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Fabrication of briquettes from charcoal fines using tannin formaldehyde resin as a binder

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ABSTRACT

Charcoal fines, a waste emanating from charcoal transportation and handling, were utilized in the fabrication of briquettes using tannin-formaldehyde resin as a binder to meet ever expanding energy demand. A collection of four briquette samples were fabricated with binder proportions of 25%, 30%, 35%, and 40%. These briquettes were characterized using Fourier transform infra-red and thermogravimetric analyses techniques. Furthermore, the briquettes were subjected to physical parameters namely bulk density, impact resistance index (IRI), water resistance index (WRI), and water boiling test. The bulk density of the briquettes was 1.153-1.495 g/cm^3, IRI was 6.79-73.33, and WRI was 99.24-99.29. The briquettes exhibited an ignition time of 5.38-6.21 minutes, boiling time of 19.50-37.20 minutes, burning rate of 3.20-8.70 g/minute, and a specific fuel consumption of 54.70-64.30 g/L. Higher heating value range for the briquettes was 19.76-23.23 MJ/kg and the briquettes with 40% binder showed the best physical qualities with great fuel potential. Therefore, the fabricated briquettes have demonstrated great potential as a source of cleaner and sustainable energy.

Keywords: briquette, tannin-formaldehyde resin, charcoal fines, bulk density, calorific value

INTRODUCTION

Exploration for clean and sustainable alternative forms of energy have been on an increase globally, especially the valorization of biomass to solid, liquid, and gaseous fuels. Current research has revealed that biomass energy conversion is one of the few verified, cost-effective and available technologies that can reduce CO_2 emissions (Onchieku et al., 2012). These investigations are based on the impacts on climate change triggered chiefly by the utilisation of fossil fuels. The need for renewable and clean sources, especially those from lignocellulosic biomass, has been ratified in every environmental and global commitment (Dias Júnior et al., 2021; Miao et al., 2023). Charcoal, a renewable and sustainable source of energy, has shown great potential as an alternative feedstock for energy production (Heinimo & Junginger, 2009; Milano et al., 2016; Onchieku et al., 2012; Taibi et al., 2012). Charcoal is produced by means of heating wood or other biomass in the absence of oxygen. The handling and transportation of charcoal often result in up to 20% losses as fines are produced, which are of low-purity and high-ash content residues that cannot be burnt by usual methods (Kivumbi et al., 2021). These fines are typically considered waste material and may be dumped, leading to environmental pollution. Fines may present wide ranging challenges such as high flammability; air pollution, water pollution and soil degradation.

As a result of lack of access to electricity, majority of people in the developing world rely on traditional biomass as fuel for heating and cooking (Rawat et al., 2022), with charcoal playing an increasingly important role. The production of briquettes from charcoal fines and organic residues has been identified as a viable and economical option to reduce the environmental impact resulting from the disposal of these waste materials (Barasa et al., 2013). Briquetting has been widely implemented to valorize fines, but the choice of binder is a critical factor in ensuring the process is both environmentally benign and economically viable. Briquetting involves mixing a binder with fine charcoal and forming the mixture into a cake or briquette in a press, which is then cured in a drying oven by driving out the water so that the briquette is firm enough to be used in the same way as a regular piece of charcoal (Kivumbi et al., 2021).

The type of binder used is critical since it should improve the binding strength and quality of the finished briquette (Benk, 2010). A flammable binder is preferred, however a non-combustible binder that is effective at low concentrations may also be appropriate. Starch, molasses, and oils are common briquette binders (Marreiro et al., 2021). The use of low-cost, locally accessible organic binders in briquette manufacture is a promising alternative to synthetic resins (Idah et al., 2013). Various techniques have been used for briquetting and the main setback in commercializing them is high binder cost and poor mechanical integrity (Miao et al., 2023). Numerous types of binders have been utilized in the literature to date, with several possessing favorable adhesive properties such as biodegradable paper soaked in water, lignin, fibers, glycerin, pitch, and plastics (Miao et al., 2023). Condensed tannins, oligomers of flavan-3-ol units derived mostly from black wattle bark are used as a natural phenol alternative in thermosetting resins such as adhesives (Miao et al., 2023; Venter et al., 2012). Previous studies have investigated the use of condensed tannins as a binder in briquette manufacture, demonstrating that they have high binding characteristics and can greatly improve the mechanical strength of the briquettes (Radebe et al., 2013; Velenzuela et al., 2012). These materials are a sustainable, cost-effective, and ecologically benign alternatives to synthetic resins in briquette production (Marreiro et al., 2021). The economic feasibility of briquetting lies in the fact that the total cost must be below or comparable to fossil fuel. Thus, the conversion of charcoal fines into briquettes with tannin-formaldehyde resin (TFR) as a binder offers a promising solution to the growing demand for sustainable energy sources while minimizing waste and improving process sustainability. TFR is an organic binder. These types of binders have several advantages like reduced silica concentration in briquettes (Miao et al., 2023). It has been observed that lowering silica levels can save energy and money (Alsaqoor et al., 2022). Furthermore, organic binders have enhanced the porosity and reducibility of burned briquettes giving them good bonding superior combustion performance, high crush strength, extraordinary drop test strength, and low ash (Alsaqoor et al., 2022; Kivimbu et al., 2021). Such desirable properties have given motivation to this study to explore the use of TFR as a binder for producing briquettes from charcoal fines.

Several studies have been conducted, where several binders have been tested in the production of briquettes from diverse biomass such as rice husk/cassava peel gel, rice husk/banana peel, maize cob/cassava peel gel, maize cob/banana peel, groundnut shell/cassava peel gel, groundnut shell/banana peel, sugarcane bagasse/cassava peel gel, sugarcane bagasse/banana peel (Abdulmalik et al., 2020; Idah et al., 2013; Miao et al., 2023; Rawat & Kumar 2022), coal fines/ sugarcane baggase binder (van der Westhuizen et al., 2023), charcoal fines and *schizolobium parahyba var. amazonicum (paricá)* wood (Dias Júnior et al ., 2020), spent coffee grounds/xanthan gum (Seco et al., 2019), coal fine-torrefied wood/pitch (Adeleke et al., 2021), *idigbo* (*terminalia ivorensis*) charcoal particles, pinewood *pi (nus caribaea*) sawdust/cassava peels (Ajimotokan et al., 2019), coal fines/polyacrylic binder (Botha et al., 2021), coal fines-sawdust/molasses (Manyuchi et al., 2018), and charcoal fines/*African elemi (canarium schweinfurthii)* resin (Kivumbi et al., 2021). Such studies have reportedly produced briquettes with desirable bulk densities, calorific values and other properties. Nevertheless, limited research is available on the use of TFR as binders in the fabrication of coal fine-based briquettes. Researchers have assessed the compatibility between a plethora of binder and raw biomass in testing the physical, chemical, mechanical, and energy properties of the as-fabricated briquettes. Nevertheless, when charcoal fines are used, there is a need for research intended at utilizing them effectively, since to agglomerate it with no binders is problematic (Dias Júnior et al., 2021; Rawat & Kumar 2022). Thus, there is ample scope for study on the use of this cheap and locally available binder judging by the ever-increasing concerns on the economics of briquettes fabrication and marketing. More studies are imperative to investigate the possibilities of using natural binders in briquette manufacture, such as condensed tannins, and their effect on the mechanical and thermal properties of the briquettes. In one study, phenolic resin was used as a binder for the production of metallurgical grade briquettes from coke breeze (Benk et al., 2008) with commercial phenol (95%) and formaldehyde (37% aqueous solution) as the main raw materials and a catalyst was added to produce the resin binder. In another study, phenol formaldehyde was utilized as a binder to produce coal-based briquettes (Nag et al., 2017). The resins produced were thermosetting, a three-dimensional polymer was formed upon heating, as a result of condensing a phenol with a molar excess of formaldehyde in the presence of a basic catalyst. TFR is a type of adhesive created by combining tannin and formaldehyde through the addition of methylene and methylene ether bridges between the tannin molecules, resulting in the formation of a three-dimensional network of crosslinked polymers that offer the resin's adhesive capabilities (Amaral-Labat et al., 2013). TFR offers various advantages as a binder (Hussein et al., 2011), it is a natural and renewable resource that can be obtained through sustainable forestry techniques, is relatively inexpensive, and has good bonding characteristics that improve the strength and longevity of the briquettes. Upon heating, the resin undergoes a gradual decomposition process, which generates volatile compounds that act as a fuel source, thereby enhancing the combustion performance of the briquette (Zhang et al., 2018a; Zhou & Du, 2020). There is limited information on the use of TFR a binder for the production of briquettes hence, the need to investigate its potential. The sticky nature of TFR is exploited for use as a binder. Tannin have been used in the production of phenolic adhesives (Zhou & Du, 2020) and due to its vast availability in Zimbabwe at the Wattle Company plantations it was envisaged to be a cheaper resource to use as a binder in charcoal fines briquetting.

Therefore, this study explored the use of TFR as a binder using available technologies to valorise coal fines into briquettes and produce a cleaner and sustainable alternative form of energy that is cost-effective and reduces CO_2 emissions. Furthermore, the study characterized the as-synthesised briquettes, explored the impact on the mechanical and thermal properties of the as-fabricated briquettes. Therefore, the fabrication of briquettes from charcoal fines using tannin formaldehyde resin as a binder could be a novel investigation.

Figure 1. Charcoal & charcoal fines at a local market (Source: Authors' own elaboration)

MATERIALS & METHODS

Materials

Charcoal fines were obtained from the local market and tannin powder was obtained from the Wattle Company, Mutare, Zimbabwe, whilst analytical grade formaldehyde (37% w/w) and sodium hydroxide were obtained from sigma-aldrich.

Charcoal Fines Preparation

Charcoal fines had a lot of sand as a result of poor handling as it is merely considered for any meaningful use. The charcoal was therefore cleaned first followed by screening using a 400 µm sieve and the larger particles further ground into fine particles to increase binder-charcoal contact points as recommended (Chaney, 2010; Kivumbi et al., 2021). A representative sample was produced and then thoroughly mixed to attain homogeneity. **Figure 1** shows charcoal and charcoal fines at a local market.

Binder Synthesis

TFR binder was prepared using a method proposed in literature with ameliorations (Li et al., 2016). The synthesis of the tannin formaldehyde resin binder was done in an 800 ml borosilicate glass beaker equipped with a thermometer and a magnetic stirrer. Wattle tannin (94 g) and 115 g of distilled water were mixed in a flask using a magnetic stirrer to attain homogeneity. After that, 31 g of sodium hydroxide solution (50 wt. %) were added, and the mixture was stirred for 30 min at room temperature. Finally, 162 g of formaldehyde solution were added to produce a brown solution. The mixture was gradually heated to 80 °C and the temperature maintained for an hour before quenching the reaction by submerging the flask in a cold-water bath (Kivumbu et al., 2021)

Briquettes Production

Binder-charcoal mixing ratios were varied so as to evaluate the most appropriate binder concentration to use for briquette production. Binder ratio had four levels (B_1=25%, B_2=30%, B_3=35%, and B_4=40%) of the charcoal fines weight, making the ratio of charcoal fines: binder 3:1, 7:3, 13:7, and 3:2, respectively. Charcoal fines were added to the hot viscous binder and stirred manually for five minutes to produce a homogenous mixture. A manual briquetting press was used for densification by feeding 100 g of the charcoal-binder mixture into each of cylindrical 16 dies of height 50 mm and diameter 40 mm of a manual briquetting machine of weight 500 N (**Figure 2**). This was then manually pressed for a constant time of five minutes before removing the briquettes from a tray underneath the press for drying.

Figure 2. Manual briquettes press (Source: Authors' own elaboration)

Figure 3. A sample of coal fines-based briquettes (Source: Authors' own elaboration)

After densification, the as-fabricated briquettes (**Figure 3**) were sun-dried for a week so as to remove the excess moisture and improve briquette binding.

Briquettes Characterization

Fourier transform infra-red & thermogravimetric analyses briquettes characterization

The functional groups contained in the fuel were analyzed using Fourier transform infra-red (FTIR) spectroscopy. FTIR spectra was measured over 1,500-4,000 cm^{-1} in a resolution of 4 cm^{-1} by means of a Nicolet 6700 Spectrometer (Thermoscientific, SA) with 32 scans. Thermogravimetric analyses (TGA) on the fuel were performed in air at a flow rate of 50 mL/min and a heating rate of 10/min using TGA 550 instrument (Shimadzu, Japan)

Impact resistance index

Impact resistance index (IRI) gives a measure on the briquette durability. For IRI determination, the briquette was placed in a plastic bag and repeatedly dropped on a tiled floor from a height of two meters until the briquette fractured (Bazargan et al., 2014). IRI was then calculated using Eq. (1).

$$IRI = \frac{n_d}{n_p} x\ 100, \quad (1)$$

where n_d is number of drops and n_p is number of pieces.

Briquettes density determination

The desirability of the briquettes in terms of transportation, handling, storage and burning time is indicated by the density (Gilvari et al., 2019).

For density calculation, Eq. (2) was applied. Vernier calipers were used to measure the dimensions (height and diameter) of a pre-weighed cylindrical briquette.

$$\rho = \frac{m}{\frac{\pi}{4}(d^2)h}, \tag{2}$$

where m is the mass of briquette, ρ is the briquette density, h is the briquette height, and d is the briquette diameter.

Water resistance index determination

The briquette water resistance index (WRI) was determined through weighing a briquette and then placing it in a beaker filled with a known volume of tap water at room temperature and left for 30 minutes (Bazargan et al., 2014). The briquette was then removed wiped and reweighed to calculate the percentage water absorbed using the Eq. (3).

$$Water\ absorbed\ (\%) = \frac{w_2 - w_1}{w_1} x\ 100, \tag{3}$$

where w_1 is the briquette weight before water submersion and w_2 is briquette weight after 30 minutes water immersion. WRI for the briquette was then calculated using Eq. (4) (Kpalo et al., 2020).

$$WRI = 100 - water\ absorbed\ (\%). \tag{4}$$

Water boiling tests

Water boiling tests (WBTs) were determined by burning a 100 g briquette sample on a charcoal stove to assess the combustibility of the fuel and the briquette binder ratio that enabled faster cooking. One liter of water at room temperature was boiled recording temperature at one-minute intervals (Onuegbu et al., 2011). The time taken for water to boil was recorded. Eq. (5) was used to compute the specific fuel consumption during WBT.

$$Specific\ fuel\ consumption = \frac{Mass\ of\ fuel\ consumed\ (kg)}{Total\ mass\ of\ boiling\ water}. \tag{5}$$

Ignition time

Briquette sample (100 g) briquette was ignited at the base in a drought free set up and the time taken for the flame to ignite the briquette was recorded (Thulu et al., 2016).

Burning rate

Briquette samples (100 g) of different blends were burnt recording time from ignition to flame extermination. The burning rate (BR) was calculated using Eq. (6) (Li et al., 2016).

$$WBR = \frac{Mass\ of\ fuel\ consumed(g)}{Total\ time(s)}. \tag{6}$$

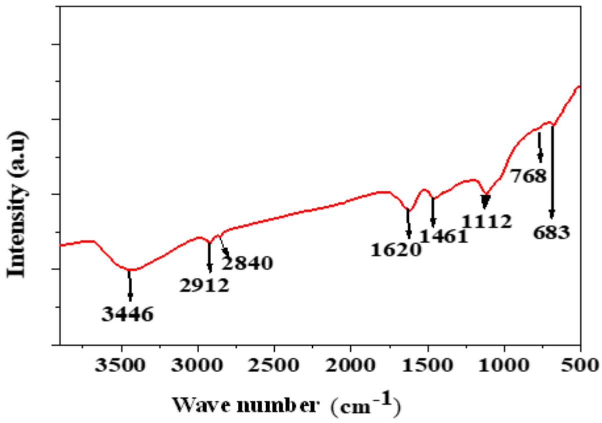

Figure 4. FTIR spectra for briquettes (Source: Authors' own elaboration)

Higher heating value determination

The calorific value of the fuel was determined using a bomb calorimeter according to ASTM D240 standard (Sukarta et al., 2017). Higher heating value (HHV) of the briquettes was calculated from WBT results using a well-known method (Sukarta et al., 2017) of calculating heat capacity. The energy required to boil one liter of water during the test was calculated using Eq. (7).

$$Energy\ required\ (Q_{req}) = m \times c_p \times \Delta T, \tag{7}$$

where m is the mass of water in grams, c_p is the specific heat capacity of water (4.18 J/g °C) and ΔT is the change in temperature of the water in °C. With the mass of briquettes used to produce this amount of energy deduced from WBT results and the specific fuel consumption in g/L known, HHV estimated by a method described by Sukarta et al. (2017).

DISCUSSION

FTIR spectra of the fuel is important for determining the functional groups in the briquets so as to elucidate the distribution of pyrolysis products (Ngangyo Heya et al., 2022). **Figure 4** shows FTIR spectrum of the briquette samples. Some widening vibrations bands ranging 1,060-1,200, 1,530-1,570, 3,300-3,400 cm^{-1} can be observed ascribed to stretching of C-OH (phenolic and ethers), quinones, carboxylic acid, and alcohols, respectively (Nag et al., 2017). The presence of alcohols is indicated by the broad O-H stretching vibrations between 3,300 and 3,400 cm^{-1} (Nyakuma et al., 2014). The two bands at 2,912 and 2,840 cm^{-1} corresponds to the C-H vibrations found in the methyl (CH_3) groups and methylene (CH_2) groups (Ngangyo Heya et al., 2022; Nyakuma et al., 2014). The presence of the carbonyl group (C=O) stretching typical of carbonyl groups is displayed by the broad intensity band between 1,490 and 1,710 cm^{-1} confirming the formaldehyde group occurrence in TFR binder in briquettes (Nyakuma et al., 2014). The peak at 1,461 cm^{-1} is attributed to the C-H deformation vibrations for alkenes (CH_2) (Ngangyo Heya et al., 2022; Nyakuma et al., 2014). Band between 1,000 and 1,300 cm^{-1} may be due to the presence of the ether groups

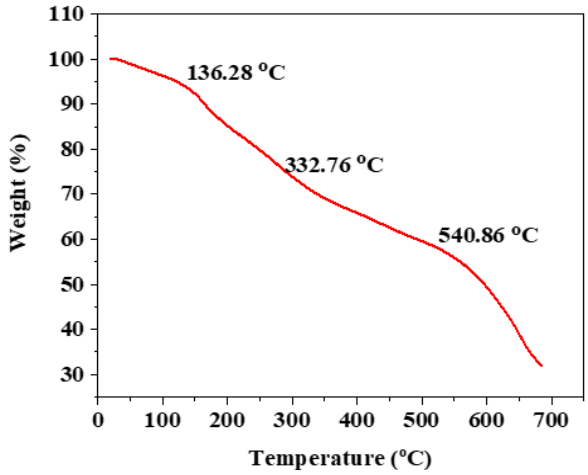

Figure 5. TGA profile of coal fines-based briquettes (Source: Authors' own elaboration)

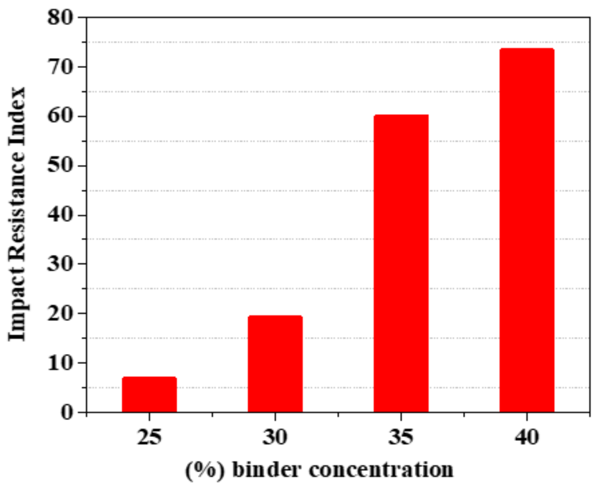

Figure 6. Effect of binder concentration on IRI (Source: Authors' own elaboration)

(Nyakuma et al., 2014) whilst peaks 768 and 683 cm^{-1} are attributed to C-H bending vibrations (Yang et al., 2016).

The thermal stability determination of the briquettes was accomplished using the TGA technique and is shown in **Figure 5**. The weight loss occurred in three stages with the initial of about 6.12% is a result of surface water and light volatile matter losses in the temperature range of 18.46-124.65 °C. A second weight loss of 24.14% around 332.76 °C is associated with the volatile matter degradation, as well as the hemicellulose, cellulose and lignin portions (Kumar et al., 2021; Raiaseenivasan et al., 2016).

A third loss in weight of 12.70% around 540.85 °C is attributed to the remaining ash content (Kumar et al., 2021; Raiaseenivasan et al., 2016). This suggests a high ash content of volatiles in the briquettes, which may affect spontaneous ignition. Similar results were reported in a study analysing briquettes obtained from coal and pretreated wood fines, biomass and coal-fine waste, coal fines polymer binder and saw dust briquette blending with neem powder, respectively (Adeleke et al., 2020; Balraj et al., 2021; Botha et al., 2021; Raiaseenivasan et al., 2016). This means ignition of these briquettes takes place around 332.76 °C and beyond that there is less energy produced. Also, to produce a briquette with good mechanical integrity and a stable or improved combustion properties (ultimate, proximate, and calorific value) from charcoal fines, curing should be around 332.76 °C (Adeleke et al., 2020).

Impact Resistance Index

IRI measures resistance to mechanical impact, which is mainly encountered during transportation and handling of the briquettes. **Figure 6** demonstrates IRI of the briquettes. IRI increased with increasing binder concentration because of improved binding performance (Zhang et al., 2018a, 2018b). Briquette B25 fractured into 12-18 fragments on impact, with an IRI of 6.79 whilst briquette B30, with an IRI of 16.97, broke into four-12 pieces on the first/second impact. Briquettes B35 and B40 fractured into two-four pieces on the first and second impact, respectively, with IRIs of 60.00 and 73.33. These findings agree with previously reported results where it was discovered that increase in briquette density result in increased IRI (Manyuchi et al., 2018; Sen et al., 2016). Briquettes B35 and B40 met IRI value of 50 that was recommended in literature for commercial briquettes (Bazargan et al., 2014). This trend can be attributed to the fact that as amount of binder increases, briquette becomes more compact and less porous, which leads to a higher degree of bonding between charcoal particles (Manyuchi et al., 2018).

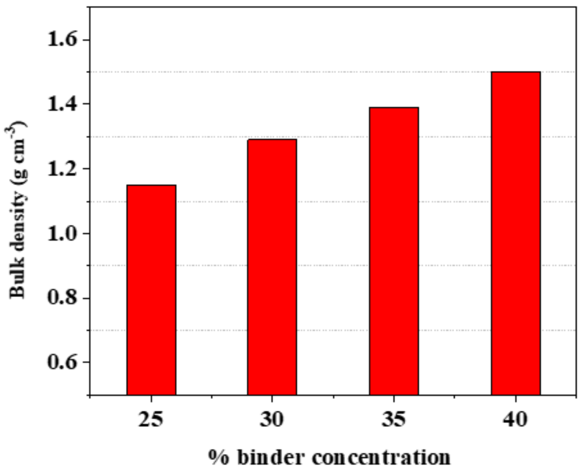

Figure 7. Effect of binder concentration on bulk density (Source: Authors' own elaboration)

Density

As depicted in **Figure 7**, the density of charcoal briquettes bound by tannin formaldehyde resin generally increases with increasing binder ratio. This is due to the fact that addition of more binder to the briquette enhances compaction and bonding between the charcoal particles, resulting in a denser and more homogeneous briquette. Such observation agrees with reported density increases as the binder ratio increases from 25% to 40% (Li et al., 2016; Zhang et al., 2018a, 2018b). This pattern can be explained by the fact that when the binder content increases, the briquette becomes more compact and less porous, resulting in a higher total density. A similar trend was reported previously by Adeleke et al. (2021). Moreover, these conform to a widely referenced report on properties of briquettes, most of the briquettes surpassed the 1.25-1.30

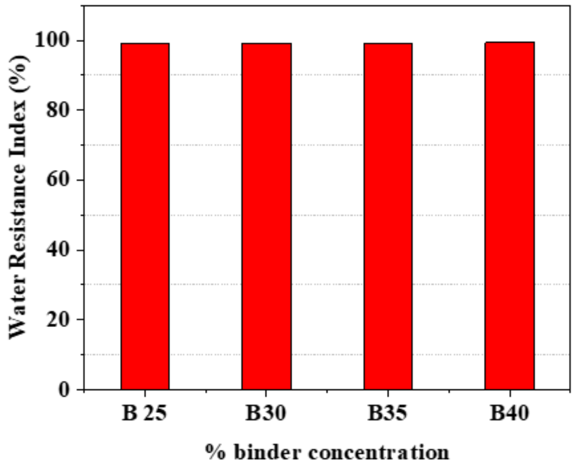

Figure 8. Effect of binder concentration on WRI (Source: Authors' own elaboration)

g/cm^3 recommended for briquettes of strong quality (Adeleke et al., 2021). Hence thee briquets are adequate for both domestic and industrial applications.

Water Resistance Index

The evaluation of the briquettes' water resistance results are illustrated in **Figure 8**.

All of the briquettes had WRI values ranging from 99.24% to 99.29%, which exceeded the recommended WRI of 95% (Adeleke et al., 2021; Gilvari et al., 2019). This study's outstanding WRI can be attributable to the use of a binder that is insoluble in water. The binder efficiently coated the charcoal particles, forming a strong bonding and making the briquettes more water resistant. It is worth noting that briquettes B25 and B30 with a smaller amount of binder had a slightly lower WRI due to the loose binding of the particles. As a result, some charcoal particles broke free during briquetting, reducing the overall water resistance. These findings are consistent with previous studies, where starch used as a binder for briquettes made from palm kernel shell biochars exhibited a WRI of less than 50%, indicating a lower resistance to water absorption in comparison to the briquettes in this study (Bazargan et al., 2014).

Water Boiling Test

Figure 9 depicts the time taken to boil water. Briquettes B30, B35, and B40 boiled water faster than briquette B25. Also, because it contained more binder, briquette B40 boiled water in the shortest time. But because briquette B25 had the least quantity of binder and burned with white smoke at first, it took a long time to boil water.

Ignition Time

The briquettes manufactured using TFR as a binder burned with a yellow flame emanating from burning volatile formaldehyde indicating simple ignition and a corresponding increase in flame length (Kivumbi et al., 2021). These findings provide light on the combustion behavior of briquettes made with TFR as a binder, emphasizing the significance of binder concentration in the ignition process and the consequent flame color. The ignition time for the briquettes ranged from 5.38 to 6.21 minutes (**Figure 10**). Similar results were disclosed

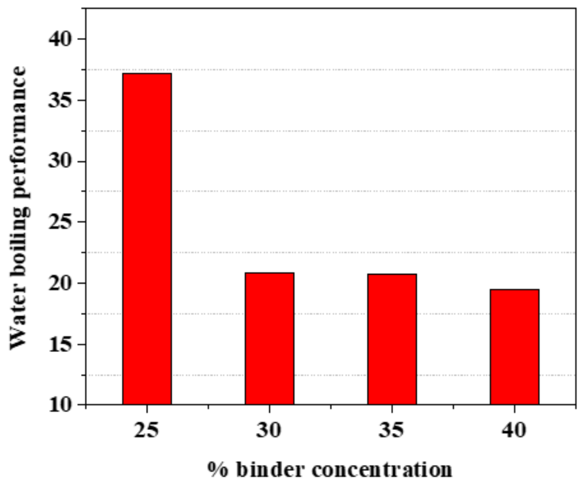

Figure 9. Effect of binder concentration on WBT (Source: Authors' own elaboration)

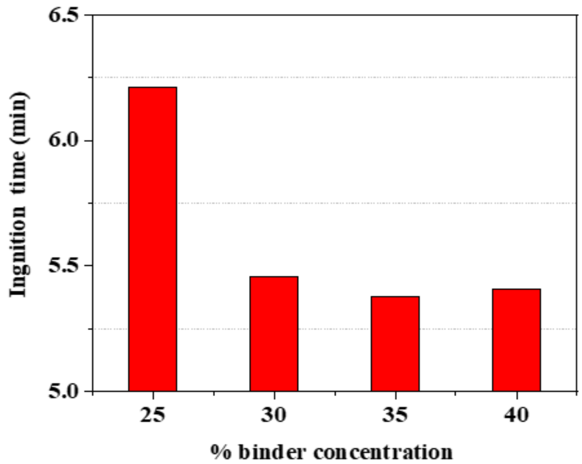

Figure 10. Effect of binder concentration on ignition time (Source: Authors' own elaboration)

(Nwaube et al., 2017), who used cassava starch as a binder to create smokeless bio-coal briquettes from plastic trash. The ignition duration for the briquettes was 0.88-2.60 minutes, which was lower than that observed in this investigation. The addition of biomass and plastic components in their study contributed to the lower ignition time as compared to results obtained in this study.

Burning Rate

Briquette BR increase with increasing binder concentration, owing to the higher volatile component of the binder utilized. The greater chemical reactivity accelerates ignition and enhances combustion efficiency (Lubwama & Yiga, 2018). In some study (Nwaube et al., 2017) it was discovered that smokeless bio-coal briquettes containing plastic trash burned at a rate of 1,300-3,800 g/min, whereas in this study the briquettes burned slowly with a range of (3.2-8.7 g/min), requiring less frequent fuel loading of the cook burner (**Figure 11**). These findings shed light on the combustion behavior of briquettes made with TFR as a binder, emphasizing the importance of binder concentration in terms of BR and combustion efficiency. This also shows the potential of

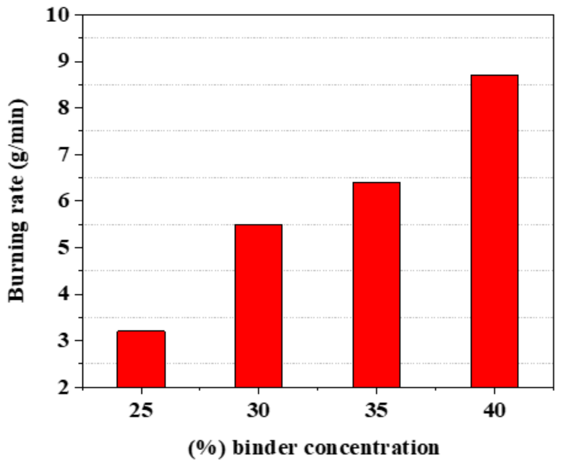

Figure 11. Effect of binder concentration on burning rate (Source: Authors' own elaboration)

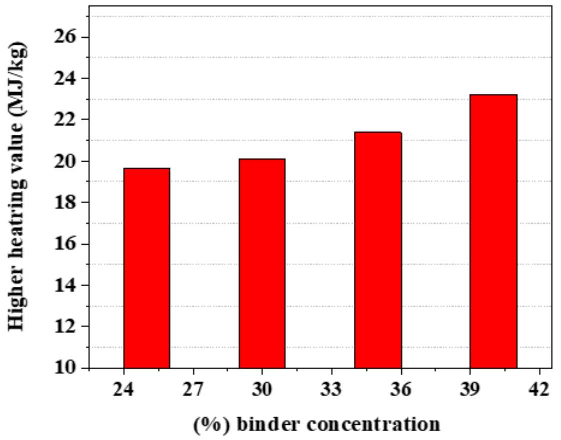

Figure 12. Effect of binder concentration on HHV (Source: Authors' own elaboration)

briquettes as a sustainable and environmentally friendly alternative to traditional fuels, with a slower burning rate that reduces the need for regular fuel loading and minimizes the environmental impact.

Higher Heating Value

HHV is a key factor in determining the fuel value of charcoal briquettes. The findings, which are reported in **Figure 12** show that HHV levels ranged from 19.76 to 23.23 MJ/kg. HHV of charcoal briquettes become more as the binder ratio increased from 25% to 40%. The briquettes with a binder ratio of 40% had the greatest HHV of 23.23 MJ/kg, while the briquettes with a binder ratio of 25% had the lowest value of 17.76 MJ/kg. This trend can be attributed to greater binder ratios increasing briquette density and decreasing porosity, which improves fuel characteristics and leads to an increase in HHV. These findings imply that adjusting the binder ratio is a promising technique for increasing the fuel value of charcoal briquettes, which can help to produce sustainable and environmentally friendly fuel alternatives. The type of biomass residue used, binder ratios, and processing conditions all have a substantial impact on the fuel characteristics and HHV of charcoal briquettes (Miao et al., 2023). Other studies were done the fuel characteristics of charcoal briquettes made from several types of biomass residues, such as sawdust, rice husk, and sugarcane bagasse, utilizing varied binder ratios and processing conditions (Dias Júnior et al., 2020; Nagarajan & Prakash, 2021; Tamilvanan, 2013). HHV values reported in the study ranged from 25.7 to 30.5 MJ/kg, which are greater than HHV values achieved in this investigation (19.7-23.23 MJ/kg). These findings emphasize the need of selecting raw materials, binders, and processing conditions carefully so as to optimize the fuel properties and HHV of charcoal briquettes. It is worth mentioning that differences in HHV levels observed in this investigation and those obtained in other studies (Nagarajan & Prakash, 2021; Tamilvanan, 2013) could be related to variance in raw materials, processing conditions, and testing methodologies used.

CONCLUSIONS

This study showed that charcoal briquettes had a low moisture content of less than 5%, which contributed to their smokeless combustion. Although the briquettes' HHV was lower than that of coal, which typically ranges from 25-30 MJ/kg, and higher than that of wood, which typically ranges from 15-20 MJ/kg, the ecological impact of conventional solid fuels such as coal and wood makes fine charcoal briquettes a sustainable and efficient alternative for household use. Coal is a nonrenewable fossil fuel with major environmental consequences, whereas wood, is less dense and emits more ash and smoke when burned. Charcoal briquettes, on the other hand, have a similar HHV to coal and are a more environmentally beneficial option than both coal and wood. The findings also showed that using tannin formaldehyde resin as a binder produced high-quality briquettes with appropriate fuel characteristics. Furthermore, quantity of tannin in Zimbabwe shows that the creation of charcoal briquettes could be a viable and sustainable fuel production option. The study's findings provide important insights into potential of charcoal briquettes as a cleaner and more sustainable alternative to traditional solid fuels, particularly for residential use.

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