Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 24 | No. 4 | Article ID D1761 | 2025

Original Research Paper

https://doi.org/10.46488/NEPT.2025.v24i04.D1761

Open Access Journal

Valorization of Agro-Waste Biomass: Impact of Process Conditions on Solid Fuel Properties

Oluwagbenga Tobi Adesina[1]†, Williams Kehinde Kupolati[1], Tamba Jamiru[2], Emmanuel Rotimi Sadiku[3], Lodewyke William Beneke[2] and Chibueze Godwin Achi[1]

[1]Department of Civil Engineering, Tshwane University of Technology, Pretoria, South Africa
[2]Department of Mechanical Engineering, Tshwane University of Technology, Pretoria, South Africa
[3]Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa
†Corresponding author: Oluwagbenga Adesina; oluwagbengaadesina@yahoo.com

Abbreviation: Nat. Env. & Poll. Technol.
Website: www.neptjournal.com

Received: 16-01-2025
Revised: 19-03-2025
Accepted: 24-03-2025

Key Words:

Biomass
Briquettes
Calorific value
Binders
Energy
Fuel

Citation for the Paper:

Adesina, O. T., Kupolati, W. K., Jamiru, T., Sadiku, E. R., Beneke, L. W. and Achi, C. G., 2025. Valorization of agro-waste biomass: Impact of process conditions on solid fuel properties. *Nature Environment and Pollution Technology*, 24(4), D1761. https://doi.org/10.46488/NEPT.2025.v24i04.D1761

Note: From 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.

ABSTRACT

Research scientists worldwide are continuously driving innovations toward achieving a safe and healthy environment across the entire ecosystem. An integral component of this pursuit, as captured in SDG-7, is ensuring access to affordable, reliable, sustainable, and modern energy for all. The discovery of the vastness of bioresources embedded in agricultural and forestry residues mirrors hope and presents an array of challenges. Over the decades, biomass densification has been implemented to upgrade and consolidate the energy value of loose biomass for industrial and domestic applications. This is projected to mitigate the overreliance on fossil fuels as energy sources. However, the combustion and energy performance of biomass have not sufficiently met the energy mix requirements for extensive renewable energy use. The performance of the compacted material is dependent on the type of binder used in the manufacturing process, among other factors. This study explored the details of the available binders and biomass compositions investigated in previous studies. The authors also reported their performance, primarily regarding energy value and combustible behavior. Limitations such as low yield and low energy content, among other performance-related issues in biomass briquettes, can be highly enhanced with the appropriate selection of biomass and compatible binders. Hence, various research attempts, approaches, and methodologies have been conducted to develop solid fuel, and the binder's influence on the energy content, density, combustion behavior, and other physical attributes of fuel briquettes has been reported.

INTRODUCTION

The United Nations Sustainable Development Goal 7 (SDG-7), which focuses on the provision of affordable, reliable, sustainable, and modern energy for all, is central to advancing sustainable global energy solutions and combating climate change. Part of this goal is the shift to the use of renewable energy sources, and here, bioresources from agricultural and forestry residues are pivotal. Biomass resources enable the generation of clean energy, thereby reducing reliance on fossil fuels and their negative impacts on the environment. Therefore, through their conversion into solid fuels, they are an optimal, affordable, and sustainable source of energy, especially for the rural and energy-starved regions of the world, and are hence highly relevant for the achievement of the seventh sustainable development goal.

The overutilization and reliance on finite conventional energy sources due to massive urbanization and industrialization across the world have resulted in a global energy crisis over the past few decades. This requires the collective intervention of researchers, scientists, and policymakers (Hanif et al. 2016, Siloto & Weselake 2012). Moreover, because these resources are finite, they pose a major threat to the environment and human health (Fawzy et al. 2020). Nevertheless, society's energy requirements are still rising owing to technological advancements and increasing population size. This has further aggravated the pressure on the current energy situation in China. This energy crisis can be mitigated by fully embracing and harnessing renewable energy, such as bioenergy and wind, to partially replace fossil energy. According to the 2019 Sustainable Development Goal Tracking for Energy Report, renewable energy accounted for approximately 20% of the world's energy consumption in 2018, with biomass accounting for 9% of the world's total primary energy supply.

The fact that biomass is clean, renewable, and CO_2-neutral makes it one of the most feasible technologies for addressing climate change, environmental pollution, and the energy crisis (Ren et al. 2017). The effects of biomass energy on the environment and fossil fuel depletion have drawn the attention of the general population. Biomass compaction and briquettes have become desirable alternatives because of their high potential for renewable energy. However, the difficulty in energy storage and transportation, unstable combustion rate, low energy density, and high particle emission serve as impediments to the direct utilization of biomass (Demirbas 1999). Naturally occurring structural binders or stabilizing substances, such as lignin and proteins, are typically present in biomass. They are released and activated during densification at relatively high pressure and temperature levels (Mani et al. 2006, Oyelaran et al. 2015). As a result, biomass briquettes exhibited better structural particle bonding. In some circumstances, extra binders could be needed in briquettes due to insufficient inherent natural binder, low lignin quantity, and densification capacity. These additional binders are used to obtain high-quality and strength of biomass briquettes. In addition, binders in briquette production confer better strength, thermal stability, improved combustion performance, and reduced costs (Zhang et al. 2018b, Ezéchiel et al. 2022).

Briquetting and pelletization are regarded as efficient techniques for enhancing the characteristics of biomass transportation and storage. The literature has reported on numerous studies that have been conducted on biomass pelletization. This study shows the link between the resultant outcome on pellet properties, feedstock/raw material characteristics, and process conditions. The pellet properties included density, compressive strength, and calorific value. The material characteristics include the moisture content and particle size, while the pelleting conditions include the size, temperature, compression velocity, and pressure. Briquettes with lower ignition temperatures, slagging indices, and ash contents can be produced using biomass binders (Isemin et al. 2017).

One of the critical expected outcomes of the valorisation of agricultural waste biomass is its energy value. Agro-waste has been explored to help mitigate the energy deficit and complement the existing renewable energy required in the global energy mix. However, to harness and optimize these bioresources, the process conditions and parameters must be optimized. This review article captures the various possible inherent energy capacities and combustion properties of accessible agricultural wastes. Previous reviews have qualitatively reported general information on biomass but not quantitatively. This review also clearly projects, through the quantitative estimate of energy value and combustion properties, the possibility of developing hybrid composites from energy-laden agro-waste. This provides greater optimism in challenging the existing energy and combustion properties of commonly used coal and bituminous coal.

However, this review provides new insights by detailing how the methods/process conditions of agro-waste valorisation impact the quality of the valorised agro-waste solid fuel and their combustion performance. In this review, effective agro-waste and binder combinations (with the most enhanced energy and combustive properties) based on experimental investigations with an equivalent or far above that obtainable in fossil fuels such as coal and sub-luminous coal are clearly identified. Hence, it converges and provides more in-depth knowledge of various agrowastes compared to the generic information available in the literature. This will assist in bioenergy adoption of viable renewable energy options and contribute to advancing the frontiers of agro-waste valorisation.

ROLE OF BINDERS IN BIOMASS BRIQUETTING

Briquette binders are classified into two major groups: organic and inorganic. Based on their composition, they can be further classified as organic, inorganic, or compound binders (Kivumbi et al. 2021, Montiano Redondo et al. 2015). The required bonding strength, low emissions, impact on the briquette combustion behavior, environmental friendliness, sustainability, and affordability are among the many factors that influence the choice of binder.

Nevertheless, these materials have low mechanical strength and poor thermal stability at high temperatures and readily break down (Han et al. 2014). Their primary attractive features are their wide availability, low cost, high heating value, and low ignition temperature. Organic binders comprise forestry and agricultural waste biomass, lignosulfonate, polymer binders (such as resins, polyvinyl, and starch), petroleum bitumen, and tar pitch.

According to Zhang et al. (2018a), organic binders often have strong binding qualities, such as excellent water resistance and strong impact and abrasion resistance.

According to Miao et al. (2023), organic binders can be classified according to their reaction with water: hydrophobic binders, such as coal tar and asphalt, and hydrophilic binders, such as biomass. The low heat stability of organic binders restricts their practical use in biomass briquetting (Yun et al. 2014). The restricted calorific value of inorganic binders results in decreased combustion efficiency, and their ash content is frequently significant. However, they have excellent adhesion, low pollution, sulfur capture features, low cost, and good hydrophilicity (Shu et al. 2012). Ammonium nitrate, bentonite, and clay are examples of such materials. Therefore, selecting binders for briquette production is crucial and must be performed carefully. Furthermore, to achieve improved yield and performance, the appropriate amount of binder must be considered during the fuel briquette manufacturing process. The performance of a briquette is dependent on several factors, among which are the binder content, particle size of the biomass, mixing ratio (composition), compaction pressure, moisture content, and type of biomass feedstock, among others (Obi et al. 2022).

Additionally, higher cellulosic binders have reduced energy values and durability with less compaction on briquettes(Obi et al. 2022). Furthermore, the performance and yield of a fuel briquette are strongly dependent on several factors, including the pressure applied, binder content, process temperature, compositional mix, moisture content, feedstock type, particle size, and ambient conditions (Olugbade et al. 2019). The impact of lignin and fat content, texture, and particle size on the binder properties of briquettes still requires further research and attention, despite the numerous studies on the production and use of fuel briquettes.

Although binding agents are naturally present in many biomass materials (Sharma et al. 2015), their binding power can be improved by adding binders to the mixture during briquette-making. However, some binders may result in problems, such as increased ash content, poor combustion characteristics, or decreased briquette compaction when converting fuel briquettes into energy (Mohammed & Olugbade 2015). This necessitates the development of eco-friendly and readily accessible binders. In making briquettes, binder materials like sawdust, wood ash, molasses, starch, biosolids, microalgae, and cow dung are frequently used (Rahaman & Salam 2017)

Inorganic binders can be divided into three primary categories: environmental (desulfurization agents, such as iron oxide, magnesium oxide, and calcium oxide), industrial (bentonite clay, cement, sodium silicate, and magnesium chloride), and civilian (limestone and clay). Nonetheless, in recent research, inorganic binders have not been used much for biomass briquettes (Pinto et al. 2012, Williams & Nugranad 2000)

Compound binders combine two or more binders to create briquettes with high thermo-mechanical strength to harness the various advantages of the various binders. Examples include molasses, carbide lime, starch and bentonite (Obi et al. 2022). A variety of parameters, such as availability, cost, raw material quality, mix, moisture content, pressure, and the expected energy content of the briquettes, frequently influence the selection of binders in biomass briquetting. The price and accessibility of binders are typically the most crucial variables considered when selecting binders for developing communities. The type and amount of binder used in biomass briquetting are related to the mechanical and combustion characteristics of the final product, briquettes. Moreover, the extent to which they affect the characteristics of biomass briquettes differs among binders.

Organic and Inorganic Binders

Rajput et al. (2020) explored different methods to enhance the properties of fuel pellets obtained from different biomass sources. Waste cooking oil (WCO), recovered polyvinyl alcohol (rPVA), and waste lubricant (WLO) were tested as binders in this study. For the palletization procedure, rPVA was selected and compared with the other two binders. However, increasing the WCO and WLO blend in the biomass enhanced the calorific value of the biomass pellet better than that of rPVA. The increasing WCO and WLO contents in the biomass reduced its strength. Hence, WCO and WLO are better binders for improving the fuel properties compared to rPVA.

Shuma and Madyira (2017) explored cow dung and cactus binders to investigate the energy value and combustion rate of biomass briquettes. The biomass was compacted at pressures of 6, 12, and 19 MPa, respectively. The maximum energy content was observed in briquettes bound with cow dung under all pressures. At 6 MPa, the energy content was 21.53 MJ.kg^{-1} in Mopani leaf briquettes, 16.85 MJ.kg^{-1} in groundnut shells at 12 MPa, and 19.11 MJ.kg^{-1} in sugarcane at 19 MPa. Yellow thatching grass had the lowest HHV of 14.84 MJ.kg^{-1} on average in cow dung under all pressure conditions. Furthermore, the cow dung-bonded briquettes exhibited higher rates of combustion with increasing pressure for groundnut shell rates. Sugarcane leaves had the lowest performance at 38.13 g.min^{-1}. Low energy content and low burning rates owing to their high moisture content and insensitivity to pressure were observed with cactus-bonded briquettes. Mopani leaves had the highest energy content for cactus-bound briquettes, at 16.49 MJ.kg^{-1}, followed by groundnut at 15.5 MJ.kg^{-1} and yellow thatching grass at 12.6 MJ.kg^{-1}. The highest combustion rate (59.48 g.min^{-1}) was found for the combination treatment, followed by the Mopani leaf treatment (53.91 g.min^{-1}), and the lowest for yellow thatching grass (3.36 g.min^{-1}). Cow dung briquettes exhibited better performance for all compaction pressures.

Rahaman and Salam (2017) produced rice straw briquettes and investigated their physical properties, such as particle size effect, mold diameters, and applied pressure. This study measured the various densities (initial and stable), ratios (density and compaction), volume change in percentage, shatter index, and energy consumed by the briquettes. Cold-densified rice straw briquettes with a comparatively high stable density and durability were prepared using particles of 2.5 mm or 0.1–150 mm, pressures $\geq$ 27.6 MPa, and mold diameters $\leq$51 mm. It is interesting to note that, despite the lower pressure, the briquettes with particles ranging from 0.1 to 150 mm had a significantly (p b 0.05) higher shatter index of N0.90 at the expense of stable density. The briquette stable density was enhanced to 600 kg.m^{-3} by using sawdust as a binding material at 3:1 and 1:1 mixing ratios. Additionally, the shatter index was dramatically improved ($p < 0.05$), the heating value was increased by 6-7.2%, and the ash content was decreased from 13.61% to 10.3% and 6.93%, respectively. For big and small molds, the energy stored in rice straw briquettes was 5.6-7.5% and 11.1-13%, respectively, owing to the energy used in briquette manufacturing.

Davies & Davies (2014) investigated some agricultural waste as binders and their effect on the physical characteristics of water lily briquettes. Banana, cassava, yam, and plantain peels with a particle size of 0.075 mm were employed as binders, along with sun-dried water lily with a particle size distribution of less than 0.25 to 3.00 mm. Grounded water lilies with binders ranging from 10-50% by weight were fed into a cylindrical die and compressed at a pressure of 9 MPa and a 45-second dwell time. The cassava peel-containing binder exhibited the best mechanical handling ability.

A factorial experiment was used in a study by Muazu and Stegemann (2015) to examine the influence of variables, including biomass source, material ratio, compaction pressure, and binder inclusion (a mixture of starch and water). The material blends were briquetted at a density up to 1.9 times the bulk density of loose biomass, as opposed to the individual ingredients. A rice husk to maize cobs of 3:7 composition with 10% binder inclusion resulted in a compressive strength of 176 kPa and a compaction pressure of 31 MPa. The analysis showed that the addition of water and starch was necessary for sufficient briquette strength, but it also greatly lowered the densities of the green and relaxed materials. Densification was significantly affected by the biomass source, highlighting the need to comprehend the mechanisms underpinning biomass fluctuation.

Kimutai & Kimutai (2019) examined the properties of cashew nutshell biomass and cassava as binders. The carbonization of cashew nut shells was carried out at 250°C, and pulverized into a briquette upon adding cassava paste as the binder. Briquettes of different particle sizes (0.5-2.0 mm) were subjected to varying pressures of 1000 kg.cm^{-2}, 200 kg.cm$^{-2,}$ and 300 kg.cm^{-2}, and binder ratios (10%, 20%, and 30%) were produced. The addition of a binder enhanced the properties of the briquette, which had a maximum HHV of 30.5 MJ.kg^{-1} at a 30% binder ratio compared to 28.3 MJ.kg^{-1} in the binder-less briquette. This value is comparable to that of wood charcoal (31.38 MJ.kg^{-1}).

Anggraeni et al. (2021) carbonized different particle sizes of dried cassava peels and rice husks mixed at different ratios with a binder to produce briquettes. The effects of particle size and composition on briquette performance are presented in this study. In this experiment, 4 g of tapioca starch binder was added to 10 g of carbonized particles and molded. Briquettes with small particles of 70:30 and 50:50 CP: RH compositions exhibited the best compressed and relaxed densities. The relaxed density ranged from 1.70 to 2.26 g.cm^{-3}. The best results for this parameter were obtained for small particles in the 0.41-0.56 g.mL^{-1} range. A compositional briquette ratio of 10:90 yielded the highest calorific value and SFC for medium- and large-sized particles. The briquette had the highest burning rate at a 90/10 CPs/RHs blend. Overall, the combustible behavior was good.

Achebe et al. (2018) studied the energy value and properties of sawdust, rice husk biowaste, and their composites using two types of binders (starch and clay). Sun-dried biowastes with uniform 0.5 mm particle sizes and 90:10 binder composition were compressed into briquettes to analyze their combustion properties. The calorific values of mahogany sawdust (4.516 kcal.g^{-1}), gmelina (4.1487 kcal.g^{-1}), oak (4.4312 kcal.g^{-1}), mahogany/gmelina/oak composite (3.8614 kcal.g^{-1}), rice husk (4.0531 kcal.g^{-1}), and gmelina/rice husk briquettes (4.067 kcal.g^{-1}) with starch binder were reported. Additionally, it was stated that the calorific values of 1.9003 kcal.g^{-1}, 1.5331 kcal.g^{-1}, 1.8156 kcal.g^{-1}, 1.2458 kcal.g^{-1}, 1.4375 kcal.g^{-1}, and 1.4451 kcal.g^{-1} were obtained when clay was used as a binder. The mahogany briquette with starch binder had the highest cooking efficiency of 45.8 %, compared to other briquettes, but its ignition time, boiling time, fuel consumption rate, and burning period of 0.206 min, 8.1 min, 33.2 g.min^{-1}, 42.21 min, respectively, were less than those obtained for other briquettes. Hence, it performed better than the other briquettes.

Oroka and Thelma (2013) used cow dung as a binding agent to develop water hyacinth briquettes at ratios of 100:0, 90:10, 80:20, and 70:30. Higher compressed densities of 1851 and 1970 kg.m^{-3} were obtained at 70:30 and 80:20 water hyacinth-cow dung ratios, respectively. The flue gas temperature increased by up to 74.5 °C with increasing cow dung content of up to 30% in the briquette compared to pristine water hyacinth, which had the lowest flue gas temperature of 60.5 °C. The fastest boiling time was recorded at 30% cow dung composition.

Narzary et al. (2023) mixed and densified three types of binders (paper, starch, and taro starch) of 10-20% w/w with carbonized rice straw to improve briquetting characteristics. The fixed carbon content varied from 20.36-37.07 %, the density from 0.382-0.518 g.cm^{-3}, and the heating value from 24.049 MJ.kg^{-1} to 28.639 MJ.kg^{-1}. Although the briquette with 20% starch binder presented the best thermal stability in this study, it has a conflicting interest. Hence, choice is discouraged in such cases. Therefore, taro can serve as a substitute binder. The results of the emission test revealed a reduction in CO, NOx, and SOx emissions with straw briquettes compared to the burning of chopped rice straw. The paper binder had the lowest range of CO (2.3-2.5 g.cm^{-3}), NOx (0.055-0.06g.cm^{-3}), and SOx (0.0175-0.015 g.cm^{-3}) emissions, whereas Tao starch had the highest range of CO (3.25 -3.5 g.cm^{-3}), NOx (0.07-0.09 g.cm^{-3}), and SOx (0.018-0.02 g.cm^{-3}). The highest specific energy consumption was observed for paper binder briquettes, followed by starch binder briquettes, and the lowest for taro binder briquettes. The water boiling test revealed that the burning rate increased with the binder content.

Yank et al. (2016) examined the physical characteristics of rice husk and bran briquettes. The study examined the impact of binder type, binder content, moisture content, and bran content on rice husks. Rice dust, okra stem gum, and cassava starch wastewater were used as binders. The briquettes manufactured from cassava starch wastewater had the maximum density (441.18 kg m3) and a greater heating value (16.08 MJ.kg^{-1}, dry basis). The briquette with the rice dust binder exhibited the strength (compressive) of 2.54kN and the highest durability (91.9%). Rice husk-based briquettes can serve as substitutes for biomass cooking fuel.

Effect of tapioca binder composition on the heating value of biomass briquettes obtained from *C. manghas* leaf waste. This study was conducted by Anggono et al. (2016). The heating values of five mixtures with 10-50% tapioca composition were examined. The highest heating value of 4164 kcal.kg^{-1} was obtained at 10% tapioca with a 90% waste leaf composition mixture, while at 50% tapioca binder, the lowest calorific value of 3985.82 kcal.kg^{-1} was obtained. The experimental results confirmed the feasibility of making biomass briquettes from *Cerbera manghas* leaf waste with tapioca as a binder.

Tahir et al. (2012) prepared different types of biomass-based charcoal briquettes from groundnut shells, durian shells, and cassava peels with binding compositions of 90:10, 80:20, and 70:30, respectively. The binding agent significantly affected the physical properties. The highest silica content was obtained from groundnut shell-based charcoal, followed by durian shell and cassava peel-derived charcoal. A high silica content indicates a high carbon content and calorific value. In its transformation to silicate, this silica has a high material strength, leading to the compressive strength of the briquette.

Sawdust-based briquettes were produced using *Abelmoschus esculentus* (Okra) waste of 5-20% composition by weight as a binder additive (Ohagwu et al. 2022) to understand their fuel and physico-mechanical properties. The briquette containing 5% okra addition has the least moisture content and ash content and moisture content of 7.6% and 1.59%, respectively, while having the maximum volatile matter and calorific values of 85.46% and 17,820 kJ.kg^{-1}. Furthermore, at 5% Abelmoschus esculentus (okra), the highest values of carbon, hydrogen, and oxygen were-42.70 %, 5.64%, and 42.76%, respectively. The shatter resistance increased as the binder concentration increased within the 96.78-98.92% range, and a 2.85 kN.m^{-2} hardness at 5% sawdust-okra briquette samples was obtained.

Wirabuana & Alwi (2021) pyrolyzed durian lai peel (*Durio kutejensis* Becc) and examined the influence of starch binder concentration of 3-6% on the quality of briquettes. A binder concentration of 3% (w/w) yielded the best quality briquettes. This attests that the binder content affects the calorific value per unit volume and provides uniform quality and size.

Handra et al. (2023) investigated the effect of the percentage of starch binders (2%, 4%, 6%, and 8% (wt%)) on the ignition quality of EFB was carried out by Handra et al. (2023). The study revealed that briquettes with an 8% binder had the highest flame temperature of 440°C. However, compared to briquettes with a lower binder percentage, adding a binder to prolong the ignition period affects the amount of black smoke that burns. Based on the calorific value, class E (3360-4201) had the highest calorific value, which was at a binder percentage of 4%, or 3676.2 kcal.g^{-1}.

Zanella et al. (2016) produced charcoal briquettes from orange bagasse (a solid waste). Orange charcoal (OC) powder was mixed with maize starch at several ratios (5, 10, and 15%

w/w), and some performance tests were conducted. These tests comprised proximate analysis, density, mechanical strength, elemental analysis, and higher heating value (HHV). OC, which has a considerable HHV of 29,000 J.g^{-1}. The HHV decreased significantly when the OC with 5% corn starch (CS), OC with 10% CS, and OC with 15% CS were mixed with the binder, although these values are still regarded as excessive. The corresponding values were 27,611, 26,857, and 26,476 J.g^{-1}, respectively. In addition to showing good mechanical strength, the 10% binder briquette also showed a loss of 14,932 % in the friability test, suggesting that it was somewhat brittle and could withstand 1.406 MPa pressure in the compression test. Therefore, 10% corn starch was selected for this study.

Espuelas et al. (2020) investigated the potential of xanthan and guar gums on spent coffee grounds (SCGs) for briquette manufacturing. The briquettes were produced with 5 and 10% binder dosages, compaction pressures ranging from 8-12 MPa, and moisture contents of 15%, 20%, 25%, and 30%. The mixture of 10% xanthan and 15% moisture achieved a maximum dry density of 0.819 g.cm^{-3} at 12 MPa.

In a study by Davies et al. (2013), the effect of process variables on the durability of briquettes produced from water hyacinth and plantain peels at different binder levels, particle sizes, and compaction pressures was investigated. These process parameters significantly affected briquette durability. The DIP4B5 composition, which implied a particle size of 0.5 mm, pressure of 9 MPa, and 50% binder, was required to produce briquettes with the highest durability and strength of 96%. The results were comparable to those of fuelwood. The densification process improved the handling characteristics of briquettes.

Carnaje et al. (2018) prepared a water hyacinth briquette with molasses as a binder at different compositions. Briquettes containing 80% molasses by weight with different charcoal/molasses mix ratios were prepared. The MC, VM, and FCC of the biochar increased when the molasses content used as a binder increased, but the ash content decreased. A briquette with a 30:70 charcoal-to-binder ratio exhibited favorable properties in terms of ignition, compressive strength, and calorific value. It has a maximum allowable load of 19.1 kg.cm^{-2}, the fastest ignition time of 133 s, and an HHV of 16.6 MJ.kg^{-1}. The briquette with a 30:70 ratio also exhibited the highest resilience to breaking.

Falemara et al. (2018) also reported the combustion properties of some selected agricultural waste/residue and *Anogeisus leiocarpus* wood particles to produce briquettes. A higher SHC of 34.4 MJ.kg^{-1} was achieved for wood residue particles. Briquettes with groundnut shells had a density range of 0.44 g.cm^{-3} to 0.53 g.cm^{-3}. *A. leiocarpus* has the lowest ash content (3.4%), and corn particles have 4.9% ash content, which is the highest. *A. leiocarpus* particles have the highest SHC of 8222 kcal.kg^{-1}. Maximum volatile matter (33.5%) and SHC (8051 kcal.kg^{-1}) were produced at 20% starch content, with the least volatile matter (24.2%) and SHC-7165 kcal.kg^{-1}. *A. leiocarpus* particle-based briquettes have the highest SHC. Briquettes made with wood particles with a groundnut shell and *A. leiocarpus* particle mixture with 25% starch binder exhibited superior density and combustion qualities.

Rajput et al. (2020) explored different methods to enhance the properties of fuel pellets obtained from different biomass sources. The waste cooking oil (WCO), recovered polyvinyl alcohol (rPVA), and waste lubricant (WLO) were tested as binders in this study. For the palletization procedure, rPVA was selected and contrasted with the other two binders. However, increasing the WCO and WLO blend in the biomass enhanced the calorific value of the biomass pellet better than that of rPVA. The increasing content of WCO and WLO in the biomass reduces the strength of the biomass. Hence, WCO and WLO are better binders in improving the properties of the fuel. Compared to rPVA.

Katimbo et al. (2014) investigated the energy value of crushed dried mango seed covers of 2 mm particle size to produce a biomass briquette using three different types of binders: starch, starch-clay soil, and starch-red soil. Seed cover particle to starch composition ratios of 4:1, seed cover: starch: clay soil (9:2:1), and seed cover: starch: red soil (16:4:1) were highlighted as the best mixing ratios. The results revealed that briquettes with starch binder only had improved fuel properties ($p \leq 0.05$), a calorific value of 16.140 kJ.kg^{-1}, 0.178% CO, and 1.14% CO_2 emissions. The (CH)X and NOx are negligible and insignificant, indicating their non-toxicity. It also has a maximum breaking strength of 34 N and a compressive stress of 273 N.mm^{-1}.

According to a study by Saenpro et al. (2019), agricultural waste, which comprises wood chips (WCs), rice straw (RS), and corn cobs (CCs), is composed of natural binders (oil palm fronds (PFs) and soybean plants (SBs)) in a range of 20%-60% by weight. The cassava starch content was set at 10%. The extruder machine used was a screw type with a 3 kW electrical motor to produce the biomass briquette. The results showed that the partial physical properties of the briquette fuels met the standards of Thailand's community briquette fuel, which uses a natural binder at a concentration of more than 60%. The interlocking properties of the oil palm fronds were superior to those of the soybean fronds. An overview of the three biomass briquette fuel experiments revealed that the cost of production decreased by > 57%. It was concluded that a natural binder could be used instead of cassava starch because the oil palm fronds had better properties than the soybean plant.

Arewa et al. (2016) examined the properties of rice husk briquettes manufactured using cassava peels and starch as binders. Briquettes with starch binder had maximum and relaxed densities of 1080.8–1159.6 kg.m^{-3} and 552.3–632.2 kg.m^{-3}, respectively. Moreover, the corresponding values of 571.1- 622.9 kg.m^{-3} and 977.6–1176.5 kg.m^{-3} were reported for briquettes containing cassava peels, respectively. The water boiling and burning rate tests showed that the binders enhanced the combustion of the briquettes. However, the rice husk- cassava peel briquettes performed better.

The effect of durian seed concentration as a binder on biomass briquette formation was explored by Cahyono et al. (2017). The briquettes contained coconut and durian shell char at a ratio of 1:1, with binder concentrations of 4%, 6%, 8%, 10%, and 12% (wt.%). According to the heating and compressive strength measurements, a saturation state was reached at an 8% binder concentration with the durian seed binder. The energy value of the briquettes declined as the binder content increased from 4 to 8% and remained constant thereafter.

Jittabut (2015) explored molasses as a binding medium for investigating the dimensions and thermal characteristics of briquettes made in ratios of 100:0, 80:20, 50:50, 20:80, and 0:100 using rice straw and sugarcane leaves. A 100:50 briquette-to-molasses binder ratio was employed. They conducted both proximate and ultimate analyses to determine the average composition of the elements. The results show an FCC of 9.06-13.63%, a VMC of 68.14-74.67%, an AC of 7.84-12.85%, and an MC of 4.2-6.2. The highest heating value was 16.33 MJ.kg^{-1} for the rice straw: sugarcane leaf (100:0) composition and 17.83 MJ.kg^{-1} for the 50:50 composition, the highest calorific value obtained. A decrease in the calorific value was observed with the addition of non-combustible calcium hydroxide inclusion in the biomass blend and with starch binder. The density ranged from 0.53-0.58 kg.m^{-3}. The compressive strength was in the range of 32.4-44.7 kg.cm^{-2}.

Davies & Davies (2014) used phytoplankton as a binder on ground water hyacinth to investigate the properties of briquettes. Water hyacinth and binder contents, ranging from 10-50% were fed into a 14.3 cm by 4.7 cm steel cylindrical die by weight of each feedstock. The powder was then compressed in a hydraulic press under a pressure of 20 MPa for a dwell time of 45 s. The calorific value (Kcal. kg^{-1}) significantly increased with increasing binder content from 10% to-50%, 3563 ±77 to 4281 ±90, the ignition time (min): 73.54±3.37 to 123.42±3.47; Burning rate (g.min^{-1}): 2.25±0.01 to 1.63±0.02.

A comparative test on the effectiveness of five specific binding materials for the manual densification of cabbage waste was conducted by Bency et al. (2023). The briquette was developed using a 20:80 combination of binder and biological waste. The sample density ranged from 545.564 to 591.278 kg.m^{-3}. Vinyl ester resin had the highest calorific value (5,800.79 kcal.kg^{-1}) as an inorganic binder, followed by beef tallow oil as an organic binder (5.357.26 kcal.kg^{-1}). Hence, the composition of the inorganic binder enhanced the HCV. This is illustrated in Fig. 1.

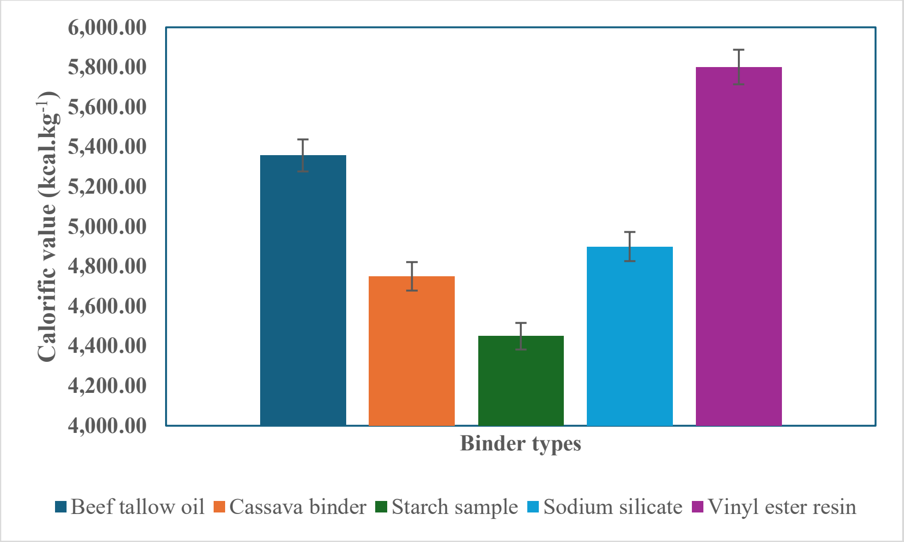

Fig. 1: Calorific value of briquettes with specific binding materials (Bency et al. 2023b).

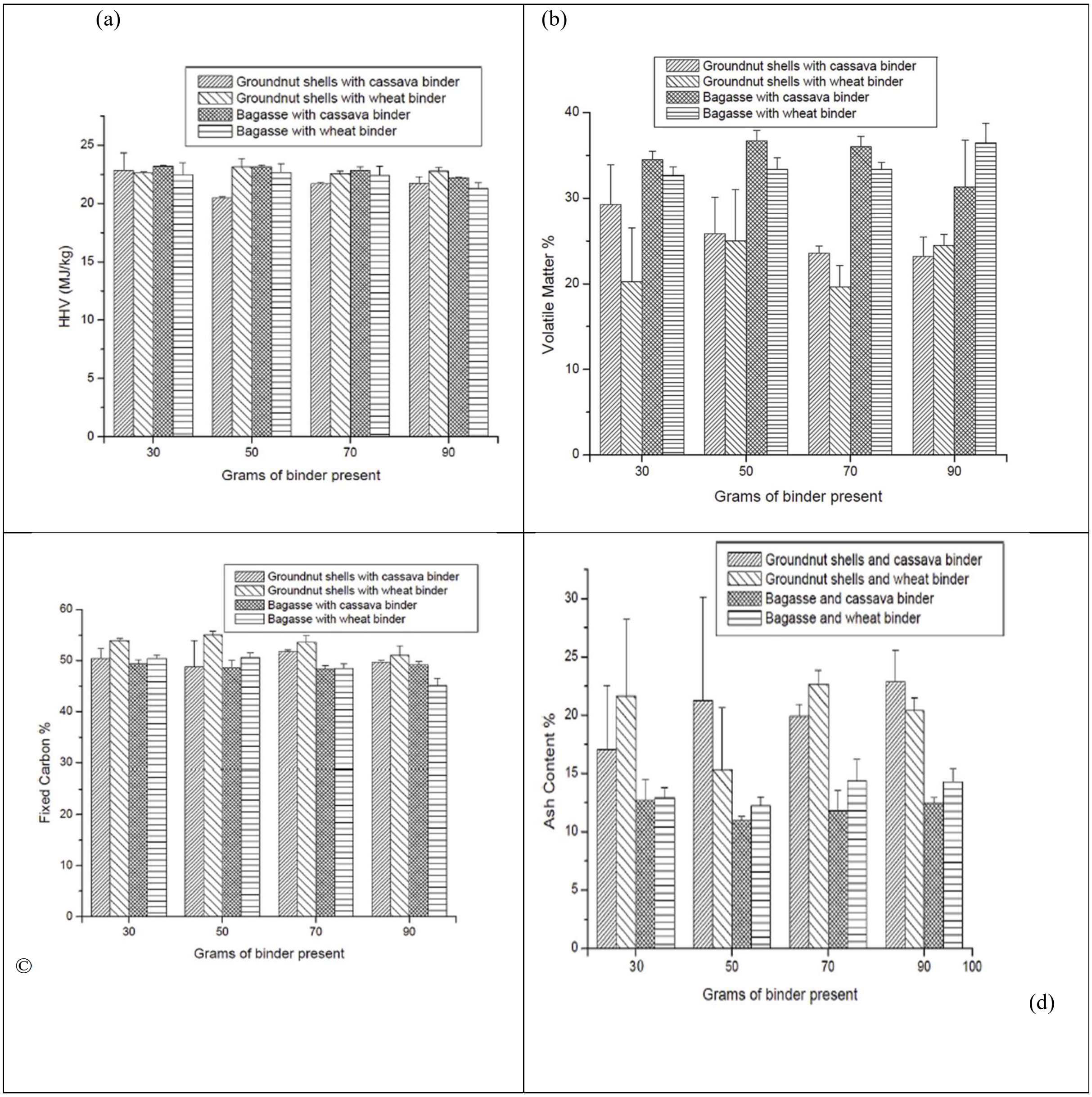

Fig. 2: (a) Higher heating value, (b) volatile matter, (c) fixed carbon content, and (d) ash content of shell and bagasse briquette (Lubwama &Yiga 2017).

Groundnut shells and bagasse briquettes were produced using high- and low-pressure techniques (Lubwama and Yiga, 2017).30, 50, 70, and 90 g of cassava flour binder and wheat flour were added to 1000 g of biochar from groundnut shells and bagasse, respectively. Biochars were produced via low-pressure carbonization. Groundnut shell briquettes were also produced at high pressure (230 MPa) using 1000 g of pristine groundnut shells, 1000 g of groundnut shells with a 250 g cassava flour starch binder, and 250 g of wheat flour starch binder for comparison. Higher heating values of 21 and 23 MJ.kg^{-1} were obtained for both cassava and wheat starch binders, as shown in Fig. 2. The results were above the 16 MJ.kg^{-1} average recorded for non-carbonized groundnut shell briquettes developed under high pressure.

The noncarbonized briquettes had a volatile matter content above 70%, irrespective of the binder type. Lower ash content in the range of 10-25% was reported for both binder type (wheat and starch) and biomass type (groundnut and bagasse) at 30 g of binder content compared to higher binder contents of 70 and 90 g, as shown in Fig. 2.

The physical properties of carbonized corncob briquettes were investigated under different binder types and compaction pressures (Aransiola et al. 2019). In this study, cassava starch, corn starch, and gelatin were used at three different binder concentrations of 10, 20, and 30% wt during briquette production at predetermined pressures of 50, 100, and 150 kPa. The 30% cassava binder and 150 kPa pressure showed improved positive physical attributes. Moreover, a binder concentration of 30% had the most significant effect on all physical parameters examined, followed by 20% and 10%. The compressive strength of the briquettes produced ranged from 1.02-8.32 MPa, with the highest obtained from 30% cassava starch binder and at 150kPa compaction pressure. The lowest compressive strength was recorded with 10% gelatin binder at 50 kPa pressure.

Thabuot et al. (2015) also considered the impact of the binder mix, among other factors, on the fuel properties of holey briquettes prepared from selected biomass waste. Pressures of 40, 50, 60, and 70 kg.cm^{-2} were applied, and the effect of the binder on the density, HH value, and burning rate of the prepared briquettes was investigated. The sun-dried and milled biomass with smaller particle sizes was mixed with 20 wt. % palm fibre with molasses. The results revealed that the amount of molasses significantly affected the

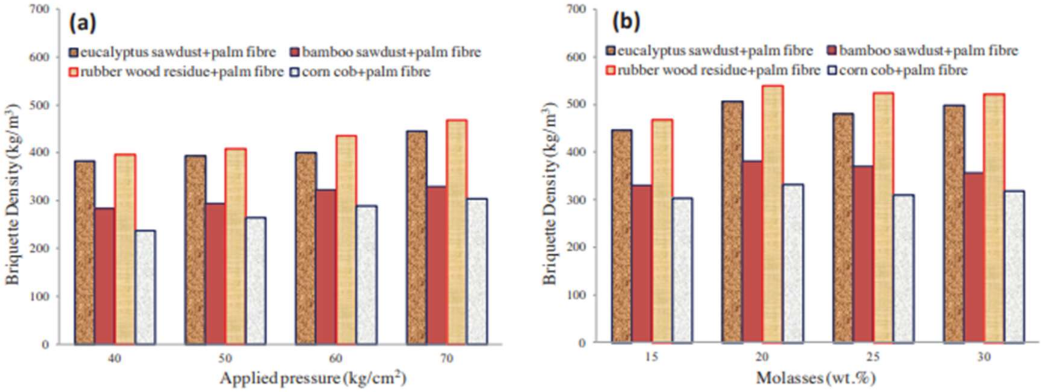

Fig. 3: Effect of applied pressure and density on the Holey briquette (Thabuot et al. 2015).

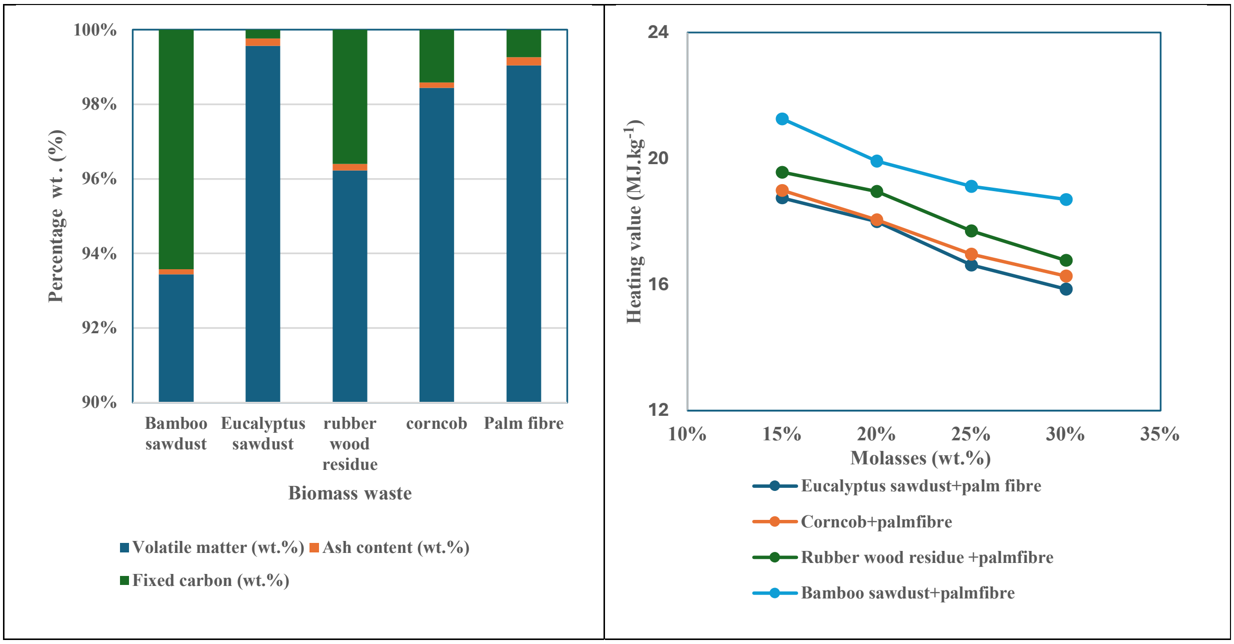

Fig. 4: The Proximate of Biomass waste and HHV relationship with percentage Molasses (Thabuot et al. 2015a).

briquette density, as shown in Fig. 3, with the densest product occurring at 20 wt. % molasses. A higher proportion of the binder resulted in a loose briquette product. The briquettes prepared from rubber sawdust and corn cob increased to 540.76 and 332.54 kg.cm^{-2}, respectively. The briquette had a greater calorific heating value than the biomass material, and the calorific value decreased with increasing binder content, as shown in Fig. 4. This further confirms the influence of the binder on the combustion properties of biomass briquettes.

An investigation on the combustible nature of water hyacinth- plantain peel binder briquettes was conducted by Davies & Abolude (2013). The performance was contrasted with that of firewood (*Anthronotha macrophylla*), charcoal, and red mangrove wood. Water hyacinth had a fuel efficiency of 28.17 ± 0.88%, followed by charcoal with 31.29 ± 0.19%, outperforming firewood and red mangrove wood. The study indicated that water hyacinth briquettes, with their high material strength and value as a combustible fuel, are a good alternative energy source. A higher calorific value was observed for water hyacinth briquettes than for firewood and mangroves, as shown in Fig. 5. This suggests that briquettes are next to charcoal in generating more heat of combustion than firewood and mangroves.

Rajaseenivasan et al. (2016) reported the performance of sawdust and neem powder briquettes and their blends produced within the 7–33 MPa pressure range. According to the results, a significantly greater strength was reported for the neem powder briquettes, although with an increasing calorific value. The briquette properties were enhanced as the pressure increased. Further experiments were conducted at a maximum pressure of 33 MPa, and neem powder was blended with sawdust at ratios of 100:0, 75:25, 50:50, 25:75, and 0:100 (sawdust: neem powder). The strength of the briquettes was enhanced as the neem binder increased in the briquettes and slightly reduced the burning rate. However, increasing the neem content reduced the calorific value of the blend, as shown in Fig. 6 (a).

Igbo (2016) explored the properties of rice husk residue with plantain peel and gum arabic as a binder as a suitable fuel for rural dwellers. Milled rice husk residue, particle

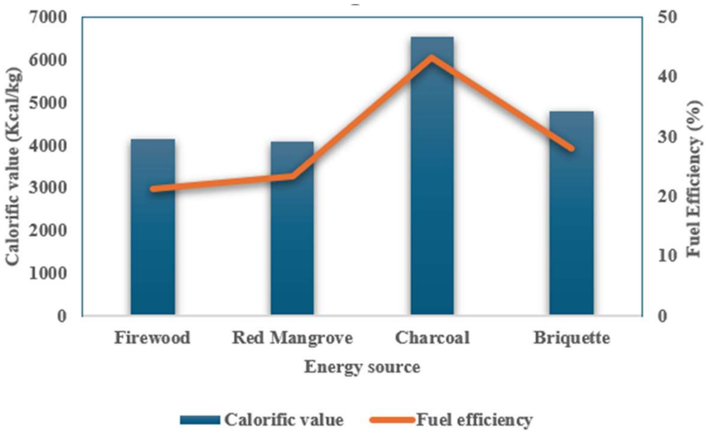

Fig. 5: Comparison of the calorific values of water hyacinth briquette, charcoal, red mangrove wood, and firewood (Davies et al. 2013).

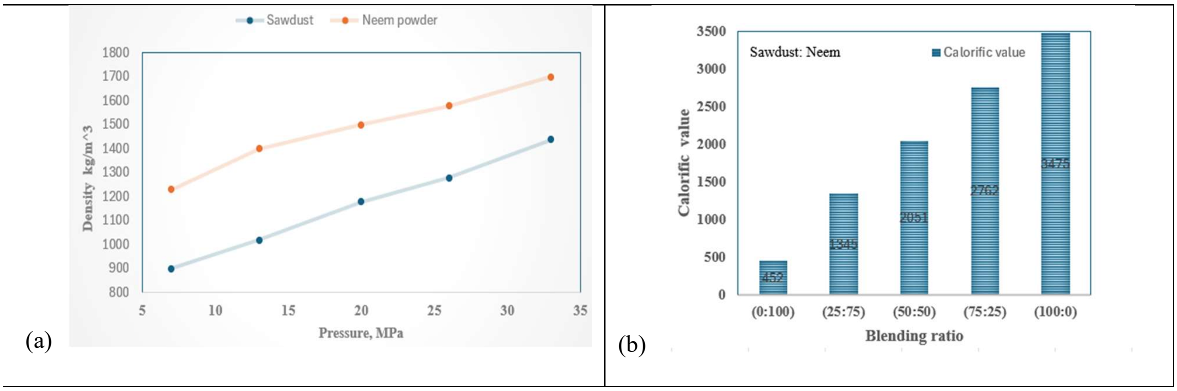

Fig. 6: Density and calorific value of sawdust and neem powder briquettes (Rajaseenivasan et al. 2016).

size of 1.18–0.6 mm and binders of 10 %, 20%, and 30% were added. The briquettes showed higher durability indices of 29.33% and 93% for plantain peel and Arabic binders, respectively, at 30% binder content. In addition, the compressive strength ranged from 1.29 to-4.77 kN.m^{-12}. Hence, the briquette with the gum arabic binder exhibited better mechanical handling characteristics than that with the plantain binder.

Nikkhah Shahmirzadi et al. (2024) produced hybrid charcoal briquettes from date palm and pistachio residues under different starch, molasses, and bitumen contents with binder inclusion. The hybrid briquettes were formed under compaction pressure levels of 100 bar, and the results revealed a 0.63-1.03 g.cm^{-3} range of relaxed density and 0.46 -22.17 N.mm^{-1} range of compressive strength. The briquettes exhibited superior properties at a starch binder content of 20%. The physicomechanical properties were optimal within the 15-20% binder content range, even for better-quality storage and transport.

Fengmin & Mingquan (2011) evaluated the effect of loess and lime binder on certain properties of briquettes, such as the calorific value, in giant reeds and reed biomass. The calorific value of the briquettes decreased with increasing binder content. The increasing binder content was suggested to be responsible for reducing the combustible component of the overall briquettes. Giant reed briquettes with loess had a higher calorific value than reed briquettes with loess. The calorific values of giant reed briquettes and reed briquettes were between 10.3 and 19.8 MJ.kg^{-1}. The briquettes exhibited optimum mechanical properties at a binder content of 30%. Giant reed briquettes and giant reed briquettes with a loess binder have calorific values of 14.2 MJ.kg^{-1} and 13.4 MJ.kg^{-1}, respectively. The giant reed briquettes and reed briquettes with lime binder had calorific values of 13.7 MJ.kg^{-1} and 14.5 MJ.kg^{-1}, respectively. The binder was confirmed to have significantly influenced the biomass performance of the briquette. The combustible component of the briquettes decreased with increasing binder content, resulting in higher ash content. The biomass content also plays a notable role in this briquette, as the optimal biomass content is 45%.

Inorganic Binders

Bentonite clay was explored as a binder to produce binary briquettes made from vegetable market waste with sawdust at ratios of 25, 50, 75, and 100% (Afsal et al. 2020). The performance of the VMW-based biomass briquettes was compared with that of firewood, coal, and conventional sawdust briquettes. The composite briquettes exhibited superior combustion properties, including a higher calorific value, compared to the pure VMW briquettes. The proportion of volatile matter increased for the VMW and SD composite briquettes from 71.72% to 83.2%, with the maximum percentage occurring at a ratio of 25:75 (VMW:SD). The composite briquette, including VMW and SD at a ratio of 25:75, yielded the highest heating value among the briquettes, with a calorific value between 14.002-15.721 MJ.kg^{-1}.

Kebede et al. (2022)examined the effects of wastepaper pulp and clay soil as binding materials on biomass residues such as coffee husk, sawdust, khat waste, and dry grass. A weight ratio of 3:1 was used to combine the biomass waste and binder, and an average pressure of 2 MPa was used to compact the materials. Among the residues, sawdust residue-produced briquettes had the highest fixed carbon content and HHV. Moreover, the sawdust residue had the lowest amounts of ash and sulfur. The study's findings also demonstrated that the paper pulp-bonded briquette had the maximum calorific value. Hence, combining sawdust residue with paper pulp briquette binding material results in a high-quality and long-lasting solid fuel briquette, and paper pulp binds better than clay soil.

Celestino et al. (2023) established that the binder type remarkably affects the physico-thermal and mechanical properties and calorific value of biocomposite briquettes. In their experiment, hybrid binders, clays, and gum arabic were considered for developing mixed biochar briquettes at low pressure ($\leq$ 7 MPa). The biocomposite briquettes with clay binder had heating values ranging from 17140 to 18336 kJ.kg^{-1}, briquettes with gum Arabic binder 18053 to 18665 kJ.kg^{-1}, and 17404 to 18232 kJ.kg^{-1} for biocomposite briquettes with hybrid binder. This indicates a higher calorific value for briquettes with gum Arabic than for briquettes with other clay and hybrid binders. However, the hybrid binders exhibited better performance (density, compressive strength, and burning rate) owing to their reduced boiling time, higher burning rate, and compressive strength. Hence, this is recommended. This suggests the potential of different binders in biocomposites for domestic and industrial applications.

Coal-rice husk and coal-corn cob briquette compositions were developed by Ikelle (2017) at various ratios. In this study, bitumen, starch, calcium sulfate, and cement were explored as binders, while calcium hydroxide served as the desulfurizing agent. The sample briquettes were produced under a force of 276.36 N and a compression pressure of 31.67 N.m^{-2}. According to Fig. 7, briquettes manufactured from coal and rice husk have calorific values in the range of (24441.12 -27083.07-33.67 KJ.kg^{-1}), while coal and corn cob had lower calorific values of (22823.93-23940.37). The briquettes made with bitumen binder ignited more quickly (16.00–37.00 s), had higher sulfur concentrations (3.01–8.22

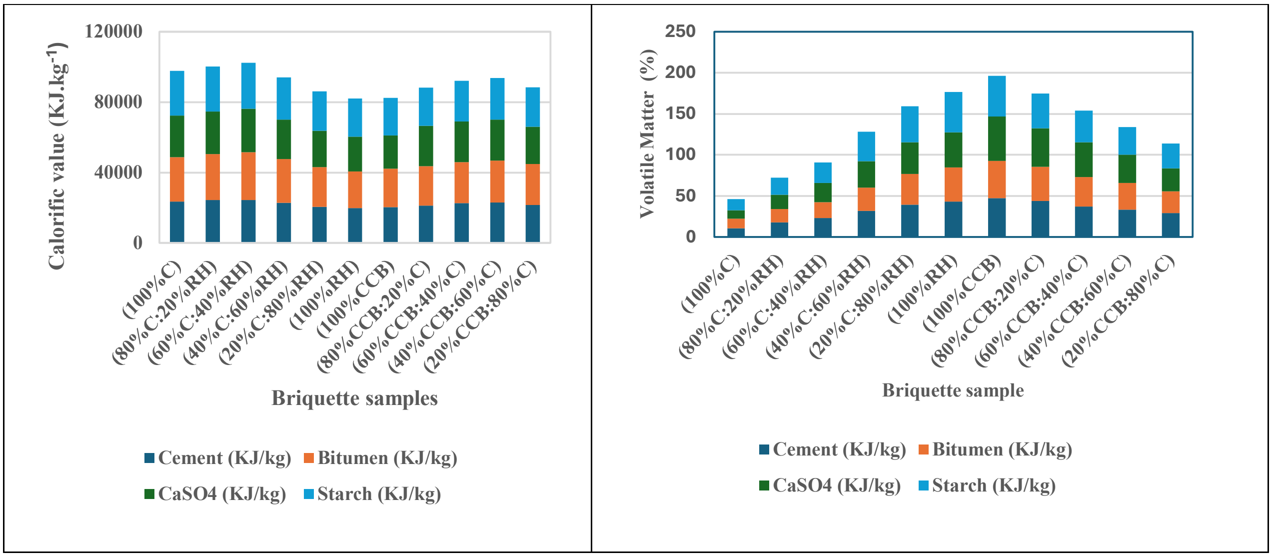

Fig. 7: Calorific value and time of briquette samples of various blends (Ikelle 2017).

%), and burned for shorter periods (11.71–24.89 min) compared with other types of binder briquettes. In addition, it has high ash contents in the ranges of 18.88-29.63% and 19.13-28.83%. Briquettes are made with calcium sulfate and binder cement, which contain non-combustible ingredients, resulting in high content. Briquettes with starch binder had the longest burning times (15.27–26.21 min), the lowest sulfur contents (3.03–6.21%), and the maximum compressive strength values (7.92–13.74 N.mm^{-3}). These properties of the starch binder are the best among all the binders studied. The briquettes with starch binder had the lowest sulfur content. The compressive strength of the coal-based briquette ranges from either 40% rice husk (11.34-13.95) or 40 % corncob (12.75-14.46) N.mm^{-3}, which is higher than 100% coal, ranging from 7.05-7.92 N.mm^{-3}.

Emerging Binders (Polymer, Coal Tar, Nano-Binders and Microalgae)

The effects of carbonization temperature (350°C, 400°C and 450°C) and two different binders (tapioca gel and polyvinyl acetate (PVAc) adhesive) on the combustion characteristics of water hyacinth biomass were examined by Pramadhana et al. (2017). The Carbonization process enhanced the HHV and fixed carbon content of the briquettes. The best performance was achieved using tapioca gel as the binder at 450°C. Under these conditions, the biomass briquette fixed carbon content improved up to 34.14% with an HHV of 3,837 kcal.kg^{-1}, although the combustion efficiency was 4.89 %.

Potato starch and carboxymethyl cellulose (CMC) waste at 5 %, 10 %, and 15 % were used as binders in briquetting food waste char in a study by Idris et al. (2021). The starch binder provided better combustion quality than carboxymethylcellulose (CMC) in the briquettes. The energy content of the food waste charcoal (23.27 MJ.kg^{-1}) was comparable to that of commercial charcoal (22.83 MJ.kg^{-1}). However, a slight decline in the calorific value was observed upon the addition of binders, which was more conspicuous when CMC was added, as shown in Fig. 8.

Afra et al. (2021) observed an enhancement at 3, 6, and 9% w/w nano lignocellulosic binder inclusion to produce shredded and ground bagasse briquettes. These binders include nano lignocellulose, nanocellulose, and lignin. The briquettes were achieved using a cylinder-piston system and a densification process at 150 MPa and 100 °C. A compressive strength of 34 N.mm^{-1}, HHV-29 MJ.kg^{-1}, of FCC-14.49%, VM-72.19% and ash content of 4% were reported with 9% nano-lignocellulose binder. A Compressive strength of 29.45 N.mm^{-1}, HHV-19.85 MJ.kg^{-1}, FFC-13.81%, VM-72.57%, and AC-7% were also reported for the nanocellulose binder at 9%. However, the lignin binder in the briquettes had a higher calorific value and superior thermal characteristics, according to the data. At 9%, the lignin binder increased the briquette calorific value by an average of 33.5%. Nanolignocellulose and nanocellulose binders have improved physical properties compared to those of the lignin binder briquette.

The potential of LLPE as a binder to torrefy biomass during pelleting was investigated byYang et al. (2018). LLDPE was added to the torrefied biomass straw, which improved the HHV, reduced the ash level, and increased the fracture load and tensile strength of the pellets. The wood pellets fulfilled all current requirements for use in commercial applications. Except for density, the best outcomes were obtained at a 10%

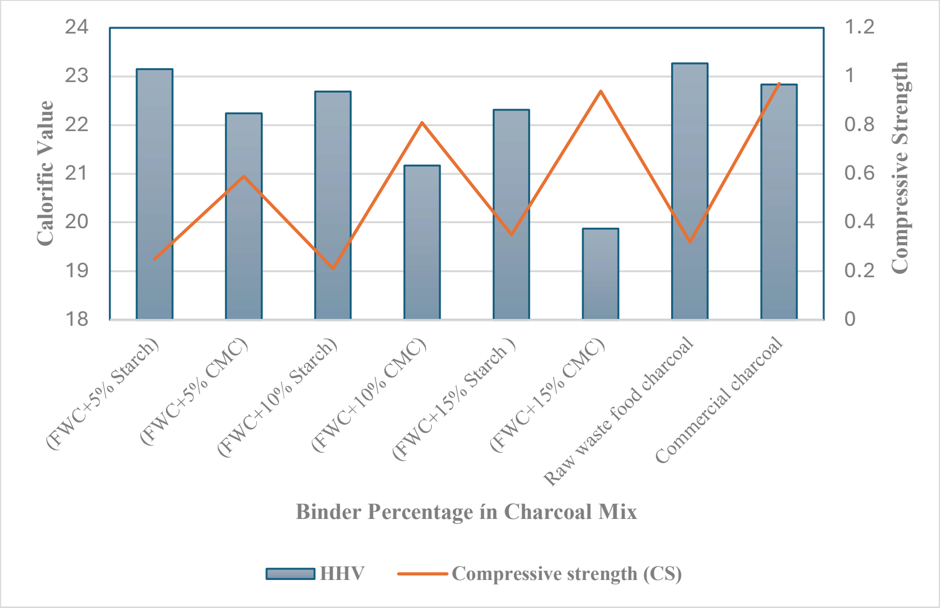

Fig. 8: Calorific value and compressive strength of each sample.

load concentration of LLDPE in the torrefied barley blend. LLDPE can be obtained from MSW, and its application may be found in torrefied biomass.

Si et al. (2017) examined the influence of coal tar residue waste as a binder for producing biomass pellets from wheat straw, bamboo, and sawdust. In this study, pollutant emissions and strategies for mitigating NO, SO_2, polycyclic aromatic hydrocarbons (PAHs), and dioxins (PCDD/Fs) during biomass pellet burning were investigated. Sawdust had the lowest NO and SO_2 emissions of the three biomass pellets, whereas bamboo and wheat straw pellets had the highest emissions.

A reduction in NO, SO_2, PAH, and PCDD/F emissions was observed by adding a 30% weight CTR binder to the biomass briquette. However, as the furnace temperature increases from 800-1300°C, a steady rise in SO_2 emissions was observed with wheat straw pellets having a 30% weight percentage CTR binder. NO production was restricted owing to the stronger reducing atmosphere generated by the biomass pellet volatiles, leading to a reduction in NO emissions. In addition, the addition of limestone sorbent further reduced SO_2 emission of wheat straw pellets by 55.6–71.0% with 30 weight percent CTR binder.

The environmental and economic benefits of coal tar residue (CTR) have necessitated its exploration and reutilization as a possible binder for preparing biomass pellets (Cheng et al. 2018). This enhances the mechanical strength and heating value. The CTR has 40.06% asphaltenes, aliphatics, aromatics, and non-hydrocarbon components, 72,276 MPa s viscosity, and HHV of 27.46 $MJ.kg^{-1}$. The heating value of the biomass pellet increased from 20.62% to 25.96% as the CTR percentage increased from 0 to 40 wt%.%. Other properties, such as abrasive resistance and ignition temperature, also significantly increased with increasing CTR binder content. They also reported a decline in the burning rate from 1.28-0.82 $mg.min^{-1}$, and an increase in the burnout temperature from 465.33–563.33°C.

To mitigate the raw material challenge of the wood pellet industry, plastic polymers as binders for torrefied and pelletized herbaceous biomass were examined in a study by Emadi et al. (2017). The mechanical, storage, and combustion characteristics of the briquettes were investigated. Four different concentrations of LLDPE (1, 3, 6, and 10%) were added to the torrefied biomass. According to the findings, 6% LLDPE inclusion in the biomass led to a density increase of 1.8 % and 1.7% for wheat and barley, respectively. An increment of 280% and 253% was observed for the tensile strength of wheat and barley, respectively, at 10% LLDPE inclusion in the torrefied biomass pellets.

Similarly, adding 1–10% LLDPE to torrefied wheat and barley straw pellets led to a 20.50 $MJ.kg^{-1}$ HHV and lower ash content of up to 6%. Except for 10%, the HHV of the pellets at all additional LLDPE levels satisfied the most recent DIN 51731 standard for commercial pellets (Fig. 9). It was observed that the ash content, except at 1% LLDPE, complied with the specifications required for pellet fuel.

The potential of tar and tapioca flour as binding agents in producing carbonized durian peel bio-briquettes was

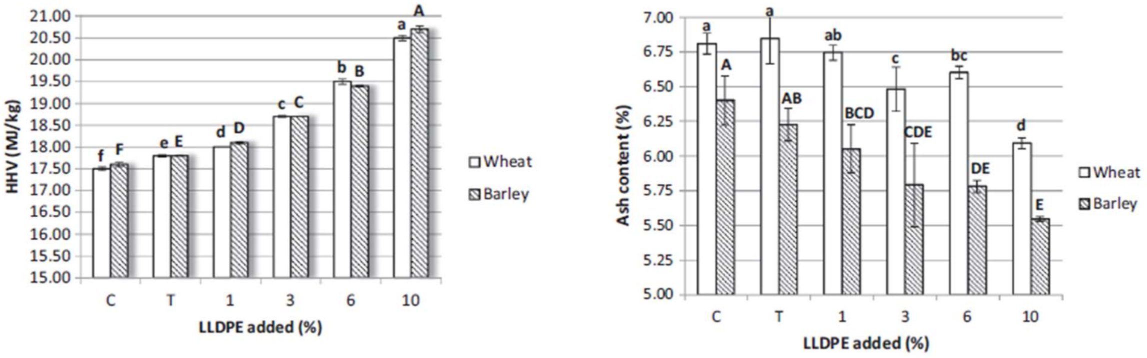

Fig. 9: HHV and AC of barley straw pellets of varying LLDPE binder (Emadi et al. 2017).

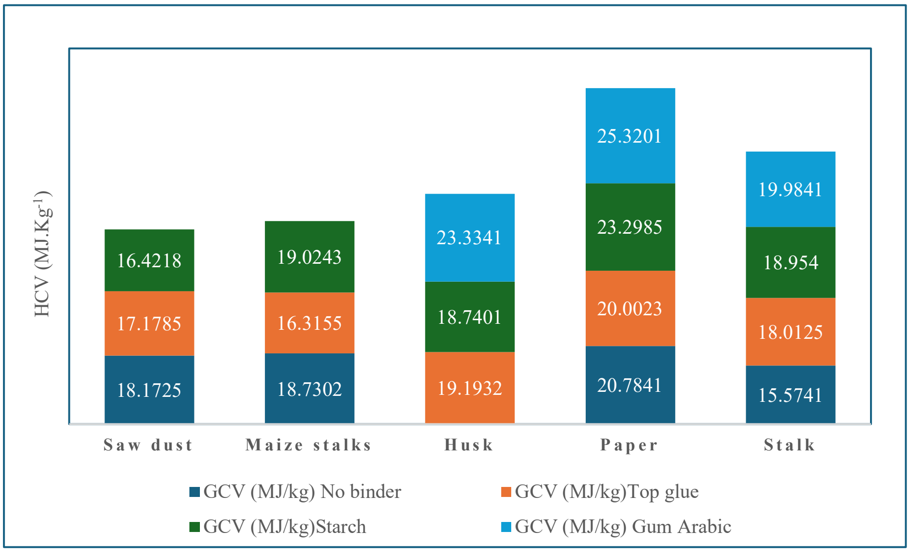

Fig. 10: Comparison among classes of binders (top burnt glue, starch, and gum arabic) (Zakari et al. 2013).

explored and confirmed by Soeherman et al. (2023). A proportionate combination of tapioca and tar fell within the 25-75% range for each blend. The calorific value was maximum (90694.53 cal.g^{-1}) at 75:25 of Tar to Tapioca blend. The briquette density ranged from 0.5029 g.cm^{-13} to 0.5685 g.cm$^{-3,}$ and the 75:25 blend absorbed the least amount of water (29.43 %).

Zakari et al. (2013) examined in a different study the impact of binder addition, among other factors, on the HC values of five (5) specific biomass briquettes. The experimental findings revealed that finely ground particles (1.75–2.00 mm) had low calorific values owing to heat loss, which made the sample susceptible to oxidation by air. The inclusion of gum Arabic binder significantly increased the HCV of all samples compared to the addition of starch, as shown in Fig. 10. Over the biomass spectrum evaluated, the top glue binder HCVs tended to decline, falling in the sequence 25.3201> 23.2985> 20.0023. Therefore, compared to top glue and polyvinyl chloride (PVC), which have lower HCV, gum arabic and starch are better binders with higher calorific values. After a thorough analysis, it was discovered that all briquette samples, except those composed of rice husks and coconut shells, had lower caloric values when PVC was used as a chemical binder and dissolved in organic toluene.

Commercially available starch and calcium hydroxide were suitable as binders for solid biofuel from briquetting durian peel, as reported by Mitan et al. (2018). Densification was carried out using a 4% weight ratio of various binders with durian peel. NC, NCC, and NCS denote noncarbonized, noncarbonized with calcium hydroxide, and noncarbonized with starch, respectively. The noncarbonized briquette had a compressive strength of 130.19 and a peak calorific value (theoretical) of 18.62 MJ.kg^{-1}, as shown in Fig. 11.

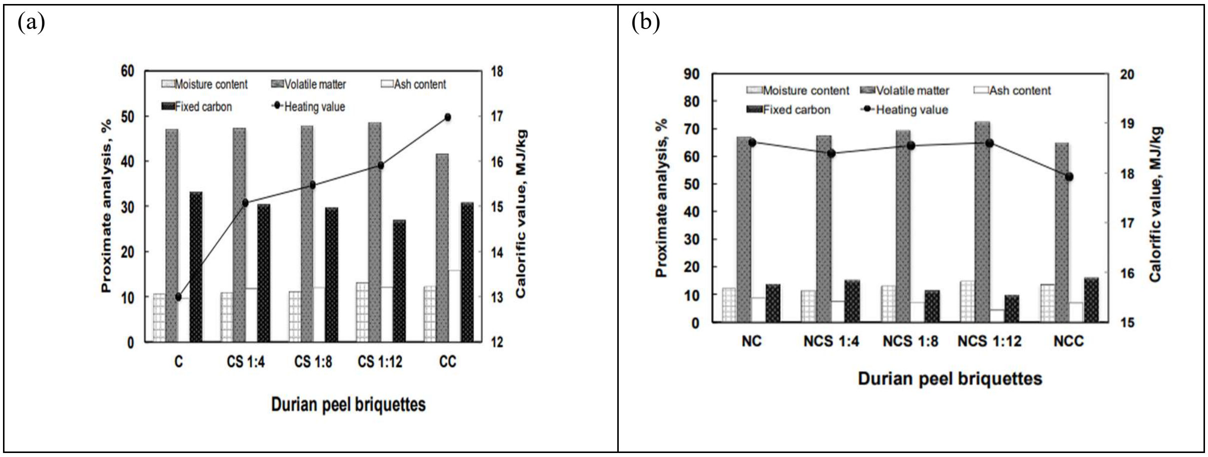

Fig. 11: Proximate analysis and heating values of (a) carbonized durian peel briquettes and (b) uncarbonized durian briquettes (Mitan et al. 2018).

Briquettes produced from blends of rice husks, corn cobs, and bagasse were examined to determine the influence of different types of binders on their energy content and physical and combustion properties. This comparative study was conducted by Muazu & Stegemann (2017) using a multilevel factorial design experiment. This study achieved a compressive strength of 175 kPa when a pressure of 31 MPa was applied to a microalgae-bonded 2:4:1 rice husk, corn cob, and bagasse blend. The briquette density was enhanced by the biosolid and microalgae binder, while a reduction in density was reported with starch binder inclusion. Conversely, a decline in briquette strength has been reported for biosolid binders. The microalgae-bonded biomass exhibited a higher energy value, slower mass loss at combustion, and greater mass loss at glow time. This result encourages the use of microalgae for biomass briquetting.

The qualities and characteristics of EFB combustion were examined by Nazari et al. (2020). The effects of carbonization and densification on briquette materials were highlighted. To carbonize the EFB, binders were used at a set ratio of 20%. The quality of carbonized EFB briquettes was investigated, and the outcomes were contrasted with those of EFB briquettes that had not been treated. Based on its moderate physicochemical features, the TS2 briquette, which has a tapioca starch solution ratio of 110/20, is the best formulation, according to the results. Furthermore, the briquette exhibited a maximum HHV of 23.62 MJ.kg^{-1}, which is approximately 30% higher than that of the briquette from untreated EFB. Overall, combining carbonized EFB with tapioca starch enhanced the quality of the briquettes and increased their potential for application in syngas manufacturing.

To manage solid waste as a substitute energy source, corn cob agricultural waste was carbonized and developed into briquettes with tapioca starch binder contents of 6.0, 10.0, 14.0, and 19.0. This study was conducted by Zubairu & Gana (2014). The properties of the developed briquettes were compared with those of wood charcoal and bagasse. The blended charcoal and tapioca briquette had an HHV of 32.4 MJ.kg^{-1} compared to bagasse (23.4 MJ.kg^{-1}) and wood charcoal (8.27 MJ.kg^{-1}). It is considered a superior fuel because of its higher bulk density and fixed carbon content.

In a study by Song et al. (2020), biomass samples of waste cotton stalk (CS) and wood sawdust (WS) were pretreated at 200, 230, and 260 °C utilizing two distinct thermal processes: dry torrefaction (DT) and hydrothermal treatment (HT). The biomass was densified to create briquettes, and the briquettes were carbonized at 400°C to create charcoal briquettes devoid of binders. The findings show that the physical characteristics of the HT charcoal briquettes, such as their mass densities and compressive strengths, are superior to those of the DT and untreated charcoal briquettes, as well as conventional BBQ charcoal that has had a binder added. HT charcoal briquettes were found to have combustion character indexes comparable to the European commercial standard for charcoal, as well as fixed carbon and ash yields. The best materials for making charcoal briquettes in this study were CS and WS, which were hydrothermally processed at 230°C.

This review has presented an array of agro-wastes and binders used in briquetting technology for waste valorization, management, and sustainable energy generation. The summarized data are presented in Table 1. Briquetting technology was also harnessed to ensure that loose agro-waste biomass is effectively compacted for improved energy density, heating value, combustion properties, and waste utilization. Critical observations affirmed that the binder type, percentage binder content, and other process conditions significantly influenced the combustion performance of the

Table 1: Summary of agro-waste, processing conditions and compressive strength.

Author	Biomass type	Binder used	Composition/process condition	Calorific value	Optimal conditions	Compressive strength(CS), Density Combustion performance (CP)
(Igbo 2016)	Rice husk	Plantain peel (PP) Gum Arabic (GA)	10,20,30 wt.%-binder (1.18-0.6 mm) particle size	-	10% (PP) 30% (GA)	CS: 1.87 KN.mm^{-2} (PP); CS: 4.77KN.mm^{-2} (GA) DI(%): 39% (PP10); 93%(GA30)
(Nikkhah Shahmirzadi et al. 2024)	Date palm and Pistachio residue	Molasses (M) Starch (S) Bitumen (B)	100 bar 5-20 wt.% -binder	(S):-22.03 M.kg^{-1}	20%	CS: 0.46 N.mm^{-2} (M20) CS: 22.17 N.mm^{-2} (S20) RD: O.62 g.cm^{-3} (M10) RD: 1.03 g.cm^{-3} (S20)
(Fengmin & Mingquan 2011)	Giants reeds (GRB) and reeds (RB) biomass	Loess Lime	Binder: 10,20,30,40 & 50%	GRB:(13.7-14.2) MJ.kg^{-1} RB:(13.4-14.5) MJ.kg^{-1}	30%	Drop strength (%) With loess: 89-96 % With Lime:65-97 %
(Pramadhana et al. 2017)	Water hyacinth biomass	Tapioca gel(TG) Polyvinyl acetate (PVAC)	carbonisation 350,400&450°C 5% binder	(TG):16.1 MJ.kg^{-1} (PVAC):15.9 MJ.kg^{-1}	5%	Combustion efficiency (CE)-4.89% (TG)
Celestino et al. 2023	Biochar briquette	Hybrid binder (HB) Clay (CY) Gum Arabic(GA)	7 MPa max. 2.4, 3.6,4.7, 5.8,6.9 &13%	HB: 17.4-18.2 MJ.kg^{-1} CY: 17.1-18.3 MJ.kg^{-1} GA: 18.1-18.7 MJ.kg^{-1}	HB-13% GA-6.9% CB-6.9%	CS:12.25 KN.m^{-2} (HB) CS: 5.13 KN.m^{-2}(CY) CS:8.3 KN.m^{-2}(GA)
(Aransiola et al. 2019)	Corn cob briquette	Cassava starch(C) Corn starch (CNS) Gelatine(GT)	Binder:(10,20,30%) Pressure: 50,100, and 150KPa	-	30%, 150KPa	Density:1437.42kg.m^{-3} ;CS:8.32 MPa (C) Density:1308.75kg.m^{-3};CS:5.42MPa (CNS) Density: 1231.53 kg.m^{-3}, CS: 5.05 MPa (GT)
(Thabuot et al. 2015)	Holey/Palm fiber Briquettes	Molasses (M)	Binder;(15,20,25,30 %) Pressure:40-70 kg.m^{-2}	18.0- 19.92 MJ.kg^{-1}	20%; 70kg.m^{-2}	Density: 540.76 kg.cm^{-3} (M)
(Davies & Abolude 2013)	Water hyacinth-plantain peel briquette	Plantain -peel briquette	Binder:(10,20,30,40,50%) Pressure: (3,5,7,9)MPa	-	50% 9 MPa	CS: 2.66 N.mm^{-2} (50%) CS: 2.28 N.mm^{-2}(9MPa)
(Rajaseenivasan et al. 2016)	Sawdust-neem briquette	Neem	Binder: (0, 25, 50, 75, 100) % Pressure (7,13, 20, 26, 33)MPa	2762 kJ.kg^{-1}	25%; 33MPa	Impact resistance: 28X
(Bency et al. 2023)	Cabbage Waste	Beef Tallow oil(BTO) Cassava binder(CB) Sodium silicate (SS) Vinyl ester resin(VER)	20%	BTO:22.4 MJ.kg^{-1} (appx.) SS:20.1 MJ.kg^{-1} VER:24.3 MJ.kg^{-1} (appx.) CB: 20 MJ.kg^{-1} (appx.)		Density:545.6- 591.3 kg.cm^{-3}
(Lubwama & Yiga 2017)	Groundnut shell and baggase biochar	Cassava (C) Wheat starch(W)	Binder:(30,50, 70 and 90g) per 1000g biomass Pressure:230 MPa	Briquette (21-23) MJ.kg^{-1}	C-30% W-70/90%	Drop strength: :95-100% (C) binder :80-90% (W)binder
(Cahyono et al. 2017)	Coconut	Durian seed	(4,6,8,10, 12)wt.%	25.1-25.9 KJ.g^{-1}	8%	CS: 10 kg.cm^{-2}

Table Cont....

Author	Biomass type	Binder used	Composition/process condition	Calorific value	Optimal conditions	Compressive strength(CS), Density Combustion performance (CP)
(Arewa et al. 2016)	Rice husk briquette	Cassava peel (CP) Cassava starch (CS)	(1-10 %) (1-5 %)	-	10% 5%	Relaxed Density(RD); Burning rate (BR) RD: 571.1 $kg.m^{-3}$(CP), BR:1.715$g.min^{-1}$ (CP) RD: 632.2 $kg.m^{-3}$ (CS); BR:1.76 $g.min^{-1}$ (CS)
(Falemara et al. 2018)	Groundnutshell, corncobs, Wood residue, particles	Starch	(15-25%)	-	25%	Specific heat of combustion (SHC):7362-8222 $Kcal.kg^{-1}$ Density: 044-0.53 $g.cm^{-3}$
(Carnaje et al. 2018)	Water hyacinth briquette	Molasses	(60, 70, 80)%	16.6 $MJ.kg^{-1}$	30:70	CS: 19.1 $kg.cm^{-2}$.
(Wirabuana & Alwi 2021)	Durian Lai Peel	Starch binder (SB)	3%, 4%,5%, and 6% (w/w)	23.01 $MJ.kg^{-1}$	3 % (w/w).	-
(Ohagwu et al. 2022)	Sawdust briquette	Okra	5-20%	17.82 $MJ.kg^{-1}$	5%	CS: 22.0- 31.0 $KN.mm^{-2}$
(Tahir et al. 2012)	Groundnut shell(GS) Durian shell(DS) Casava peel(CP)	Binding agent	10-30%	GS:24.03 $MJ.kg^{-1}$ CP:19.87 $MJ.kg^{-1}$ DS: 21.87 $MJ.kg^{-1}$	70:30 70:30 90:10	CS:50.4 $KN.mm^{-2}$ (GS) CS:29.5 $KN.mm^{-2}$(DS) CS: 38.0 $KN.mm^{-2}$(CP)
(Anggono et al. 2016)	C.manghas waste	Tapioca binder	(10-50%)	17.422 $MJ.kg^{-1}$	90:10	-
(Afsal et al. 2020)	Vegetable market waste (VMW) Sawdust (SD)	Bentonite clay	VMW:SD composite 25, 50, 75, and 100%	15.721 $MJ.kg^{-1}$	VMW: SD=25:75	-
(Afra et al. 2021)	Shredded (SB) and ground (GB)bagasse	Non-lignocellulosic (NCS) Nanocellulose (NC) Lignin (LB)	3,6,9 w/w of binder 150 MPa, 100°C	29.85 $MJ.kg^{-1}$ -NCS 19.85 $MJ.kg^{-1}$-NC	9% NCS	CS: 34 $N.mm^{-1}$ (SB) VM-72.57% (SB) CS: 29.45 $N.mm^{-1}$ (GB) VM-72.15 (GB)
(Cheng et al. 2018)	Wheat straw(WS) Sawdust(SD) Moso bamboo(MB) pellets	Coaltar (CTR)	0-40 wt.%	19.32 $MJ.kg^{-1}$ (WS) 21.35 $MJ.kg^{-1}$ (SD) 21.00 $MJ.kg^{-1}$ (MB)	30% (WS) 35%(SD)	BR: 0.82 $mg.min^{-1}$ (WS) BR: 0.81 $mg.min^{-1}$ (SD) -
(Emadi et al. 2017)	wheat Straw Barley straw pellet	LLDPE	(1,3,6 & 10%)	20.50 $MJ.kg^{-1}$ (Wheat) 20.7 $MJ.kg^{-1}$ (barley)	10% 10%	Density 1087.55 $kg.m^{-3}$ -wheat 1085.37 $kg.m^{-3}$- Barley
(Soeherman et al. 2023)	Carbonised durian peel / Tapioca flour	Tar	(25-75)%	40.56 $MJ.kg^{-1}$	Tar: Tapioca 75:25%	Density 0.5685 $g.cm^{-3}$

Table Cont....

Author	Biomass type	Binder used	Composition/process condition	Calorific value	Optimal conditions	Compressive strength(CS), Density Combustion performance (CP)
(Zakari et al. 2013)	Saw dust Maize stalk Hsuk Paper stalk	Gum Arabic (GA) Top glue (TG) Starch (ST)	Particle sizes (1.70 mm,2.0 mm and 3.35 mm)	(GA):25.3-20.0 MJ.kg^{-1} (TG):16.3-20.0 MJ.kg^{-1} (ST):16.4-23.2 MJ.kg^{-1}	3.35 mm Particle size	-
(Mitan et al. 2018)	Duran peel	Starch Calcium hydroxide	4%	18.62 MJ.kg^{-1} 18.0 MJ.kg^{-1}	4%	CS: 130.19 MPa
(Ikellle 2017)	Coal-corn cob(CCB)/ Rice husk(RH) briquette	Bitumen (B) Starch (S) Calcium sulphate (CS) Cement(C)	20,40,60,80 &100%	(B):27.1 MJ.kg^{-1} (CS):24.8 MJ.kg^{-1} (S): 25.9. MJ.kg^{-1} (C): 24.4 MJ.kg^{-1}	60%:40% (CCB/RH)	CS: 11.34-13.95 N.mm^{-3}(C/RH) CS: 12.75-14.46) N.mm^{-3}(C/CCB)
(Jittabut 2015)	Rice straw and sugar cane leaves	Molasses	50%	17.83 MJ.kg^{-1} sugar cane leaf	50:50	CS-32.4-44.7 kg.cm^{-3}
(Davies & Abolude 2013)	Water hyacinth	Phytoplankton	10, 20, 30, 40 & 50% 20MPa	17.9 MJ.kg^{-1}	50%	Burning rate (BR) 2.25 g.m^{-1} Ignition time (IT): 73.54-123.42 min.
(Espuelas et al. 2020)	Spent coffee grounds	Xanthan and guar gum	8,10, 12 MPa 5&10% binder	Guar:(24.321-24.398) MJ.kg^{-1} Xanthan:(23.503-24.450) MJ.kg^{-1}	5%; 10MPa	-
(Muazu & Stegemann 2017)	Rice husk (RH) Corncob(CC) baggase	Starch, Treated biosolid Microalgae	6%; 19-31 MPa	-	6%,; 31MPa	25RH:65CC Energy density (ED): 1237-1247 kJ.m^{-3}; CS: 175KPa (Microalgae) ED: 1186-1196 KJ.m^{-3} ;CS: 146KPa-(Biosolid) ED: 1162 KJ.m^{-3} ;159 KPa (Starch)
(Rajput et al. 2020)	Groundnut shell (GNS) Sawdust (SWD) Leaf litter waste (LLW)	Polyvinyl Alcohol (rPVA) Waste cooking oil (WCO) Waste Lubricating oil (WLO)	(2,4 & 6)% 20:40:60 biomass blend	17.08 MJ.kg^{-1} 16.03 MJ.kg^{-1} 21.61-21.83 MJ.kg^{-1} 20.54-21.78 MJ.kg^{-1}	6% binder	-
(Song et al. 2020)	Cotton stalk (CS) Sawdust (WS)	Hydrothermal treatment(HT)	(200-260)°C; 75-80 MPa	CS-HT:25.66 MJ.kg^{-1} WS-HT:27.94 MJ.kg^{-1}	260°C	Ignition tempt CS-274.68°C WS-291.25°C
(Yank et al. 2016)	Rice husk Bran briquette	Cassava waste water Rice dust Okra gum	RH: 0,5 &10% Binder: 0,5,10& 15%	16.0-16.45 MJ.kg^{-1}	10%	Density: 2.54KN 475 Kg.m^{-3} (CSW) 465 kg.m^{-3} (RD) 440 kg.m^{-3} (OSG)

Table Cont....

Author	Biomass type	Binder used	Composition/process condition	Calorific value	Optimal conditions	Compressive strength(CS), Density Combustion performance (CP)
(Shuma & Madyira, 2018)	Peanut shell (PS) Yellow thatching grass (YG) Mopani leaves (ML)	Cow dung Cautus plants	6,12, 19 MPa	PS: 15.5-17.1 MJ.kg^{-1} YG: 12.6-15.79 MJ.kg^{-1} ML: 16.36-21.53 MJ.kg^{-1}	12MPa	-------------------
(Narzary et al. 2023)	Waste rice straw	Starch Paper Taro starch	10,15,20	(24.049-28.64 MJ.kg^{-1})	20%	Specific fuel consumption (SFC) Taro-43.3 g.L^{-1} Paper-48.72 g.L^{-1} Starch-56.41 g.L^{-1}
(Kimutai & Kimutai 2019)	Cashew nut shell	Cassava binder	10%,20% & 30% Pressure:100 -300 kg.cm^{-2}	30.5 MJ.kg^{-1}	30% 0.5mm 300 kg.m^{-3}	BR: 9.416 g.m^{-1} IT: 29sec CS: 65-75 kg.cm^{-3}
(Idris et al. 2021)	Food waste (FWC) charcoal	Potato starch carboxyl cellulose (CMC)	5%,10% &15%	(19.87-23.15) MJ.kg^{-1}	5%	IT: 222.45sec (FWC) IT: 242-247.0 sec (FWC+Starch/CMC) IT: 251.3 sec (Commercial charcoal)
(Katimbo et al. 2014)	Mango waste seed cover (MWSC)	Starch (S) Starch-clay soil(SC) Starch red soil(SR)	-	Starch clay:15.92 MJ.kg^{-1} Starch red:15.10 MJ.kg^{-1} Starch: 16.14 MJ.kg^{-1}	-	CS: 22.9 N.mm$^{-2;}$; Density: 1.66 kg.m^{-3} (SC) CS:16.7 N.mm^{-2}; Density:1.55 kg.m^{-3} (SR) CS:34.0 N.mm^{-2}; Density:1.46 kg.m^{-3} (S)
(Oroka & Thelma 2013)	Water hyacinth(WH)	Cow dung (CD)	cow dung 10,20 &30 %	WH-13.4 MJ.kg^{-1} Cowdung:14.4 MJ.kg^{-1}	70:30 80:20	Relaxed density RD: 70:30 (1157 kg.m^{-3}) 80:20 (1296 kg.m^{-3}) Flue tempt 69.0°C (80:20) 74.5°C(70:30)
(Handra et al. 2023)	Empty fruit brunches (EFB)	Starch binder	2,4,6, and 8%	15.39 MJ.kg^{-1}	4%	Flame tempt-440°C(8%)
(Zanella et al. 2016)	Orange baggase solid waste	Corn starch	5,10, 15%	26.5-27.6 MJ.kg^{-1}	15%	Density: (0.594-0.629)g.cm^{-3} Friability: 5.84%
(Kebede et al. 2022)	Coffee husk (CH) Sawdust (SD) Khat waste (KW) Dry gas (DG)	Waste pulp Clay soil	Biomass waste: binder(3:1) 2 MPa	SD: 19.15 MJ.kg^{-1} CH: 17.78 MJ.kg^{-1} KW: 16.65 MJ.kg^{-1} DG: 17.43 MJ.kg^{-1}	3:1	-
(Nazari et al. 2020)	Empty fruit brunches (EFB)	Corn starch	20% binder	23.62 MJ.kg^{-1}	100:20	-
(Zubairu & Gana 2014)	Corn cob	Tapioca starch	6,10,14, 19%	30.57-34.73 MJ.kg^{-1}	-	358.3-425 kg.cm^{-3}

biomass. A significant upgrade in the solid fuel quality and performance was more pronounced with agro-waste such as shredded and ground bagasse, durian seed and peel, wheat straw, and moso bamboo, which have a calorific (heating) value of $\geq$20 MJ.kg^{-1}. Emerging binders such as LLDPE polymers, bitumen, and coal tar (CTR) significantly upgraded the energy value at $\leq$30% binder content compared to organic binders such as starch and molasses. Therefore, agricultural waste biomass could be harnessed under optimal process conditions to achieve combustion capacity equivalent to or greater than commonly used coals, bituminous coal, and lignite, which fall within the ranges of 23-35 MJ.kg^{-1}.

According to Bency et al. (2023), a good biomass briquette is expected to be rich in carbon and volatile with low moisture and ash content. Reported studies have shown that agro-biomass has a higher volatile content than coal, which is indicative of its faster ignition. In addition, several agro-wastes have shown lower ash content within the ranges of 0-13% as against the common bituminous coal (34%), coal (5-40%), and lignite (44.8%) (Narayanan & Natarajan 2006, Manyuchi et al. 2018, Tippayawong et al. 2006). A high ash content in any fuel indicates more remnants, and incomplete combustion has occurred. This is characterized by the transfer of heat and oxygen diffusion to the surface of the fuel during combustion, which consequently reduces the fixed carbon and heating value.

CONCLUSIONS

Briquetting of biomass has been a potential and promising route for sustainable alternative bioenergy generation over the past few decades. However, researchers have not been able to standardize biomass briquette quality due to insufficient holistic, explicit knowledge and literature on the biomass composition, compatibility, nature of the binder, quality, and appropriate percentage composition required for briquetting selected biomass. This review comprehensively explored the performance of various binders reported in a wide range of studies on biomass, as they affect the combustion and energy (heating) value of biomass. It can be concluded that there are organic and inorganic binders, and in recent times, emerging binders such as linear low-density polyethylene (LLDPE), recovered polyvinyl alcohol (rPVA), other polymeric materials, and coal tar residue (CTR) have been introduced as binders to produce briquettes. These emerging binders have been discovered in this review to greatly contribute to enhancing the energy and combustive performance of agro-waste to values equivalent to or probably higher than coal and sub-bituminous coal, even at lower binder content than organic and inorganic binders. According to the literature, a 10-30% binder range provided the best combustive performance and heating value across different selected biomasses, with 30% binder providing optimal performance across various ranges of properties (physical, thermal, and combustive characteristics). Hence, there was limited waste of resources. This approach has provided a variety of possible alternatives to the most commonly used binders (starch products), which also conflict with food resources. Hence, food shortages are reduced. In addition, certain thermal treatment methodologies, such as torrefaction and carbonization, have been used to optimize the combustive performance of the selected biomass.

FUTURE DIRECTIONS

The conversion of agro-waste biomass into solid fuels is therefore considered a viable approach for waste management and energy production. However, creating efficient and high-quality solid fuels requires consideration of critical tasks. Hence, preliminary investigations such as proximate and ultimate (elemental) analyses are necessary to determine the environmental friendliness, combustion properties, and sustainability of the solid fuel. Composite biomasses have shown promise for upgrading solid fuels. Furthermore, low-energy pretreatments, such as torrefaction and carbonization, before briquetting could help achieve the expected balance in fixed carbon content and volatile matter requirements for better energy and combustive properties. There is also a strong demand for new binder materials (emerging/non-edible binders) to reduce over-dependency on starch and molasses, which compete with food sources. Better densification methods to increase the mechanical properties, energy storage, and chemical stability of bio-derived fuels have also been proposed.

Furthermore, there are many opportunities in the research of composite biomass blends, as they provide an opportunity to achieve maximum synergy of biomass characteristics. A series of advanced technologies and specially designed blending methods promoted for the binding and densification of biomass materials can also be important for achieving the formation of high-quality solid fuels with better combustion characteristics and lower emission rates. More research should be dedicated to applying these improvements to harness the full capacity of agro-waste biomass for energy production applications.

ACKNOWLEDGMENTS

This work is supported by the Department of Research and Innovation and the Faculty of Engineering and the Built Environment, Tshwane University of Technology.

REFERENCES

Achebe, C., Umeji, A. and Chukwuneke, J., 2018. Energy evaluation of various compositions of biomass waste briquettes. *Advances in Research*, 13(1), pp.1-11.

Afra, E., Abyaz, A. and Saraeyan, A., 2021. The production of bagasse biofuel briquettes and the evaluation of natural binders (LNFC, NFC, and lignin) effects on their technical parameters. *Journal of Cleaner Production*, 278, pp.1-12.

Afsal, A., David, R., Baiju, V., Suhail, N.M., Parvathy, U. and Rakhi, R.B., 2020. Experimental investigations on combustion characteristics of fuel briquettes made from vegetable market waste and sawdust. *Materials Today: Proceedings*, 33(5), pp.3826-3831.

Anggono, W., Suprianto, F.D., Sutrisno, S. and Kasrun, A.W., 2016. Investigation on biomass briquette as an energy source from waste leaf *Cerbera manghas*. *International Journal of Industrial Research and Applied Engineering*, 1(2), pp.45-52.

Anggraeni, S., Hofifah, S., Nandiyanto, A.B.D. and Bilad, M.R., 2021. Effects of particle size and composition of cassava peels and rice husk on the briquette performance. *Journal of Engineering Science and Technology*, 16(4), pp.527-542.

Aransiola, E., Oyewusi, T., Osunbitan, J. and Ogunjimi, L., 2019. Effect of binder type, binder concentration and compacting pressure on some physical properties of carbonized corncob briquette. *Energy Research*, 5(3), pp.909-918.

Arewa, M.E., Daniel, I.C. and Kuye, A., 2016. Characterisation and comparison of rice husk briquettes with cassava peels and cassava starch as binders. *Biofuels*, 7(6), pp.671-675.

Bency, P., Anish, M., Jayaprakash, V., Jayaprabakar, J., Yanmaz, E., Joy, N., Ramulu, P.J. and Sathasivam, K., 2023. Comparative assessment of compression strength of solid biobriquette using different binding materials. *Journal of Nanomaterials*, 2023, pp.1-7.

Cahyono, R.B., Santoso, J. and Miliati, R., 2017. Biomass briquettes using Indonesian durian seeds as binder agent: The effect of binder concentration on the briquettes' properties. *Chemical Engineering Transactions*, 56, pp.1663-1668.

Carnaje, N.P., Talagon, R.B., Peralta, J.P., Shah, K. and Paz-Ferreiro, J., 2018. Development and characterisation of charcoal briquettes from water hyacinth (*Eichhornia crassipes*)-molasses blend. *PLOS ONE*, 13(11), e0207135.

Celestino, J.M.T., Lating, P.O., Nabuuma, B. and Yiga, V.A., 2023. Effects of clay, gum arabic and hybrid binders on the properties of rice and coffee husk briquettes. *Renewable and Sustainable Energy*, 20, p.101488.

Cheng, J., Zhou, F., Si, T., Zhou, J. and Cen, K., 2018. Mechanical strength and combustion properties of biomass pellets prepared with coal tar residue as a binder. *Fuel Processing Technology*, 179, pp.229-237.

Davies, R. and Abolude, D., 2013. Mechanical handling characteristics of briquettes produced from water hyacinth and plantain peel as binder. *Journal of Scientific Research and Reports*, 2(1), pp.93-102.

Davies, R.M. and Davies, O.A., 2014. Physical and combustion characteristics of briquettes made from water hyacinth and phytoplankton scum as binder. *Journal of Combustion*, 2013, pp.1-7.

Davies, R.M., Davies, O.A. and Mohammed, U.S., 2013. Combustion characteristics of traditional energy sources and water hyacinth briquettes. *International Journal of Sustainable Research in Energy Science*, 1(1), p.144.

Demirbas, A., 1999. Evaluation of biomass materials as energy sources: Upgrading of tea waste by the briquetting process. *Energy Sources*, 21(3), pp.215-220.

Emadi, B., Iroba, K.L. and Tabil, L.G., 2017. Effect of polymer plastic binder on mechanical, storage and combustion characteristics of torrefied and pelletized herbaceous biomass. *Applied Energy*, 198, pp.312-319.

Espuelas, S., Marcelino, S., Echeverría, A., del Castillo, J. and Seco, A., 2020. Low-energy spent coffee grounds briquetting with organic binders for biomass fuel manufacturing. *Fuel*, 278, p.118310.

Ezéchiel, K., Joel, T.K., Abdon, A. and Roger, D.D., 2022. Accessibility and effects of binder types on the physical and energetic properties of ecological coal. *Heliyon*, 8(2), p.e10562.

Falemara, B.C., Joshua, V.I., Aina, O.O. and Nuhu, R.D., 2018. Performance evaluation of the physical and combustion properties of briquettes produced from agro-wastes and wood residues. *Recycling*, 3(2), p.23.

Fawzy, S., Osman, A.I., Doran, J. and Rooney, D.W., 2020. Strategies for mitigation of climate change: A review. *Environmental Chemistry Letters*, 18, pp.2069-2094.

Fengmin, L. and Mingquan, Z., 2011. Technological parameters of biomass briquetting of macrophytes in Nansi Lake. *Energy Procedia*, 5, pp.2449-2454.

Han, H., Duan, D. and Yuan, P., 2014. Binders and bonding mechanism for RHF briquette made from blast furnace dust. *Ironmaking and Steelmaking*, 54(8), pp.1781-1789.

Handra, N., Abuzar, A., Perdana, M., Junaidi, J. and Indra, A., 2023. The effect of percentage binder on fiber bio-briquettes EFB on ignition quality. *AIP Conference Proceedings*, AIP Publishing, pp.1-7.

Hanif, M.U., Capareda, S.C., Iqbal, H., Arazo, R.O. and Baig, M.A., 2016. Effects of pyrolysis temperature on product yields and energy recovery from co-feeding of cotton gin trash, cow manure, and microalgae: A simulation study. *PLOS ONE*, 11(4), e0152230.

Idris, S.S., Zailan, M.I., Azron, N. and Abd Rahman, N., 202. Sustainable green charcoal briquette from food waste via microwave pyrolysis technique: Influence of type and concentration of binders on chemical and physical characteristics. *International Journal of Renewable Energy Development*, 10(3), pp.425-433.

Igbo, K.P., 2016. Physico-mechanical characteristics of rice husk briquettes using different binders. *Applied Energy and Industrial Chemistry Journal*, 18(2), pp.70-81.

Ikelle, I.I., 2017. Effect of binders on the properties of coal briquette blends produced with different biomasses. Department of Pure and Industrial Chemistry, Faculty of Physical Sciences, University of Nigeria, pp.1-150.

Isemin, R., Mikhalev, A., Klimov, D., Grammelis, P., Margaritis, N., Kourkoumpas, D.S. and Zaichenko, V., 2017. Torrefaction and combustion of pellets made of a mixture of coal sludge and straw. *Fuel*, 210, pp.859-865.

Jittabut, P., 2015. Physical and thermal properties of briquette fuels from rice straw and sugarcane leaves by mixing molasses. *Energy Procedia*, 79, pp.2-9.

Katimbo, A., Kiggundu, N., Kizito, S., Kivumbi, H.B. and Tumutegyereize, P., 2014. Potential of densification of mango waste and effect of binders on produced briquettes. *Applied Energy and Industrial Chemistry Journal*, 16(1), pp.146-155.

Kebede, T., Berhe, D.T. and Zergaw, Y., 2022. Combustion characteristics of briquette fuel produced from biomass residues and binding materials. *Journal of Energy*, 2022, Article ID 4222205, pp.1-10.

Kimutai, S.K. and Kimutai, I.K., 2019. Investigation of physical and combustion properties of briquettes from cashew nut shell and cassava binder. *International Journal of Education and Research*, 7(6), pp.15-26.

Kivumbi, B., Jande, Y.A., Kirabira, J.B. and Kivevele, T.T., 2021. Production of carbonized briquettes from charcoal fines using African elemi (*Canarium schweinfurthii*) resin as an organic binder. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 43(18), pp.1-17.

Lubwama, M. and Yiga, V.A., 2017. Development of groundnut shells and bagasse briquettes as sustainable fuel sources for domestic cooking applications in Uganda. *Renewable Energy*, 111, pp.532-542

Mani, S., Sokhansanj, S., Bi, X. and Turhollow, A., 2006. Economics of producing fuel pellets from biomass. *Applied Engineering in Agriculture*, 22(3), pp.421-426.

Manyuchi, M.M., Mbohwa, C. and Muzenda, E., 2018. Value addition of coal fines and sawdust to briquettes using molasses as a binder. *South African Journal of Chemical Engineering*, 26, pp.70-73.

Miao, Z., Zhang, P., Li, M., Wan, Y. and Meng, X., 2023. Briquette preparation with biomass binder. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 45(55), pp.9834-9844.

Mitan, N.M.M., Ramlan, M.S., Nawawi, M.Z.H. and Gazali, M.H.M., 2018. Performance of binders in briquetting of durian peel as a solid biofuel. *Materials Today: Proceedings*, 5(10), pp.21753-21758.

Mohammed, T. and Olugbade, T., 2015. Burning rate of briquettes produced from rice bran and palm kernel shells. *International Journal of Materials Science Innovations*, 3(2), pp.68-73.

Montiano Redondo, M.D.G., Fernández Fernández, A.M., Díaz-Faes González, E. and Barriocanal Rueda, C., 2015. Tar from biomass/coal-containing briquettes: Evaluation of PAHs. *Journal of Chemical Engineering Science*, 120(4), pp.201-209.

Muazu, R.I. and Stegemann, J.A., 2015. Effects of operating variables on durability of fuel briquettes from rice husks and corn cobs. *Fuel Processing Technology*, 133, pp.137-145.

Muazu, R.I. and Stegemann, J.A., 2017. Biosolids and microalgae as alternative binders for biomass fuel briquetting. *Fuel*, 194, pp.339-347.

Narayanan, K. and Natarajan, E., 2006. Cofiring of coal and biomass in a travelling grate boiler in India. *Journal of Energy Technology*, 12(2), pp.55-63.

Narzary, A., Brahma, J. and Das, A.K., 2023. Utilization of waste rice straw for charcoal briquette production using three different binders. *Cleaner Engineering and Science*, 5, Article ID 100072.

Nazari, M.M., Idroas, M.Y. and Ayuni, F.A., 2020. Carbonization effect on EFB briquettes prepared with different type of binders. *IOP Conference Series: Earth and Environmental Science*, 476, pp.1-8.

Nikkhah Shahmirzadi, A., Najafi, S.K. and Younesi, H., 2024. Characterization of hybrid charcoal briquettes from date palm and pistachio residues and bio-based binders. *Biofuels*, 15(6), pp.801-809.

Obi, O.F., Pecenka, R. and Clifford, M.J., 2022. A review of biomass briquette binders and quality parameters. *Energies*, 15(7), Article ID 2426.

Ohagwu, C., Amaefule, D., Anyanwu, C. and Nwaezeh, C., 2022. Physico-mechanical and fuel properties of sawdust briquettes using *Abelmoschus esculentus* waste as a binder. *Applied Energy and Industrial Chemistry Journal*, 24(2), pp.115-123.

Olugbade, T., Ojo, O. and Mohammed, T., 2019. Influence of binders on combustion properties of biomass briquettes: A recent review. *Biomass Research*, 12(4), pp.241-259.

Oroka, F. and Thelma, E.J., 2013. Fuel briquettes from water hyacinth-cow dung mixture as alternative energy for domestic and agro-industrial applications. *Energy Technology and Policy*, 3(2), pp.56-62.

Oyelaran, O.A., Bolaji, B.O., Waheed, M.A. and Adekunle, M.F., 2015. Performance evaluation of the effect of binder on groundnut shell briquette. *Applied Science and Engineering Progress*, 8(1), pp.11-19.

Pinto, J., Cruz, D., Paiva, A., Pereira, S., Tavares, P., Fernandes, L. and Varum, H., 2012. Characterization of corn cob as a possible raw building material. *Construction and Building Materials*, 34, pp.28-33.

Pramadhana, A.N., Widiputri, D.I. and Pari, G., 2017. Improvement of combustion quality of biomass briquette from water hyacinth (*Eichhornia crassipes*) for alternative energy. *Journal of Renewable Energy Research*, 9(3), pp.115-124.

Rahaman, S.A. and Salam, P.A., 2017. Characterization of cold densified rice straw briquettes and the potential use of sawdust as binder. *Fuel Processing Technology*, 158, pp.9-19.

Rajaseenivasan, T., Srinivasan, V., Syed Mohamed Qadir, G. and Srithar, K., 2016. An investigation on the performance of sawdust briquette blending with neem powder. *Alexandria Engineering Journal*, 55(3), pp.2833-2838.

Rajput, S.P., Jadhav, S.V. and Thorat, B.N., 2020. Methods to improve properties of fuel pellets obtained from different biomass sources: Effect of biomass blends and binders. *Fuel Processing Technology*, 199, Article ID 106293.

Ren, C., Zhao, F., Shi, Z., Chen, J., Han, X., Yang, G., Feng, Y. and Ren, G., 2017. Differential responses of soil microbial biomass and carbon-degrading enzyme activities to altered precipitation. *Soil Biology and Biochemistry*, 115, pp.1-10.

Saenpro, B., Homdoung, N., Chaichana, T., Chaiyat, N. and Ramaraj, R., 2019. Briquette physical properties with using oil palm leaves and soybean plant as natural binder. *Journal of Cleaner Energy Systems*, 11(4), pp.215-222.

Sharma, A., Pareek, V. and Zhang, D., 2015. Biomass pyrolysis—A review of modelling, process parameters and catalytic studies. *Renewable and Sustainable Energy Reviews*, 50, pp.1081-1096.

Shu, M.Y., Yin, H.Y. and Liu, G.H., 2012. Experimental researches on composite bentonite-based briquette binder. *Advanced Materials Research*, 496, pp.276-280.

Shuma, M.R. and Madyira, D.M., 2018. Combustion and energy content comparison of loose biomass briquettes produced from cow dung and cactus binders. In: *Proceedings of the International Conference on Industrial Engineering and Operations Management*, Pretoria, South Africa, pp.1962-1971.

Shuma, R. and Madyira, D.M., 2017. Production of loose biomass briquettes from agricultural and forestry residues. *Procedia Manufacturing*, 7, pp.98-105.

Si, T., Cheng, J., Zhou, F., Zhou, J. and Cen, K., 2017. Control of pollutants in the combustion of biomass pellets prepared with coal tar residue as a binder. *Fuel*, 208, pp.439-446.

Siloto, R.M. and Weselake, R.J., 2012. Site saturation mutagenesis: Methods and applications in protein engineering. *Bioengineering and Biotechnology*, 1(2), pp.181-189.

Soeherman, G.P., Putri, P.G., Joen, D.A.Z., Indrawan, I. and Pratiwi, N., 2023. Characterization of biobriquette from carbonized durian peel using coconut shell as the binder. *Asian Journal of Applied Research for Community Development and Empowerment*, 7(2), pp.129-135.

Song, X., Zhang, S., Wu, Y. and Cao, Z., 2020. Investigation on the properties of the bio-briquette fuel prepared from hydrothermal pretreated cotton stalk and wood sawdust. *Renewable Energy*, 151, pp.184-191.

Tahir, D., Gareso, P.L. and Suriamiharja, D.A., 2012. Physical properties of briquettes based on charcoal from selected biomass. *Journal of Biomass Energy Research*, 4(1), pp.55-62.

Thabuot, M., Pagketanang, T., Panyacharoen, K., Mongkut, P. and Wongwicha, P., 2015. Effect of applied pressure and binder proportion on the fuel properties of holey bio-briquettes. *Energy Procedia*, 79, pp.890-895.

Tippayawong, N., Tantakitti, C. and Thavornun, S., 2006. Investigation of lignite and firewood co-combustion in a furnace for tobacco curing application. *Asian Journal of Applied Sciences*, 3(12), pp.1775-1780.

Williams, P.T. and Nugranad, N., 2000. Comparison of products from the pyrolysis and catalytic pyrolysis of rice husks. *Energy*, 25(6), pp.493-513.

Wirabuana, A.D. and Alwi, R.S., 2021. Influence of starch binders composition on properties of biomass briquettes from durian peel (*Durio kutejensis* Becc). In: *Proceedings of the 4th International Seminar on Chemistry*, Makassar, Indonesia, pp.101-108.

Yang, W., Zhu, Y., Cheng, W., Sang, H., Xu, H., Yang, H. and Chen, H., 2018. Effect of minerals and binders on particulate matter emission from biomass pellets combustion. *Applied Energy*, 215, pp.106-115.

Yank, A., Ngadi, M. and Kok, R., 2016. Physical properties of rice husk and bran briquettes under low pressure densification for rural applications. *Biomass and Bioenergy*, 84, pp.22-30.

Yun, Z., Dongsheng, F., Huaan, Z., Yang, Y. and Wenjing, W., 2014. Research progress of briquette binder. *Chinese Coal Technology*, 20(3), pp.88-95.

Zakari, I., Ismaila, A., Sadiq, U. and Nasiru, R., 2013. Investigation on the effects of addition of binder and particle size on the high calorific value of solid biofuel briquettes. *Journal of Natural Science Research*, 3(12), pp.30-34.

Zanella, K., Goncalves, J.L. and Taranto, O., 2016. Charcoal briquette production using orange bagasse and corn starch. *Chemical Engineering Transactions*, 49, pp.313-318.

Zhang, G., Sun, Y. and Xu, Y., 2018a. Review of briquette binders and briquetting mechanism. *Renewable and Sustainable Energy Reviews*, 82, pp.477-487.

Zubairu, A. and Gana, S.A., 2014. Production and characterization of briquette charcoal by carbonization of agro-waste. *Energy and Power*, 4(2), pp.41-47.