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Review Paper

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

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ABSTRACT

Research scientists worldwide are in continuous drive for innovations toward achieving a safe and healthy environment across the entire ecosystem. An integral component of this pursuit, 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 residue mirrors hope and an array of challenges. Over decades, densification of biomass 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 an energy source. However, biomass's combustion and energy performance have not sufficiently met the energy mix requirements for extensive renewable energy use. The performance of the compacted material is own to kind of binders used in the manufacturing, among other factors. This literature explored the details of the available binders and biomass compositions investigated in reported studies. The authors also reported their performances, primarily regarding energy value and combustive behavior. Limitations such as low yield and low energy content among other performance-related issues in biomass briquette can be highly enhanced with the appropriate selection of biomass and compatible binders. Hence, these various research attempts, approaches, and methodologies in developing solid fuel and the binder's influence on the energy content, density, combustion behavior, and other physical attributes of fuel briquettes have 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, hence reducing reliance on fossil fuels and negative impacts on the environment. Through their conversion into solid fuels, they are therefore an optimal, affordable, and sustainable source of energy especially for the rural and energy-starved regions of the world 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 et al., 2012). Moreover, because these resources are finite, they are also a major threat to the environment and harm to human health (Fawzy et al., 2020). Nevertheless, society's energy requirements are still on the rise due to advancements in technology and increasing population size. This has further aggravated the pressure on the current energy situation. This energy crisis can be mitigated by fully embracing and harnessing renewable energy such as bioenergy and wind to partly replace fossil energy. According to the Sustainable Development Goal Tracking for Energy Report in 2019, 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 the issues of climate change, environmental pollution, and energy crisis (Ren et al., 2017). The effects of biomass energy on the environment and fossil fuel depletion are drawing attention from the general population. Biomass compaction and briquettes have become a desirable alternative 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 the impedance to direct utilisation of biomass (Demirbas, 1999). Naturally occurring structural binders or stabilizing substances, such 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 have better structural particle bonding. In some circumstances, extra binders could be needed in the briquette due to the insufficient inherent natural binder, low lignin quantity, and densification capacity. These additional binders are to obtain the desired biomass briquette's high quality and strength. In addition, binders in briquette productions confer better strength, thermal stability, improved combustion performance, and reduced cost (Zhang et al., 2018b, Ezéchiel et al., 2022).

Briquetting and pelletization are regarded as efficient techniques to enhance 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 include 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 of lower ignition temperatures, lower slagging indices, and lower ash contents are produced using biomass binder (Isemin et al., 2017).

One of the critical expected outcomes in the valorisation of agricultural waste biomass is the energy value. Agro-waste is been explored to help mitigate the energy deficit and complement the existing renewable energy required in the global energy mix. However, to harness and optimise this bioresources, the process conditions and parameters must be optimised. This review article captures at a glance the various possible inherent energy capacity and the combustion properties stored up in accessible agricultural wastes. Previous review have reported general information on biomass qualitatively but not quantitatively. This review also clearly projects through the quantitative estimate of energy value and combustion property, the possibility as developing hybrid composites from the energy ladened agro-waste. This gives greater optimism to challenge the existing energy and combustion properties of commonly used coal and bituminous coal.

However, this review provide new insights by detailing how methods/process conditions of agro-waste valorisation impacts the quality of the valorised agro-waste solid fuel and their combustion performance. In this review, effective agro-waste and binder combination (with most enhanced energy and combustive properties) based on experimental investigation with an equivalent or far above that obtainable in fossil fuel such as coal and sub-luminous coal are clearly identified. Hence, converging and giving more indepth knowledge of various agrowaste compared to the generic information in available literatures. This will assist in bio-energy adoption of viable renewable energy options and contributing towards the advancing the frontiers of agro-waste valorisation.

ROLE OF BINDERS IN BIOMASS BRIQUETTING

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

According to(Zhang et al., 2018a) organic binders often have strong binding qualities, such as excellent water resistance, strong impact, and abrasion strengths. 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, inexpensive 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 (Miao et al., 2023), organic binders can be classified according to how they react to water: hydrophobic binders, like coal tar and asphalt, and hydrophilic binders such as biomass. Organic binders' low heat stability has restricted 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, little pollution, sulfur capture features, low cost, and good hydrophilicity (Shu et al., 2012). Ammonium nitrate, bentonite, and clay are a few examples. As a result, selecting binders for briquette production is crucial and needs to be done carefully. Furthermore, to achieve improved yield and performance, the right amount of binders must be considered during the fuel briquette manufacture 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 value and durability with a lesser compaction on briquettes(Obi et al., 2022).Furthermore, the performance and yield of a fuel briquette are strongly dependent on several factors among which are the pressure applied, binder content, process temperature, compositional mix, moisture content, feedstock type, particle size, and ambient (Olugbade et al., 2019). The lignin and fat content, texture, and particle size impact of binder properties on the briquettes performance still require further research and attention, despite the numerous studies on the production and use of fuel briquettes. Even though binding agents are present in many biomass materials by nature (Sharma et al., 2015), the binding power can be improved by adding binders to the mixture while briquette-making. However, some binders might result in problems such as increased ash content, poor combustion characteristics, or decreased briquette compaction when converting fuel briquettes into energy (Mohammed and Olugbade, 2015). This makes an eco-friendly, readily accessible binder necessary. In making briquettes, binder materials like sawdust, wood ash, molasses, starch, biosolids, microalgae, and cow dung are frequently used (Rahaman and Salam, 2017)

Inorganic binders can be divided into three primary categories: environmental protection (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 and Nugranad, 2000)

Compound binders combine two or more binders to create briquettes with high thermo-mechanical strength to harness the various binding 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 qualities, 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 choosing binders in developing communities. The kind and amount of binders used in biomass briquetting have been related to the mechanical and combustion characteristics of the final product, briquettes. Moreover, the extent to which they impact 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. 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 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.

(Shuma and Madyira, 2017) explored cow dung and cactus binders in investigating the energy value and combustive rate of biomass briquette. The biomass was compacted at pressures of 6, 12, and 19 MPa. The maximum energy content was discovered in briquettes bound with cow dung under all pressures. At 6 MPa, 21.53 MJ/kg in Mopani leaf briquettes, 16.85 MJ/kg in groundnut shells at 12 MPa, and 19.11 MJ/kg in sugarcane at 19 MPa. Yellow thatching grass was found to have the lowest HHV of 14.84 MJ/kg average in cow dung, under all pressure conditions. Furthermore, the cow dung-bonded briquettes exhibited higher rates of combustion with pressure increase for groundnut shell rates. Sugarcane leaves had the lowest performance of 38.13 g/min. Low energy contents and low burning rates due to its high moisture content and insensitivity to pressure were observed with Cactus-bonded briquettes. Mopani leaves had the best energy content for cactus-bound briquettes, at 16.49 MJ/kg, groundnut at 15.5 MJ/kg, and yellow thatching grass at 12.6 MJ/kg. The highest combustion rate (59.48 g/min) was found for the combination treatment, followed by the Mopani leaf treatment (53.91 g/min) and the least for yellow thatching grass (3.36 g/min). Cow dung briquettes show a better performance for all the compaction pressure.

(Rahaman and Salam, 2017) produced rice straw briquettes and their physical properties were investigated for particle size effect, mold diameters, and applied pressure. This study measures 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 ≥ 27.6 MPa, and mold diameters ≤51 mm. It's interesting to note that, despite 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/m3 by using sawdust as a binding material at 3:1 and 1:1 mixing ratios. Additionally, the shatter index was dramatically improved (p b 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, due to the energy used in briquette manufacturing.

Davies and Davies (2014) investigated some agricultural waste as binders and how they affect the physical characteristics of the water lily briquettes. Peels from bananas, cassava, yams, and plantains with a particle size of 0.075 mm were employed as binders, along with a 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. Cassava peel-containing binder was observed to have 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, the material ratio, the compaction pressure, and the 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 having 10% binder inclusion resulted in a compressive strength of 176 kPa and a compaction pressure of 31 MPa. The analysis's findings showed that the addition of water and starch was necessary for sufficient briquette strength, but it also greatly lowered the densities of green and relaxed materials. Densification was significantly impacted by the biomass's source, highlighting the need to comprehend the mechanisms underpinning biomass fluctuation.

A study by (Kimutai and Kimutai, 2019) examined the properties of cashew nutshell biomass and cassava as binders. The carbonisation of cashew nut shells was carried out at 250 °C and pulverized into a briquette upon adding cassava paste as the binder. The briquette of different particle sizes (0.5-2.0 mm) was 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 binder enhances the properties of the briquette, which has a maximum HHV of 30.5 MJ/kg at a 30% binder ratio compared to 28.3 MJ/kg in binder-less briquette. This value is comparable to wood charcoal (31.38 MJ/kg).

(Anggraeni et al., 2021)carbonised different particle sizes of dried cassava peels and rice husks mixed at different ratios with a binder to produce a briquette. The particle size and composition effects on briquette performance are presented in the study. In this experiment, 4g of tapioca starch binder was added to 10 grams of carbonized particles and moulded. Briquettes with small particles of 70:30 and 50:50 CP:RH composition gave the best compressed and relaxed density. The relaxed density ranged between 1.70 and 2.26 g/cm^3. The best results for this parameter were obtained for small particles in the 0.41-0.56 g/mL range. A compositional briquette ratio of 10:90 gave the highest calorific value and SFC for particles that are medium and large. The briquette has the highest burning rate at 90/10 CPs/RHs blends. In the overall, all combustive behaviour was good.

The energy value and properties of sawdust, rice husk biowaste, and their composites were studied by (Achebe et al., 2018) with two types of binders (starch and clay). Sun-dried biowastes of uniform 0.5 mm particle sizes and 90:10 binder composition were compressed into briquettes, to analyse their combustion properties. The calorific value of mahogany sawdust (4.516 kcal/g), gmelina (4.1487 kcal/g), oak (4.4312 kcal/g), mahogany/gmelina/oak composite (3.8614 kcal/g), rice husk (4.0531 kcal/g) and gmelina/rice husk briquettes (4.067 kcal/g) with starch binder were reported. Additionally, it was stated that the calorific values of 1.9003 kcal/g, 1.5331 kcal/g, 1.8156 kcal/g, 1.2458 kcal/g, 1.4375 kcal/g, and 1.4451 kcal/g were obtained when clay was used as a binder.

The mahogany briquette with starch binder has 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, 42.21 min respectively are less than those obtained for other briquettes. Hence, performing better than the other briquettes.

(Oroka and Thelma, 2013) used cow dung as the binding agent in developing water hyacinth briquette 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 compositions, 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 the 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 to 28.639 MJ/kg. Although briquette with 20% starch binder is presented as having the best thermal stability in this study, it has a conflicting interest. Hence, choice is discouraged. Taro can therefore 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 chopped rice straw. The paper binder has the lowest range of CO (2.3-2.5 g/cm^3), NOx (0.055-0.06g/cm^3) and SOx (0.0175-0.015g/cm^3) emission while Tao starch has the highest range of CO (3.25 -3.5g/cm^3), NOx (0.07-0.09g/cm^3) and SOx (0.018-0.02g/cm^3). The highest specific energy consumption is observed with paper binder briquettes, then starch binder briquettes, and the least with taro binder briquettes. The water boiling test reveals that the burning rate increased with the binder content.

(Yank et al., 2016b) examined the physical characteristics of rice husk and bran briquette. It examines the impact of binder type, binder content, moisture content, and bran content made from rice husks. Rice dust, okra stem gum, and cassava starch wastewater were utilized 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 dry basis). Briquette with rice dust binder gave the strength (compressive) of 2.54kN and the highest durability (91.9%). Rice husk-based briquette can serve as a substitute in biomass cooking fuel.

The effect of the composition of tapioca binder on the heating value of biomass briquettes obtained from *C. manghas* leaf waste. This study was carried out by (Anggono et al., 2016). The heating values of five mixtures of 10-50% tapioca compositions were examined. The highest heating value of 4164 kcal/kg 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 was obtained. The experimental results confirmed the feasibility of making biomass briquettes made of *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. The binding agent was found to affect the physical properties significantly. The highest silica content was obtained from groundnut shell-based charcoal, followed by durian shell and cassava peel. A high silica content indicates a high carbon content and calorific value. In its transformation to silicate, this silica has high material strength, leading to the compressive strength of the briquette.

Saw dust-based briquettes were produced using *Abelmoschus esculentus* (Okra) waste of 5-20% composition by weight as a binder additive by(Ohagwu et al., 2022), to understand its 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. Furthermore, at 5% Abelmoschus esculentus (okra), the highest values of carbon -42.70%, Hydrogen- 5.64%, and Oxygen- 42.76% were obtained. A shatter resistance increases as binder concentration increases within the 96.78-98.92% range, also a 2.85 kN/m^2 hardness at 5% sawdust-okra briquette samples was obtained.

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

An investigation on how the percentage of starch binders (2%, 4%, 6%, and 8% (wt%) affects the ignition quality of EFB was carried out by (Handra et al., 2023). It was revealed in the study that Briquettes with an 8% binder percentage had the greatest flame temperature, which was 440 °C. However, compared to briquettes with a lower binder percentage, adding a binder to prolong the ignition period does affect the amount of black smoke that burns. Based on the calorific value, class E (3360-4201) includes the value with the highest calorific value, which was at 4% binder percentage, or 3676.2 kcal/g.

(Zanella et al., 2016) produced charcoal briquettes from orange bagasse (solid waste). Orange charcoal (OC) powder was mixed with several ratios of maize starch (5, 10, and 15% w/w), and some performance tests were conducted. These tests comprise proximate analysis, density, mechanical strength, elemental analysis, and higher heating value (HHV). OC which has a considerable HHV of 29,000 J/g. The HHV fell significantly when the OC with 5% corn starch (CS), the OC with 10% CS, and the OC with 15% CS were mixed with the binder, although these values are still regarded as excessive. They were 27,611 J/g, 26,857 J/g, and 26,476 J/g, 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, it was decided that 10% corn starch was suitable for this development.

(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 range of 8-12 MPa, and moisture contents of 15%, 20%, 25%, and 30%. The mixture of 10% xanthan and 15% moisture achieved the maximum dry density of 0.819 g/cm^3 at 12 MPa.

In a study by(Davies et al., 2013a), 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 the durability of the briquette. The DIP4B5 composition, which implies a particle size of 0.5 mm, pressure of 9 MPa, and 50% binder, was required to produce the briquette with % highest durability and strength of 96%. The results compared favorably with those of fuelwood. The densification process improved the handling characteristics of the briquettes.

A study by (Carnaje et al., 2018) prepared a water hyacinth briquette with molasses as a binder at different compositions. The briquette was prepared to contain 80% by weight molasses with different charcoal/molasses percentage mix. The MC, VM, and FCC of the biochar rose when the molasses content used as a binder increased, but the ash content dropped. A briquette with a 30:70 ratio of charcoal to binder had 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 igniting time of 133 sec., and the HHV of 16.6 MJ/kg. The briquette with a 30:70 ratio also demonstrated 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 for wood residue particles of 34.4 MJ/kg, was achieved. Briquettes with groundnut shells have 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. Maximum volatile matter (33.5%) and SHC (8051 kcal/kg) were produced at 20% starch content, having least volatile matter (24.2%) and SHC-7165 kcal/kg. *A. leiocarpus* particle-based briquettes has the highest SHC. Briquettes made with wood particles with a groundnut shell and *A. leiocarpus* particle mixture with 25% starch binder gave 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 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 which are 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 ratio. 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 ,0.178% CO and 1.14% CO_2 emissions. The (CH)X, and NOx are very negligible and insignificant indicating their non-toxicity. It also has a maximum breaking strength of 34 N and compressive stress of 273 N/mm).

According to a study (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 fixed at 10%. The extruder machine used was a screw type and 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 higher than 60%. The interlocking properties of the oil palm fronds were greater than those of the soybean fronds. An overview of the three biomass briquette fuel experiments revealed that the cost of production decreased by more than 57%. It was concluded that a natural binder could be used instead of cassava starch because the oil palm frond had better properties than the soya bean plant.

(Arewa et al., 2016)examined the properties of rice husk briquettes manufactured having peels and starch from cassava as binders. Briquettes with starch binder have maximum and relaxed densities of 1080.8- 1159.6 kg/m^3 and 552.3- 632.2 kg/m^3. Moreover, the corresponding values ranged from 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 test and burning rate test shows 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 also 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.%). A saturation state was reached at an 8% binder concentration with the durian seed binder according to the heating and compressive strength measurements. The energy value of the briquettes declines as the binder content moves from 4 to 8% and remains constant after.

(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 find the average composition of their elements. The results show a FCC of 9.06-13.63%, a VMC of 68.14-74.67%, an AC of 7.84-12.85%, and a MC of 4.2-6.2%. The result from the elemental analysis is shown in Table 2. The highest heating value was 16.33 MJ/kg for the rice straw: sugarcane leaf (100:0) composition and 17.83 MJ/kg for the 50:50 composition, the highest calorific value obtained. A decrease in the calorific value is 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 and Davies, 2013)) used phytoplankton as a binder on ground water hyacinth to investigate the properties of the briquettes. The water hyacinth and binder content ranging from 10-50% were fed into 14.3 cm by 4.7 cm steel cylindrical die by weight of each feedstock. It is then compressed in a hydraulic press under pressure of 20 MPa for a dwell time of 45 seconds. The calorific value (Kcal/kg) significantly increased with increasing binder content from 10%-50%, 3563 ±77 to 4281 ±90, the ignition time (min): 73.54±3.37 to 123.42±3.47; Burning rate (g/min): 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 carried out by(Bency et al., 2023b). The briquette was developed with a 20:80 combination of binder and biological waste. The sample density ranges from 545.564 to 591.278 kg/m^3. Vinyl ester resin had the highest calorific value (5,800.79 kcal/kg) as an inorganic binder, followed by beef tallow oil as an organic binder (5.357.26 kcal/kg). Hence, it was confirmed that the composition of the inorganic binder enhanced HCV. This is shown in Figure 1.

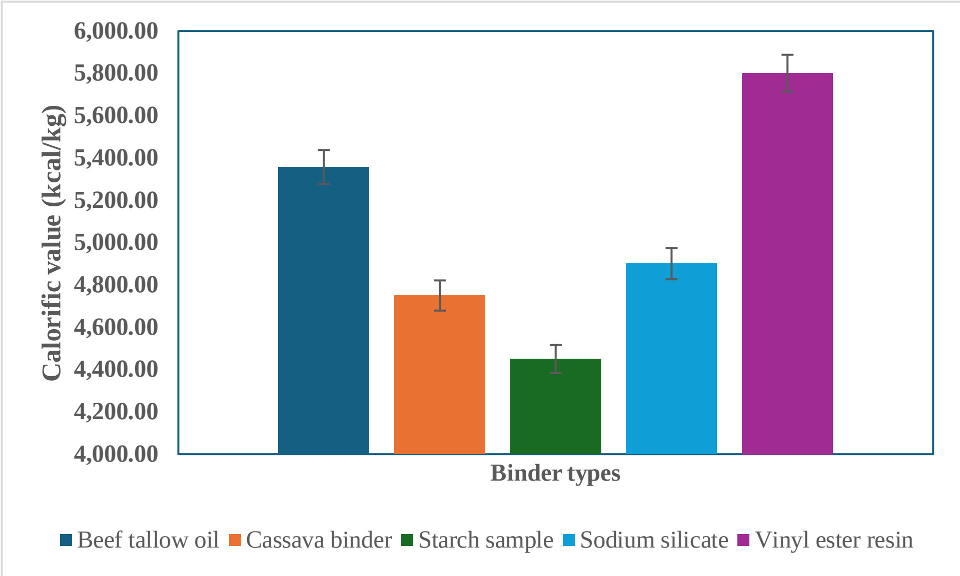

Fig. 1: Calorific value of briquette with specific binding materials (Bency et al., 2023b).

Groundnut shells and bagasse briquettes were produced under high and low-pressure techniques (Lubwama and Yiga, 2017).30, 50, 70, and 90 g of Cassava flour binder and wheat flour were added 1000 g biochar each from groundnut shells and bagasse biochar, respectively. These biochars were produced under low-pressure carbonization. 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, groundnut shell briquettes were created at high pressure (230 MPa) were also produced in different compositions for comparison. Higher heating values of 21 and 23 MJ/kg were obtained for both cassava and wheat starch binders as shown in Figure 6. The results were above the 16 MJ/kg average recorded for noncarbonized groundnut shell briquettes developed under high pressure.

The noncarbonized briquette 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 grams of binder content compared to higher binder contents of 70 and 90 g, as shown in Figure 2.

(a)	(b)

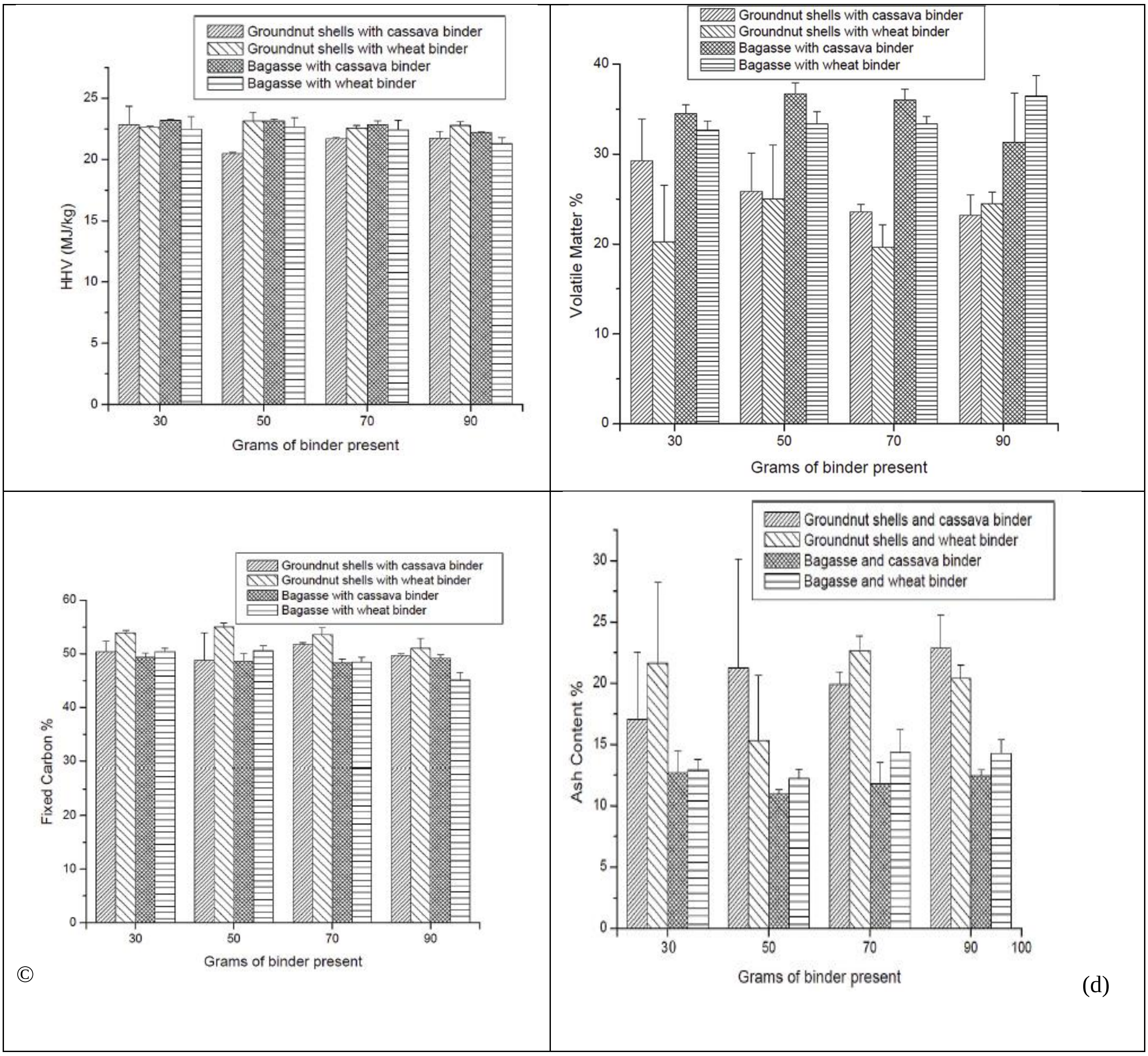

Fig. 2: (a) Higher heating value, (b) volatile matter, (c) fixed carbon content, and (d) ash content of shell and bagasse briquette (Lubwama and Yiga, 2017)

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

30% cassava starch binder and at 150kPa compaction pressure. The lowest compressive strength was recorded with 10% gelatine binder at 50 kPa pressure.

(Thabuot et al., 2015b) 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 binder on the density, HH value, and burning rate of the prepared briquettes was investigated. The sun-dried and milled biomass of smaller particle size was mixed with 20 wt. % palm fibre with molasses. The results revealed that the amount of molasses significantly affected the briquette density, as shown in Fig. 3, with the most densified product occurring at 20 wt. % molasses. A higher proportion of binder was observed to have resulted in a loosened briquette product. The briquettes prepared from rubber sawdust increased to 540.76 kg/cm^2, and the density of the corn cob briquette increased to 332.54 kg/cm^2. 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 binder's influence on biomass briquettes' combustion properties.

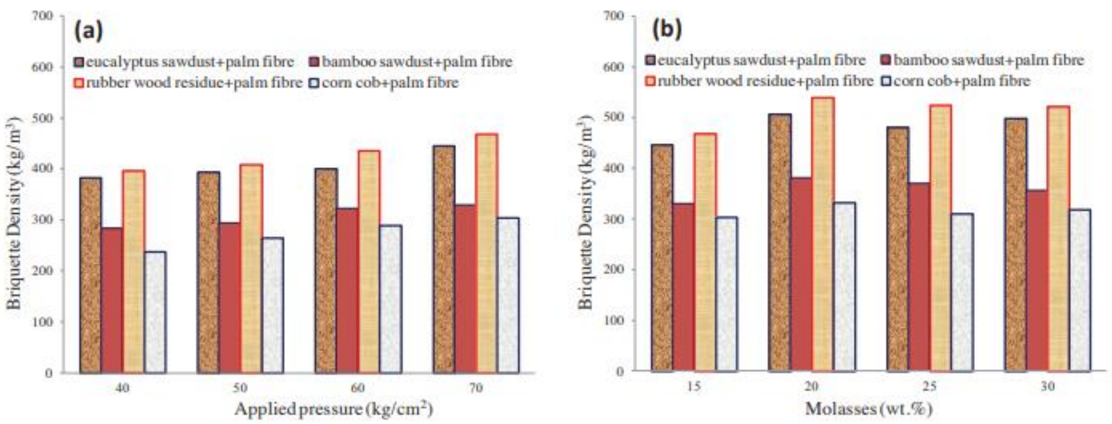

Fig. 3: Effect of applied pressure and density on the Holey briquette (Thabuot et al., 2015a).

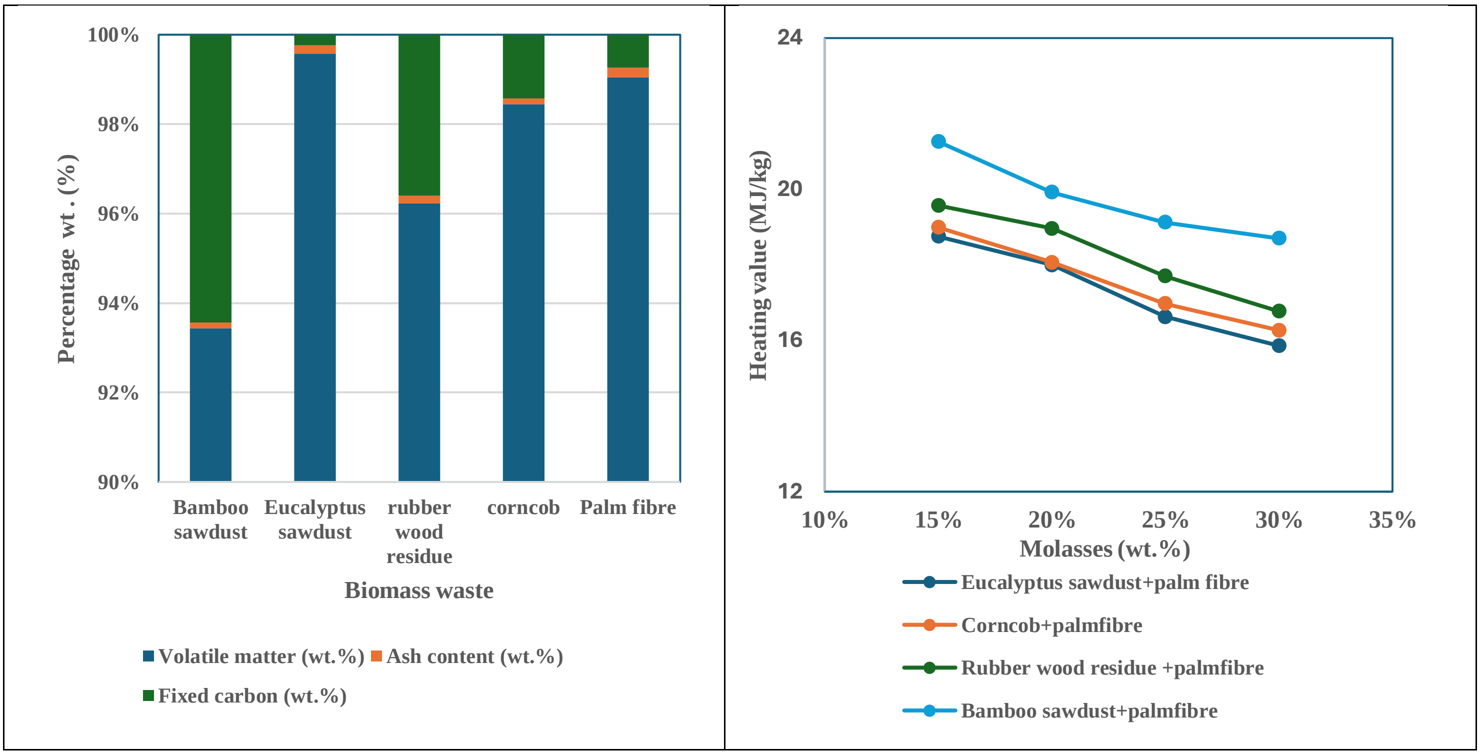

Fig.4: The Proximate of Biomass waste and HHV relationship with percentage Molasses (Thabuot et al., 2015a)

An investigation on the combustive nature of water hyacinth- plantain peel binder briquette was carried out by(Davies and Abolude, 2013). The performance contrasted with firewood (*Anthronotha macrophylla*), charcoal, and red mangrove wood. Water hyacinth has 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 high value as a combustible fuel, are a good alternative energy source. Higher calorific value was observed with water hyacinth briquettes than that of firewood and mangroves, as shown in Fig. 5. This suggests that briquette is next to charcoal to generate more heat of combustion than firewood and mangroves.

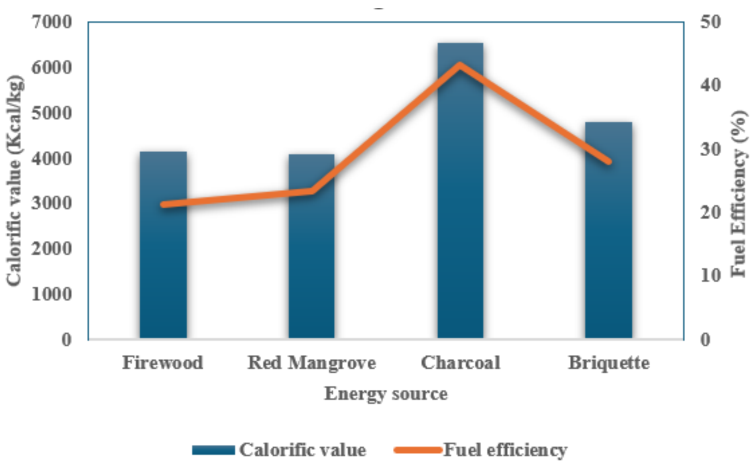

Fig. 5: Comparison of the calorific values of water hyacinth briquette, charcoal, red mangrove wood, and firewood (Davies et al., 2013b)

(Rajaseenivasan et al., 2016) reported the performance of sawdust and neem powder briquette and its blends produced within the 7–33 MPa pressure range. According to the results, a significantly greater strength was reported for the neem powder briquette, although with an increasing calorific value. The briquette properties were enhanced with increasing pressure. Further experiments were carried out under a maximum pressure of 33 MPa, and the 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 briquette was enhanced as the neem binder increased in the briquette and slightly reduced the burning rate. However, increasing the neem content reduces the calorific value of the blend, as shown in Figure 6.

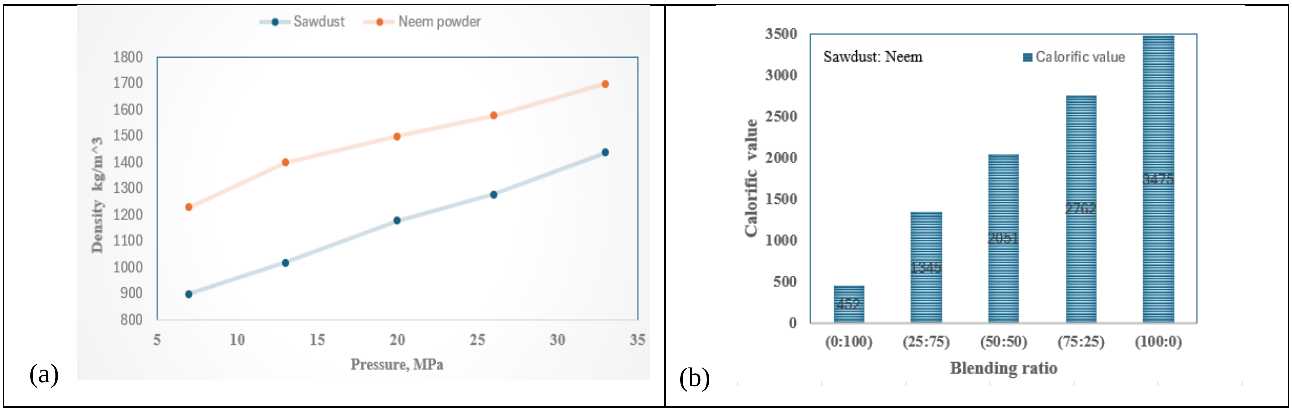

Fig. 6: Density and calorific value of Sawdust and Neem Powder Briquette (Rajaseenivasan et al., 2016).

(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 size of 1.18–0.6 mm, and binder of 10 %, 20%, and 30 % were added. The briquette shows a higher durability index of 29.33% for plantain peel binder and 93% for Arabic binder at 30% binder content. Also, a compressive strength range of 1.29 -4.77 kN/m^2. Hence, the gum arabic binder briquette has better mechanical handling characteristics than the briquette with plantain binder.

(Nikkhah Shahmirzadi et al., 2024) produced hybrid charcoal briquettes from datepalm and pistachio residue 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 range of compressive strength. The superior properties of the briquettes were obtained at a 20% starch binder content. The physico-mechanical properties were at their best within the 15-20% binder content, even for better-quality storage and transport.

(Fengmin and Mingquan, 2011) evaluated the effect of loess and lime binder on certain properties of briquette such as the calorific value, in giant reeds and reeds biomass. The calorific value of the briquette decreased with increasing binder content. The increasing binder content was suggested to be responsible for reducing the combustive component of the overall briquette. Giant reed briquettes with loess have a higher calorific value than reed briquettes with loess. The calorific value of giant reed briquettes and reed briquettes is between 10.3 and 19.8 MJ/kg. It was observed that the briquette has optimum mechanical properties at 30% binder content. Giant reed briquettes and reed giant briquettes with loess binder have calorific value 14.2 MJ/kg and 13.4 respectively. Giant reed briquettes and reed briquettes with lime binder have calorific values of 13.7 MJ/kg and 14.5 MJ/kg, respectively. The binder was confirmed to have significantly influenced biomass the performance of the briquette. The combustive component of the briquettes reduces with increasing binder content, resulting in more ash content. The biomass contents also play a notable role in this briquette as the best addition of biomass is 45%.

Inorganic binders

Bentonite clay was explored as a binder to produce binary briquettes made from vegetable market waste having sawdust at ratios of 25, 50, 75, and 100% by (Afsal et al., 2020). The performance of the VMW-based biomass briquette was compared with that of firewood, coal, and conventional sawdust briquettes. Composite briquettes had better combustion properties, such as a higher calorific value, as compared to 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.

(Kebede et al., 2022)examined the effect 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 material. Among the residues, sawdust residue-produced briquettes were found to have the highest fixed carbon content and HHV.Moreover, the residue made of sawdust had the least amount of ash and sulfur. The study's findings also demonstrated that the paper pulp bonded briquette had the maximum calorific value. Hence, making sawdust residue combined with paper pulp briquette binding material, a high-quality and long-lasting solid fuel briquette, and that paper pulp binds better than clay soil.

(Celestino et al., 2023) established that binder type remarkably affects the physico-thermal and mechanical properties and calorific value of biocomposite briquette. In their experiment, hybrid binders, clays, and gum arabic were taken into consideration for developing mixed biochar briquettes at low pressure (≤ 7 MPa). Biocomposite briquettes with clay binder have heating values ranging from 17140 to 18336 kJ/kg for biocomposite briquettes, briquettes with gum Arabic binder 18053 to 18665 kJ/kg, and 17404 to 18232 kJ/kg for biocomposite briquettes with hybrid binder. This indicates a higher calorific value for briquettes with gum Arabic compared with briquettes with other briquettes of clay and hybrid binders. However, hybrid binders had better performance (density, compressive strength, burning rate) based on their reduced boiling time, higher burning rate, and compressive strength. Hence, it is recommended. This suggests the potential of different binders in biocomposite for domestic and industrial applications.

Coal-rice husk compositions and Coal-corn cob briquette compositions were developed by (IKELLE, 2017) at ratios. In this study, bitumen, starch, calcium sulfate, and cement were explored as binders while calcium hydroxide serves as the desulfurizing agent. The sample briquettes were produced under the subjected force of 276.36 N and 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) 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), higher sulfur concentrations (3.01–8.22 %), and burned for shorter periods (11.71–24.89 min) compared with other type of binders briquettes. Also, 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 contains noncombustible ingredients resulting in high contents. Briquettes with starch binder had the longest burning times (15.27–26.21 minutes), 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 of all the binders studied. The briquettes with starch binder had the lowest sulfur content. The compressive strength of the coal-based briquette range having either 40% rice husk (11.34-13.95) and 40 % corncob (12.75-14.46) N/mm^3, which is higher than 100% coal ranging from 7.05-7.92 N/mm^3.

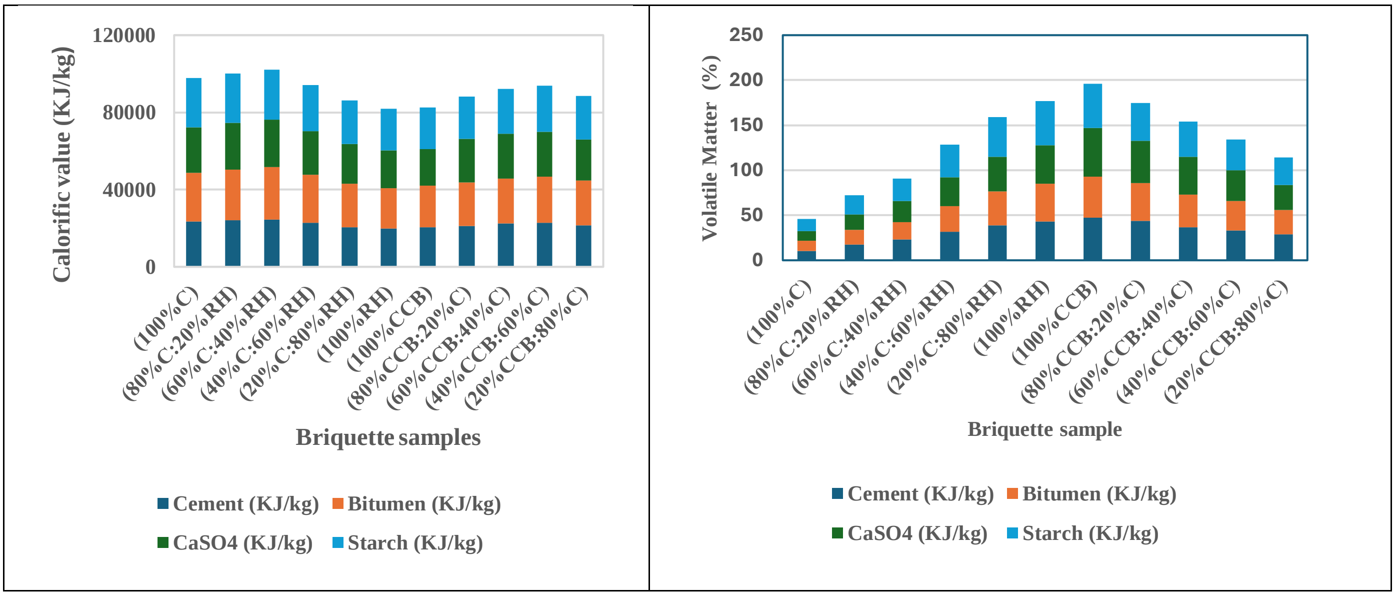

Fig. 7: Calorific value and time of briquette samples of various blends (Ikelle, 2017).

Emerging binders (Polymer, coal tar, nano-binders and Microalgae)

The effect 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 was examined by(Pramadhana et al., 2017). The Carbonization process enhanced the HHV and the fixed carbon content of the briquette. The best performance was achieved with 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, although the combustion efficiency was 4.89 %.

Potato starch and carboxymethyl cellulose (CMC) waste at 5 %, 10 %, and 15 % are used as binders in briquetting food waste char in a study by (Idris et al., 2021b). Starch binder gave a better combustion quality than carboxymethylcellulose (CMC) in the briquette. The food waste charcoal (23.27 MJ/kg) was comparable to that of commercial charcoal (22.83 MJ/kg). However, a slight decline in the calorific value was observed upon the addition of binders, which is more conspicuous even when CMC is added as shown in **Figur**e 7:

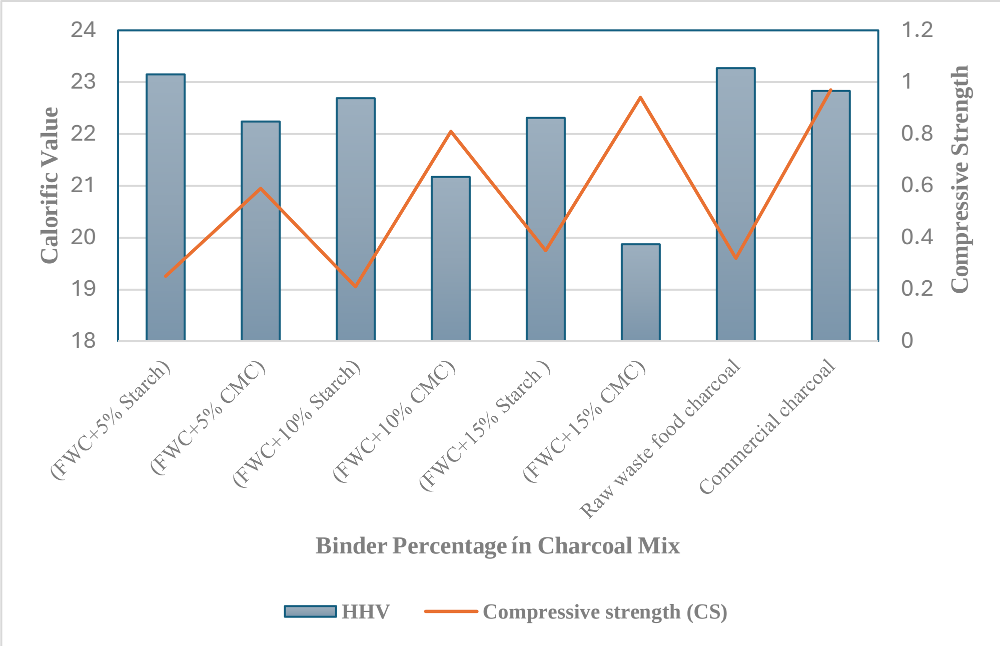

Fig. 8: Calorific value and compressive strength of each sample

(Afra et al., 2021)observed an enhancement at 3, 6, and 9% w/w nano lignocellulosic binder inclusion to produce shredded and ground bagasse briquette. These binders included nano lignocellulose, nanocellulose, and lignin. The briquettes were achieved using a cylinder-piston system and a densification process of 150 MPa and 100 °C. Compressive strength of 34N/mm, a HHV-29MJ/kg, the FCC-14.49%, VM-72.19% and ash content of 4% were reported nano-lignocellulose binder at 9%. A Compressive strength of 29.45 N/mm, HHV-19.85 MJ/kg, FFC-13.81 %, VM-72.57 %, and AC-7% was also reported for nanocellulose binder at 9%. However, the lignin binder in the briquettes had 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 than those of the lignin binder briquette.

The potential of LLPE as a binder to torrefy biomass during pelleting was investigated by(Yang et al., 2018)). LLDPE was added to the torrefied biomass straw, which improved the HHV, reduced the ash level, and raised the pellets' fracture load and tensile strength. The wood pellets fulfilled all current requirements for usage in commercial applications. Except for density, the best outcomes were obtained at a 10% load concentration of LLDPE in the torrefied barley blend. LLDPE can be obtained from MSW, and an application may be found as a biomass that has been torrefied.

(Si et al., 2017) examined the influence of coal tar residue waste as a binder in producing biomass pellets made from wheat straw, bamboo, and sawdust. In this study, pollutant emission and the strategies for mitigating NO, SO2, polycyclic aromatic hydrocarbons

(PAHs), and dioxins (PCDD/Fs) during biomass pellet burning were investigated. Sawdust was observed to have the lowest NO and SO2 emissions out of the three biomass pellets, whereas bamboo pellets and wheat straw pellets had the highest emissions.

A reduction in the NO, SO2, PAH, and PCDD/F emissions was observed by adding a 30% weight percentage CTR binder to the biomass briquette. However, as the furnace temperature increases from 800-1300 °C, a steady rise in SO2 emission was observed with wheat straw pellets having a 30% weight percentage CTR binder. NO production was restricted due to a stronger reducing atmosphere generated by the biomass pellet volatiles, leading to a reduction in NO emission. In addition, the addition of limestone sorbent further reduced SO2 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 to prepare biomass pellets as explored (Cheng et al., 2018). This is to enhance mechanical strength and heating value. The CTR has 40.06% asphaltenes, aliphatics, aromatics and nonhydrocarbon components and 72,276 MPa s viscosity with HHV of 27.46 MJ/kg. The heating value of the biomass pellet increased from 20.62- 25.96% as the CTR percentage increased from 0 to 40 wt. %. Other properties, such as the abrasive resistance and ignition temperature, also significantly increase with increasing CTR binder content. It also reported a decline in burning rate from 1.28-0.82 mg/min, and an increase in burnout temperature from 465.33- 563.33 °C.

In the event of mitigating the raw material challenge of the wood pellet industry, polymer plastic as a binder for torrefied and pelletized herbaceous biomass was examined in a study by(Emadi et al., 2017). Its mechanical, storage, and combustion characteristics 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 to the torrefied biomass pellets.
Similarly, adding 1–10% LLDPE to torrefied wheat and barley straw pellets led to 20.50 MJ/kg HHV and lower ash content of up to 6%. Except for 10 %, the pellets' HHV at all additional LLDPE levels satisfied the most recent DIN 51731 standard standards for commercial pellets (Fig. 9). It was observed that the ash content except at 1% LLDPE complied with the pellet fuels required specification.

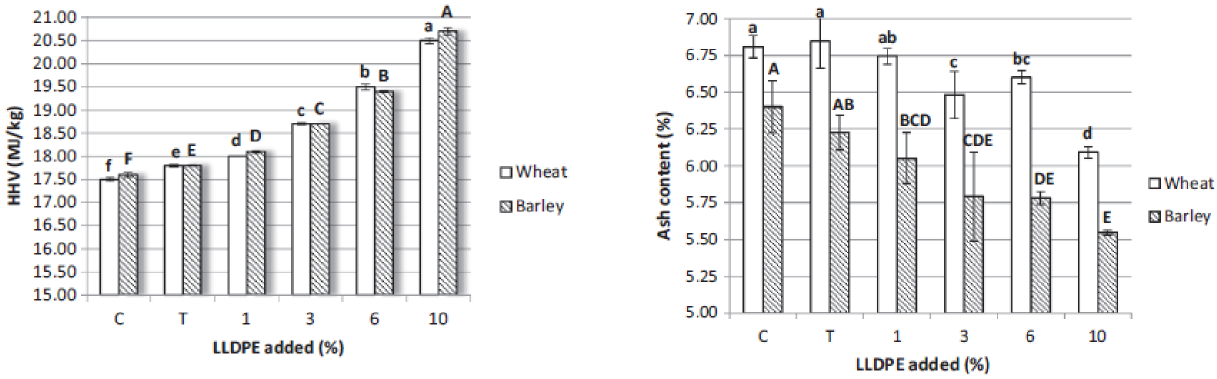

Fig.9: HHV and AC of barley straw pellets of varying LLDPE binder (Emadi et al. 2017)

The potential of tar and tapioca flour as binding agents in producing carbonized durian peel bio briquette was explored and confirmed by(Soeherman et al., 2023). A proportionate combination of tapioca and tar falls within the 25-75% of each blend. The calorific value was maximum (90694.53 cal/g) at 75: 25 of Tar to Tapioca blend. The briquette density ranges from 0.5029 g/cm^3 - 0.5685 g/cm^3 and 75:25 blend was noted to absorb 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 reveal that finely ground particles (1.75 - 2.00 mm) had low calorific values due to heat loss and left the sample susceptible to oxidation by air. Gum Arabic binder inclusion significantly raised the HCV of all the samples more than the addition of starch, as seen in Fig. 10. Over the biomass spectrum evaluated, the top glue binders' 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 aside from those composed of rice husk and coconut shell—had lower caloric values when PVC was used as a chemical binder and dissolved in organic toluene.

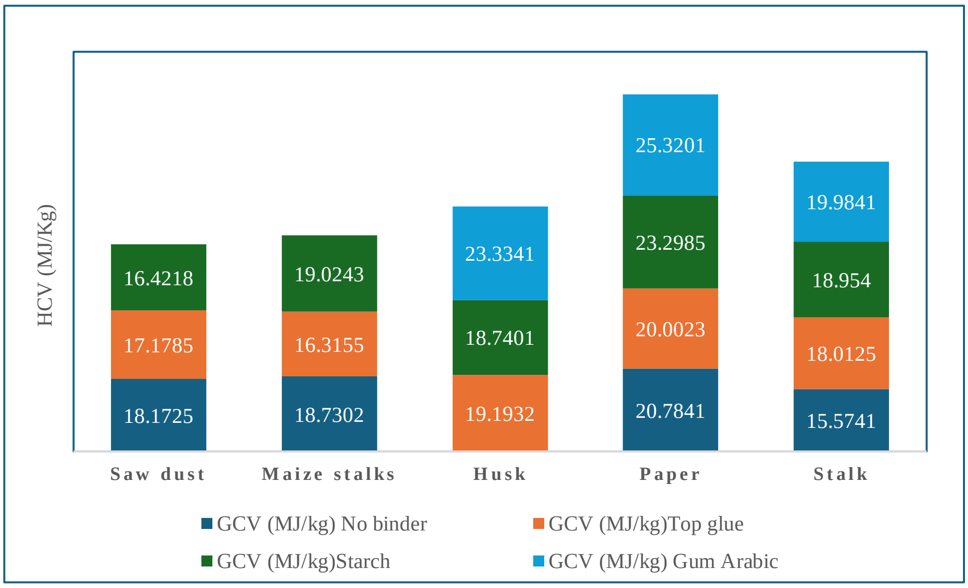

Fig. 10: Comparison among classes of binders (top burnt glue, starch, and gum arabic) (Zakari et al., 2013)

Commercially available starch and calcium hydroxide were suitable as binders for solid biofuel from briquetting durian peel in the investigation by (Mitan et al., 2018). This study treated the durian peel by drying, milling, and carbonizing at 370 °C. Densification was carried out using a 4% weight ratio of various binders with the durian peel. NC denotes noncarbonized, NCC denotes noncarbonized with calcium hydroxide, and NCS denotes noncarbonized with starch. The noncarbonized briquette had a compressive strength of 130.19 and peak calorific value (theoretical) of 18.62 MJ/kg, and its MPa as shown in Figure 11.

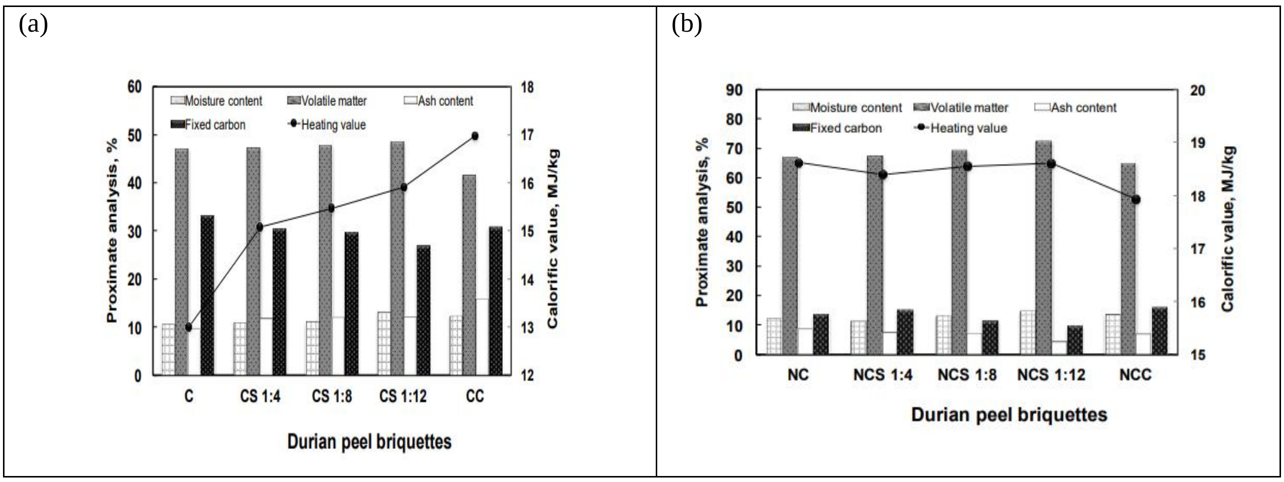

Fig. 11: Proximate analysis and heating values of (a) carbonized durian peel briquettes and (b) uncarbonized durian briquette (Mitan et al. 2018)

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

The qualities and characteristics of EFB's combustion were examined by(Nazari et al., 2020). The effect of carbonization process and their 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 the maximum HHV of 23.62 MJ/kg, around 30 % compared to the briquette from untreated EFB. Overall, it was discovered that combining carbonized EFB with tapioca starch enhanced the briquette's quality and increased its potential for application in syngas manufacturing.

In a bid to manage solid waste as a substitutive energy source, corn cob, agricultural waste was carbonized and developed into briquettes at percentage tapioca starch binder content of 6.0, 10.0, 14.0, and 19.0. This study was carried out by (Zubairu and Gana, 2014). The properties of the developed briquette were contrasted with wood charcoal and bagasse. It was observed that the blended charcoal and tapioca briquette have an HHV of 32.4 MJ/kg compared to baggase (23.4 MJ/kg) and wood charcoal (8.27 MJ/kg). It was considered a superior fuel due to its higher bulk density and fixed carbon content.

In (Song et al., 2020) study, 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). To create biomass briquettes, they were densified, and to create charcoal briquettes devoid of binders, they were carbonized at 400 °C. The findings show that the HT charcoal briquettes' physical characteristics, 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 briquette was found to have comparable combustion character indexes with 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.

The review has presented arrays of agro-wastes and binders used in the briquetting technology towards achieving waste valorisation, management and sustainable energy generation. A summarized data is as 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 utilisation. Critical observation affirmed that binder type, its percentage binder content and other process conditions grossly influence combustion performance of the biomass. Significant upgrade in the solid fuel quality and performance was more pronounced with agro-waste such as shredded and ground baggase, Durian seed and peel, wheat straw and moso bamboo having calorific (heating) value of ≥20 MJ/kg. Emerging binders such as LLDPE polymers, bitumen and Coaltar (CTR)significantly upgraded the energy value at ≤30% binder content compared to organic binders such as starch and molasses. It is therefore very clear that agricultural waste biomass could be harnessed at optimal process condition to combustion capacity equivalent or greater than commonly patronised coals, bituminous coal and lignite which falls within the ranges of 23-35 MJ/kg.

According to (Bency et al., 2023a), a good biomass briquette expected to be rich in carbon and volatile with a low-moisture and ash content. Reported studies have shown that agro-biomass has sufficient volatile content more than coal, which is indicative of its faster ignition. Also, a number of agro-wastes has 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 and Natarajan, 2006, Manyuchi et al., 2018, Tippayawong et al., 2006).High ash content of any fuel shows that more remnant and incomplete combustion. This characterised by the transfer of heat and oxygen diffusion to the surface of the fuel during combustion which will consequently reduce the fixed carbon and heating value.

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

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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 MJ/kg	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 and Mingquan, 2011)	Giants reeds (GRB) and reeds (RB) biomass	Loess Lime	Binder: 10,20,30,40 & 50%	GRB:(13.7-14.2) MJ/kg RB:(13.4-14.5) MJ/kg	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 (PVAC):15.9 MJ/kg	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 CY: 17.1-18.3 MJ/kg GA: 18.1-18.7 MJ/kg	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., 2015a)	Holey/Palm fiber Briquettes	Molasses (M)	Binder;(15,20,25,30 %) Pressure:40-70 kg/m^2	18.0- 19.92 MJ/kg	20%; 70kg/m^2	Density: 540.76 kg/cm^3 (M)
(Davies and 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	25%; 33MPa	Impact resistance: 28X
(Bency et al., 2023b)	Cabbage Waste	Beef Tallow oil(BTO) Cassava binder(CB) Sodium silicate (SS) Vinyl ester resin(VER)	20%	BTO:22.4 MJ/kg (appx.) SS:20.1 MJ/kg VER:24.3 MJ/kg (appx.) CB: 20 MJ/kg (appx.)		Density:545.6- 591.3 kg/cm^3

(Lubwama and 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	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	8%	CS: 10kg/cm^2
(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:1.715g/min (CP) RD: 632.2 kg/m^3 (CS); BR:1.76 g/min(CS)
(Falemara et al., 2018)	Groundnutshell, corncobs, Wood residue, particles	Starch	(15-25%)	------------	25%	Specific heat of combustion (SHC):7362-8222 Kcal/kg Density: 044-0.53 g/cm^3
(Carnaje et al., 2018)	Water hyacinth briquette	Molasses	(60, 70, 80)%	16.6 MJ/kg	30:70	CS: 19.1 kg/cm^2.
(Wirabuana and Alwi, 2021)	Durian lai Peel	Starch binder (SB)	3%, 4%,5%, and 6% (w/w)	23.01 MJ/kg	3 % (w/w).	---------------
(Ohagwu et al., 2022)	Saw dust briquette	Okra	5-20%	17.82 MJ/kg	5%	CS: 22.0- 31.0KN/mm^2
(Tahir et al., 2012)	Groundnut shell(GS) Durian shell(DS) Casava peel(CP)	Binding agent	10-30%	GS:24.03 MJ/kg CP:19.87 MJ/kg DS: 21.87 MJ/kg	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	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	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 -NCS 19.85 MJ/kg-NC	9% NCS	CS: 34 N/mm (SB) VM-72.57% (SB) CS: 29.45 N/mm (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(WS) 21.35 MJ/kg (SD) 21.00 MJ/kg(MB)	30% (WS) 35%(SD)	BR: 0.82 mg/min (WS) BR: 0.81 mg/min (SD) ----------------
(Emadi et al., 2017)	wheat Straw Barley straw pellet	LLDPE	(1,3,6 & 10%)	20.50 MJ/kg (Wheat) 20.7 MJ/kg (barley)	10% 10%	<u>Density</u> 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	Tar: Tapioca 75:25%	Density 0.5685 g/cm^3
(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 (TG):16.3-20.0 MJ/kg (ST):16.4-23.2 MJ/kg	3.35 mm Particle size	---------------
(Mitan et al., 2018)	Duran peel	Starch Calcium hydroxide	4%	18.62 MJ/kg 18.0 MJ/kg	4%	CS: 130.19 MPa
(IKELLE, 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 (CS):24.8 MJ/kg (S): 25.9. MJ/kg (C): 24.4 MJ/kg	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 leave	Molasses	50%	17.83 MJ/kg sugar cane leaf	50:50	CS-32.4-44.7 kg/cm^3
(Davies and Abolude, 2013)	Water hyacinth	Phytoplankton	10, 20, 30, 40 & 50% 20MPa	17.9 MJ/kg	50%	Burning rate (BR) 2.25g/m Ignition time (IT): 73.54-123.42 min.
(Espuelas et al., 2020)	Spent coffee ground	Xanthan and guar gum	8,10, 12 MPa 5&10% binder	Guar:(24.321-24.398) MJ/kg Xanthan:(23.503-24.450)MJ/kg	5%; 10MPa	--------------
(Muazu and 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 16.03 MJ/kg 21.61-21.83 MJ/kg 20.54-21.78 MJ/kg	6% binder	--------------------------------
(Song et al., 2020)	Cotton stalk (CS) Saw dust (WS)	Hydrothermal treatment(HT)	(200-260)°C; 75-80 MPa	CS-HT:25.66 MJ/kg WS-HT:27.94 MJ/kg	260°C	Ignition tempt CS-274.68°C WS-291.25°C
(Yank et al., 2016a)	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	10%	Density: 2.54KN 475 Kg/m^3 (CSW) 465 kg/m^3 (RD) 440 kg/m^3 (OSG)

(Shuma and 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 YG: 12.6-15.79 MJ/kg ML: 16.36-21.53 MJ/kg	12MPa	-------------------
(Narzary et al., 2023)	Waste rice straw	Starch Paper Taro starch	10,15,20	(24.049-28.64 MJ/kg)	20%	Specific fuel consumption (SFC) Taro-43.3 g/L Paper-48.72 g/L Starch-56.41 g/L
(Kimutai and Kimutai, 2019)	Cashew nut shell	Cassava binder	10%,20% & 30% Pressure:100 -300 kg/cm^2	30.5 MJ/kg	30% 0.5mm 300 kg/m^3	BR: 9.416 g/m IT: 29sec CS: 65-75 kg/cm^3
(Idris et al., 2021a)	Food waste (FWC) charcoal	Potato starch carboxyl cellulose (CMC)	5%,10% &15%	(19.87-23.15) MJ/kg	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:15.92MJ/kg Starch red:15.10 MJ/kg Starch: 16.14 MJ/kg	-------------	CS: 22.9N/mm$^{2;}$; Density: 1.66 kg/m^3 (SC) CS:16.7 N/mm^2; Density:1.55 kg/m^3 (SR) CS:34.0N/mm^2; Density:1.46 kg/m^3 (S)
(Oroka and Thelma, 2013)	Water hyacinth(WH)	Cow dung (CD)	cow dung 10,20 &30 %	WH-13.4 MJ/kg Cowdung:14.4 MJ/kg	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	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	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 CH: 17.78 MJ/kg KW: 16.65 MJ/kg DG: 17.43 MJ/kg	3:1	------------
(Nazari et al., 2020)	Empty fruit brunches (EFB)	Corn starch	20% binder	23.62 MJ/kg	100:20	--------------
(Zubairu and Gana, 2014)	Corn cob	Tapioca starch	6,10,14, 19%	30.57-34.73 MJ/kg	---	358.3-425 kg/cm^3

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CONCLUSIONS

The briquetting of biomass has been one of the potential and promising routes 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 the briquetting of selected biomass. This review comprehensively explored the performance of various binders reported in a wide range of studies on biomass as they affect the biomass's combustion and energy (heating) value. It can be concluded that there are organic and inorganic binders, and in recent times,emerging binders 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 or probably higher than coal and sub-bituminous coal, even at lower binder content compared to organic and inorganic binders. According to the overall 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 a 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, reducing food shortages. In addition, certain thermal treatment methodologies, such as torrefaction and carbonization, were used to optimize the combustive performance of the selected biomass.

FUTURE DIRECTIONS

The conversion of agro-waste biomass into solid fuels is therefore being considered a viable approach to waste management as well as energy production. However, on the way to creating efficient and high-quality solid fuels, it is necessary to consider critical tasks. Hence preliminary investigations such as proximate analysis and ultimate (elemental) analysis is germane to determine the environmental friendliness,combustion properties and sustianbility of the solid fuel. Composite biomasses has shown prospect in upgrading solid fuel. Further more, low-energy pretreatments such as torrefaction and carbonisation before briquetting could help achieve the expected balance in fixed carbon content and volatile matter requirement toward better energy and combustive properties. There is also a strong demand for new binder materials (emerging/non-edible binders) should be explored to reduce over dependency on starch and molasses which competes a food sources. Better densification methods to increase the mechanical properties, energy storage, and chemical stability of bio-derived fuels is also proposed. Furthermore, there are plenty of opportunities in the research of composite biomass blends as it provides an opportunity to reach maximum synergy of biomass characteristics. A series of advanced technologies and specially designed blending methods promoted for binding and densification of biomass materials can be also 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.

AUTHOR CONTRIBUTION

OTA: conceptualize the review article, literature search and prepared the original draft.

WKK: reviewed, revised and supervised.

TJ: reviewed, revised and supervised

ERS: reviewed, revised and supervised

LB: reviewed and revised

CGA: reviewed and revised

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Data Availability

All data generated or analyzed during this study are included in this article.

Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose with respect to the research, authorship and/or publication of the article.

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