gums produced good mechanical properties in briquettes. However, Xanthan and guar gums required high moisture content to be effective. 5 % of xanthan gum and 30 % of moisture made the best briquettes. In addition, Xanthan and guar gums modified spent coffee grounds combustion characteristics. Adeleke et al. [104] studied the densification of coal fines and mildly torrefied biomass into composite fuel using different organic binders. They found pitch-molasses bonded briquettes have better mechanical properties than briquettes produced from an individual binder. The combustion properties of the briquettes made from the pitch, molasses, starch, and the blend of pitch and molasses binder were similar to raw coal slacks, with a slight increase in the carbon content and about 8 % addition to the calorific values.

Binder plays an essential role in the briquetting of loose, bulky biomass. Therefore, a binder should have the following properties: easy availability, ease of extraction from the plant matter, outside the human food chain, and good adhesive properties. Furthermore, adding such a binding agent should not degrade the thermal properties of the briquettes made [105]. Binders are also desired to be: a) Capable of solid bonding, b) Pollution-free, c) little or no effect on the burning characteristics d) outside the human food chain. Organic binders are agriculture waste, aquatic plants, forestry biomass, paper mill waste, lignin derivative, lignin, and starch [106] [29] [26]. Different natural binders used in literature are cow dung, wheat flour and paper pulp [30], cactus plant [31], cassava starch and clay [92], molasses [99], sawdust [107], alkaline lignin, and starch [35]. **Table 2.2** lists the best ratio out of the ratios studied for the binder for particular raw materials and binder types.

Table 2.2: Binders used in pieces of literature and their best ratio

Binder used	**Raw materials**	**Binder ratios**	**Best ratio**	**Remarks**	**Reference**
Cassava starch, corn starch and gelatine	Carbonized corncob	10, 20 and 30 % wt/wt	30 %	The higher the binder concentration and compacting pressure, the better the briquettes.	Aransiola et al. [90]
Nano-lignocellulose, nano-cellulose, and lignin	Bagasse	3, 6, and 9 % w/w	9 %	Nano-lignocellulose and nano-cellulose binders were more effective in the physical and mechanical properties but Lignin binder showed better thermal properties	Granado et al. [108]
Starch	Cashew nutshell waste	5 %, 10 %, and 15 %	12.917 %	Starch content of 12.917 %, water content of 50 %, and a drying duration of 7 days gave the best briquettes	Kumar and Ramesh [109]
Sodium silicate	Mango seed shell	0, 15, and 20 %	0 %	Briquette without binder prepared at high pressure and temperature showed better characteristics	Kumar et al. [110]
Sawdust	Cassava starch	100:15 100:25 100:35 100:45	100:25	Density: 726.9 Kg/m^3	Obi et al. [111]

Sawdust	Cassava starch and gum Arabic	100:15 100:25 100:35 100:45	Starch 100:25 Gum Arabic 100:35	Starch gave superior quality briquettes	Sotannde et al. [112]
Mango leaves, Acacia leaves, sawdust.	Cowdung	40:25:25:10,25:40:25:10 25:25:40:10,30:30:25:15 30:25:25:20,25:20:30:25	25:25:40:10	Density : 2.71Kg/m^3 at ratio of 25:25:40:10 for Mango leaves:Acacia leaves: sawdust:cowdung.	Birwatkar et al. [113]
Sawdust and dry leaves	Coffee husk and wheat flour	NR	NR	CV= 20.037 MJ/kg for coffee husk CV= 20.318 MJ/kg for wheat flour	Kishan et al. [114]
Sawdust, Lignite, and cassava starch 75 % sawdust 25 % lignite and 40 % natural binder(16.6 % cassava and 83.3 % water)	Rice husk	3:1	--------	Density:941.2 kg/m^3 At the smallest particle size of 150 microns	Saptoadi [52]

Paper pulp	Dry leaves	30 % binder	---------------	Density: 538.9 Kg/m^3 The use of binder decreased production energy costs.	Bhatkar et al. [115]
Starch	Rice husk, sawdust Sugarcane bagasse	30 % & 40 %	40 %	Sawdust density 5.2 kg/m^3	Agidi et al. [116]
Binderless	Corn stover, switchgrass, prairie cord grass, sawdust, pigeon pea grass, and cotton stalk	-----------------	-------------------------	Cotton stalk had the highest bulk density of 964 kg/m3	Karunanithy et al. [117]
Binderless	Reed canary grass			Maximum density 899–964 kg/m3	Kronbergs et al. [118]
Binderless	Rice straw and rice bran	-------------	-------------------	The thermo-energy used for briquetting of rice straw would be minimized if a certain percentage of	Chou et al. [119]

				the binder (such as rice bran, sawdust, or other biomass waste) was used.	
Binderless	Rice Straw	-------------	---------------------	Particle size has great effects on the energy consumption and product quality	Wang et al. [120]
Sawdust	Rice Straw	3:1 and 1:1	1:1	The addition of sawdust with rice straw significantly improved the briquette’s stable density and shatter index, and has the potential to reduce compaction pressure requirement	Rahaman and Salam [121]
Cassava wastewater, rice dust, and okra stem gum	Rice husk	0,5,10 and 15 %	10 %	Water addition of around 60 % w/w benefited the low-pressure densification of rice husk.	Yank et al. [122]

2.5 Machine used versus the quality of briquettes

The machine used for briquetting of biomass materials into briquettes influences its quality. According to Granado et al. [108], the compaction pressure directly affects the density of the briquettes and their durability and resistance to compression.

Yank et al. [123] used a locally fabricated low-power manual press that exerted a maximum of 4.2 MPa to densify Rice husk and rice bran. Locally available binder cassava wastewater, rice dust, and okra stem gum were used by mixing 60 % w/w water. They reported a maximum density of the briquettes as 471.3 kgm^{-3} and the lowest density of 382.4 kgm^{-3}. The maximum durability of the briquettes was 91.9 % and the highest compressive strength observed was 2.54 kN.

Nino et al. [124] densified rice husk and pine sawdust using a hydraulic press whose maximum applied load were 69 kN, causing a compaction pressure of 97 MPa. As a result, the highest briquettes density was 1181.48 kgm^{-3}. The mechanical durability index obtained was 99.15 % with a compaction time of 60 seconds and 99.20 % for 40 seconds, respectively.

Ajimotokan et al. [125] used a lab-scale 1560 kN hydraulic jack machine for briquetting rice husk and corn cob fines. The compressive strength of the produced briquettes varied from 39 kN/m^2 to 111 kN/m^2. The compressive strength of the produced briquettes increased with the decrease in particle size. It was found that the green density of the produced briquette varied from 1.1 g/cm^3 to 1.86 g/cm^3. It was seen that the green density increased with a decrease in particle size and also increased as the percentage of rice husk in the blends increased and with an increase in compaction pressure.

Soares et al. [126] briquetted coffee ground and sugar cane bagasse using a stainless mold steel compression exerting a force of 98,07 KN. Their findings state that when the percentages of coffee ground increased and the ratios of sugarcane bagasse decreased, the mechanical resistance of briquettes decreased since reinforcing the sugarcane bagasse in the material decreased. The maximum mechanical resistance reported was 0.27±2 MPa. Some of the other reported machines used for briquetting along with their specifications and some of the mechanical properties obtained are reported in **Table 2.3** below.

Table 2.3: Machine used versus mechanical properties obtained

Machine used	Machine specification	Mechanical property	References
Hydraulic press	Temp > 100 °C under 78 kg/cm^2	CS : 0.206 MPa D:890 kg/m^3	Muhyin and Mahdiani [127]
Hydraulic jack and die	die compression ratio (1:7, 1:8.5, and 1:10)	CS: 9.8 MPa D:674–1005 kg/m^3	Ali et al. [128]
Hydraulically operated machine	30 MPa	CS: 0.0018 MPa D: 5.2 kg/m^3	Agidi et al. [116]
Fabricated manual cylindrical piston press	50mm diameter	D: 625 kg/m^3 SR: 95.4 %	Nagarajan and Prakash [129]
Universal testing machine (TUF-C-1000 SERVO, EIE Instruments Pvt. Ltd, India)	Pressure: 1000KN	CS:17.29 MPa D:584 kg/m^3 to 620 kg/m^3	Velusamy et al. [130]
Hydraulic briquetting press, Tecnobriq HBP-60T model,	With a 60-ton maximum force cylinder	Energy density: 17523 MJ/m³ CS:19.8 ± 5.40 MPa	Maia et al. [131]
Screw press machine	1 hp motor	CS:0.743 Mpa, D:687 kg/m^3	Narzary and Das [132]
High-pressure briquetting press		durability 99.29 % CS:150.82 N·mm^{-1} ,	Brunerova et al. [133]
Electric hydraulic press (Marconi - MA098/A110)	15 min under pressure 15, 20, and 25 MPa and temperature 120, 140, and 160 °C.	CS:2.96 Kpa D:1336.46 kg/m^3	Oliviera et al. [134]

*D-density, CS-compressive strength, SR-shatter resistance

2.6 Rice straw briquettes

The density of loose rice straw ranges from 13 to 18 kgm^{-3} in dry matter [135]. According to Kargbo et al. [136], the moisture content of rice straw before compression should be between 12 and 17 %. The calorific value of rice straw ranges from 14.08 to 15.09 MJ/kg [135] [137]. In addition, rice straws possess high volatile matter (VM) of around 60.55–69.70 %, almost similar in value to other biomass by-products, such as Wheat straw, sugar cane bagasse, and corn stover, etc. High Volatile matter content has advantages, such as easier ignition and burning, leading, but it also leads to a rapid and difficult-to-control flame easily [138]. Fixed carbon is the carbon left behind after the volatiles burns off. Rice straw is reported to have a fixed carbon ranging from 11.10 % to 16.75 %.

The ultimate analysis reveals rice straw's elemental carbon, hydrogen, oxygen, nitrogen, and sulfur composition. The carbon content of rice straw is lower compared to fossil fuels, while the oxygen and hydrogen contents are higher. The ratio ranges of H: C and O: C in rice straw is 1.1–1.36 and 0.94–1.06, respectively. Rice straw ash content, including non-combustible residues, is around 18.67–29.1 %. It decreases the calorific value of rice straw and causes problems in energy conversion. In addition, a high potassium and alkali content in ash may increase corrosion and fouling problems in ingrates since alkali metals are known triggers for these phenomena. Rice straw is found to have low nutritional value, and it is of poor quality to serve as livestock feed. It has a low C: N ratio and high Neutral Detergent Fibre (NDF) and Acid Detergent Fibre (ADF), which affects its nutritive value. Rice straw contains 38 % cellulose, 25 % hemicellulose, and 12 % lignin [139]. Compared to other plant biomass, rice straw has lower cellulose and lignin content and higher hemicellulose content.

Rice is the most important cultivated crop in Southeast Asia. Ninety percent of the global rice production is in Asia, equivalent to 639 million tonnes per year in 2010-2012 [140]. **Table 2.4** displays some of the briquetting and pre-treatment conditions versus the properties and cost of rice straw briquettes.

Table 2.4: Pretreatment conditions and briquette properties of rice straw

Pre-treatment	Briquetting process	Properties	Cost	Reference
Smashing and sieving using a 2.24 kW machine	100 kgf/cm^2 compression force at max temp 200^{0}C	Max CS of 28.4 kgf/cm^2 HHV: 18.6 MJ/kg	NR	Chou et al. [42]
Grounded in a hammer mill	Laboratory scale hydraulic briquette machine, at a temperature of 120 °C and pressure of 95 Bar	Bulk density 145.39 Kg/m^3 CV: 17.65MJ/kg	NR	Brand et al. [29]
Size reduction using a hammer mill and knife cutting mill	Locally fabricated manual hydraulic piston-press cold densification system. Max press: 48.3MPa	Bulk density 114.9Kg/m^3 HHV: 14.68MJ/kg	NR	Rahman and Salam [34]
Crushing and milling	Universal testing machine 100KN and (1-250)^{0}C Max briquetting energy consumption: 90.78J	Density: 1.006 g/cm^3 CS: 11.339 MPa	NR	Wang et al. [120]
Drying and manual cutting and sieving	Manual briquetting press	Density :0.58 kg/m^3. CS: 44.7 kg/cm^2	NR	Jittabut [141]
Motor-operated chaff cutter with 15hp electric motor	Commercial briquetting machine of 1200 kgh^{-1} capacity connected with 59 hp. electric motor	Density:1159.22 kg m^{-3} CV:15.61 MJ kg^{-1}	Cost: 0.041 USD per kg and 0.00281 USD per megajoule of energy	Gill et al. [93]

Carbonization	Cold extruder machine	Density:0.925 g/cm^3 CS: 2,609 kN/m^2	NR	Jamradloedluk and Wiriyaumpaiwong [142]

2.7 Forest waste briquettes

Table 2.5 shows some briquetting process conditions along with some important properties and costs of briquettes made from forest residues.

Table 2.5: Briquetting process condition versus properties and cost of forest residue briquettes

Forest waste	**Briquetting process**	**Properties studied**	**Cost**	**Reference**
Unidentified leaves and branches	Screw press machine with 4 mold temperatures (225, 250, 275, 300 °C) and grounded biomass sizes (2, 4, 6 mm)	C.S = 1092 kgm^{-3} C.V = 4339 kcal/kg	Rs.8.89 /kg	Ullah et al. [75]
Mesua ferrea dried leaves	Manually operated hydraulic piston-press, pressure: 5.1, 10.2, and 15.3 MPa, and room temp.	Density (0.24 –0.37 g/cm^3), shatter index (79.18–99.9 %), and calorific values (15.77 – 18.99 MJ/kg)	NR	Kpalo et al. [48]
Saraca asoca leaves and sawdust	Laboratory scale hydraulic press 150 MPa	Density (1.193 g/cm^3) heating value (4789 kcal/kg), shatter resistance (89 %), and water resistance (68.56 %) and fixed carbon (25.58 %)	NR	Kumar et al. [143]
Grass and leaves	Pressures of 3, 5, and 6 tons/cm2, followed by carbonization at 600 °C for an hour	Density of 919.8, 934.9, and 945.5 kg/m^3 for grass briquettes, and 1102.7, 1117.0, and 1123.0 kg/m^3 for leaf briquettes		Khorasgani et al. [68]

2.8 Effect of pretreatment/ material addition to raw material for briquetting

Zubairu and Sadiq [144] compared briquette charcoal with sugarcane bagasse and wood charcoal and found it to be better as it had the highest fixed carbon content and bulk density. However, even though the ash content of carbonized corn cobs was higher than wood charcoal and sugarcane bagasse, the briquette charcoal displayed a mean calorific value of 32.4 MJ/kg, which were distinctly higher than the bagasse and wood charcoal prepared in their study, whose calorific value were 23.4 MJ/kg and 8.27MJ/kg respectively.

Sengar et al. [145] found Carbonized biomass more suitable than raw and hydrolyzed biomass for briquetting in a screw press extruder briquetting machine for different combinations of biomass such as Cashew nutshell, grass, and rice husk.
Suryaningsih et al. [146] carbonized rice husk and jatropha seed using a carbonization drum at an average temperature of 131°C for 130 minutes and 150°C for 120 minutes, respectively. They prepared charcoal briquettes with a maximum density of 1.1582 g/cm3and a calorific value of 5,650 cal/gm.

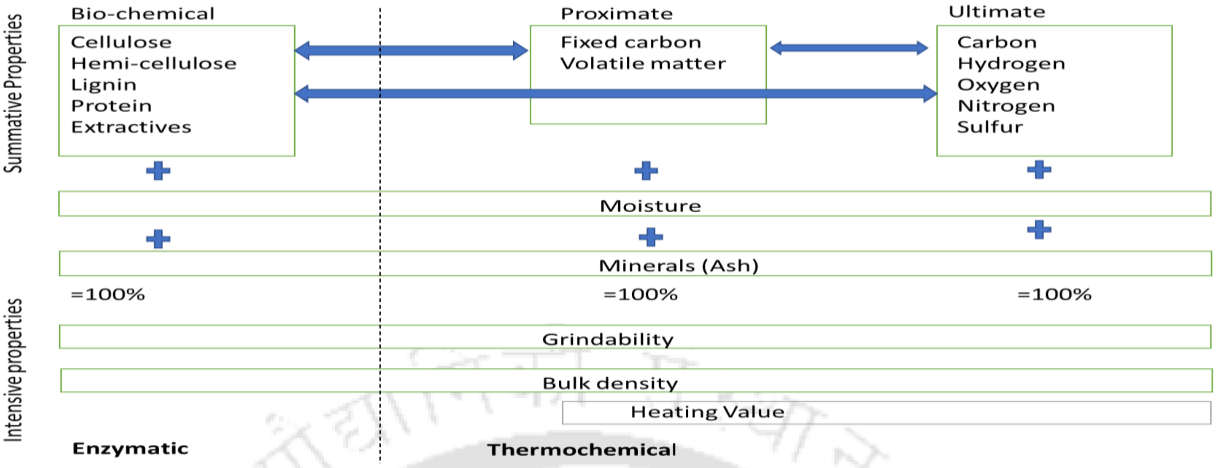
Kumar et al. [147] found that pure charcoal possesses a higher calorific value than that binder and biomass. However, the addition of a binder can reduce ash content, moisture content, and volatile matter, which may lead to the benefits of a reduced corrosion effect.
Amarasekara et al.[69] conducted a test on the samples to resolve the residual strength of the briquettes before and after the carbonization process at 800 °C. Ignition temperatures for the non-carbonized briquettes under 2, 3, and 5 tons/cm2 were 492, 510, and 520 °C, respectively; however, after carbonization, these temperatures were reduced to 474, 487, and 492 °C, respectively. Even though carbonization reduces the residual strength, they have stated that briquetting and carbonization processes can reduce the environmental effects of fossil fuels to some degree.

Aransiola et al. [90] suggested that carbonizing the biomass before briquette production is another method of enhancing briquette properties. Carbonization removes volatile materials from the feedstock in the absence (or limited supply of) air. In this processing method, the biomass is partially burnt in an environment where the air is controlled to give a char product high in carbon.

Guo et al. [148] conducted combustion and emission characteristics with charcoal briquettes on a self-built platform for sulfur and nitrogen pollutants. The results indicated that is optimum carbonization temperature for biochar preparation as fuel is 450–500 °C, along with a 180 min holding time and 5°C min−1 heating rate. In addition, biochar briquettes had solid mechanical strength at briquetting pressure of 25 MPa, less than 1 mm particle size, and a binder corn starch ratio of 4.32 wt %. Compared with other biomass, biomass charcoal briquettes had better combustion performance, and the emissions of pollutants were reduced. Carnage et al.2018 prepared briquette using carbonized water hyacinth and molasses as a binder and found that charcoal to binder ratio of 30:70 showed desirable characteristics in terms of compressive strength, calorific value, and ignition; it also showed the highest resistance to breakage with a maximum tolerable load of 19.1 kg/cm^2, quickest ignition time of 133 seconds and had the highest high heating value of 16.6 MJ/kg.

Ofori and Akoto [149] characterized briquette made from cocoa pod husk and a mixed sample comprised of cocoa pod husk mixed with sawdust. Their observations found that carbonized cocoa pod briquette had lower hydrogen content, which led to lower volatile matter content. Even though hydrogen content in the mixed briquette sample was higher than the standard charcoal and the carbonized cocoa pod briquette samples, the content was within an acceptable range of 5 % to 6 %. The percentage carbon content recorded for charcoal (57 %) was significantly higher than that of both the carbonized cocoa pods husk (54.0 %) and mixed briquette (32.7 %) samples. The high carbon content obtained for the carbonized cocoa pod and the standard charcoal indicates that it will burn fast than the mixed sample because high carbon content in fuel aids combustion. In the case of oxygen content, non-carbonized biomass tends to have a higher oxygen content than fully carbonized briquettes. The Sulphur content was higher for the mixed sample, and this could be attributed to the portion of the non-carbonized portion of sawdust which may contain some amount of Sulphur in its natural state. Sun et al. [150] used maize straw, wheat straw, and wood branches and their processed products (i.e., briquettes and charcoals) to investigate the emission factors (EFs) of PM2.5 (delicate particulate matter) components found that Charcoals showed over 90 % emission reduction efficiency compared to raw fuels. In addition, the emission factors s of PM2.5, OC (organic carbon), and elemental carbon (EC) showed that charcoal was more efficient in reducing PM2.5 and carbonaceous fraction emissions, followed by briquettes compared with raw fuels in household burning. Zhang et al. [83] proved that the addition of 4 % ammonium hydroxide along with vacuum sealing pretreatment was the best pretreatment for making briquettes from wheat straw.

2.9 Characteristics analysis of biomass briquettes



Properties	**Primary Methods**	**ASTM Standards**
Proximate		D3172, D7582
Fixed Carbon (FC)	Mass loss after heating (VM)	E872
Volatile Matter (VM)	By subtraction (FC)	
Ultimate		D3176
C,H,O	GC of combustion products (O by subtraction)	E777
N	Acid digestion to ammonia salts, GC of combustion products	E778
S	Precipitation of ash, GC of combustion products	E775
Moisture	Mass loss after oven drying	E871
Total ash	Mass remaining after complete combustion	E1755
Elemental ash	Atomic absorption spectroscopy (AAS), ICP-OES, ICP-MS	D3682
Grindability	Energy consumption of grinding equipment	D409
Bulk density	Mass per volume of sample ground to a certain size	E873
Heating value	Bomb calorimetry	D5865

Figure 2.2: Overview of the biomass properties, and common methods of quantification (adopted from Tanger et al. [151]).

Figure 2.2. shows the intensive, extensive, enzymatic, and thermochemical properties of biomass and the most common analysis methods.

Saptoadi [52] tried to find the best briquette dimensions by making cylindrical briquettes of diameter 13mm made from 75 % wooden sawdust and adding 25 % lignite as a binder.

Some of the findings are listed below:

Smaller bio briquettes produce better combustion characteristics due to the large specific surface area available for reaction. The smaller the particle size, the lower the porosity and higher the density. Lower porosity will hinder drying, devolatilization, and char-burning processes due to fewer spaces for mass diffusion. Consequently, its combustion rate will be lower. Briquettes from larger particle sizes burn for 19.25 sec, whereas smaller particle size briquettes burnt for up to 28sec. Demirbas [152] tested some briquetting properties such as moisture content, heating value, shatter index, compressive strength, water resistance, and combustion of briquettes from pulping reject and spruce wood sawdust. They also studied the effects of the briquetting pressure of pulping discard and spruce sawdust on the compressive strength and shatter index. The following conclusions were brought forward:

1. Both briquette properties increased with an increase in the briquetting pressure.
2. The increase in densities of the briquettes decreased their ignitabilities.
3. The moisture content of the briquettes had a distinct effect on the briquette strength.

The strongest briquettes (shatter index 20,500 and compressive strength 49.5 MPa) produced using spruce wood sawdust were achieved with a moisture content of 15 % at a briquetting pressure of 350 MPa. Gómez et al. [153] characterized Briquettes made from seven agroforestry residues. They experimentally determined all variables such as the actual density, Young's modulus of elasticity (axial and radial), the particle-particle restitution coefficient, and the particle–wall friction coefficient that is required to construct a DEM (discrete element method) models for briquettes made from maize stalk, maize stalk plus pine wood chips, rice husk, vine shoots, rape straw, cereal straw, and sawdust plus cereal straw. The DEM technique can be used to determine the behavior of biomass during handling and storage, which can help avoid problems related to corrosion, obstruction, wear, and breakage caused by the presence/movement of the biomass. Saikia and Baruah [154] experimented with wet briquettes to study the following:

- Effect of die pressure on the density of briquettes
- Effect of die pressure on shear strength

- Effect of die pressure on durability
- Impact resistance of briquettes
- Calorific values of briquettes.

It was found that the quality of the briquette improved by increasing die pressure and keeping dwell time at an optimum value of 40 seconds. Shear strength and durability increase with applied die pressure, while impact resistance is constant for briquettes of all types at all applied die pressure. Die pressure above 600 kPa for rice straw, 500kPa for banana leaves, and 700 kPa for teak leaves yields durable briquettes. Therefore corresponding densities of rice straw, banana leaves, and teak leaf briquettes are 207.48 kg/m^3, 179.69 kg/m^3, and 227.53 kg/m^3, respectively. Mani et al. [155] determined the mechanical properties of wheat straw, barley straw, corn Stover and switch grass at various compressive forces, particle sizes, and moisture contents. After Grinding, the biomass materials were made at compressive forces of 1000, 2000, 3000, 4000, and 4400 N and particle sizes of 3.2, 1.6, and 0.8 mm and moisture contents of 12 % and 15 % to establish compression and relaxation data. Results were: Corn Stover attained the highest density at low pressure during compression. Compressive force, raw material particle size, and moisture content significantly affected the pellet density of barley straw, corn Stover and switch grass.

Wheat straw at all particle sizes did not produce any significant difference in pellet density. Pellets made from barley straw were more rigid than the other pellets obtained in the study.

2.10 Summary

An extensive literature review has been done on the use and effect of different binders and binder ratios on the briquette quality. The impact of pre-treatment, carbonization and the addition of secondary elements have also been studied. Literature also reports briquetting condition, raw material conditions, and their effect on the quality of the briquettes. The most common topic of study was the effect of pressure and temperature on briquette properties. Most of the literature report on the use of lab scale machine or high-cost business purpose machine and manual hydraulic press machine. Minimal literature report on cost and specific energy consumption while briquetting. Also, minimal literature compares charcoal briquettes, charcoal-added briquettes, and raw biomass briquettes. The comparison of low-power screw press machines and manual hand press machines has seldom been reported.

Therefore the present study targets to find the best ratio of charcoal-added briquettes and compare it with charcoal briquettes using the same low-power screw press machine and charcoal briquettes from a manual hand press machine.

The raw material used in the study is *Polyalthia longifolia*, as it is a commonly available tree native to India, and no literature reported making briquettes using these leaves. The tree is a leafy evergreen tree that grows up to 10 m in height. It is from the family of Annonaceae and is widely available in tropical Asian countries [156]. Assam is situated in northeast India and covers 3.5 % of India's total tropical forest [157]. *Polyalthia longifolia* is one of the tree species found extensively in both rural and urban parts of Assam. The tree is commonly known as Debadaru in the Assamese language. *Polyalthia longifolia* tree is mainly planted in the garden as an ornamental tree for noise reduction; apart from that, the tree is known to have medicinal and antibacterial properties [158], [159] [160]. There is a massive amount of leaf shedding during the pre-monsoon season. Unlike rural areas, which can allow these leaves to degrade and increase soil fertility due to large available land areas, urban areas require a way to dispose of this plant waste [161]. Briquetting can be an effective way to utilize those leaves, as many kinds of literature report using dry leaves to make briquettes. However, most of the literature uses cassava starch and other plant derivatives as natural combustible binders, either from the human food chain or challenging to extract and requiring complex, costly procedures. Therefore, the present study uses an easy-to-process, readily available weed known as Colocasia esculenta (taro), found in Southeast Asia and belongs to the Araceae family. These plants have large elephant ear shape leaves. The tubers of wild taro have high starch content of up to 80 %. In addition, the plant contains insoluble pointed crystals of calcium oxalate that have toxic effects on humans when consumed [162]; therefore, being out of the human food chain, this material can be a suitable alternative to cassava.

The second raw material used is rice straw, as Assam is one of the central rice-producing states in India [163]. The total rice production in Assam for the financial year 2020 was 4.98 million metric tonnes [164]. The agricultural residue from rice cultivation is rice straw and husk. Apart from using as fodder for cattle, straw cover for some crops, and other domestic applications, 428 kt of rice straw is a surplus in Assam, and 22,289 kt is a surplus in India, according to the reports from National Biomass Resource Assessment (NBRA) Programme [165]. However, these residues are primarily burnt in the open field fire due to difficulty in transportation because of their bulky nature, which creates unnecessary pollution. Also, rice straws cannot give controlled flame while burning, so they cannot be used for household heating purposes. Moreover, there is no scientific method of waste disposal in this region. Therefore, the present study aims to turn rice straw waste into a functional product by converting them into briquettes in the field using local technology.

Chapter 3: Motivation And Objectives

3.0 Motivation

Briquetting is a way to make use of biomass residues that would otherwise be waste, and replace the use of wood and charcoal as well as fossil fuels, thus reducing greenhouse gas emissions. Briquetting is also one of the most straightforward biomass conversion techniques.

The bioenergy conversion process occurs mainly through four methods, i.e., thermal, thermochemical, and biochemical/biological, chemical technologies. Among many reported techniques, densification is a promising way to overcome obstacles such as complex conversion techniques, high cost of conversion, time consuming processes etc. to using biomass as fuel as it is a simple process of applying pressure to densify. Densification occurs when biomass is mechanically compressed, increasing its density about ten times [5]. Therefore, the densification of biomass materials could be very effective in reducing the costs of transportation, handling, and storage. Because of their uniform shape and sizes, densified products can be easily handled using standard handling and storage equipment. Therefore, they can be quickly adopted in direct combustion or co-firing with coal, gasification, pyrolysis, and other biomass-based conversions. Commercially, biomass densification is performed using pellet mills, other extrusion processes, briquetting presses, or roller presses. Biomass densification is a technology for converting plant residues into usable energy fuel. These technologies are also known as briquetting, pelleting, or accumulation. It makes handling easier for transport, storage, etc. [7].

Many commercial briquette production technologies are available in the market. Some of them produce high-quality briquettes but are very costly, whereas some are low in cost but inefficient. Most of these machines target either large business organizations or wealthy farmers. There are hardly any machines made feasible for small farmers or domestic use of small rural families. Hence, the author is motivated to adopt biomass briquetting of agro-waste and forest waste to find a solution to waste management and solid fuel production at a low cost.

3.1 Objectives of the present work

The present work aims to suggest a suitable process for biomass densification using locally available raw materials and technology that could be beneficial to the local farmers holding small fragmented lands. The following are the objectives of the present research:

1.Characterization of Rice straw, *Eleusine indica* grass, and *Polyalthia longifolia* tree leaves, and densification and analysis of the physical, thermal and mechanical properties.

2.Study the effect of various parameters like raw materials, binder ratio, charcoal addition, and binder preparation method on the briquettes' physical, thermal and mechanical properties and obtain the optimum briquette qualities.

3.Comparison of carbonised rice straw briquette made using taro binder with briquettes made using common binder such as starch and paper, based on properties such physical, thermal, mechanical, emission analysis, and specific energy consumption.

4.Fabrication, testing and validation of self fabricated, easily replicable briquette press .

Chapter 4: Materials And Methods

4.0 Introduction

This chapter gives the details of all the materials and methods used to successfully carry out the work required to fulfill the objectives of the present study. All the types of equipments, softwares, equations, etc. are listed out in this chapter.

4.A Briquette made from grass, dry leaves, and straw

4.A.1 Collection

4.A.1.1 Grass

Freshly cut grass using a lawnmower within the IIT Guwahati campus was collected manually and stored for 2-3 days for briquetting in plastic bags. *Eleusine indica* grass is the type of grass that is mainly found on the campus. The grass generally comes 3 to 4 cm in length and 1mm in width. The grass was dried for 6 hours in the sun after cutting. This grass, when directly used for briquette, chokes the machine. Hence, they have to be chopped to smaller particle sizes for better binding. A particle size of 3mm was considered in this study for briquetting as it gave the best result for a study done on the effects of particle size on mechanical and combustion characteristics by Huko [46].

4.A.1.2 Dry leaves

Polyalthia longifolia leaves were collected on a bright sunny day from the roadside of the IIT Guwahati campus in April (2017) when they fell from the tree and were added to the solid waste material that had no other use and would be thrown away at the dump. The leaves were carefully dried and chosen carefully to have uniform feedstock. The dried leaves were pulverized in a wood pulverizer to reduce the size of the collected leaves and finally screened by 3mm mesh.

4.A.1.3 Straw

The price of straw is site specific, therefore straw was procured from a nearby village at Rs.167 per m^3 after comparing with other prices from nearby sellers. At the time of purchase, the straw had a moisture content in the range of (6-10) % approximately. The average length of the straw was (1-1.3) m.

Figure 4.1: Photograph of briquette made from grass, dry leaves and straw

4.A.2 Characteristics of raw materials

The ultimate analysis of all the raw materials was done using a CHNS (Euro EA3000, Euro vector, Italy) analyzer, and a Proximate analysis was done using ASTM E871-82. The moisture content; ash content were determined using the ASTM D1102-84 procedure, volatile matter content was determined using the (ASTM D-3175) method, and fixed carbon was obtained from the differences. The details of the proximate analysis procedure are given below:

4.A.2.1 Moisture Content

Kumar and Ramesh [109] found that the moisture content required 6 days of sun-drying to attain the optimum level, therefore the briquette samples were dried for six days before testing. The moisture content of the biomass was measured by the oven-dry method. The sample was placed in the oven at 105^0 C for 16 h. The loss in weight was calculated by using the formula 4.1.

$$M.C.\,(\,\%\,wb) = \frac{W2-W3}{W2-W1} \times 100 \tag{4.1}$$

Where,

W1 = weight of empty crucible, g

W2 = weight of empty crucible + sample, g

W3 = weight of empty crucible + sample, after drying, g

4.A.2.2 Volatile Matter

The dried sample left in the crucible was covered with a lid and placed in a muffle furnace, maintained at 950 ± 20 ºC for 7 minutes. Loss in weight was reported as a volatile matter on a percentage basis

$$\text{V. M. (\%)} = \frac{W3-W4}{W2-W1} \tag{4.2}$$

Where,

W1 = weight of empty crucible, g

W2 = weight of crucible + sample taken

W3 = weight of crucible + sample from the stage (I), g

W4 = weight of crucible + weight of after heating in a muffle furnace, g

4.A.2.3 Ash Content

The residual sample in the crucible was heated without a lid in a muffle furnace at700 ± 50 ºC for one-half hour. The crucible was then taken out, cooled first in the air, then in desiccators, and weighed. Heating, cooling, and weighing were repeated, till a constant weight was obtained. The residue was reported as ash on a percentage basis.

$$\text{A. C. (\%)} = \frac{W3-W1}{W2-W1} \times 100 \tag{4.3}$$

Where,

W1 = weight of empty crucible, g

W2 = weight of crucible + sample taken from stage 2nd

W3 = weight of crucible + ash left in the crucible, g

4.A.2.4 Fixed Carbon

The fixed carbon content was calculated by applying the mass balance for the biomass sample.

$$FC, (\ \%) = 100 - \ \%\ of(MC + VM + AC) \tag{4.4}$$

Where,

FC = Fixed carbon (%), MC = Moisture content (%), VM = Volatile matter (%), AC = Ash Content (%).

4.A.2.5 High Heating Value

$$HHV = \{0.036 \times C + 1.418 \times H - 0.145 \times O\} \tag{4.5}$$

Where,

C = Carbon content

H = Hydrogen content

O = Oxygen content data from the CHNS analyzer.

4.A.3 Size reduction

5 Kg of dry grass and Polyalthia longifolia were obtained at a moisture content of (6-14) % dry basis (d.b) from the Indian Institute of Technology, Guwahati. Rice straw with a moisture content of (6-10) % dry basis (d.b) was procured from a local farmer at Amingaon. These raw materials were chopped using a motorized woodcutter: NUTECH-WC-1 multi-purpose machine, hammering blades, Feeding material size 25mm to 60 mm; output: equipped with a screen size of 3mm to 15mm; interchangeable sieves: output 20 kg/hr; Motor 3 HP; to run on 440V (**Figure 4.2**).

Figure 4.2: Photograph of the chaff cutter machine

4.A.4 Binder preparation

The taro tubers were obtained from a nearby pondside, and then the tubers were washed and cleaned; the taro was first peeled and weighed for the required amount, then cut into smaller pieces (**Figure 4.3**). Then, water was added to the tuber pieces at a ratio of 2:3 (w/w) as described by Agama et al. [166] as it is an established method to bring out the adhesive property of taro tubers. The mixture was heated till it boiled, and the taro pieces were mashed to bring out its adhesiveness. This method of binder preparation was used for briquette grass, dry leaves, and straw at different ratios and percentages.

Figure 4.3: Photograph of wild taro tuber

4.A.5 Briquetting

The processed binder was added to chopped grass and sawdust, dry leaves, and straw at three ratios each to find the best percentage of the binder.

The prepared mixture ratios were fed to the machine through the hopper and then extruded by the single-phase one-hp motorized screw press machine purchased from a local manufacturer in Guwahati. The engine builds the temperature, which helps the binder to bind better. The measured temperature at the outlet of the machine was 70^{o} C. The device's capacity is 10 Kg output per hour, to run on 220V (**Figure 4.4**). Feeding material size $\leq$ 3mm; output: 3 cm average diameter briquettes.

Figure 4.4: Photograph of mini briquette machine

4.A.6 Analysis of briquettes

All prepared samples were dried in the sun for ten days before analysis. Three pieces were randomly picked from each ratio for the examination. The properties tested in this study were moisture content, ash content, volatile matter content, and fixed carbon content, as explained in the previous section (eq. 4.1- eq. 4.5). The other test performed on the briquettes were: calorific value, density, shatter resistance, compressive strength, and water resistance, as done in most of the literature to determine the quality of the briquettes [75][57] [143].

4.A.6.1 Calorific value

The calorific value was tested using an oxygen bomb calorimeter (Make Analysentechnik, Gmbh, Germany). Calorific value is the measure of heat released when the unit mass of fuel is entirely burnt in an excess oxygen environment. The biomass sample was placed in a closed vessel and burnt at a constant volume in the presence of extra oxygen by electrically igniting it. The water equivalent of the bomb calorimeter is determined by burning a known amount of benzoic acid, and the heat liberated during the combustion process is absorbed by a known quantity of water.

The combustion was carried out in an environment with 25 atmospheric pressure of oxygen to ensure complete combustion. The calorific value of solid fuel using the bomb calorimeter experiment was calculated as:

$$\text{Calorific value (Kcal/kg)} = \frac{(\mathrm{W} + \mathrm{w}) \times (\mathrm{T2} - \mathrm{T1})}{X} \tag{4.6}$$

Where,

W = Mass of water placed in the calorimeter (2000 g),

w = Water equivalent of the apparatus (455 g),

T1 = Initial temperature of water in the calorimeter (˚C),

T2 = Final temperature of water in the calorimeter (˚C),

X = Mass of fuel sample taken in the crucible (g)

4.A.6.2 Density

Density was measured as described in the literature where the volume of the briquette is measured directly and the mass by volume ratio gives the value of the density[113].

$$D = \frac{w}{v} \tag{4.7}$$

Where, w = weight of sample in g and

v = volume of sample in cm^3

4.A.6.3 Compressive Strength

The compressive strength was measured using a digitally controlled closed-loop Servo hydraulic 100 kN dynamic testing machine (Make: INSTRON, Model 8801). This test was done in a repetition of three samples each.

4.A.6.4 Shatter resistance test

This test was performed to see the strength of the briquettes against external forces. A piece of briquette would be dropped three times on a hard floor from a known height and the previous and later weight minus the initial weight would give the shatter resistance of the sample

$$\text{Percent weight loss} = \frac{W1 - W2}{W1} \times 100 \tag{4.8 a}$$

$$\%\ \text{shatter resistance} = 100 - \%\ \text{weight loss} \tag{4.8 b}$$

Here, W1 is the weight of the briquette before shattering

W2 is the weight of the briquette after shattering in grams.

4.A.6.5 Water Resistance Test

The briquette sample was taken and dipped in water for 30 sec at room temperature. The water gained by the briquette was measured in percentage. The percentage of water gained subtracted from 100 gives resistance to water penetration [116].

$$\text{Water gained (\%)} = \frac{W\,2 - W1}{W1} \times 100 \qquad (4.9\text{ a})$$

Where, W1 = Initial weight of briquette

W2 = Final weight of briquette

$$\text{Resistance to water penetration} = 100 - \text{water gained (\%)} \qquad (4.9\text{ b})$$

4.B Briquette from the addition of charcoal to the raw materials

4.B.1 Raw materials

The sieved raw materials from the previous study were mixed with charcoal obtained from a gasifier plant situated at Amingaon near the IIT Guwahati campus. The bamboo Charcoal was tested for proximate and ultimate analysis. The levels of charcoal and binder are given in **Table 4.1**

Table 4.1: Process parameters and levels of the experiment

Process Parameters	Levels		
	1	2	3
Charcoal(%)	0	25	50
Binder(%)	10	15	20
Raw materials	Grass	Leaves	Straw
Binder Preparation	1	2	3

4.B.2 Binder Preparation

As starch extraction process is time consuming, therefore two other method of binder preparation: one described by Granado et al. [108] for cassava binder and second by Agama et al. [166] for taro binder was studied to see their effect on the quality of briquette.

For the first level of analysis, the taro was peeled and weighed for the required amount, then cut into smaller pieces. Then, water was added to the tuber pieces at a ratio of 2:3(w/w) and brought to a boil.

For the second level of analysis, the taro tubers were cut, dried, powdered, stored, and later mixed with water and boiled.

For the third level, the dried taro powder (100 gm) was mixed with 300 ml water, homogenized, and left overnight; the solid layer settled below was washed and collected by filtering through the Whatman filter [114].

The three-level binder preparation was tested to see the influence of the binder preparation method on the quality of briquettes prepared by mixing charcoal and biomass at different levels.

4.B.3 Characterization

Along with proximate, ultimate, Physical, and mechanical analysis as described in eq. (4.1-4.5) and section (4.A.6.1-4.A.6.5) the other investigation done were:

4.B.3.1. Emission analysis

The emission of CO, NO_x, and SO_2 was measured. **Figure 4.5** gives the schematic diagram of the setup of a self-built combustion unit to measure the emission gases, similar to the study found in the reference [160]. The design consists of a closed chamber and a chimney outlet at the top. An updraft gasifier stove was used to burn the briquettes to be tested. The furnace is an improved updraft gasifier cookstove with dimensions 20.3cmx20.3cmx33cm, a wood-feeding capacity of 1kg, and a 1-watt fan at the bottom powered by an ac adapter. To take the reading, a flue gas analyzer Testo 350, was used. The tip of the modular flue gas probe was inserted through the chimney after 5 min of constant burning, and the value of CO, NO_x, and SO_2 were obtained from the machine. The measurement principle for the three gas was electrochemical. The GHG emissions include CO_2, N_2O, and CH_4. Straw is assumed to be Carbon neutral; thus, the study did not include CO_2 emissions from straw combustion in the calculation of GHG emissions [45]. The air pollutants involved in this study included CO, NO_x, and SO_2.

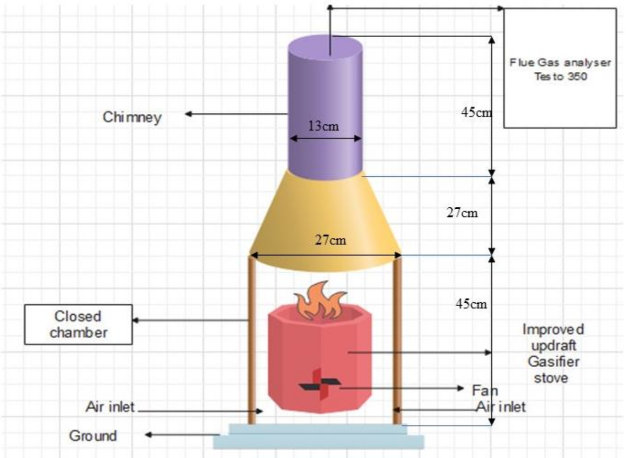


Figure 4.5: Experimental setup for Emission test [167].

4.B.3.2 Water boiling test

The amount of time required for each set of briquettes to boil an equivalent quantity of water under a similar environmental setting is achieved by conducting a water boiling test. The following were used for the experiment; tongs for holding the briquettes; a spatula for removing char from the cookstove, a digital thermocouple for measuring temperatures; a timer for recording time; a metal tray for holding briquette fuel, and a precision scale of ±1 g correctness. About 250 g of briquette fuels were used to boil 500 ml of water with the updraft gasifier cookstove. First, the temperature of the water was recorded with a digital thermocouple. At full boil, the temperature was measured over five minutes, with the highest and lowest temperatures recorded. Next, the mean of the lowest and highest temperatures was calculated. The boiling point was deemed to have been achieved when the average temperature was consistent for about 10 s. Finally, it measured the time consumed for each set of briquettes to boil an equivalent volume of water under similar conditions. During this test, other fuel properties of the briquettes, like burning rate and specific fuel consumption, were also determined using equations given in Eq.4.10a and 4.10b [170]. The water boiling setup is given in **Figure 4.6.**

$$\text{Burning rate} = \frac{\text{mass of fuel consumed (kg)}}{Total\ time\ taken\ (min)} \qquad 4.10a$$

$$\text{Specific fuel consumption} = \frac{\text{mass of fuel consumed (kg)}}{\text{mass of boiling water (litre)}} \qquad 4.10b$$

Figure 4.6: Photograph of the Setup for the water boiling test

4.B.3.3 Thermogravimetric analysis

The Thermogravimetric analysis (TGA) was done to compare briquettes made with three different binders at three binder levels. From the TGA plot, it is seen that briquette decomposition occurs in four (4) stages; drying (A), heating (B), devitalization (C), and char aggregation (D). TGA experiments use an inert sample purge gas. It is done to see how the sample reacts to temperature during decomposition. Change is recorded in terms of the piece's mass as a function of temperature. The three ratios of paper, starch, and taro binder were subjected to TGA at the air heating rate of 10°C per minute. A small sample size was taken to ensure the uniformity of the temperature and good reproducibility. The sample (10 mg) was heated from ambient to 900 °C at a slow heating rate of 10°C min-1. The data was analyzed to determine the thermal degradation rate [171].

4.B.3.4 Burning Characteristics

The burning test was done using a steel mesh stand mounted on a weighing scale (**Figure 4.7**). The sample was mounted on the mesh and ignited using kerosene oil. The weight was monitored per minute after the ignition of the sample till a stable value was obtained for five consecutive readings. The weight loss was then plotted in a graph where mass degradation was plotted against time.

Figure 4.7: Photograph of the setup of open burning combustion test of briquette sample**.**

4.B.3.5 Specific energy consumption

Energy consumed during briquette preparation was estimated for the size reduction and compression stages. The electrical current was measured with a clamp meter (MECO 1080-TRMS), and the readings were used to calculate the electrical energy consumption.

The power consumed by the machines was calculated using Eqs.4.11 and 4.12, respectively.

$$Single\ phase\ P = \frac{V*I*Cos\Phi}{1000} \quad \text{for single phase briquetting machine} \qquad (4.11)$$

$$P = \frac{\sqrt{3}V*I*Cos\Phi}{1000} \quad \text{for a three-phase winding machine} \qquad (4.12)$$

The electrical energy consumption during grinding was calculated using Eq. 4.13.

$$E = P \times t \qquad (4.13)$$

The specific energy consumption for briquetting was calculated using Eq. 4.14: [172]

$$SEC = \frac{Energy\ reqired\ to\ produce\ briquette(KJ)}{Amount\ of\ rice\ straw\ briquette(Kg)} \qquad (4.14)$$

The units are *P* = kW, *A* = ampere, *V* = volt, *P.F.* = no unit, *E* = kJ, *t* = second, and *SEC* = kJ/kg.

The total energy expenditure (TEE) method was used to estimate the labor energy used for briquette preparation [173]. Two male laborers aged 27 and 29 years weighing 70 kg and 64 Kg spent 6h/day for collecting, grinding, mixing, and briquette making. The average physical activity ratio (PAR) of 3.0 was selected for performing this activity as given in the literature [39]. Eq. 4.15 was used to estimate the labor energy consumption

Labour energy Consumption (MJ/day),

$$EC_{\text{Labour energy}} = \frac{work\ time(hr) \times Avg.PAR}{24hr/day} \times [(0.063 \times body\ weight, Kg) + 2.896] \tag{4.15}$$

4.B.4 Design and analysis of experiment

4.B.4.1 Taguchi-Grey relational analysis

Genichi Taguchi developed Orthogonal Array experiments, which deliver optimal settings of process control parameters by minimizing variances of the experiments [42]. Therefore, Taguchi Grey relational analysis was performed to optimize the pelleting process for material variables considering multiple responses. The orthogonal array (OA) technique (Taguchi L9 OA) was used to design the experiment using Minitab®17.2.1.

Taguchi uses a statistical measure of performance known as signal to noise (S/N). The quality characteristics with "larger the better" were selected for all performance characteristics (bulk density, durability, diametrical compressive strength or hardness, and calorific value).

Therefore, S/N for a "larger the better'" characteristic is calculated as Eq.(4.16)

$$\text{S/N ratio } (\eta) = -10\log_{10}\frac{1}{n}\sum_{1}^{r}\frac{1}{Y_{ij}^{2}} \tag{4.16}$$

Where,

Y_{ij} = Observed response value (i = 1, 2,…, n; J = 1,2,…..k)
n = number of replications

The following formulas were used for the standardized transformations. When the target value is "larger is better", the original sequence is normalized as Eq.(4.17)

$$x_i^*(k) = \frac{x_i(k) - min x_i(k)}{max\, x_i(k) - min x_i(k)} \tag{4.17}$$

where,

$x_i^*(k)$ is the normalized value of the kth performance characteristic in the ith experiment.; and x_i (k) is the original kth performance value in the ith experiment.

The deviation coefficient is determined by using Eq. (4.18)

$$\Delta x_i(k) = |x_0(k) - x_i^*(k)| \tag{4.18}$$

where,

$\Delta x_i(k)$ is a deviation coefficient

$x_0(k)$ is the reference sequence or ideal series, and

$x_i^*(k)$ is a comparability sequence

The Grey relational coefficient is calculated using Eq. (4.19)

$$\xi_i(k) = \frac{\Delta_{\min} + \psi \Delta_{max}}{\Delta x_i(k) + \psi \Delta_{max}} \tag{4.19}$$

ξik is grey relational coefficient and Ψ is a distinguishing coefficient, and Δmin is the smallest value of $\Delta x_i(k)$ whereas Δmax is the largest value of $\Delta x_i(k)$.

The Grey relational grade (GRG) is calculated by Eq. (4.20)

$$Y_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \tag{4.20}$$

Where,

n is the number of output response characteristics

Optimal values of GRG can be predicted using Eq. (4.21)

$$\gamma_e = \gamma_m + \sum_{i=1}^{q} (\overline{Y_i} - Y_m) \tag{4.21}$$

where,

γ_m = The total mean of the GRG

q = Number of input parameters/factors

$\overline{Y_i}$ = Mean GRG value at the optimal level for the ith parameter

Now, the Grey relational grades are considered for optimizing the multi-response parameter design problem[174]

4.B.5 Cost analysis

The theoretical cost analysis of the briquette production using this process was calculated to see the practicality [99]. All the assumptions and formulas are given as follows:

4.B.5.1 Inbound cost

$$\text{Depreciation cost} = \frac{P-S}{L} \tag{4.22}$$

Where,

P = Machine price

S = Residual value of machine = 10 % of P

L = Useful life of the machine in years

Taxes, insurance, and shelter (Rs/year) = 2 % of P

Repair and maintenance cost = 5 % P

Total cost of briquette machine P = Rs. 10,000

The residual value of machine S = Rs. 1,000

The useful life of the machine =10 years (6 days a week =288 days a year)

Depreciation cost = Rs 3.125/day

Repair and maintenance = Rs 500/year = Rs. 1.736/day

The total cost of a charcoal drum P = Rs. 8,000

The residual value of machine S = Rs. 800

The useful life of the machine =10 years (6 days a week =288 days a year)

Depreciation cost = Rs. 2.5/day

Repair and maintenance = Rs. 400/year=Rs.1.39/day

Total cost of chaff cutter machine P = Rs. 20,000

The residual value of machine S = Rs. 2,000

The useful life of the machine is = 15 years (6 days a week =288 days a year)

Depreciation cost = Rs. 4.167/day

Repair and maintenance = Rs. 1,000/year=Rs.3.472/day

4.B.5.2 Direct Labour cost

Trained labour cost = Rs. 334.8 per person-day of 8 hours [93].

Therefore, two labourers are required to do the job for 8 hours a day. Thus labour cost equals Rs. 669.60.

4.B.5.3 Utility cost

The electricity cost was calculated based on the use of the briquetting machine and chaff cutter machine.The machines were used for 8h per day. The average energy consumption for densification and size reduction was found to be 0.0753 MJ/kg. If the electricity charge was calculated as Rs. 5 per unit then the electricity cost per kg of briquette produced = 0.021KWh×5 = Rs. 0.105/Kg.

4.C Briquette from carbonized rice straw

4.C.1 Raw materials

Three sets of nine samples were made using carbonized rice straw with a separate binder and different binder ratios, as shown in **Table 4.2**. Three binders newspaper waste, starch, and Taro starch were used in this study. As discussed later in this report, the three binders were prepared by mixing with water at different ratios. This was done to find the best binder combination to produce carbonized rice straw briquette.The binder ratio was selected at 10 %, 15 % and 20 % ratio following the work of Yank et al.[123], Kumar [110], Kumar and Kamesh [109].

Table 4.2: Raw material, binder type, and level used in the study

Sample ID	Raw material	Binder	Binder percentage
P10	Carbonized rice straw	Paper	10
P15			15
P20			20
S10		Starch	10
S15			15
S20			20
T10		Taro Starch	10
T15			15
T20			20

4.C.2 Machine used

For carbonization of the straw, a Laboratory fabricated drum kiln was used. It consisted of a drum with a chimney on top, and the bottom had uniform punched holes, all mounted on a stand (**Figure 4.8**).

Figure 4.8: Photograph of carbonization drum [168]

4.C.3 carbonization of straw

The straw was dried and carbonized in a limited supply of air to give a high carbon product Char. The carbonized drum kiln was fired from the bottom using firewood, and once it is fired, the smoke starts coming out from the chimney. After some burning time, the black smoke ceases to come out and, and the carbonized straw becomes brittle and easy to crush into smaller pieces as shown in **Figure 4.9**. The carbonized straw was then pulverized with hands and further sieved using a 3mm sieve to obtain fine particles.

Figure 4.9: Photograph of carbonized rice straw

4.C.4 Preparation of Binders

Three binders were used in this study. Among the most used binder in works of literature, are starch [136, 116, 96, 123] and paper [122, 113, 52] was taken to compare with taro starch.

4.C.4.1 Paper pulp: Newspaper waste was weighed according to the weight ratio of the sample used. For every 10 g of paper, 100 ml of water was added (**Figure 4.10 a**). The mixture is allowed to soak until the paper softens in the water. Then, the paper is mixed thoroughly with water to get a homogeneous mixture of Paper pulp, which later is combined with the carbonized straw.

4.C.4.2 Starch: The starch used in this study was Lab grade soluble starch (**Figure 4.10 b**). The starch was weighed and mixed with water so that for every 10gm of starch, 50 ml of water was added. The mixture was then heated on a heating plate and brought to a boil until the starch became gelatinized. It was then poured over the carbonized straw and mixed properly.

4.C.4.3 Taro starch: The taro tubers were obtained from a nearby pondside, and then the tubers were washed and cleaned like the work done by Narzary et al. [168]. The starch extraction procedure was followed by Moorthy et al. [176]; Nand et al. [177]. The Tubers were peeled (**Figure 4.10 c**), cut into small pieces, disintegrated in a blender at low speed, and mixed with water in a ratio of 1:10 (w/v). The mixture was passed through a steel mesh screen twice and settled overnight. The supernatant was decanted off, and the sediment was subjected to washing and settling. The Precipitate, i.e., the starch at the bottom, was removed and dried at 45-50°C for 24 h. The resultant starch was used for the study. The starch was mixed with water in a ratio of 1:5 (w/v) and heated in a heating pan to bring out its adhesiveness before using it as a binder.

(a) (b) (c)

Figure 4.10: Photograph of (a) Carbonised straw (b) Paper pulp (c) Taro tuber

All experiments involving plant materials in this study were performed following "IUCN policy statement on Research involving species at risk of extinction,1989" guidelines and regulations.

4.C.5 Briquette production and quality evaluation

For each batch, 100 gm of dried carbonized straw was mixed with the binder and compressed to obtain carbonised briquette under this study. The proportions of the binder in the mixture were 10 %, 15 %, and 20 %. The mixture was then hand-fed into a mini briquette machine. Finally, each briquette sample measuring (6.5cm×3.8cm) on an average (**Figure 4.11**) was analyzed in three replicates for the properties as mentioned in 4.1.2, 4.1.6, and 4.2.3 previously.

Figure 4.11: Photograph of Briquette sample

4.D Briquette preparation using carbonized rice straw in a low-cost briquette machine

4.D.1 Machine fabrication

A self-designed, easily replicable and low-cost machine was fabricated at a local welding shop (**Figure 4.12 a**). The design of the device represents a simple manual hand press machine. The pressure can be applied by lifting and pressing the handle downward with body force. The apparatus consists of a piston, mold, and a base plate mounted on a stand. A hollow cylindrical cast iron pipe of 1.5 inches in diameter and 4 inches in height was used as the mold. A circular 5mm iron sheet was used as the base plate. A small iron rod of 3mm diameter was bent to form a ring and welded near the mold as the briquette mixer container holder. The opening of the cylindrical pipe consists of a hopper that allows the raw material input easily.

(a) (b)

Figure 4.12: a) Photograph of Manual briquette press **b)** Screw press mini briquette machine

4.D.2 Briquette production and quality evaluation

For each batch of briquette, 100 gm of dried carbonized straw was mixed with the binder under study. The mixture was then hand-fed into the cylindrical pipe that served as a mold and covered at the end with the movable disk. The Carbonized straw-binder mix inside the mold is compacted at a pressure of 5 kg cm^{-2} for 5 min before the briquette was removed following Sotannde et al. [119], who used a hydraulic press to compress the raw materials. Finally, 5-6 briquette samples were obtained which were then analyzed in three replicates for physical and physiochemical properties as mentioned in sections 4.1.2, 4.1.6, and 4.2.3 previously. The briquette samples obtained are shown in **Figure 4.13**.

Figure 4.13: Briquette samples from carbonized rice straw using a manual hand press

4.E Comparison

According to Wang et al. [59] the main factors of a biomass briquette production system are economy, cleanliness and environmental protection, production capacity, product quality, and production stability. Based on these factors, the briquette produced using a manually fabricated hand-pressed machine was compared with the briquette from the screw press machine (**Figure 4.12 b**). Therefore, the best briquette sample obtained from objective two was compared with the same binder and binder percentage briquette prepared in a screw press and manual hand press machine.

Figure 4.14: Photograph of briquette from carbonised rice straw using screw press machine

Chapter 5: Results and Discussion

5.0 Introduction

The previous chapter discusses the materials and methods applied to obtain the objectives of this research. In this chapter, the results are presented in forms of tables, graphs and figures. The chapter discusses the findings and compare them with other values obtained in the works of literatures.

5.A Briquette making using grass, dry leaves and straw

5.A.1 Proximate and ultimate analysis of raw materials

Table 5.1 presents the proximate and ultimate analysis of Grass (*Eleusine indica)*, Dry leaves (*Polyalthia longifolia*), and straw after sun drying for six days. It is clear from the data that all three feedstocks have Ash content (9.34-13.5) %, Volatile matter (67.605-80.33) %, fixed carbon content of (9.47-14.96) % and moisture content (6.7-8.1) % which indicates potential for obtaining good quality briquettes. The ultimate analysis of the feedstocks also shows a high value of carbon and a moderately lower value of oxygen which is a sign of good value for conversion of biomass the high-quality solid fuel, which can be compared with similar values from other works of literature [49][138]. The volatile matter/fixed carbon ratios are an indicator of fuel's reactivity; therefore, knowing these values before briquetting can be helpful. Fixed carbon content value can range from 11.4 %-23.9 % (Approximately), whereas the present feedstocks (grass, leaves, and straw) are in the moderate range, showing a value (of 12.99-14.96) %. Therefore when comparing the proximate and ultimate analysis value of the feedstocks to the literature values, it is clear that the particular grass, leaves, and straw that were taken for the present study have a high potential to be used as feedstock for briquette-making.

Table 5.1: Proximate and ultimate analysis of raw materials after sun drying

Sample	Proximate analysis (%) dry basis				Ultimate analysis			
	Moisture	Ash	Volatile Matter	Fixed Carbon^a	C	H	N	O^a
Grass (*Eleusine indica)*	6.7	9.47	70.33	13.5	42.6	4.8	1.9	50.7
Leaves (*Polyalthia longifolia*)	8.1	9.34	67.6	14.96	48.9	5.6	1.3	44.2
Straw	7.8	10.5	68.71	12.99	46.5	5.9	1.1	46.5

^{a}: Calculated by the difference

5.A.2 Taro (*Colocasia esculenta*)

Table 5.2 shows the proximate and ultimate analysis of wild taro tubers. The tuber is seen to have low ash content and high volatile matter content and carbon content, which are the signs of a good binder [169].

Table 5.2: Proximate and ultimate analysis of wild taro tubers

Proximate analysis (%) dry basis				Ultimate analysis			
Moisture	Ash	Volatile Matter	Fixed Carbon	C	H	N	O
11.6	1.2	74.3	12.9	47.4	5.3	0.8	46.5

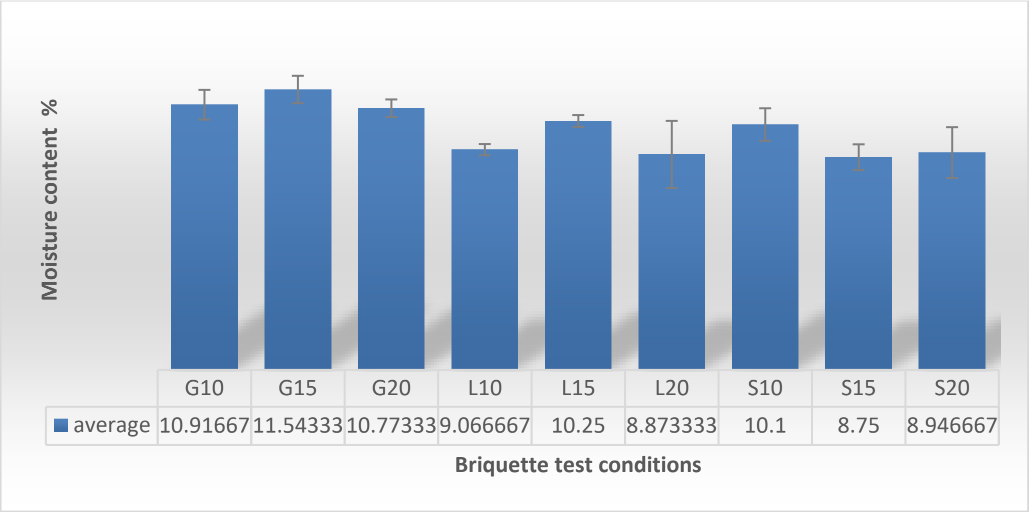
5.A.3 Physiochemical Properties

Figure 5.1 (A) shows the moisture content of the briquettes from grass, leaves, and straw at 10, 15, and 20 % binder levels. It is seen from the figure that the grass briquette at all binder percent shows higher moisture content than leaves and straw briquettes. The optimum range of briquette moisture stated by Mani et al. [23] and Chungcharoen and Srisang [54] were in the range of (6-12) %, and the results from the present study lie in the range. The moisture content value was higher for grass sample followed by leaves briquette and straw briquette.

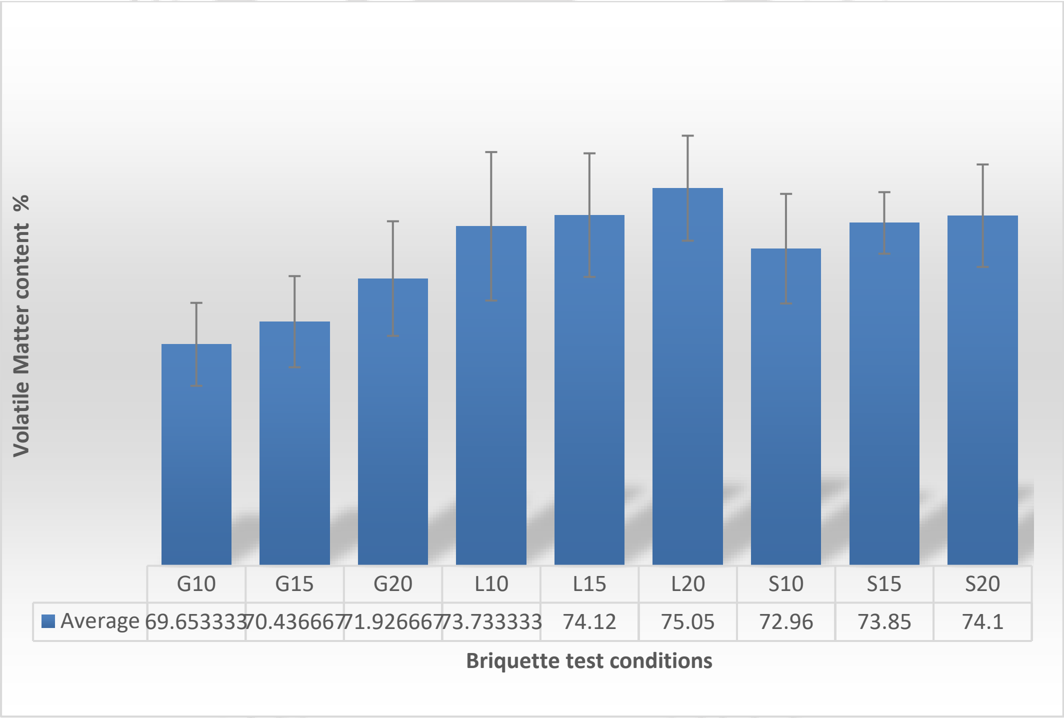
Figure 5.1 (B) shows the volatile matter content of the briquettes. The volatile matter is the number of organic substances present in the briquettes. The main components of the volatile matter include combustible components (CH_4, C_2H_2, H_2, CO, etc.) and non-combustible components (CO_2, H_2O, NO_x, etc.) [170]. The volatile matter was found to be highest for the straw briquette and lowest for the grass briquette. Higher volatile matter is an indicator of rapid ignition and combustion leading the increased chemical reactions [48]. The volatile matter is directly proportional to the combustion rate [79]. The only disadvantage of high volatile matter content is the higher production of smoke due to the larger production of volatile gases [54].

Figure 5.1 (C) displays the ash content of the briquettes. The undesirable component obtained from the combustion process is the ash content. Ash is the non-combustible component that remains after combustion. The ash is made up of inorganic components like phosphorous, potassium, silicon, chlorine, and calcium [171]. High ash content can give rise to lower calorific value and lead to slag deposition in the combustion chamber [92]. The briquette with the lowest ash content are the leaves briquettes and the highest ash content are the grass briquettes. The ash content is in the range of (9.2-13.22) %.

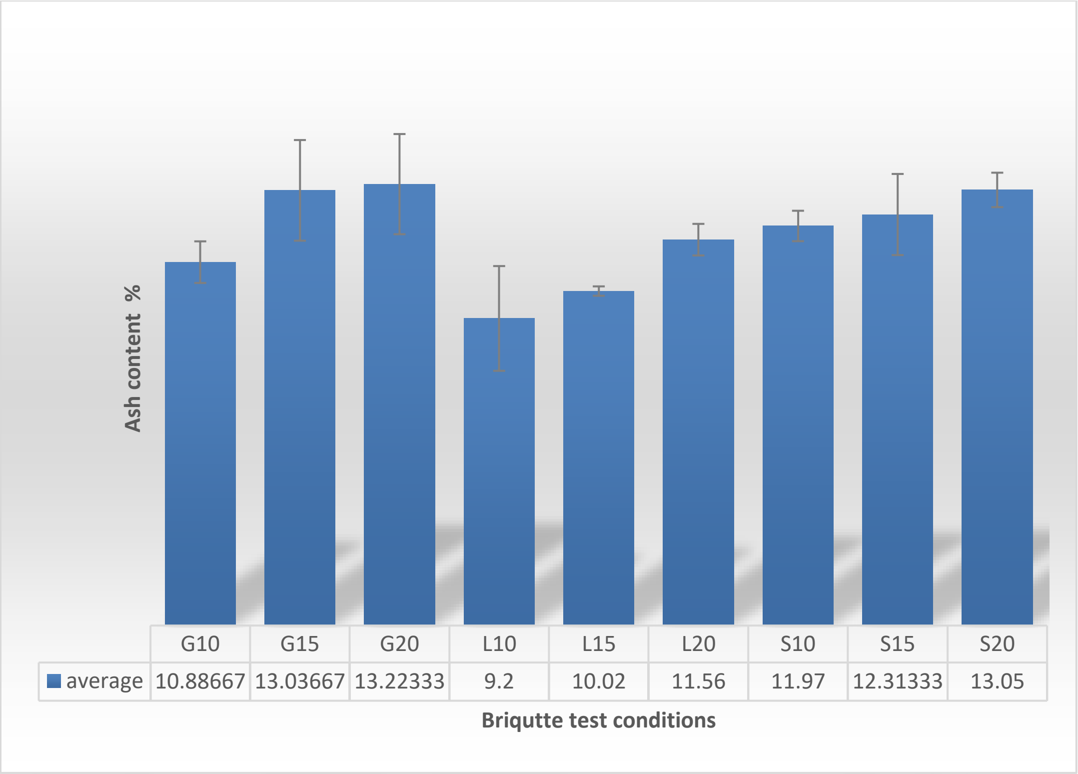
Figure 5.1 (D) is the graph of the fixed carbon content of the briquettes prepared. The value ranged from (9.5-14) %. From the results, it could be noted that volatile matter is inversely proportional to the fixed carbon content. This is similar to the findings of Kpalo et al. [48]. Fuel with higher fixed carbon content tends to burn longer. The ignition is also affected by the presence of fixed carbon. The fixed carbon content lies in the range of fixed carbon content values obtained by Jittabut [141] who also briquetted rice straw and leaves.


Moisture content %
G10
G15
G20
L10
L15
L20
S10
S15
S20
■ average
10.91667
11.54333
10.77333
9.066667
10.25
8.873333
10.1
8.75
8.946667
Briquette test conditions

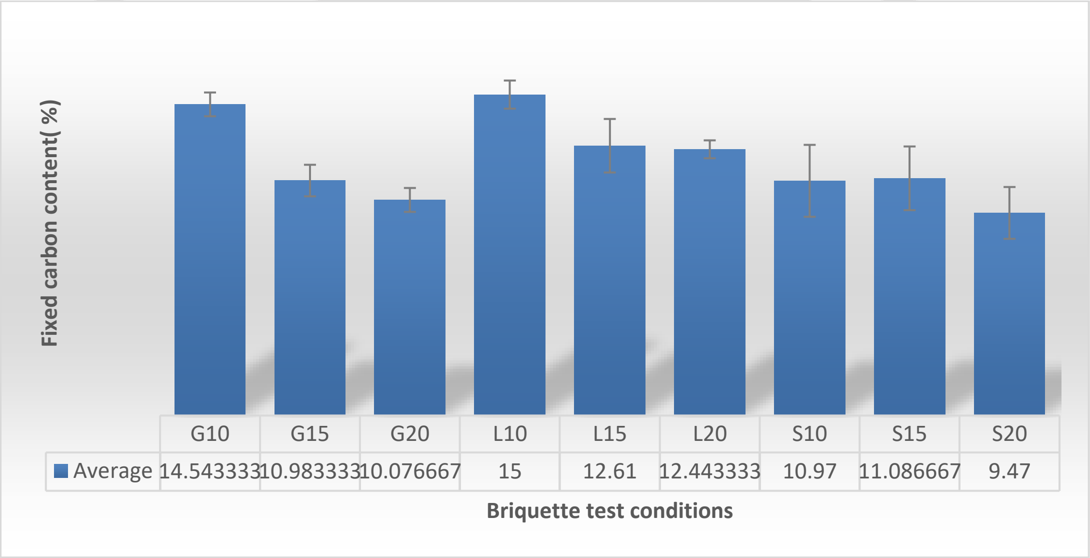
(A)


Volatile Matter content %
G10
G15
G20
L10
L15
L20
S10
S15
S20
■ Average
69.653333
70.436667
71.926667
73.733333
74.12
75.05
72.96
73.85
74.1
Briquette test conditions

(B)



(C)



(D)

Figure 5.1: (A) Moisture content, (B) Volatile matter content, (C) Ash content, and (D)

Fixed carbon content.

5.A.4 Calorific Value

Figure 5.2 displays the calorific value of the samples prepared in this study. The value ranges from (15.46-21.88)MJ/kg. These values are higher than the grass and the leaves briquette obtained by Shuma and Madyira [172]. It is can be seen that increase in binder increased the calorific value. The energy content depends on the density of the briquette which is influenced by the type of binder used by Olugbade et al. [47]. The straw briquette sample displayed the highest calorific value at a 20 % binder percentage.

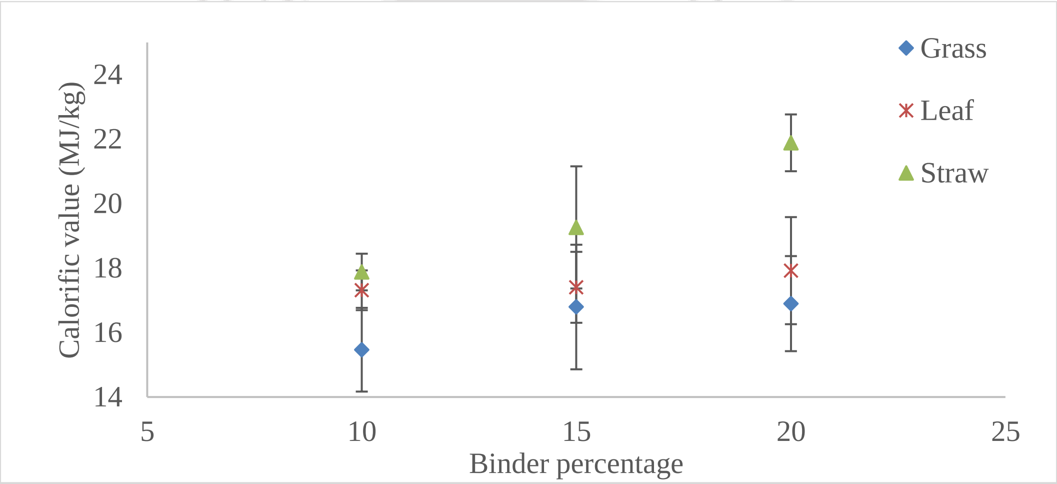
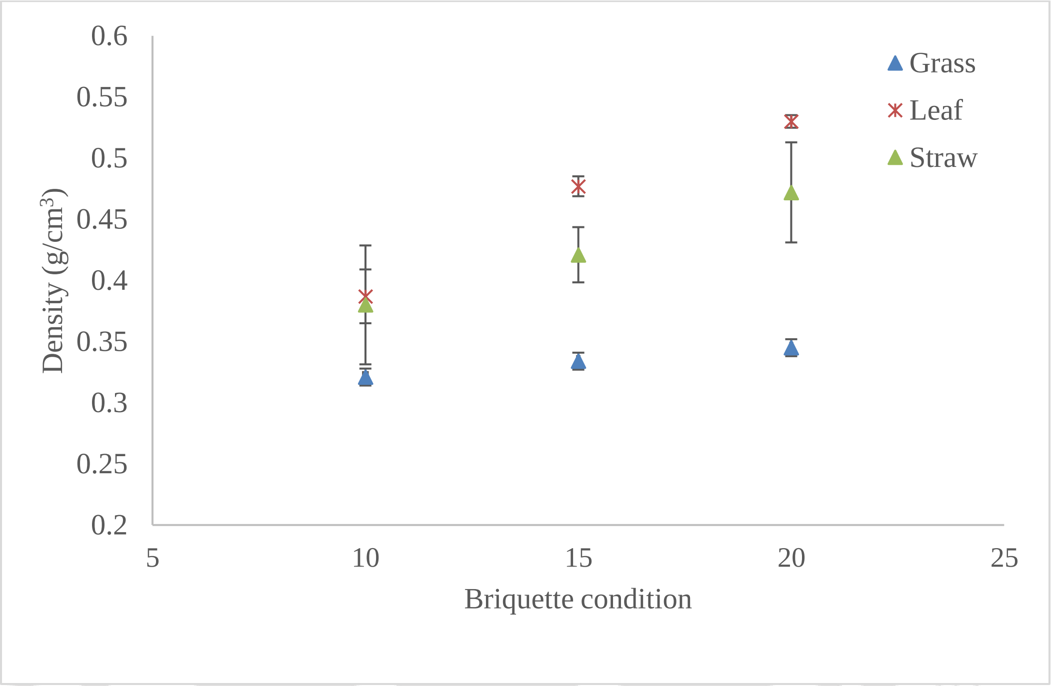


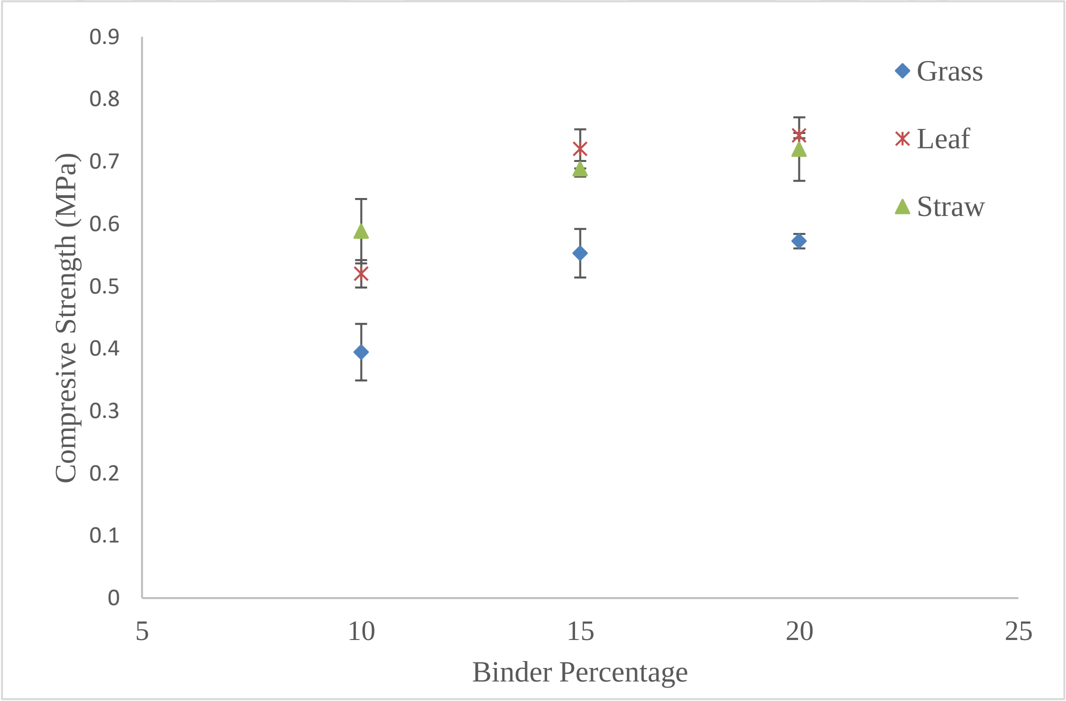
Figure 5.2: Calorific value of grass, leaves, and straw briquettes

5.A.5 Physical and Mechanical Properties

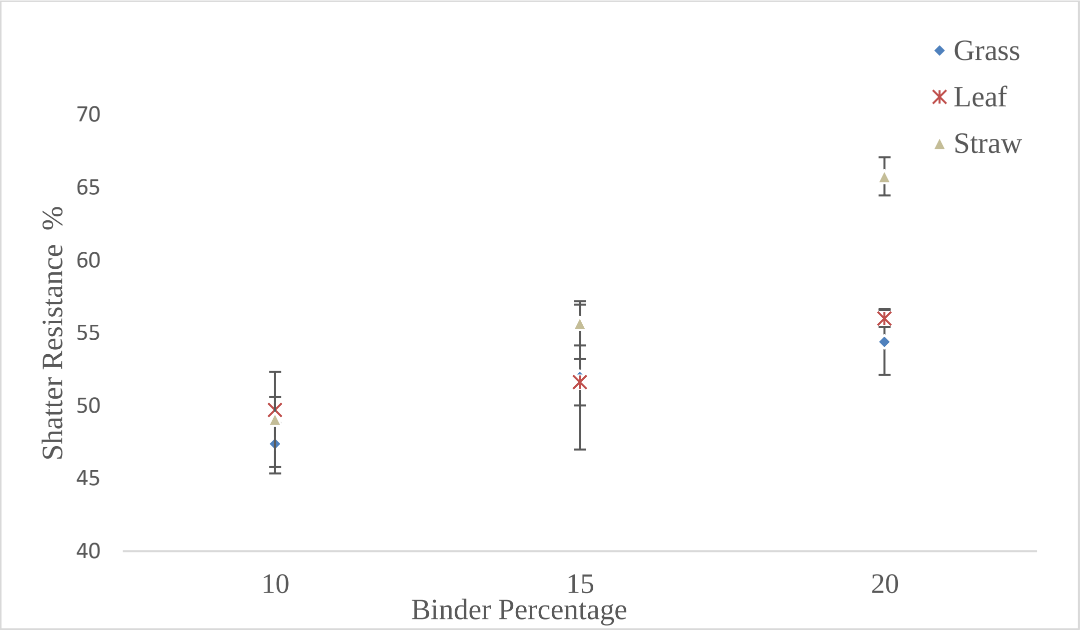
Figure 5.3 (A) displays the density of the briquettes prepared. It can be seen from the graph that the density increased with the increase in the binder [43]. The leaf briquettes attained the highest density value of 0.477 g/cm3. Figure 5.3(B) shows the compressive strength of the samples prepared. The higher density briquette showed higher compressive strength except for the straw sample [123]. The highest compressive strength was found for leaf briquette at 20 % binder level, which is 0.74 MPa.This value was higher than the value obtained by Sawadogo et al. [173], who also used a low-power screw press briquetting machine. Figure 5.3 (C) displays the shatter resistance of the samples, and it can be seen clearly that straw at 20 % binder has the highest shatter resistance of 65.76 %. Sunnu et al. [174] states that the shatter resistance of briquettes is a function of the density and moisture content. Therefore, it can be seen from the graph that straw briquette tends to have higher shatter resistance as it has lower moisture content and higher bulk density than the other two samples in the study. Figure 5.3(D) is the graph of the water resistance of the briquettes. The leaf sample shows the highest resistance to water penetration. A water resistance test is crucial regarding the briquettes' storage quality [129]. The highest water resistance value obtained was 56.96 %.



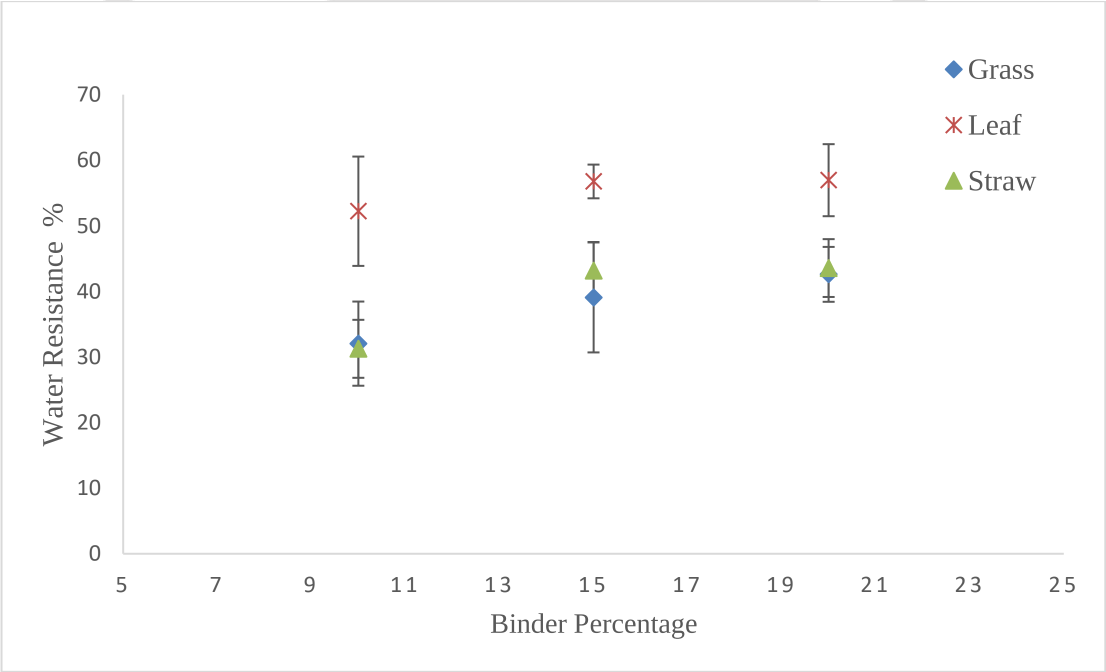
(A)



(B)



(C)



(D)

Figure 5.3: (A) Density (B) Compressive strength (C) Shatter resistance (D) Water resistance values of the samples prepared

5.B Briquette from the addition of charcoal to raw materials

5.B.1 Proximate and ultimate analysis of the bamboo charcoal.

Table 5.3 presents the value of proximate and ultimate analysis of the charcoal used in the study. The values fall in the range of results obtained by Park et al.[175] who studied on carbonization of different bamboo species and Wilk et al. [176] who reported carbonized wood residue at low temperatures.

Table 5.3: Proximate and ultimate analysis of the bamboo charcoal

Proximate analysis (%) dry basis				Ultimate analysis			
Moisture	Ash	Volatile matter	Fixed Carbon	C	H	N	O
11.83	4.22	52.81	31.14	57.33	4.76	0.8	37.11

5.B.2 Proximate and ultimate analysis of briquettes.

Table 5.4 shows the proximate analysis results for nine different combinations of the analysis done in this study. Straw briquette with 50 % charcoal addition and 10 % binder and third binder preparation method showed the highest fixed carbon content of 31.49 %. As seen from the table the increase in charcoal content increases the fixed carbon content of the briquette [167]. An increase in binder and charcoal also increase the ash content. As reported by Martinez et al. [177] the ash content of more than 10 % causes wear and tear on the combustion equipment, therefore we can conclude that all the briquettes obtained in this study have low ash content.

Table 5.4: Output responses corresponding to parameter settings in Taguchi experimental design.

Sl. No.	Charcoal (%)	Binder (%)	BP	Feedstock	Mean MC	Mean AC	Mean VM	Mean FC
1	0	10	1	Grass	6.12	4.45	76.32	13.11
2	25	10	2	Leaf	6.37	5.08	63.29	25.26
3	50	10	3	Straw	5.97	10.31	55.23	31.49
4	0	15	3	Leaf	5.11	6.37	77.15	11.37
5	25	15	1	Straw	6.21	7.29	64.23	23.27
6	50	15	2	Grass	5.38	9.41	53.9	31.31
7	0	20	2	Straw	7.31	5.94	77.35	9.4
8	25	20	3	Grass	7.32	7.63	70.21	14.84
9	50	20	1	Leaf	4.66	9.52	55.66	32.16

Abbreviations: MC- Moisture content; AC- Ash content; VM – Volatile Matter content; FC-Fixed carbon content; BP- Binder preparation.

5.B.3 Optimization using Taguchi - Grey analysis

Table 5.5: Taguchi OA (3^4) and mean responses for each experimental run

Sl. No.	Charcoal (%)	Binder (%)	BP	Feedst--ock	Mean BD	Mean SR	Mean CS	Mean WR	Mean CV
1	0	10	1	Grass	0.537	85.12	0.727	57.889	5891.67
2	25	10	2	Leaf	0.456	72.09	0.400	56.35	4750.83

3	50	10	3	Straw	0.35	73.63	0.303	58.99	5539.23
4	0	15	3	Leaf	0.466	87.44	0.743	53.77	4436.55
5	25	15	1	Straw	0.321	73.17	0.427	52.73	4121.37
6	50	15	2	Grass	0.52	73.89	0.643	60.78	6278.83
7	0	20	2	Straw	0.427	89.65	0.766	57.212	5094.11
8	25	20	3	Grass	0.513	80.56	0.718	63.334	6102.88
9	50	20	1	Leaf	0.588	83.47	0.654	60.099	6381.35

Abbreviations: BD - Bulk Density in g/cm^3; SR - Shatter Resistance (%); CS - Compressive strength (MPa); WR - Water Resistance (%); CV- Calorific Value (Kcal/Kg); BP - Binder preparation.

Table 5.5 displays the physical, mechanical, and thermal properties of the samples according to the parameter setting in Taguchi's experimental design**.** As seen from the table the bulk density increases with the increase in the binder and charcoal [178]. The highest bulk density obtained is 0.588 g/cm^3 for leaf briquettes. An increase in the binder also increases the shatter resistance and compressive strength but a higher percentage of charcoal addition decreases the shatter resistance and compressive strength. The results agree that higher density briquettes display higher mechanical properties as stated by Kpalo et al. [48]. The highest shatter resistance obtained in this study was for straw briquettes at a 20 % binder level and the same sample also displayed the highest compressive strength of 0.766 MPa.

The water resistance increases with the increase in the charcoal addition, this could be due to the smaller particle size of the charcoal, as the particle size is one of the most influential factors for water resistance in briquettes Kumar and Ramesh [109]. The calorific value with higher charcoal content shows a higher value, this is due to the higher calorific value of the charcoal than biomass [147] [68].

5.B.4 Taguchi-based single objective optimization

Genichi Taguchi introduced the concept of the loss function. The basic tenet of the loss function is that the loss in quality of a product results due to its variation or deviation from the target value. The loss function "larger the better" characteristics were selected for each of the performance characteristics, namely BD, SR, CS, WR, and CV. Mean responses were transformed to signal to noise (S/N) ratio. The greater signal-to-noise ratio indicates better performance and the corresponding process parameters that deliver it were regarded as optimal settings of parameters and their levels. **Table 5.6** displays the mean response transformed into signal-to-noise ratios for each performance characteristic.

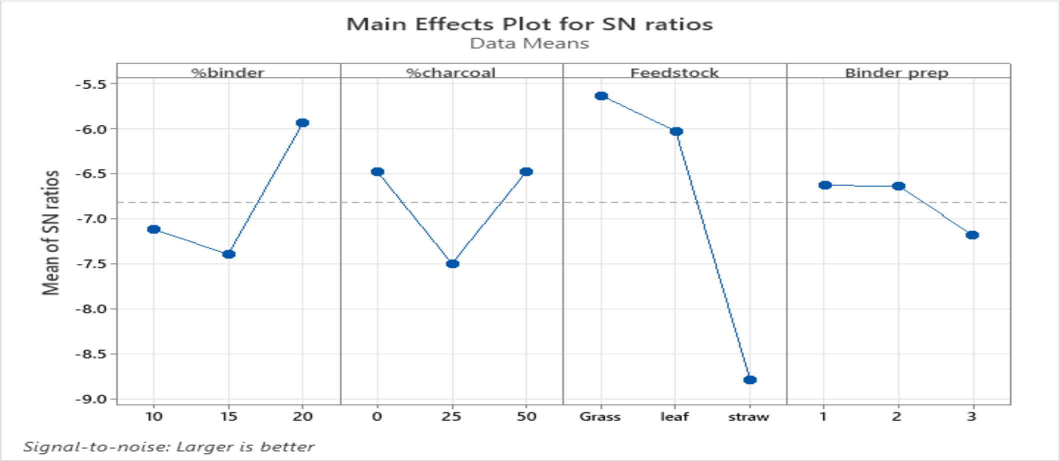
Table 5.6: Signal to noise ratios for thermal and mechanical properties.

Sl. No.	Charcoal (%)	Binder (%)	BP	Feedstock	Signal-to-noise ratio				
					BD	SR	CS	WR	CV
1	0	10	1	Grass	-5.401	-38.601	-2.769	35.252	75.405
2	25	10	2	Leaf	-6.821	-37.158	-7.959	35.018	73.535
3	50	10	3	Straw	-9.119	-37.341	-10.371	35.416	74.869
4	0	15	3	Leaf	-6.632	-38.834	-2.580	34.611	72.941
5	25	15	1	Straw	-9.870	-37.287	-7.391	34.441	72.301
6	50	15	2	Grass	-5.680	-37.372	-3.836	35.675	75.958
7	0	20	2	Straw	-7.391	-39.051	-2.315	35.150	74.141
8	25	20	3	Grass	-5.798	-38.122	-2.878	36.033	75.711
9	50	20	1	Leaf	-4.612	-38.431	-3.688	35.577	76.098

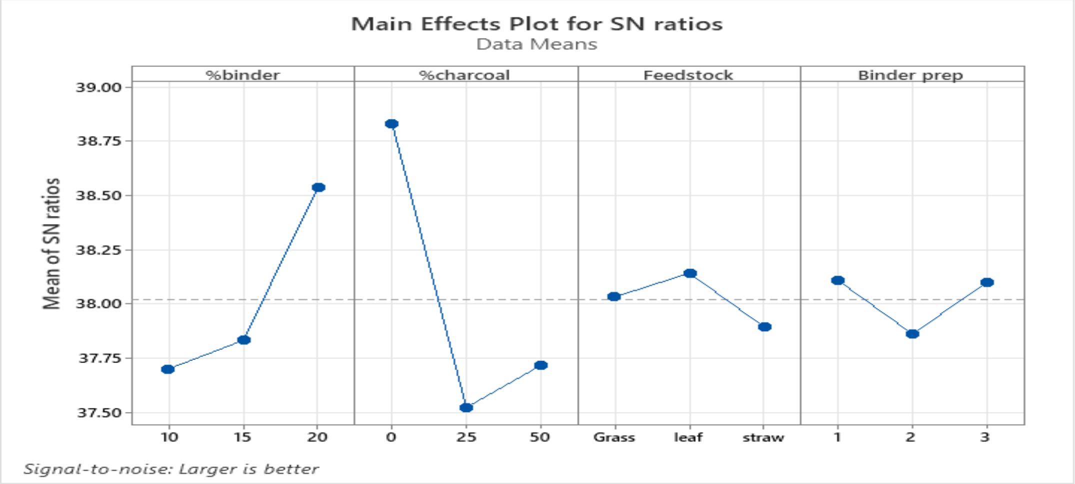
5.B.5 Analysis of results for single objective optimization

The Taguchi method can determine the optimal conditions of process parameters for single quality characteristics by using signal-to-noise (S/N) ratios. A Higher S/N ratio determines the factor settings that minimize the effect of noise factors. The S/N ratios for BD, SR, CS, WR, and CV were calculated using Eq. (1). Taguchi method was used to analyze process parameters with larger the better criteria for each performance characteristic (SR, CS, WR, and CV) are represented in **Figure 5.4.**

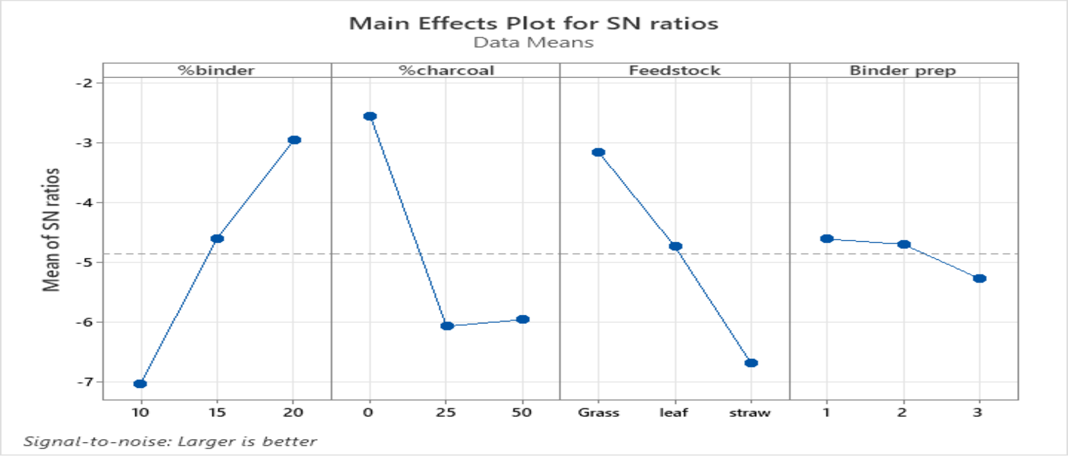
5.B.5.1 Main effects plot (of data means) for S/N ratios



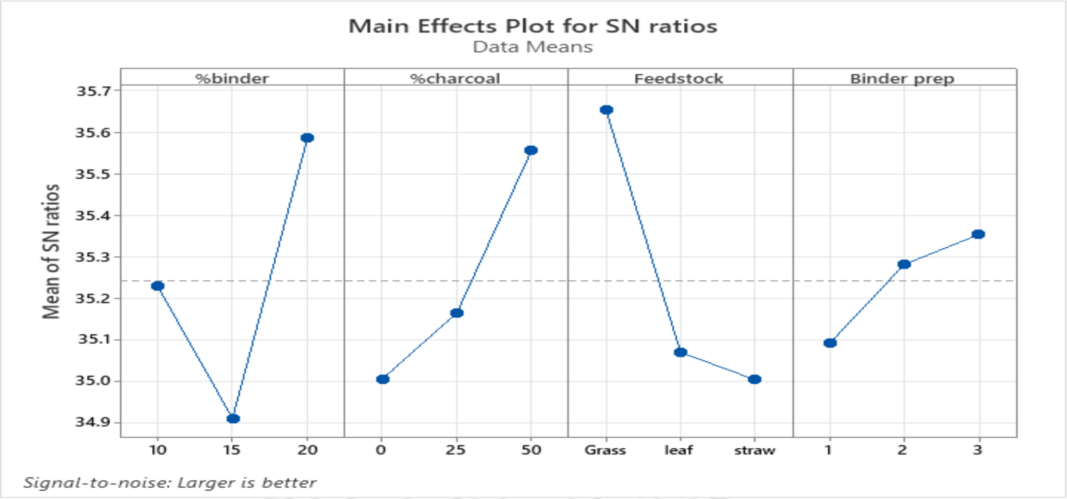
(a)



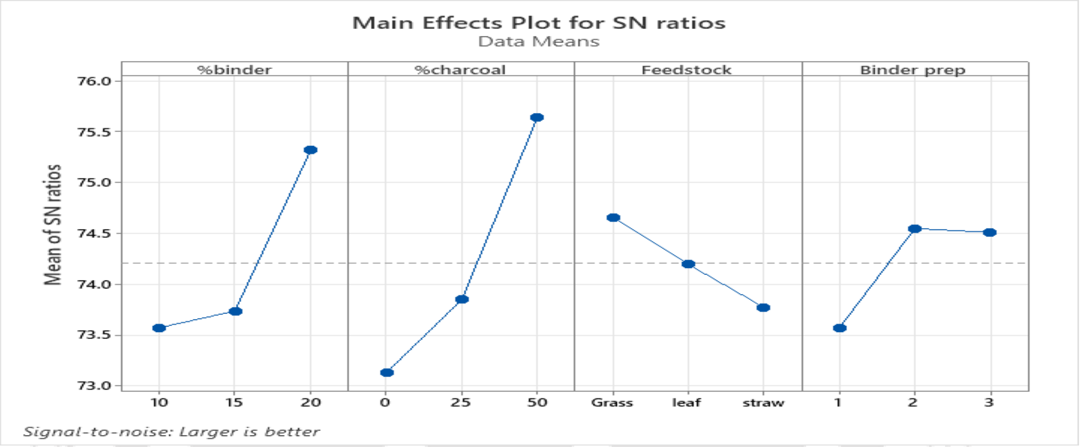
(b)



(c)



(d)

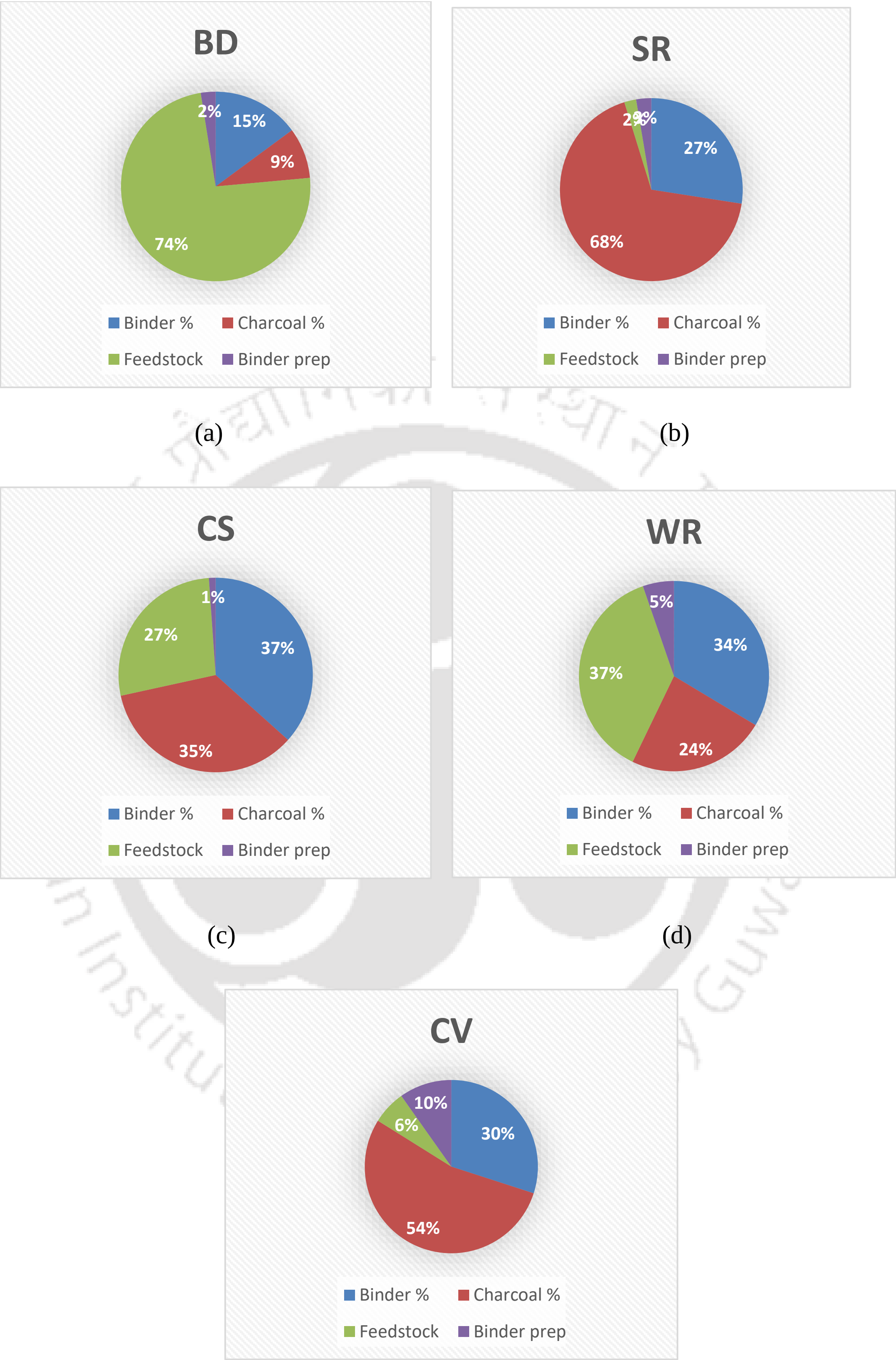


(e)

Figure 5.4: Factor effects plot on S/N ratios for (a) BD (b) SR (c) CS (d) WR (e) CV.

5.B.5.2 Percentage contribution

ANOVA table of S/N ratios for BD, SR, CS, WR, and CV was utilized to deduce the percentage contribution of the control factor for each performance characteristic (BD, SR, CS, WR, CV). The influence of each parameter on quality characteristics is depicted in **Figure 5.5**.



(a) (b)

(c) (d)

(e)

Figure 5.5: Percentage contribution of control factors for (a) BD (b) SR (c) CS (d) WR (e) CV.

For bulk density feedstock showed to be the most influential factor (74 %) followed by binder percentage (15 %) and charcoal (9 %) and the binder preparation method has a negligible influence of 2 %. Charcoal addition is the most influential factor for shatter resistance and calorific value with 68 % and 54 % influence. Binder percentage is the most influential factor for compressive strength (37 %). Feedstock and binder have almost equal influence on the water resistance property of the briquettes obtained. In most of the cases, the binder preparation method showed to have very little influence. Charcoal and binder showed significant influence on all properties under this study. The optimal level setting for parameters that leads to higher BD, SR, CS, WR, and CV is depicted in **Figure 5.4** . The main effect plots for S/N ratios **Figure 5.4** showed that optimum parameter levels for higher bulk density, shatter resistance, compressive strength, water resistance, and calorific value are A3B2C1D1, A3B1C2D3, A3B1C1D1, A3B3C1D3, and A3B3C1D3 respectively.

5.B.6 Multi-objective optimization using Grey relational analysis

The result from single objective optimization shows us which parameter affects the quality of the briquettes, but we cannot conclude which combination of factors is the best. Therefore, equitable analysis was needed to determine the degree of influence of parameters for the best quality of the briquette. The result was thus analyzed using Grey relational analysis as it was hard to investigate the effect of each input factor on the performance characteristics or briquette quality. Therefore, the multiple objective optimizations for the targets have been transformed into a single objective optimization problem using the grey relational analysis applying a higher the better loss function approach. The mean values were normalized and converted into Grey relational coefficients per the stages involved in grey relational research and tabulated in **Table 5.7**.

Table 5.7: Grey relational generation and grey relation co-efficient

Exp No.	Normalized data					Grey relation co eff					GRG	S/N for GRG	Rank
	BD	SR	CS	WR	CV	BD	SR	CS	WR	CV			
1	0.850	0.238	0.944	0.509	0.817	0.370	0.678	0.346	0.495	0.380	0.567	4.924	6

2	0.580	1.000	0.299	0.362	0.325	0.463	0.333	0.625	0.580	0.606	0.652	3.717	5
3	0.143	0.903	0.000	0.612	0.676	0.778	0.356	1.000	0.450	0.425	0.752	2.474	3
4	0.616	0.114	0.967	0.107	0.169	0.448	0.814	0.341	0.824	0.748	0.794	2.007	2
5	0.000	0.932	0.370	0.000	0.000	1.000	0.349	0.575	1.000	1.000	0.981	0.167	1
6	0.797	0.887	0.811	0.775	0.963	0.386	0.361	0.381	0.392	0.342	0.465	6.645	9
7	0.471	0.000	1.000	0.445	0.485	0.515	1.000	0.333	0.529	0.508	0.721	2.839	4
8	0.775	0.490	0.930	1.000	0.898	0.392	0.505	0.350	0.333	0.358	0.484	6.295	8
9	1.000	0.328	0.830	0.714	1.000	0.333	0.604	0.376	0.412	0.333	0.515	5.769	7

Table 5.7 shows the experimental run 5, with the highest Grey relational grade value and corresponding highest S/N ratio. A higher GRG implies being closer to the ideal value. Thus, Experiment number 5 has the optimal parameter setting for better multi-response characteristics. In other words, experimental run 5 depicts the optimal experimental settings of input control factors that produce the best output responses in this case.

Table 5.8: Response Table for Means for Grey relational grade

Parameter	Grey relational grade			Max-Min (Rank)
	Level1	Level 2	Level 3	
Binder %	0.6571	0.7467	0.5734	(2) 0.1733
Charcoal %	0.6941	0.7058	0.5774	(3) 0.1284
Feedstock	0.5057	0.6534	0.8181	(1) 0.3124
Binder prep	0.6877	0.6128	0.6768	(4) 0.0109

Table 5.8 shows the average of each response characteristic for each level of each parameter. The highest averages of each parameter level in **Table 5.8** determine the best possible result. The delta values or ranks evinced that the feedstock and binder ratio has the most significant impact among the parameters considered. The next most significant one is the charcoal addition. The binder preparation method has the least

effect of all. Therefore, based on our analysis, the type of feedstock and binder ratio was very significant in affecting briquette quality. The main effects plots (**Figure 5.6**) confirm the above result, as feedstock has a larger value of S/N than the binder ratio, followed by charcoal addition and binder preparation method.

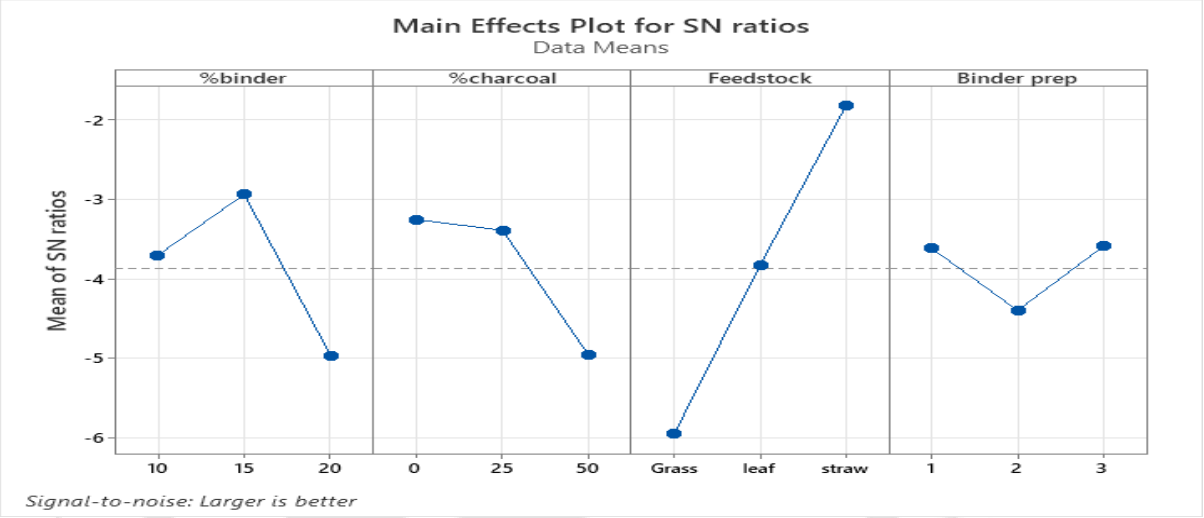


Figure 5.6: Main effect plot for means of Grey Relational Grade.

The magnitude of the effect of factors was determined by evaluating total variability in overall performance or GRG and calculating contributions by each of the parameters considered in the study.

Table 5.9 shows that the result from ANOVA is in concordance with the response table for means of Grey relational grade. The feedstock materials showed the highest significant factor. Secondly, the binder ratio greatly affects the quality of briquettes, with a contribution of 19.43 %. Charcoal addition and binder preparation contribute less, with 13.04 % and 4.23 % in the overall quality characteristics of briquettes.

Table 5.9: Analysis of variance of GRG

Process Parameter	MS	DOF	SS	% contribution
Binder %	0.0225	2	0.0450	19.43
Charcoal %	0.0151	2	0.0302	13.04

Feedstock %	0.0733	2	0.1465	63.25
Binder prep %	0.0049	2	0.0098	4.23
	Total	8	0.2316	

Table 5.10: Confirmatory tests under optimal conditions

Setting level	Initial condition (hypothesized)	Optimal parameter	
		Prediction	Experimental
		A2B2C1D3	A2B2C1D3
BD	0.466		
SR	87.44		
CS	0.743		
WR	53.77		
CV	4436.55		
Mean GRG	0.721	0.981	0.996

5.B.7 Confirmation test

The final step in Taguchi-Grey relational analysis is to run confirmation tests using optimal levels for the control parameters. The predicted GRG with the optimal level of parameters applying Eq. was found to be 0.981. Since the value was so close to 1, it is expected this combination of optimal parameters would give the best quality briquettes. Thus the combination of optimal levels of parameters that were estimated to provide the highest quality briquettes was tested. And so produced briquettes were analyzed for their performance characteristics.

Table 5.10 shows the comparison of briquettes produced under hypothesized conditions and optimal conditions. The signal-to-noise ratio of optimized briquettes for each performance characteristic was higher than the hypothesized condition, as well as those produced in each experimental run. The mean GRG showed that the experimental condition A2B1C3D3 has a higher GRG and is close to the predicted value. Therefore, briquettes produced under optimal conditions were of better quality as determined by multi-response criteria.

5.B.8 Emission characteristics of the best combination

Straw mixed with 25 % charcoal, 15 % binder, and the number 1 method of binder preparation showed the better characteristics than other briquettes prepared under this study; therefore, this combination was tested for emission, water boiling test, TGA, Specific energy consumption, and cost analysis. As seen in **Figure 5.7**, the CO emission is around 3.253 g/m^3 , NO_x 0.074 g/m^3 , and SO_2 is 0.0178 g/m^3. The value of CO emission is almost twice the value obtained by Wang et al. [179], who tested the emission of corn straw briquettes, whereas the NO_x value is almost in the range. CO emissions result from low combustion temperature, insufficient Oxygen, poor air mixing, etc. [180]. The emission value of the three gases was lower than that of the briquettes studied by Malatak et al. [181] using four different types of grass. The emission values are also in the range of matter obtained by Narzary and Das [167] , who studied the emission of leaves briquettes.

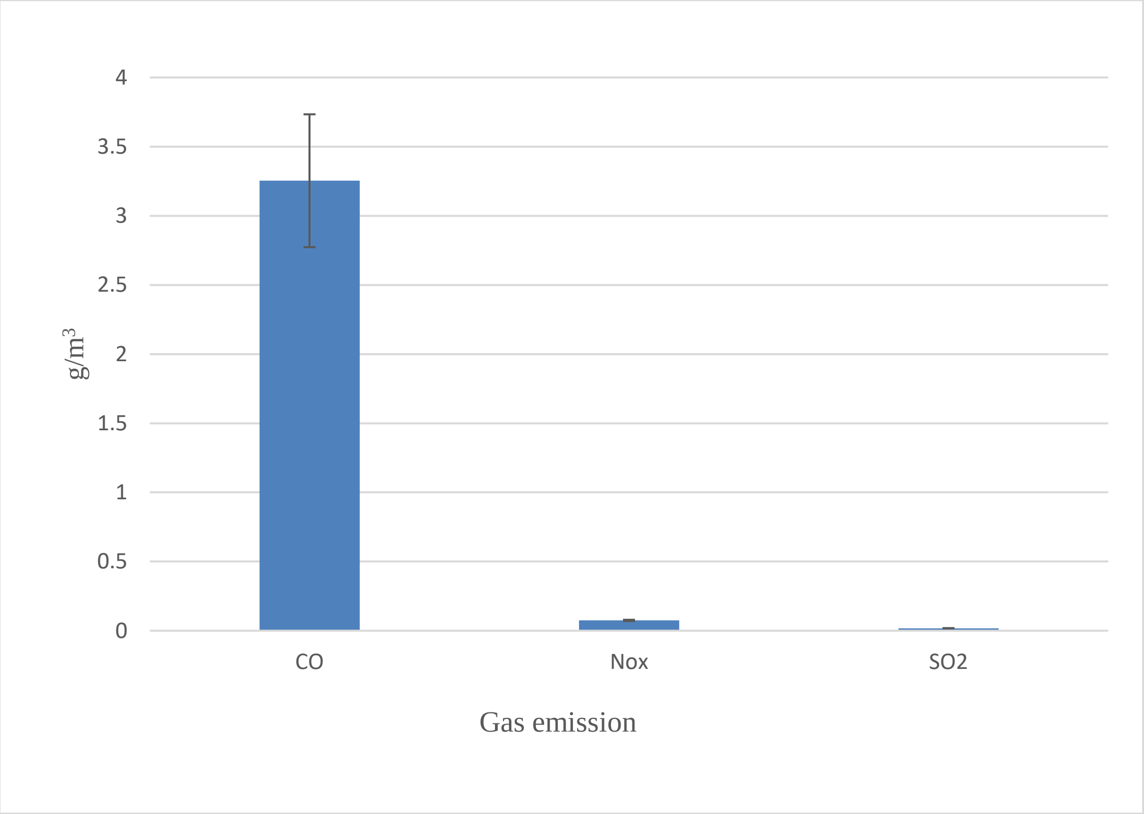


Figure 5.7: Gas emission test result

5.B.9 Water boiling test

The result of the water boiling test is given below:

Time is taken to boil 1000ml of water with 250 g of briquette = 9.5min
Burning rate = 0.013 kg/min
Specific fuel consumption = 0.124 kg/L

The burning rate was found to be higher than Kizito et al. [182] who studied food market waste briquette and found the burning rate as 0.008 kg/min, 0.007 kg/min water hyacinth briquette [183], 0.001-0.0082 kg/L charcoal fines [91]. This could be explained due to the lower density of the briquettes under study.

5.B.10 Thermo-gravimetry Analysis (TGA)

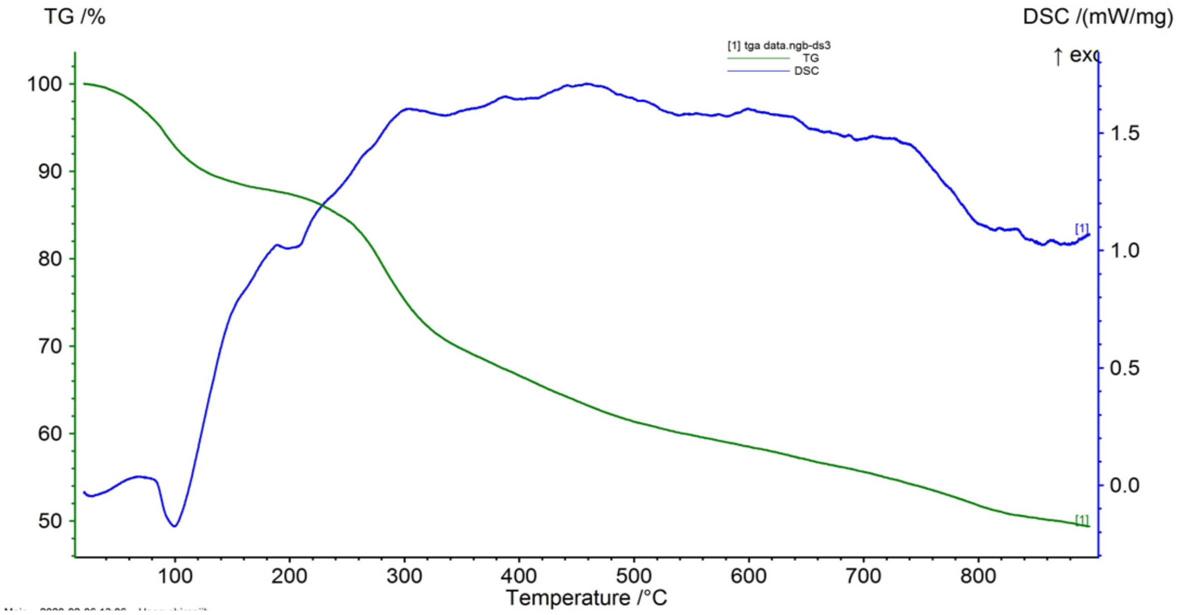


Figure 5.8: TGA and DSC analysis plot

Figure 5.8 show the thermogravimetric curve for the 25 % charcoal and straw sample. The thermal degradation process was conducted in three stages. Stage one is the dehydration stage, in which weakly bonded water molecules are released. The second stage, the decomposition stage, is where hemicellulose, cellulose, and lignin decomposed at a temperature range of 200 °C – 450 °C. In the third stage, lignin degradation and heavier VM were observed.

From 100 to 200 °C, the mass reduction is nearly linear, and there is no sample decomposition in the temperature range. After 200 °C, the sample indicates the single stage decomposition, where the sample mass is gradually reduced to 350 °C. In this region, decomposing is possible because the presence of carbon in the sample goes off to carbon monoxide and carbon dioxide. After 350 °C, sample mass loss reduces gradually; this is caused by the total decomposition of hemicellulose, cellulose, and partial decomposition of lignin by pyrolysis at lower temperatures. The weight loss at around 800 °C is found to be 49.40 % due to less reactivity, high ash content, low volatile matters, or the presence of non-combustible substances. A similar trend was seen by Panwar et al. [184], Correa et al. [185], and Massaro et al. [186]. The major inorganic component in the ash is SiO_2 (generally higher than 70 %-weight), and among the minor elements, Al_2O_3, Fe_2O_3, K_2O, CaO, and TiO_2 have the highest concentrations. The higher non-combustible matter is a function of the soil composition where the biomass was grown. Teixeira et al. [187] suggest a cyclone separator to reduce the ash content from charcoal.

It is noticed that an endothermic phase of the DSC curve attained the peaks at 100 °C, which is pertinent to the energy prerequisite for the evaporation of moisture content in the sample. The reaction becomes exothermic at 200 °C due to the outlet of energy by the combustion of organic matter. The distinct peak is attained at 459.602 °C in the DSC curve, which is associated with the combustion of the briquettes. The exothermic peaks were achieved as a result of releasing energy by decomposing fixed carbon and residual lignin.

5.B.11 Specific Energy consumption

Table 5.11: Specific energy consumption

Raw materials	Straw + 25 % Charcoal (15 % binder)
Energy consumption for size reduction (MJ/kg)	4.06
Energy consumption for densification(MJ/kg)	0.0671

Labour energy consumption(MJ/kg)	0.548
Total energy consumption (MJ/kg)	4.6751

The specific energy requirements for the densification of biomass rely on certain factors like the briquetting system, process variables such as temperature and pressure, feedstock variables like moisture content, particle size, and distribution, and biochemical composition like starch, protein, fat, and other lignocellulosic components. In screw press densification processes, extrusion requires more energy than compression because the material has to overcome friction during compression and pushing. Miles and Miles [188] used straw and binders in a pallet mill and cubing machine and found the specific energy consumption of the pellet mill in the range (0.133-0.23) MJ/kg and 0.270 MJ/kg of cubing machine. Carre et al. [189] used a screw press machine to make straw briquettes and found Specific energy consumption in the range of (0.540-0.792) MJ/kg.

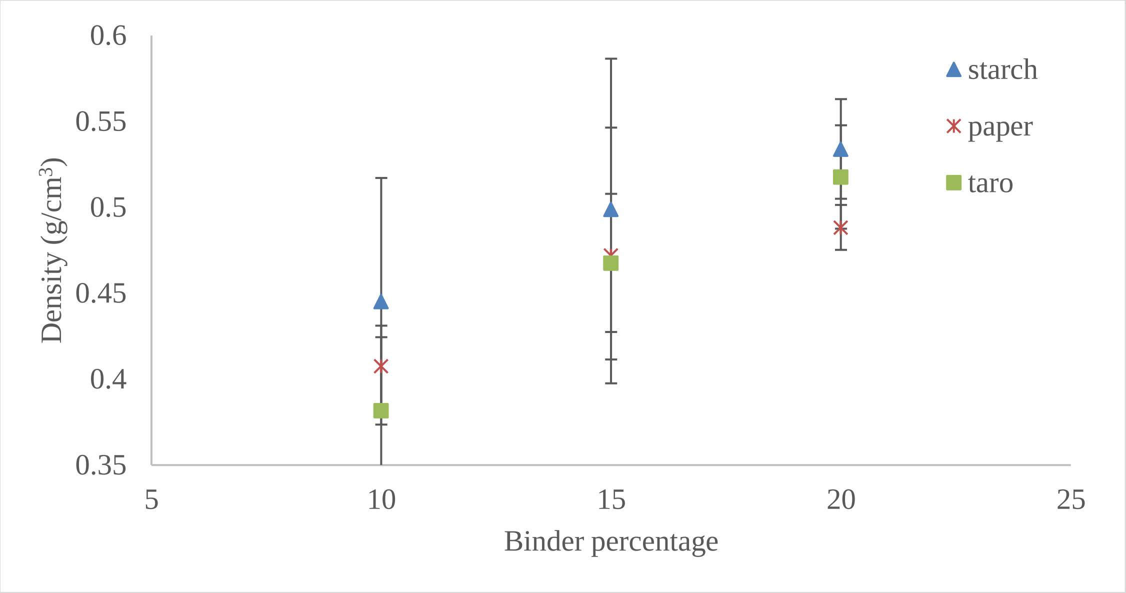
Laloon et al. [190] made charcoal briquettes using a screw press machine with a bulk density of 676.0 kg/m^3 and compressive strength of 0.235 MPa. The working capacity of the machine was 131.5 kg/h, and specific energy consumption was 0.058 MJ/kg. Tumuluru et al. [28] stated that the chemical composition of biomass and methods of pre-treatment before densification significantly influence the specific energy consumption.

5.C Briquettes made from carbonized rice straw

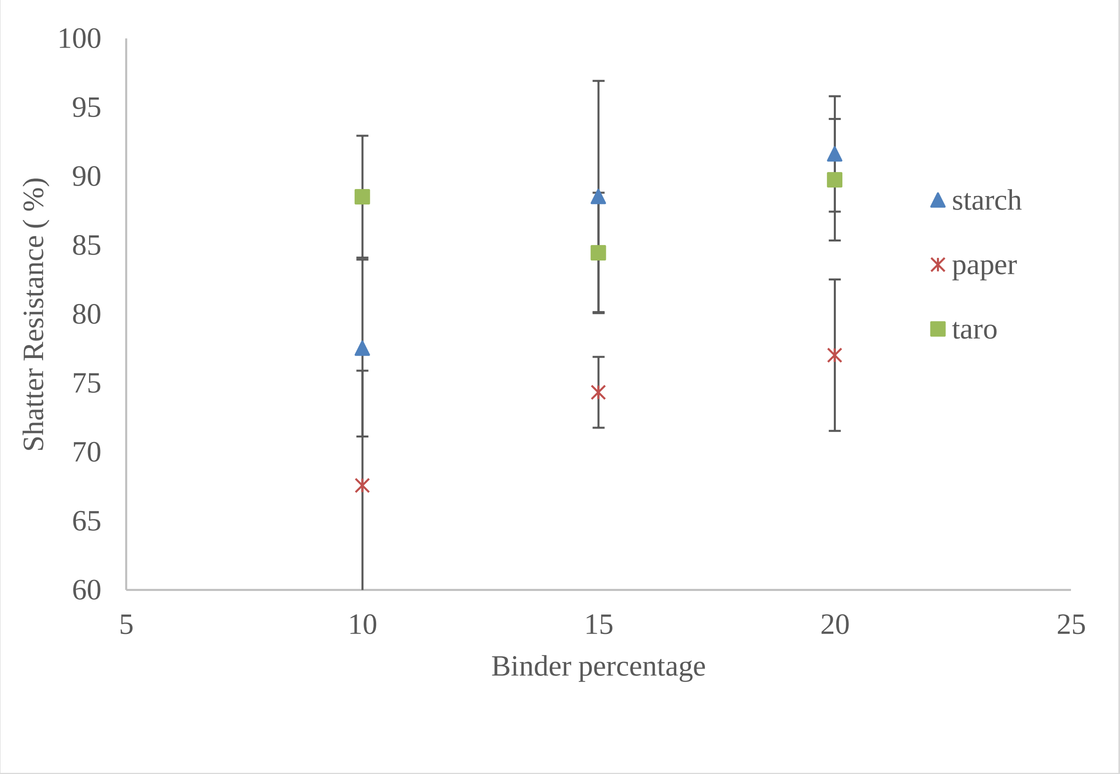
5.C.1 Briquette properties

Briquettes made using 20 % starch showed the highest density of 0.534 g/cm^3 shown in (**Figure 5.9 A**), which is similar to the finding of Sotannde et al. [191], who studied briquettes properties from neem wood charcoal. The lowest density was seen at a 10 % binder level for all the binders used for briquette making. However, for all three types of binder, an increase in binder ratio increased the density of the briquettes, as found in studies done by Aransiola et al. [90], who studied briquettes that used cassava starch, corn starch, and gelatin as binders at 10, 20 and 30 %.

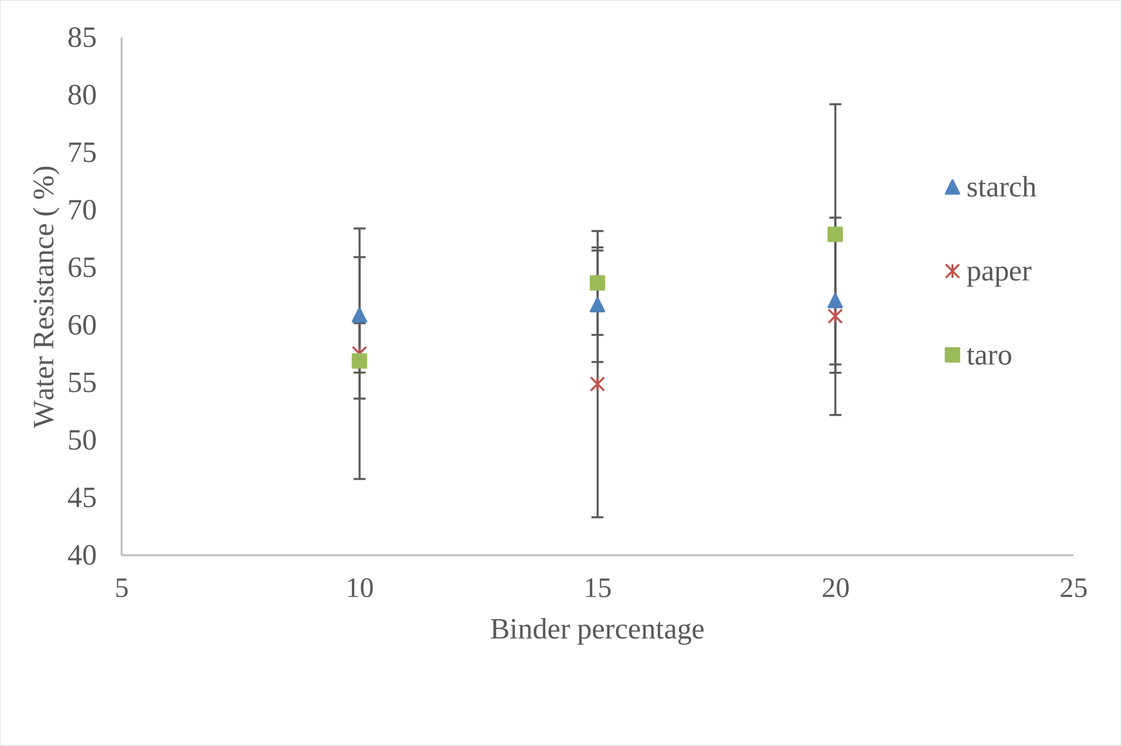
Briquette containing 20 % taro starch showed the highest water-resistance property (**Figure 5.9 C**). The water resistance property is essential for biomass briquettes that must be transported and stored in high humidity. Therefore, an increase in the binder was seen to be proportional to the water resistance property of the briquettes.



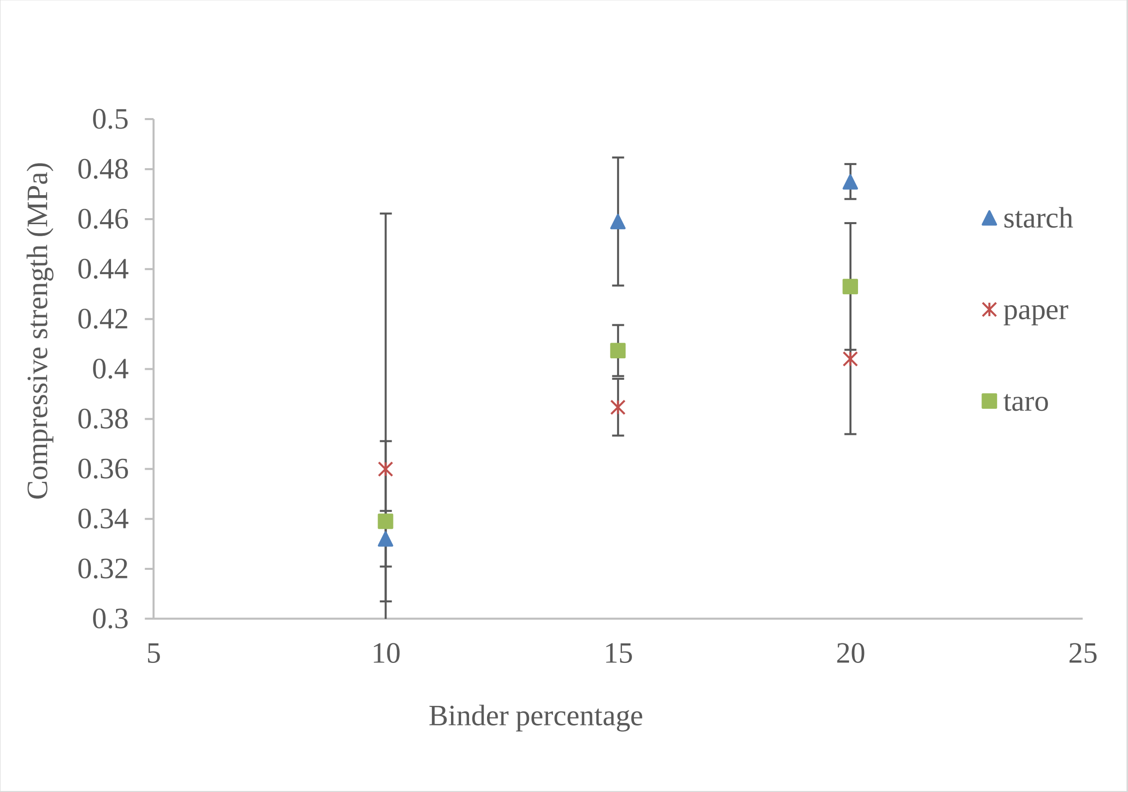
(A)



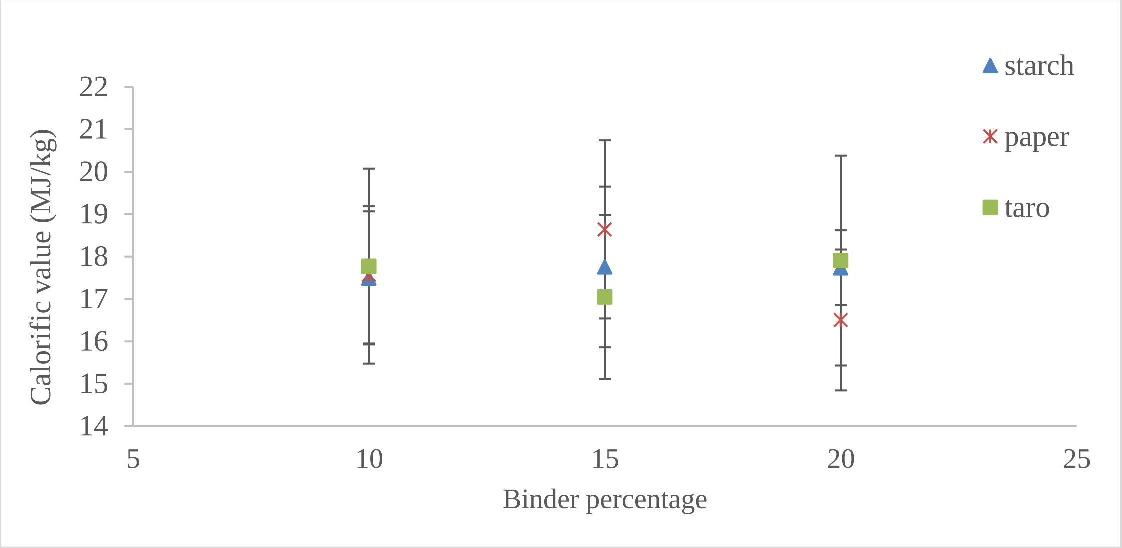
(B)


Water Resistance (%)
85
80
75
70
65
60
55
50
45
40
5
10
15
20
25
Binder percentage
starch
paper
taro

(C)


Compressive strength (MPa)
0.5
0.48
0.46
0.44
0.42
0.4
0.38
0.36
0.34
0.32
0.3
5
10
15
20
25
Binder percentage
starch
paper
taro

(D)



(E)

Figure 5.9: A) Density B) Shatter resistance C) Water resistance D) Compressive strength E) Calorific value of briquettes made from starch, paper and taro binder at 10, 15 and 20% binder levelfrom carbonised rice straw.

The shatter resistance of the briquette using a 10 % paper binder was the lowest (**Figure 5.9 B**). The highest shatter resistance of 91.621 % was seen for briquettes with 20 % starch. A higher binder ratio displayed higher bulk density and shatter resistance, as reported by Adam et al. [192], who also prepared charcoal briquettes from rice straw. Samples made using paper binders displayed the lowest shatter resistance. Samples with starch binder had the highest shatter resistances; this result can be validated by a study by Wasfy and Awny [193], on rice straw, cotton stem, corn stalk charcoal briquette using starch and paper binder. **Figure 5.9 D** shows the compressive strength of the samples and it can be seen that it is high for higher density briquette. **Figure 5.9 E** shows the calorific value of the samples, it is seen that the calorific value increased with binder percentage in case of starch binder, taro binder showed highest calorific value at 20% level and paper binder at 15% binder level.

5.C.2 Physiochemical properties

15 % starch showed the highest volatile matter content (**Table 5.12**), the value of which can be validated from the value for volatile matter content in the work of Akowuah et al. [194]. Therefore, it has better value than charcoal briquettes made from sawdust. Furthermore, carbonization decreases the volatile matter content and increases the fixed carbon content,

enhancing the briquettes' combustion properties [195].

15 % Taro starch briquettes showed the highest fixed carbon content of 32.07 % (**Table 5.12**). The value falls above the fixed carbon content value range obtained by other researchers [195] [196]for charcoal briquettes.

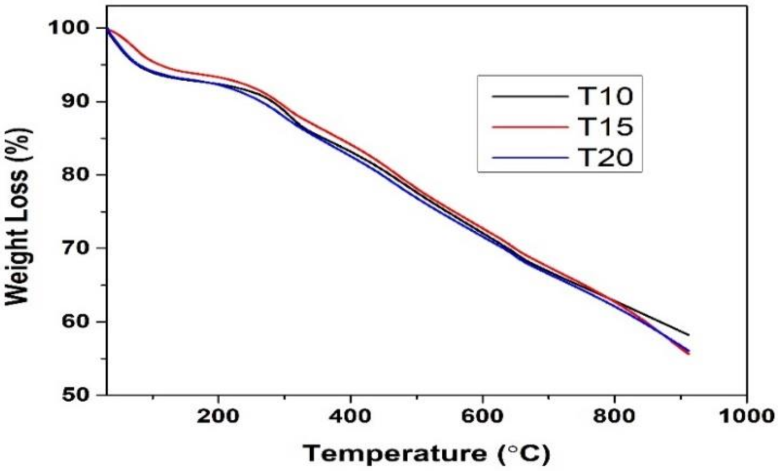
Table 5.12: Mean value of Physiochemical Characteristics

Characteristics	Binder Concentration	Starch	Paper	Taro starch
moisture content(%)	10	7.52	9.18	8.11
	15	4.81	8.75	4.79
	20	4.63	7.76	4.71
volatile matter content (%)	10	49.48	46.55	38.14
	15	57.98	49.61	39.22
	20	56.66	46.9	41.77
Ash content(%)	10	18.466	16.78	24.34
	15	16.85	15.07	23.97
	20	17.04	17.9	22.56
fixed carbon content (%)	10	24.534	27.49	29.41
	15	20.36	26.57	32.07
	20	21.67	27.44	30.96

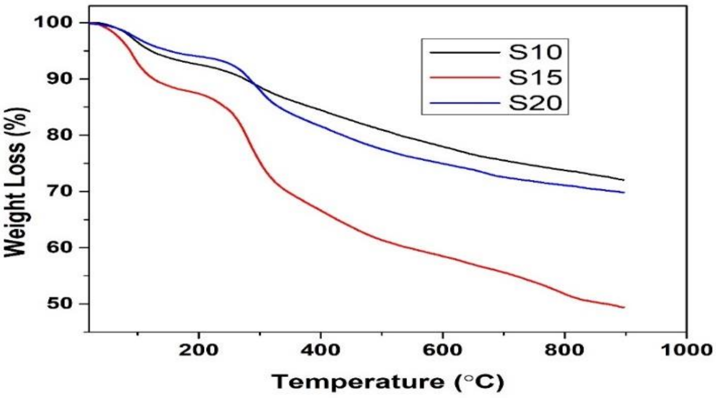
15 % paper binder briquettes had the lowest ash content of 15.07 % (**Table 5.12)**, which fits the range found in Lubwama et al.'s [195] study. Ash content recorded a higher value than raw straw as the carbonization process increased the ash content. The moisture content was higher for paper binders as paper tends to absorb and hold the moisture, unlike starch [193],

given in **Table 5.12**.

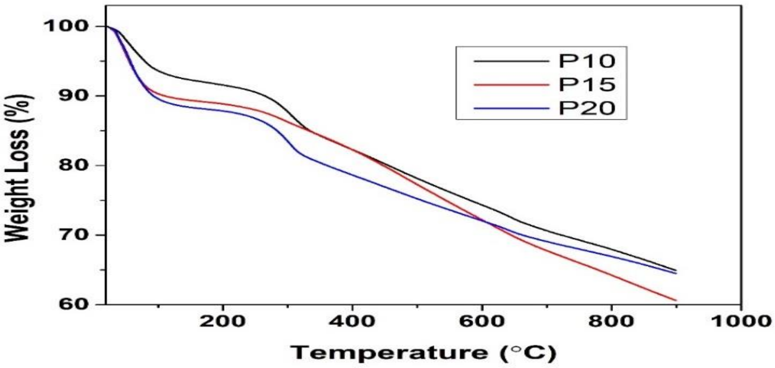
5.C.3 Thermo-gravimetry Analysis (TGA)



(a)



(b)



(c)

Figure 5.10. TGA graph for (a) Taro starch (b) Starch (c) Paper as a binder at 3 ratios

T_5 % (°c) indicates Degradation Temperature for 5 % weight loss

T indicates Taro starch binder

S indicates starch binder

P indicates paper binder

Table 5.13: Degradation temperature for 5 % weight loss [197]

Specimen	P10	P15	P20	T10	T15	T20	S10	S15	S20
T_5 % (°c)	78	54	56	76	111	80	121	86	147

In **Table 5.13**, T_5 % (°c) indicates the Degradation Temperature for 5 % weight loss

T indicates taro starch binder

S indicates starch binder

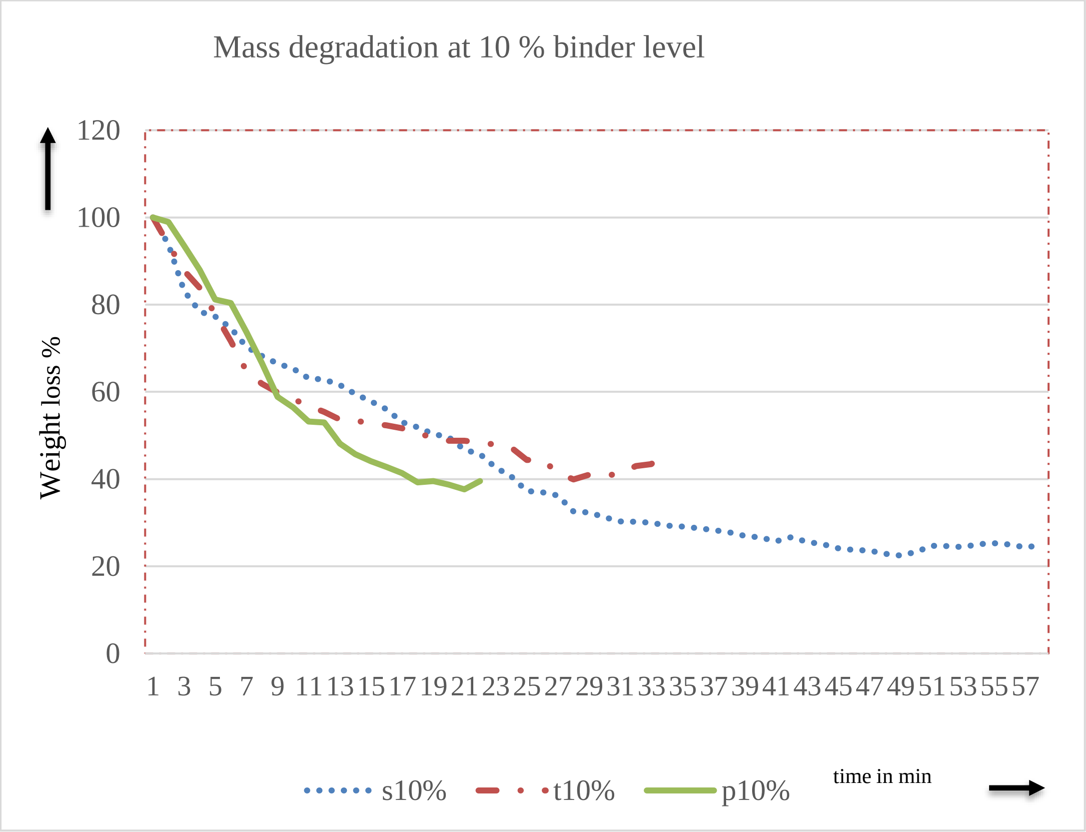
P indicates paper binder

The curve remains stable from the TGA graphs until around 100 °C, where the first significant weight loss is seen. This is due to the loss of moisture from the briquettes. The low rise in the curve is due to the carbonization of the raw materials because carbonized briquettes contain less water due to the destruction of hydrophilic hydroxyl groups. Volatile matter also decreases to a considerable extent after carbonization. Devolatization occurs between 230 °C to 330 °C up to about 600 °C. Between 600 °C and 900 °C, degradation of lignin occurs. The remaining weight in the curve is due to residues, including ash, tars, and fixed carbon.

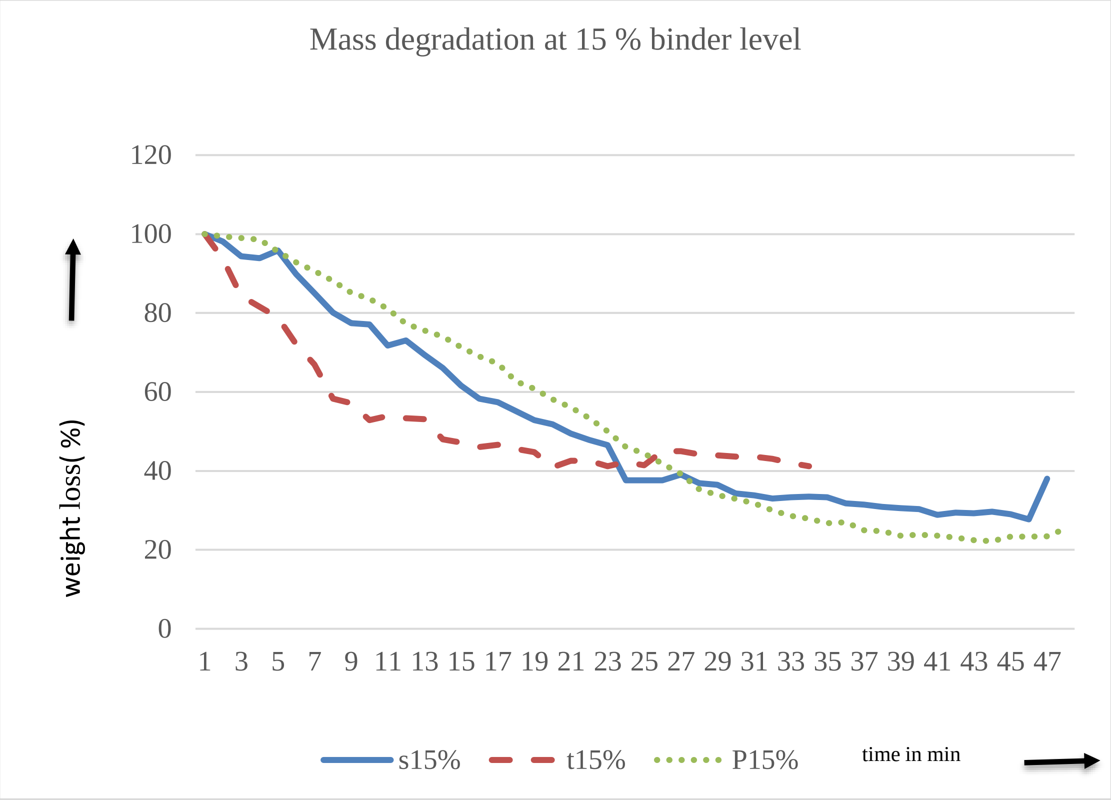
From the 5 % weight loss value (**Table 5.13**), Taro starch at a 15 % binder level showed high thermal stability (**Figure 5.10a**). Starch binder (**Figure 5.10b**) at 20 % level showed the most increased thermal stability, followed by starch at 10 % binder level. Paper binders had the lowest thermal stability among the three binders used (**Figure 5.10c**). Wang et al. [198] used maize straw charcoal and found that devolatilization temperature ranged from (250 to 450) °C. TGA was seen till 1000°C. Lubwama and Yiga [92] found devolatilization temperatures around (330 - 600) °C. The highest weight loss was 53.69 %, and the lowest was 36.0 %, using biochar obtained from coffee, rice, and ground nutshell. The TGA temperature was done till 900 °C. Hu et al. [35] found that the maximum residue with biochar and starch binder was 33.98 when TGA was done till 800 °C.

5.C.4 Burning Characteristics [197]

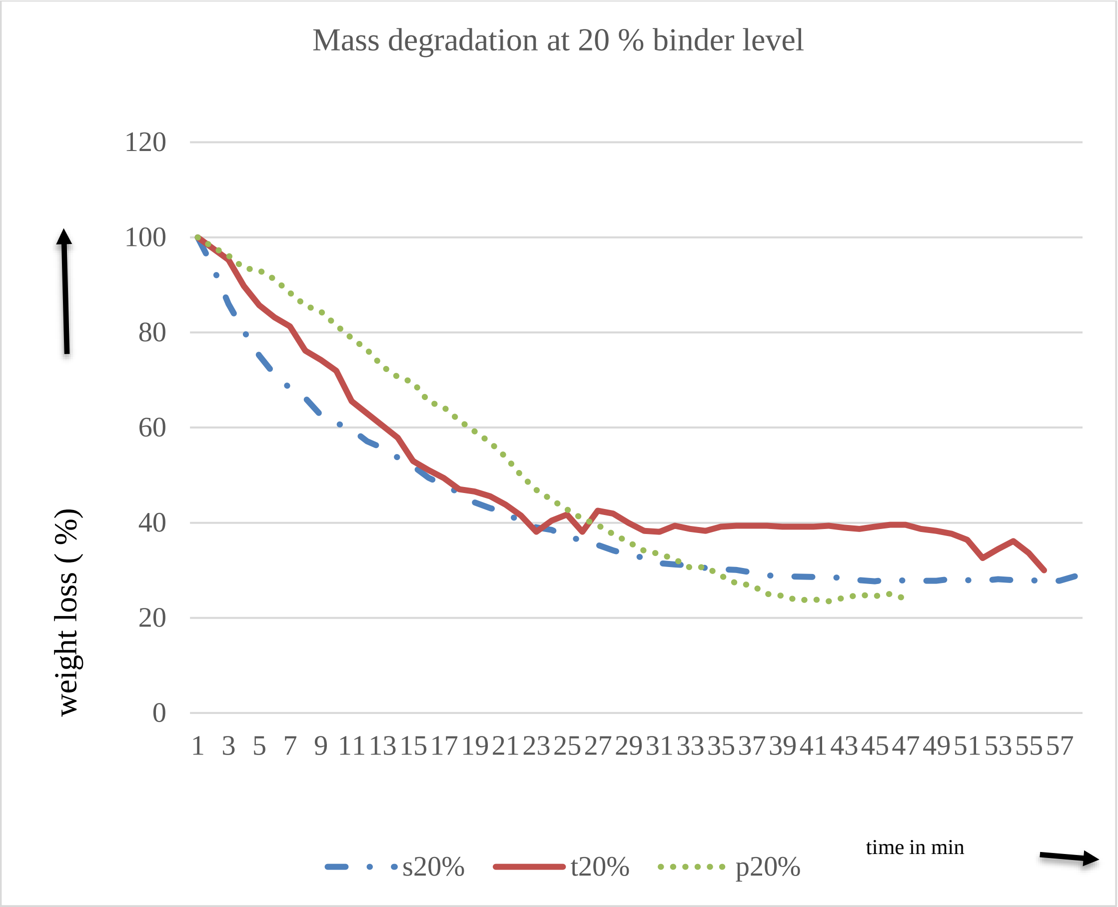
The combustion profiles of briquettes produced containing the biomass blends with starch, taro starch, and paper, i.e., percentage mass loss over time, in an uncontrolled environment, can be viewed in **Figure 5.11a**, **Figure 5.11b**, and **Figure 5.11c**.



(a)


Mass degradation at 15 % binder level
weight loss(%)
120
100
80
60
40
20
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47
s15%
t15%
P15%
time in min

(b)



(c)

Figure 5.11: Change in mass with time during atmospheric combustion of briquettes made from carbonized rice straw with different binders at (a) 10 % binder level (b) 15 % binder level (c) 20 % binder level.

Briquettes produced with 15 % and 10 % taro starch burnt most quickly, followed by paper at 10 %. Briquettes with paper binder at 20 % and 15 % burnt slower than briquettes produced with starch at 10, 15 and 20 % (**Figure 5.11a, Figure 5.11b, and Figure 5.11c**). Combustion rates of briquettes highly depend on their morphological aspect and the air trapped within the free spaces of the briquettes. The briquettes made with paper binder at 15 % and 20 % are superior to those made in the study regarding energy density.

5.C.5 Emission analysis

Jamradloedluk and Wiriyaumpaiwong et al. [142] reported that the CO emission from rice husk and rice straw briquette was 2,821 g/m^3 and NO_x emission of 10.2 g/m^3. Kritee et al. [199] found that burning 1 kg of dry rice straw produced nearly 700–4100 mg of methane

(CH_4) and 19–57 mg of nitrous oxide (N_2O). CO emission results from low combustion temperature, insufficient oxygen, poor fuel mixing with the combustion air, etc. The T20 sample containing 20 % taro binder displayed the highest CO emission of (3.4067±0.1014) g/m^3, and the model containing 10 % paper binder emitted the lowest CO of (2.37±0.274) g/m^3. The bar graph **Figure 5.12a** shows that the samples containing paper binder radiated the lowest CO as paper binder briquettes had lower density than starch and taro binder, and starch and taro produced similar emissions. Wang et al. [200] reported lower values of CO emission of 0.138 g/m^3 from burning briquettes made of corn straw. The value tally with the result of Ravichandran and Corscadden [201], whose value for CO emission was 2.32 g/m^3 .

NO_x formation during biomass combustions results from:

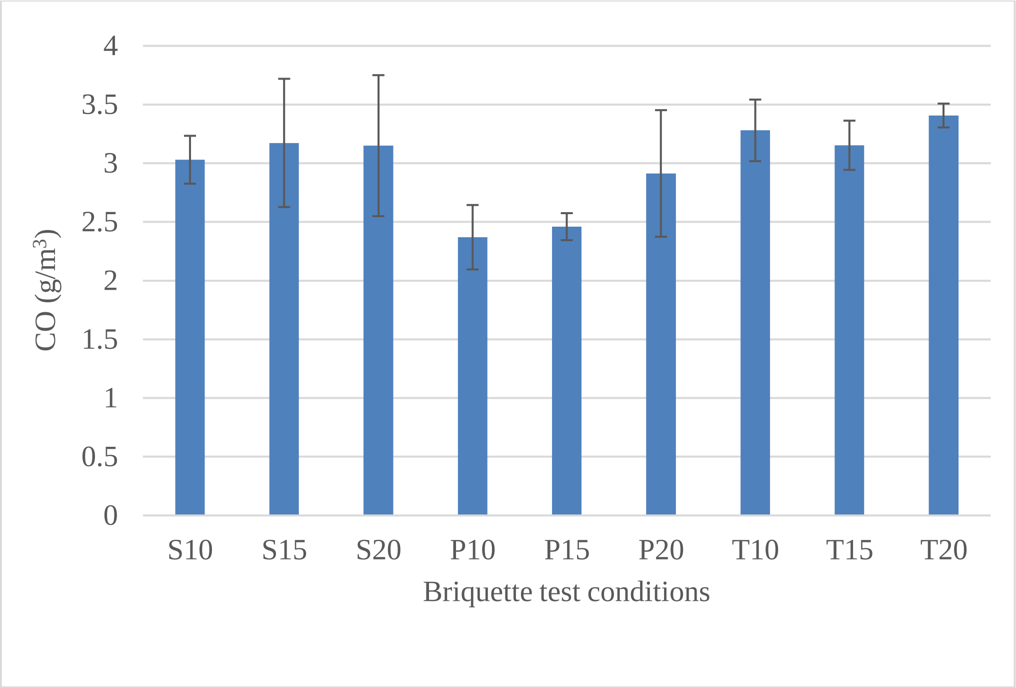
1. Thermal NO_x formed from atmospheric nitrogen at a temperature above 1300 °C.
2. The prompt NO_x formed at the flame front.
3. The fuel-NO_x is created from the elemental nitrogen contents of the fuel.

However, in the case of the domestic cookstove, only fuel NO_x is formed as the temperatures are below 1300 °C [202]. Therefore, a higher value of NO_x emission in starch and taro starch binder briquette (seen in **Figure 5.12b**) can probably be explained by the presence of nitrogen in the binder.

SO_2 emissions vary as a function of fuel-bound sulfur [203]. (**Figure 5.12c**) shows that SO_2 content was higher for a sample containing starch and taro binder. (0.013±0.0049) g/m3 was the lowest average value of SO_2 emission displayed by sample S20, and the highest value of (0.01967+0.003) g/m3 was displayed by sample T20.

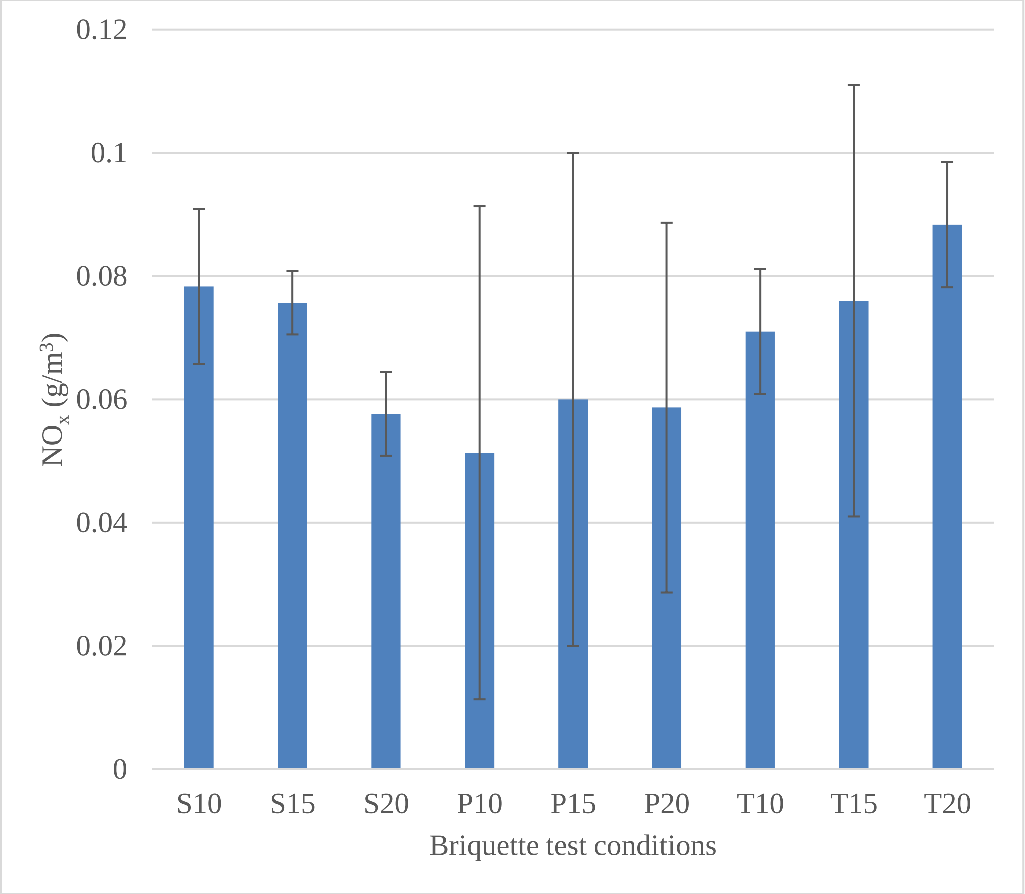
The result for CO, NO_x, and SO_2 for the sample with carbonized rice straw was comparatively lower than the result found in the study, which reported chopped rice straw with 1.3 g/Nm^3 CO, and 0.06 g/Nm^3 NO_x [142].

Sun et al. [150] stated that carbonization of raw biomass before briquetting is one of the best ways to reduce emission pollution. However, all the emission tests did not show a significant difference in the value range for the three different binders used in this study.



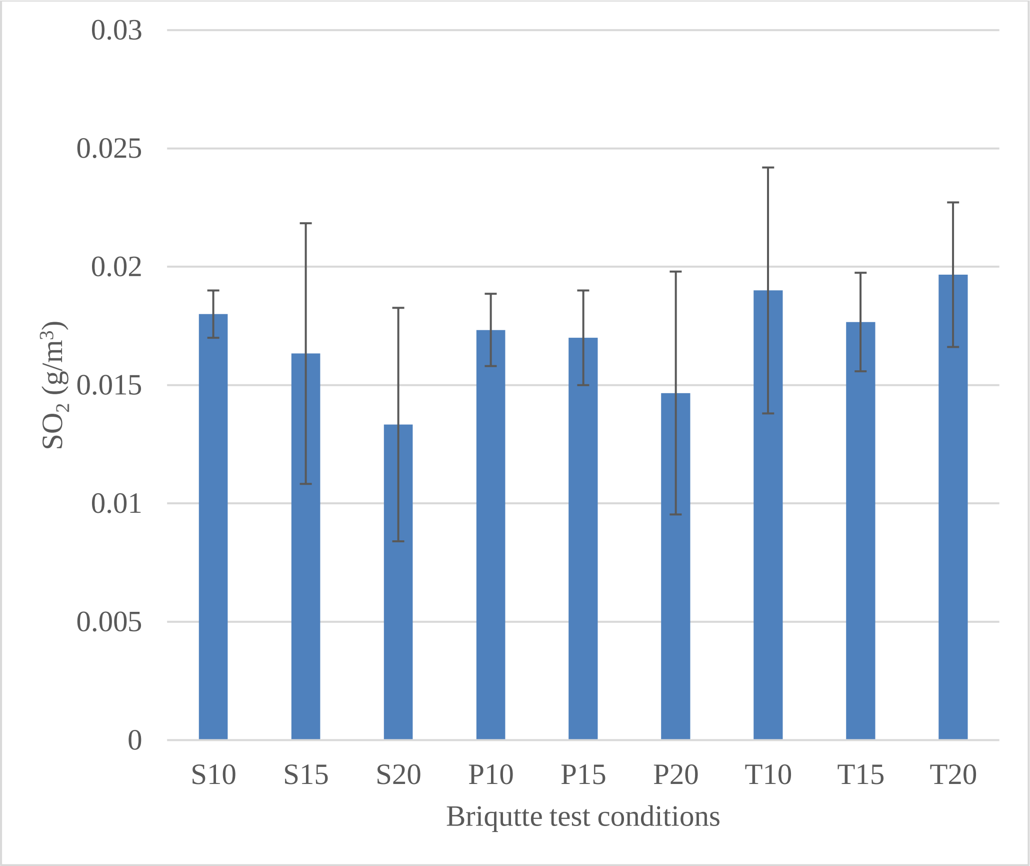
4
3.5
3
2.5
2
1.5
1
0.5
0
CO (g/m³)
S10
S15
S20
P10
P15
P20
T10
T15
T20
Briquette test conditions

(a)



0.12
0.1
0.08
0.06
0.04
0.02
0
NOx (g/m³)
S10
S15
S20
P10
P15
P20
T10
T15
T20
Briquette test conditions

(b)



(c)

Figure 5.12: a) CO emissions b) NO_x emissions c) SO_2 emissions from different samples

5.C.6 Specific Energy consumption

The specific energy requirements for biomass densification depend on

1) Briquetting system

2) Process variables such as temperature and pressure

3) Feedstock variables like moisture content, particle size, and distribution

4) Biochemical composition like starch, protein, fat, and other lignocellulosic components.

In screw press densification processes, extrusion requires more energy than compression because the material has to overcome friction during contraction and pushing. Miles and Miles [188] used straw and binders in a pallet mill and cubing machine and found the specific energy consumption of the pellet mill in the range (0.133 - 0.23) MJ/kg and 0.270 MJ/kg of cubing machine. Carre et al. [189] used a screw press machine to make straw briquettes and found Specific energy consumption in the range of (0.540 - 0.792) MJ/kg.

Laloon et al. [190]made charcoal briquettes using a screw press machine with a bulk density of 676.0 kg/m^3 and a compressive strength of 0.235 MPa. The working capacity of the device was 131.5 kg/h, and specific energy consumption was 0.058 MJ/kg. Tumuluru et al. [106] stated that the chemical composition of biomass and pre-treatment methods before densification significantly influence the specific energy consumption. The paper binder required more power while densification; hence it showed higher specific energy consumption than the starch binder and taro binder (**Table 5.14**). This could be explained by higher friction in the case of paper binders due to their poor flow characteristics. It is also seen that the increase in binder decreases the energy consumption while briquetting.

Table 5.14: Specific energy consumption of briquettes

Binder	Starch			Paper			Taro starch		
Binder percentage	10	15	20	10	15	20	10	15	20
Energy consumption densification (MJ/kg)	0.0771	0.0666	0.0658	0.0833	0.0866	0.095	0.0733	0.0679	0.0642
Labour energy consumption (MJ/kg)	1.096	1.096	1.096	1.096	1.096	1.096	1.096	1.096	1.096
Total energy consumption (MJ/kg)	1.1731	1.1626	1.1618	1.1793	1.1826	1.191	1.1693	1.1639	1.1602

5.C.7 Water boiling test

Table 5.15: Burning rate and Specific fuel consumption

Binder	Starch			Paper			Taro starch		
Binder percentage	10	15	20	10	15	20	10	15	20
Burning rate (g/min)	0.41	0.67	0.98	0.33	0.65	0.88	0.66	0.86	0.91
Specific fuel consumption (g/L)	21.1	23.5	56.41	43.3	48.72	44.2	27.3	35.8	43.3

The result of the burning rate can be validated from the values obtained by Bonsu et al. [204] who also did a water boiling test for charcoal briquette and found the burning rate ranging from 0.42 g/min-3.48 g/ml.

Kongprasert et al. [205] found the burning rate of charcoal briquette from 0.44 - 0.53 g/min and Kivumbi et al. [91] found the burning rate of charcoal briquette ranging from 1.1-8.2 g/min, and Specific fuel consumption was reported as 21.7 - 70.1 g/L. It was seen from the water boiling test results that the burning rate of briquettes increased with the binder concentration due to an increase in the volatile matter in the binder used (**Table 5.15**) [97]. Lubwama and Yiga [92] stated that higher volatile matter content gives better ignition and improves combustion due to increased chemical reactivity.

5.D Biomass briquette making using rice straw charcoal with taro tuber as a natural binder in a low-power manual hand press machine

5.D.1 Proximate, physical, thermal, and mechanical properties of briquettes

Table 5.16: Mean value of proximate, physical, thermal, and mechanical properties

Analysis	**Results**
Moisture content (%)	11.2±5.67
Volatile matter content (%)	41.23±7.22

Ash content (%)	10.5±2.5
Fixed carbon content (%)	37.07±3.9
Density (g/m^3)	0.426±0.08
Shatter Resistance (%)	64.4±12.18
Water Resistance (%)	63.84±9.34
Compressive strength (MPa)	0.327±0.11
Calorific value (MJ/kg)	15.35±5.67

Table 5.16 shows the values obtained for the briquettes' physical, mechanical, and thermal properties using a locally fabricated simple hand press machine. The briquettes obtained have a higher density and compressive strength than the sample prepared by Yank et al. [123] using a low-power screw press machine to make rice husk briquette. The fixed carbon content was higher than Ngusale et al. [206] who briquettes vegetable market waste using a low-power manual hand press. The briquettes had lower ash content and bulk density than Adam et al. [192] who also prepared carbonized rice straw briquettes using a hand press machine.

5.D.2 Comparision of briquettes from two processes

Since taro starch binder at 15% binder level showed optimum result for objective number 2 from this study, therefore, carbonised rice straw briquettes were made using screw press and self-fabricated manual hand press machine. The two types of briquette obtained were then compared for physical, thermal, and mechanical properties, to see how the machine used for densification affects the briquette properties and to justify the acceptability of the manual handpress (**Table 5.17**).

Table 5.17: Comparison of physical, thermal, and mechanical properties of briquettes made using screw press and manual hand press

Properties	**Screw press briquette**	**Handpress briquette**
Moisture content	4.79±7.21	11.2±5.67
Volatile matter content	39.22±11.5	41.23±7.22
Ash content	23.97±5.33	10.5±2.5
Fixed carbon content	37.07±4.44	37.07±3.9
Density	0.4676±0.04	0.426±0.08
Shatter Resistance	84.442±23.64	64.4±12.18
Water Resistance	63.667±14.53	63.84±9.34
Compressive strength	0.4073±0.08	0.327±0.11
Calorific value	17.049±3.67	15.35±5.67
Burning rate	0.86±0.16g/min	0.93±0.07g/min

5.D.3 Comparison of Specific energy consumption of briquettes

Table 5.18: Comparison of Specific energy consumption of briquettes made using screw press and manual hand press

Machine used	Screw press	Screw press (25 % straw+ Charcoal)	Hand press
Energy consumption densification (MJ/kg)	0.0679	0.0679+1.124(for size reduction)	-------
Labour energy consumption (MJ/kg)	1.096	1.096	1.644 (one extra labor)

Total energy consumption (MJ/kg)	1.1639	2.2879	1.644

The manual handpress requires one extra labour to produce the same quantity of briquette at the given amount of time. The specific energy consumption of a hand press machine is higher as it is labour intensive then the SEC using a machine. The specific energy consumption of raw material briquetting is higher as the grinding process consumes the highest energy in the whole process. The cost analysis of the three types of briquetting process is given in **Table 5.19**.

5.D.4 Comparision of cost of briquette production processes

Table 5.19 shows the comparision of cost of production for briquette produced from carbonised rice straw in a screw press machine and a manual hand press machine fabricated for this study, in order to justify the use of manual handpress machine for production of carbonised rice straw briquettes.

The cost of 80Kg rice straw= Rs. 278

The cost of preparation of 12Kg (15% binder level) taro tuber = Rs.52.50

The cost of 20Kg (25 % of the raw material) charcoal procured from the market = Rs 750

The production cost values are obtained by using the calculations used in section 4.B.5.

Table 5.19: Comparison of cost of briquettes made using screw press and manual hand press for 80Kg of briquettes

Stage	Category	Screw press	Manual hand press	Screw press (straw + char)
Inbound (Rs.)	Raw material + binder	330.50	330.50	1080.50
Production (Rs.)	Machine depreciation	9.25	5.005	13.75
	Repair and maintenance			

Tax, Insurance, and Shelter	1.5	0.709	2.503
Labour Cost	669.6	1004.40	669.6
Electricity Cost	26.25	NA	116.25
Total	1037	1340.614	1882.603

Okwara et al. [207] found that briquettes produced using a low-power hand press displayed higher specific fuel consumption and had a higher burning rate than the ones made using a screw press. The wear and tear of screw press machines are increased, requiring higher maintenance costs [7]. As seen in **Table 5.19**, the initial investment cost is higher for the chaff cutter and screw press machine, whereas the manual press cost is 5 % of the screw press machine. As the manual hand press is a labor-intensive process, the labor charge increases the total cost of production. This can be reduced by modifying the device to produce more briquettes. 15.17 % decrease in bulk density is seen while using a manual hand press. The screw press produces a briquette with 24.55 % and 5.34 % higher compressive strength and fixed carbon content than the manual press. Briquettes obtained using a screw press also shows 31.12 % and 8.20 % higher shatter resistance and water resistance. The briquette produced using a manual press displayed an 8.14 % higher burning rate than screw press briquettes. The specific energy consumption of the process using a chaff cutter was 32.54 % higher than the process using a manual hand press. The process using carbonized rice straw in a screw press machine consumed 41.25 % lower specific energy than a manual hand press. This was due to the low production rate and labor-intensive process of the manual hand-press, but in anyways the farmer has to employ labour to clean his field for the next cropping so considering from that point of view, the process of insitu briquetting seems to be economically feasible.

The cost of production for the three processes are INR 12.96, INR 16.75, and INR 23.53 for screw press carbonized briquettes, manual hand press briquettes and charcoal added screw press briquettes respectively.

Chapter 6: Key Contributions And Conclusions

6.0 Introduction

The previous chapter discusses the different mechanical, thermal and physiochemical properties of the briquettes obtained from waste raw materials such as grass, dry leaves and straw. The cost of production and specific energy consumption while production of the briquettes has also been discussed. This chapter describes the key contributions of the present thesis works along with few recommendations. Further, concluding remarks, limitations and future scope of the present study have also been presented in this chapter.

6.1 Background

Biomass briquetting is one of the simplest technology available to convert waste to energy. This technology helps in tackling problems related to waste management or disposal by converting it to solid fuel which in turn solves the problem of fuel wood demands [5].

The present thesis work has been carried out with the aim to address the problem related to solving waste disposal problem in this region. In achieving that, the total thesis work has been grouped into three major parts *viz*., implementation of a locally available invasive plant as binder, the fuel properties of briquettes obtained, the specific energy consumption while briquetting, and comparision in terms of quality and cost using two different process of briquetting. Further, a manual piston press was developed in a local welding shop. The machine can be easily replicated by any local welding shop workers and can also be carried to the agriculture fields where the farmer can briquette his waste in the field itself, thereby saving the transportation cost of the raw materials.The next section discusses the key contributions of the present thesis works.

6.2 Key contributions from the present thesis work

The present work provides a number of contributions towards the development of briquette using locally available waste. Few of the key contributions are discussed in subsequent sections.

6.2.1 Physiochemical Properties of Taro tubers

Before this study, wild taro (*Colocasia esculenta*) was never used as binder for briquetting even if the study reports that it contains around 80 % starch. Wild taro tubers cannot be used for human or animal consumption as it contains oxalic acid which causes itching when comes in contact with any body parts [162]. Moreover, it is an invasive plant that grows and spreads very fast in the swamps. The physiochemical analysis in chapter 4 shows that taro tuber (dry basis) contains moisture content (11.6 %), Ash (1.2 %), volatile matter (74.3 %) and fixed carbon (12.947 %). The ultimate analysis shows 45.3 % carbon, 0.8 % Hydrogen and 46.5 % oxygen.

Overall this study will help the researchers in using this novel binder for briquetting different waste raw materials for studying different briquette techniques and properties.

6.2.2 Physiochemical properties of *Polyalthia longifolia* leaves' briquettes

Prior to this study, the *Polyalthia longifolia* leaves were never briquetted, despite their wide availability and huge leaves shedding during the pre-monsoon season [159]. In this study these leaves were briquetted and studied for different fuel properties including emission analysis and water boiling test. The proximate and ultimate analysis result stated in chapter 4 shows good fuel quality.

6.2.3 Emission analysis of briquettes made using taro as binder

In this study, emission analysis of briquettes made by mixing charcoal at different ratios and taro as a binder was reported for the first time. The emission analysis graph plotted in chapter 4 shows moderate emission for CO, NO_x and SO_x for briquettes studied in this thesis. A self designed setup was prepared to analyse the emission of the different briquette developed in this study.

6.2.4 Specific energy consumption study during briquette production process

Earlier, there was an absence of literature that compared the specific energy consumption of a mini briquette machine and a manual hand press machine for making same composition of briquettes. From this study one can clearly visualize the difference in specific energy consumption at different steps of the briquette production using two different machine and process. The Specific energy consumption for size reduction and labour energy are found to be the highest as repoted in chapter 4 of this study.

This study would help the researchers in optimisation of specific energy consumption while making briquettes.

6.2.5 Comparision of briquette production using two different briquette machines and processes in terms of cost of production, specific energy consumption and quality

This thesis gives a clear comparision of specific energy consumption for briquetting process by a) carbonisation for size reduction and b) chaff cutter for size reduction. It is found that size reduction consumes significant amount of specific enrgy in the whole briquetting process and also requires huge machine in for grinding to smaller particle size. Therefore, from this study it is found that carbonisation reduces the cost of production and specific energy consumption of briquette production using rice straw. Briquettes made using 15% taro starch binder and carbonised rice straw was found better than the other combination and ratios of raw materials and binder and binder level in terms of most of the quality analysis done in this study along with cost and specific energy consumption.

6.3 Recommendations from the present thesis work

Several important output results have been found from the present study. Typical output results of the present study have been discussed in chapters 5. When numbers of conclusionsare deduced based on the results and discussions of the present study and accordingly, recommendations are made to implement briquetting in rural households. Few important recommendations are highlighted here as follows:

- 15 % taro starch binder, carbonised rice straw produced using a low cost, portable and easily replicable machine was found to produce good quality, low cost briquette.

- Charcoal addition or carbonisation plays an important role in improving the fixed carbon content and calorific value of the briquette.

- Taro can be used as a organic binder for briquetting as it is cheap, widely available, easy to harvest and outside human food chain.

- Specific energy consumed while size reduction of the raw materials for briquetting can be reduced or eliminated by adopting the process of carbonisation therby improving the fixed carbon content of the raw materials used for briquetting.

- Insitu briquetting using a portable briquette machine can cut down the cost of transportation of raw material, which is one of the significant cost in the briquetting process.

6.4 Concluding remarks

Different factors add up to the quality and cost of briquette production which are the properties such as moisture content, ash content, size, volatile matter content, calorific value, bulk density, binder, availability of the raw material, location of raw materials from the briquetting plant etc. All these factors and their influences couldnot be covered in this study and also lots of literatures are available on these factors and their influences on briquette production. Therefore, the present study covered the study on a novel binder for briquetting and also validated its use as binder by comparing it with the most commonly used binder in the literatures. This study have also successfully compared two methods of briquetting process with an aim to reduce the cost and specific energy consumption while briquetting.

6.5 Limitations of present study and scope of future works

Serious efforts have been made to generate the best results. However, few errors are beyond the controls of the experimenter, effects of those errors may present in the results. Again, due to limited period of time and repetitive lockdowns because of CoVID 19 pandemic has put further restrictions on the development and field testing of the workstation designed as part of the present study. In the future, research work for the further improvement of the briquette quality and cost of production, the following study can be undertaken:

- Study on different other factors that affect the briquette quality.
- A more developed machine that had higher production could be developed.

THESIS NOVELTY

The present thesis work represents a detailed report on various important aspects of the briquette production process in terms of waste utilisation, quality of products, cost and energy consumption reduction. In this study, a pioneer work is made to reduce the transportation cost of raw material, use of professional heavy machineries, introduction of a competent binder and a process of briquette production for farmers holding small and fragmented lands. For the first time, this study has identified the use of taro as a binder and

Polyalthia longifolia leaves were briquetted. Physiochemical properties of taro were also reported for the first time in this study.

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Appendix A

Dimensions and weight of the samples

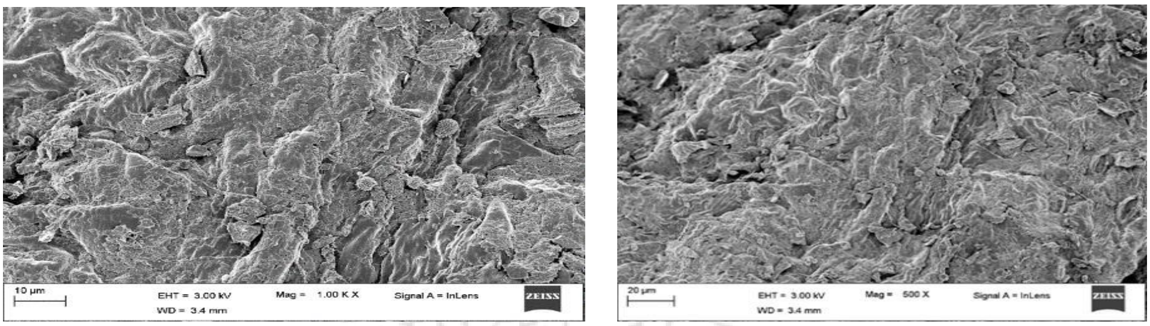
Carbonised straw sample	Height (cm)	Diameter (cm)	Weight (g)
Starch 10 % binder	7.5	3.87	25.569
Starch 15 % binder	6.2	3.81	22.216
Starch 20 % binder	5.9	3.79	18.068
Taro 10 % binder	6.7	3.81	22.646
Taro 15 % binder	6.6	3.8	22.191
Taro 20 % binder	7.1	3.81	21.575
Paper 10 % binder	7.9	3.77	26.760
Paper 15 % binder	6.4	3.74	21.673
Paper 20 % binder	6.1	3.72	19.574

Sample calculation for proximate analysis

Ash content

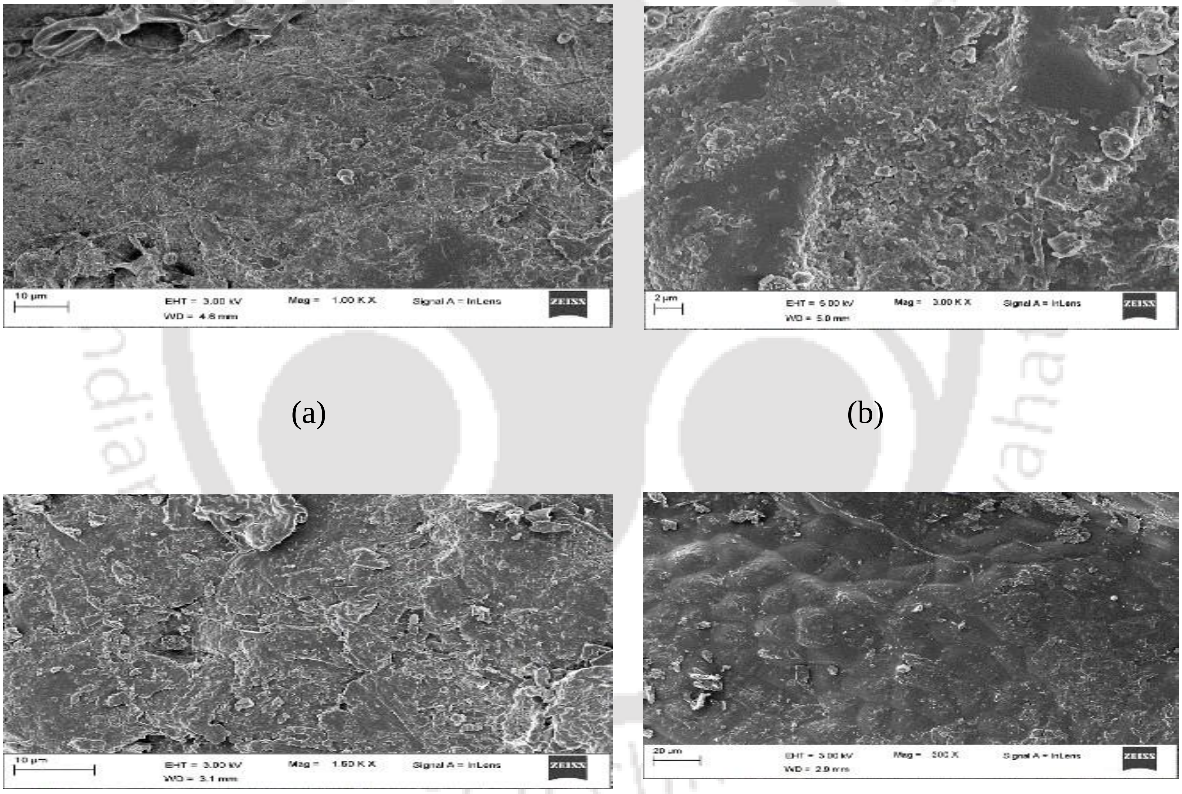
Sample	Weight of empty crucible	Initial weight of sample	Weight after oven drying	Weight after removing from muffle furnace
Starch 10 %	25.981	1.004	26.895	26.220
Starch 15 %	23.824	1.000	24.737	24.054
Starch 20 %	23.366	1.005	24.280	23.567
Paper 10 %	21.546	1.002	22.472	21.768
Paper 15 %	21.514	1.008	22.416	21.752
Paper 20 %	23.372	1.006	24.281	23.600
Taro 10 %	25.986	1.008	26.894	26.213
Taro 15 %	23.820	1.005	24.734	24.028
Taro 20 %	23.375	1.018	24.016	23.533

Annexure A



(a) (b)

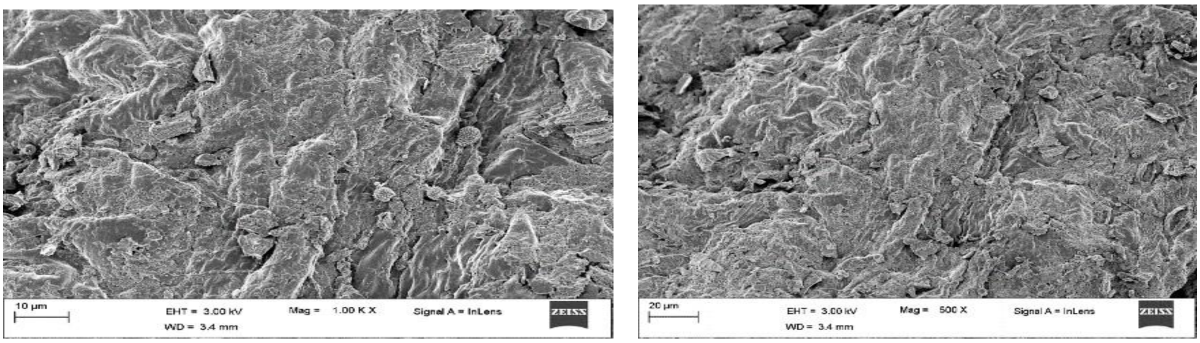
Figure: FESEM image of grass and sawdust at (a) 1kx and (b) 3kx



(a) (b)

(c) (d)

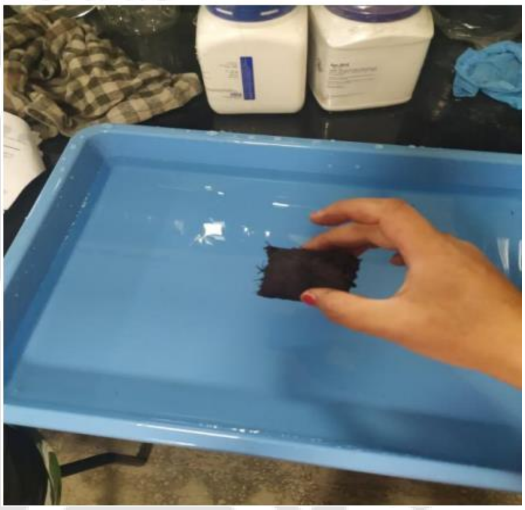
Figure:FESEM image(a) 3:1 DL:C at 1kx (b)3kx (c) 1:1 DL:C at 1.5kx (d) 500x



(a) (b)

Figure: FESEM image of straw briquette at (a)1kx and (b)500x

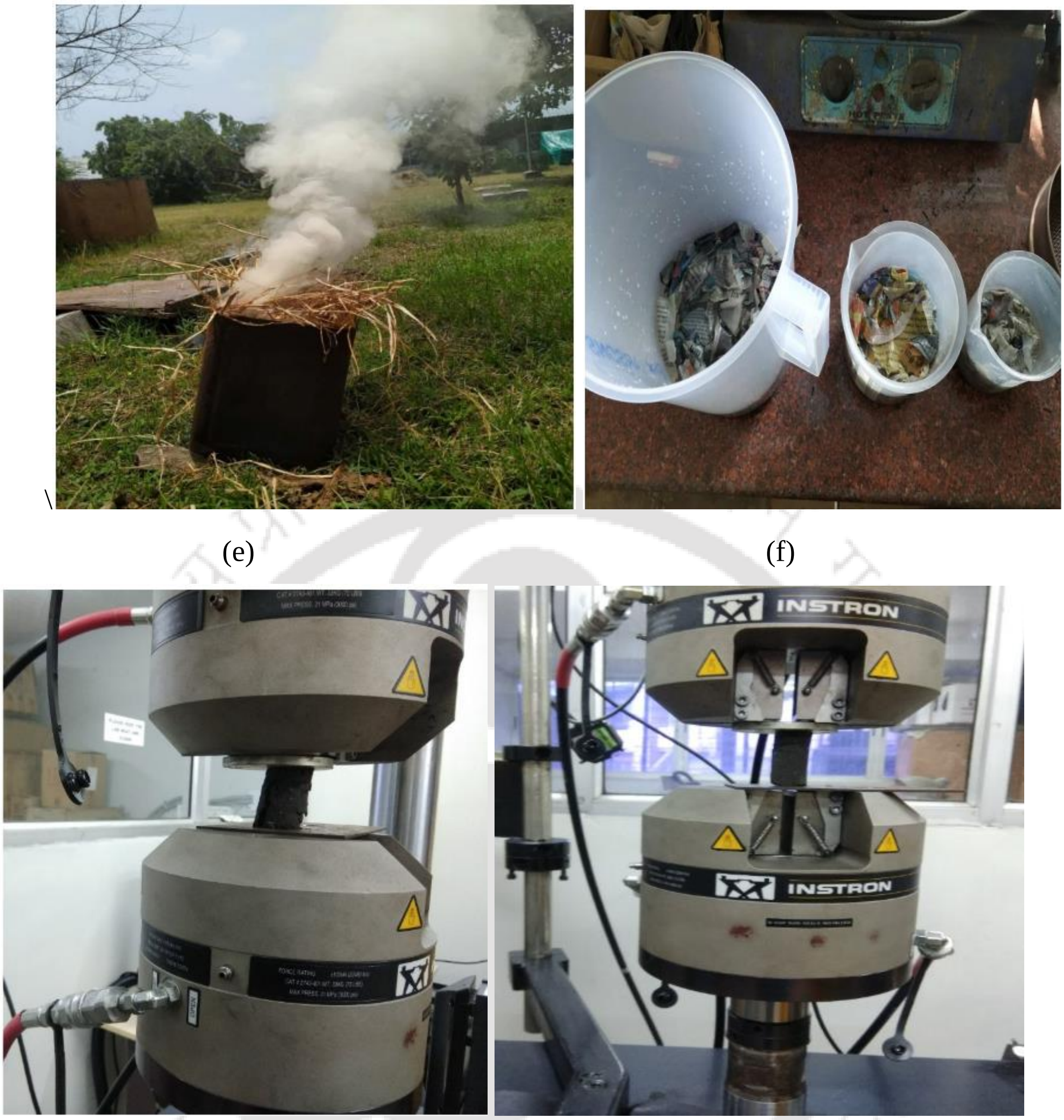
(a)



(b)

(C)

(d)



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(e) (f)

(g) (h)

Figure: Photograph of (a) Carbonised sample briquettes (b) Water resistance test (c) Briquette length (d) mixture of carbonised rice straw and binder (e) Carbonisation in a small drum (f) Paper pulp making (g) and (h) Compressive strength testing in an UTM

Annexure B

Table: Influence of binder and charcoal percentages on thermal properties of briquette

Run	Variables		Responses									
	Charcoal (%)	Binder (%)	M.C (%)		A.C (%)		VM (%)		FC (%)		CV (MJ/kg)	
			Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
1	0	10	6.70	0.189	8.13	0.196	70.29	0.910	21.72	0.517	4121.37	19.605
2	0	15	10.06	0.613	8.47	0.435	72.11	0.435	19.76	0.451	4268.91	76.073
3	0	20	13.023	0.634	8.99	0.208	73.22	0.465	17.55	0.845	4169.71	66.089
4	25	10	6.78	1.213	15.17	0.280	45.05	0.879	39.81	1.427	5930.54	36.497
5	25	15	9.86	0.568	13.25	0.469	46.07	1.911	42.11	0.586	6091.67	105.257
6	25	20	12.94	0.509	12.18	0.321	47.61	0.636	39.43	0.591	6004.57	21.391
7	50	10	6.99	0.317	17.46	0.852	42.12	1.009	40.59	0.686	4925.59	37.202
8	50	15	8.90	0.500	22.07	0.296	42.00	0.387	36.00	0.299	4223.90	42.932
9	50	20	13.53	).323	19.10	0.231	42.09	0.567	38.89	0.295	5067.14	74.561
Significance level Charcoal percentage Binder percentage Charcoal+binder			$\rho = 0.917$ $\rho < 0.05$ $\rho = 0.137$		$\rho < 0.05$ $\rho < 0.05$ $\rho < 0.05$		$\rho < 0.05$ $\rho = 0.002$ $\rho = 0.083$		$\rho < 0.05$ $\rho < 0.05$ $\rho < 0.05$		$\rho < 0.05$ $\rho < 0.05$ $\rho < 0.05$	

Table: Influence of binder and charcoal percentages on physical properties of briquette

Run	Variables		Responses							
	Charcoal (%)	Binder (%)	Bulk Density (g/cm^3)		Compressive strength MPa		Shatter Resistance (%)		Resistance to water penetration (%)	
			Average	S.D	Average	SD	Average	SD	Average	SD
1	0	10	0.525	0.011	0.427	0.015	77.903	0.307	50.667	2.887
2	0	15	0.531	0.005	0.727	0.006	83.197	0.346	47.667	2.082
3	0	20	0.555	0.006	0.743	0.030	87.363	1.298	52.000	1.000
4	25	10	0.538	0.007	0.303	0.011	70.783	0.584	60.333	1.527
5	25	15	0.540	0.012	0.400	0.036	81.160	0.249	55.000	2.000
6	25	20	0.552	0.003	0.643	0.032	82.993	0.635	61.000	4.000
7	50	10	0.540	0.002	0.340	0.010	69.453	0.691	65.667	2.517
8	50	15	0.687	0.004	0.337	0.021	78.403	0.336	60.667	4.509
9	50	20	0.606	0.008	0.533	0.047	77.947	0.201	64.667	2.082

Significance level Charcoal percentage Binder percentage	$\rho < 0.05$ $\rho < 0.05$ $\rho < 0.05$	$\rho < 0.05$ $\rho < 0.05$ $\rho < 0.05$	$\rho < 0.05$ ρ < 0.05 ρ < 0.05	$\rho < 0.05$ ρ $= 0.002$ ρ $= 0.88$

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