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ORIGINAL ARTICLE

Effects and interactions of the agricultural waste residues and binder type on physical properties and calorific values of carbonized briquettes

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Abstract

Multiple factors are responsible for the properties of developed briquettes. The effect of the agricultural residue type in determining resulting properties of developed briquettes is seldom elucidated. Agricultural residue biochars from groundnut shells, sugarcane bagasse, coffee husks, and rice husks were used in developing carbonized briquettes using the low-cost compression method. In this study, a general factorial multi-level categorical experimental design method was used to investigate the effects and interactions of the carbonized agricultural type, binder type, and binder amount on physical properties and calorific values of developed briquettes. Statistically significant models ($p < 0.05$) were obtained for physical property responses of fixed carbon, ash content, volatile matter, and moisture content as well as calorific values for the developed briquettes. In experiments where only cassava starch binder (30 g and 50 g) was used, carbonized agricultural residues played a significant role in the resulting physical property. Increasing the cassava starch binder from 30 to 50 g had a minimal impact on the resulting briquette physical property. In experiments where cassava starch binder and wheat starch binder were used, it was clear that the physical property of the developed briquette was affected significantly by the carbonized agricultural residue used and binder type. Calorific values of groundnut shell and bagasse briquettes were observed to be significantly affected by the agricultural residue type. The highest calorific values of 23.9 MJ/kg and 23.3 MJ/kg were obtained for groundnut shell and bagasse biochar briquettes, respectively, when only 30 g of cassava starch binder was used. Changes in cassava and wheat starch binder amounts did not significantly affect heating values of developed groundnut shell and bagasse briquettes.

Keywords Agricultural waste residues · Binder type · Carbonized briquettes

1 Introduction

Africa faces serious energy choices in its immediate future given the rise of the African consumer, an urban population explosion where half a billion people will be added by 2040, and the recent large discoveries of oil and natural gas made in recent years [1]. Energy demand in Africa grows twice as fast as the global average. Africa's contribution to global energy-related carbon dioxide (CO_2) emissions at just 2% is extremely low, but the content is disproportionately affected by its impacts. In East Africa, countries such as Kenya, Ethiopia, and Uganda have made remarkable progress in providing modern energy services to millions over the past 5 years. Nonetheless, much remains to be done to deliver universal access to electricity and in particular to expand access to clean cooking, where progress is being outpaced by population growth [2].

Access to clean cooking facilities means access to (and primary use of) modern fuels and technologies, including natural gas, liquefied petroleum gas (LPG), electricity, bioethanol and biogas, or improved biomass cook stoves which deliver significant improvements compared with basic biomass cook stoves and three-stone fires traditionally used in some

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developing countries [2]. Cooking fuels in Africa are mainly dominated by fuelwood (in rural areas) and charcoal (in urban areas). More than 70% of the population in Africa, around 900 million people, lack access to clean cooking. Approximately 80 to 90% of urban households in the region depend on unsustainable sources of charcoal for cooking and heating [3]. The resulting household air pollution from traditional cooking fuels is responsible for approximately 500,000 premature deaths a year. Fuelwood and charcoal also contribute to forest depletion resulting from unsustainable harvesting of fuelwood, as well as imposing a considerable burden and loss of productive time, mostly on women [2]. Alternatives and possible solutions to this status quo have seen the pioneering of briquettes developed from agricultural residues.

Briquettes are solid fuels made from carbonized biomass or densified biomass that is subsequently carbonized. Briquetting is the process of converting low–bulk density biomass into high-density and energy-concentrated fuel [3]. Utilization of agricultural residues as a primary source of raw material in the development of briquettes as alternative cooking fuels presents a significant opportunity to develop sustainable cooking fuels, while at the same time handling the waste management and environmental challenge that arises when these agricultural residues are left to rot or burned in open fields. Briquetting of agricultural residues provides a cooking fuel in a sustainable manner and provides an alternative to fuelwood and charcoal. Briquetting can be carried out using high compaction pressure or low compaction pressure [4–6]. High compaction pressure is associated with high costs required to ensure densification of the loose agricultural residues. A more commonly used approach in Africa is briquetting under low pressure after the agricultural residues have been carbonized and then mixed with a binder prior to densification to enhance cohesion [3]. Low-pressure densification costs much less and easily utilizes locally available materials making it ideal for local farmers, youth, and women groups in Africa.

Studies on the development of carbonized briquettes from agricultural residues exist in the literature. During carbonization, biomass is converted into carbon through pyrolysis at high temperatures and low-oxygen conditions [3]. In each of these studies, a binding agent or simply binder must be included to enhance cohesion of the biochars [7, 8]. Binders have been categorized as either inorganic, organic, or composite/compound binders. Inorganic binders have many excellent advantages, such as being abundantly available, low cost, excellent thermal properties, and hydrophilicity. However, inorganic binders are associated with increased ash content of the developed briquette. Organic binders have advantages of good bonding, good combustion performance, and low ash formation after briquette combustion. But organic binders easily decompose and burn when heated, resulting in poor mechanical strength and thermal stability of the resulting developed briquettes. Organic binders are usually purchased, and some of the starch binders are made from common food crops [4–6, 8]. Composite/compound binders are composed of two binders at least; Compound binders can make full use of the advantages of each binder present, such as reducing the supplying amount of inorganic binder, reducing the cost of organic binder, improving the quality of briquettes, and getting better performance of briquettes [8]. Despite the additional cost, binders are often added in the densification of biomass residues, as they may not naturally contain adequate proportions of binders. The effects and interactions between the type of agricultural residue and binder type with the responses are seldom presented in the literature [9–11].

Lubwama and Yiga [4, 5] and Lubwama et al. [6] developed carbonized briquettes from different agricultural residues including rice husks, coffee husks, sugar cane bagasse, and groundnut shells. Results indicated that the combination of carbonization and the presence of binders had a net positive effect on physical properties of the developed briquettes including moisture content, volatile matter, and fixed carbon. Calorific values were higher compared with those of the non-carbonized briquettes. Drop strength results were lower than those of the non-carbonized briquettes due to the weak van der Waals forces because of carbonization and binder inclusion [4–6]. More specifically, groundnut shell and bagasse biochar briquettes with cassava and wheat starch binders clearly indicated that binder inclusion influenced physical properties, heating value, drop strength, and briquette durability [4]. Clay and cassava starch were used as binders in the production of carbonized briquettes from coffee and rice husks. Average higher heating values for briquettes developed with cassava starch binder ranged from 21.9 to 23.0 MJ/kg for coffee husks and 15.9 to 16.6 MJ/kg for rice husks. For coffee and rice husk briquettes developed with clay binder, average higher heating values ranged from 13.0 to 19.5 MJ/kg and 9.5 to 13.8 MJ/kg, respectively [5]. Cassava starch binder imparted higher drop strengths (over 95%) onto the briquettes than clay binder material [4–6]. The inclusion of binders has been reported to influence the properties and performance of the developed carbonized briquettes from agricultural residues, with most of the effects presented in a one-factor-at-a-time representation. These studies did not consider the effect of the agricultural residue biochar type which is the major constituent in the developed briquettes, further emphasizing the need for multiple factor analysis in explaining briquette properties and performance [4–6]. Aransiola et al. [10] determined the effect of different binders with varying concentrations and applied die pressures on some physical properties of carbonized corncob briquettes using a randomized complete block design with three replications. Cassava starch, corn starch, and gelatin at three different concentrations of 10, 20, and 30% wt/wt were used as binders in the production of the briquettes at the predetermined compaction pressure levels of

50, 100, and 150 kPa using hydraulic press. It was noted that variables with cassava binder at concentration of 30% and compaction pressure of 150 kPa exhibited the most positive attributes. The higher the binder concentration and compaction pressure, the better the briquettes, and this results in higher quality briquettes for both storage and transportation [10]. Aransiola et al. [10] observed that the binder type, binder concentration, and compaction pressure affected the physical properties of briquettes produced from carbonized corncobs [10]. In the carbonization process of bamboo pellets, natural binders could be softened at some temperature interval, which resulted in stronger bonding of bamboo particles and improved strength properties of bamboo pellets. It was concluded that carbonization conditions affected the properties of bamboo pellets. After being carbonized, the properties of bamboo pellets, such as pellet absorption, durability, fine, gross calorific value, combustion rate, and heat release rate, were improved [12]. Borowski et al. [13] studied the effect of a native wheat and a modified wheat starch binder on the mechanical, physical, and burning properties of charcoal briquettes. The type of starch binder had no effect on toughness, calorific heating value, volatiles, fixed carbon content, and ash content. Onchieku et al. [14] optimized parameters for the formulation of charcoal briquettes using bagasse and clay as binders. Garcia et al. [15] pelletized biomass after torrefaction with solid and liquid bioadditives, namely, pine sawdust and dried grape pomace (solid) and glycerol (liquid). Raw pine, grape pomace, and glycerol are good additive candidates due to the binder and/or lubricant role in the pelletization process. Grape pomace is a lignin-rich biomass solid waste that resulted to be an effective natural binder as it enhanced the durability of torrefied pine. Glycerol served the dual purpose of acting as binder and lubricant in the pelletization process [15]. Sub-bituminous, plastic, and biowaste materials were partially carbonized, pulverized, and used in varying proportions with limestone dust, cassava flour, and laterite as binders to produce solid fuel briquettes. Results of the briquette characterization showed that the briquettes produced with the compositions 20–70% coal, 2–8% limestone, 10% plastic waste, 2.5–10% cassava flour, and 10–60% biomass were of medium to high quality in terms of burning and cooking characteristics, smokeless, environmental friendliness, binding, and mechanical strength [16]. Davies and Davies [17] investigated the physical and combustion characteristics of briquettes made from water hyacinth and phytoplankton scum as binder. Phytoplankton scum improved the mechanical handling characteristics of the developed briquettes [17]. In another study on the development of carbonized briquettes from water hyacinth, molasses were used as binder. Volatile combustible matter and fixed carbon increased with increasing amount of binder while ash content decreased [18]. Tumutegyereize et al. [19] performed a comparative analysis of carbonized briquettes and charcoal fuels in Kampala-urban in Uganda. Starch binder and soil were used for binding and filler purposes [19]. Kpalo et al. [20] produced and characterized hybrid briquettes from corncobs and oil palm trunk bark under low-pressure densification technique using waste paper pulp (10% by weight) as binder. Results showed that paper pulp binder contributed to increased compressive strength of the developed briquettes [20]. Khlifi et al. [21] investigated the production of high-quality briquettes from olive mill starch waste mixed with corn starch as a binder for energy production. Nino et al. [22] performed an experimental study on the mechanical properties of biomass briquettes from a mixture of rice husk and pine sawdust and noted that it was possible to obtain briquettes from the mixture without the need for prior preparation of the waste material or the addition of binders. Ndindeng et al. [23] developed briquettes from rice husks with rice bran as binder. It was observed that the higher the proportion of rice bran binder, the harder the briquettes. Ndindeng et al. [23] further observed that rice husk char briquettes had lower heating values and higher specific fuel consumption rates than rice husk bran briquettes produced from non-carbonized raw materials. However, the binder used for rice husk char briquettes was clay and that used for rice husk bran briquettes was palm press sludge and binder. In another study, rice husk and bran briquettes were developed under low pressure using cassava wastewater, rice dust, and okra stem gum as briquettes. Briquettes made with rice dust had the highest durability (91.9%) and compressive strength (2.54 kN), while the briquettes made with cassava starch wastewater had the greatest density (441.18 kg/m^3). Water added to the rice husk before densification positively influenced the briquette quality while bran seemed to mostly increase the density, but not necessarily the briquette quality. The briquette formulation did not significantly influence the calorific value [7]. Francik et al. [24] noted that in the production of briquettes, the technological and material variables significantly influence the densification process and as a result influence the end quality of the developed briquettes.

A careful review of these studies indicates that the effect of binders was described in a one-factor-at-a-time approach, implying that the robustness of the developed briquettes was inadequate from an engineering product design and development viewpoint [25]. Very few studies have investigated the impact of more than one factor including multiple factor studies [7, 9, 10]. This implies that the effect of the agricultural residue itself is usually not taken in consideration in describing both effects and interactions of two or more factors on the properties and performance of the developed briquette. In this study, a general multiple factorial design of the experiment approach has been used to study the combined effect of the agricultural residue type, binder type, and binder amount on physical properties and calorific values of the developed carbonized briquettes. This approach enabled us to determine what effects the agricultural type and binder type as well as binder amount have on physical properties and calorific values of the developed carbonized briquettes.

2 Methodology

2.1 Materials

Biochars carbonized from agricultural residues, namely, groundnut shells, sugarcane bagasse, coffee husks, and rice husks, were used in developing briquettes. Groundnut shells used in this study were obtained from Gulu district in Northern Uganda. Sugarcane bagasse was obtained from sugarcane growers in Jinja district, Eastern Uganda. Rice husks were obtained from rice growers in Butaleja district in Eastern Uganda. Coffee husks were obtained from local coffee factories in Uganda. Over 1000 kg of agricultural residues were collected for use in this study. Over 50 kg of cassava flour and wheat flour was purchased locally from Kampala district in Central Uganda. Typical biochemical and physical properties of these agricultural residues are shown in Table 1. These agricultural residues have cellulose compositions above 30 wt%, which is a requirement for enhancing mechanical properties of developed briquettes [28].

2.2 Briquette production process

Agricultural residues, namely, groundnut shells, sugarcane bagasse, coffee husks, and rice husks, were sun-dried for 6–8 h. The dried materials were then carbonized using the method described by Lubwama and Yiga [4]. Dried groundnut shells, sugarcane bagasse, coffee husks, and rice husks were fed into a 200-l-capacity steel drum of a height to diameter ratio of 2:1. Holes of diameter 0.02 m were made on the surface of the drum. During carbonization, these agricultural residues underwent slow pyrolysis in low-air conditions by systematically covering the carbonizer surface holes with mud at specific intervals in order to create agricultural residue biochars. This process was carried out at ≤ 450 °C, and residence times were 4 h. The obtained agricultural residue biochar was measured in 1000-g portions and then mixed with cassava and wheat starch binders as follows: (i) 30 g and 50 g of cassava starch binder were mixed separately with each of the agricultural residue biochar for experimentation of physical properties and calorific values; (ii) cassava starch binder amounts were then increased to 70 g and 90 g for mixing with groundnut shell and bagasse agricultural residues, and wheat starch binder was added to determine the effect of the binder type and binder amount on the resulting physical properties and calorific values. Wheat and cassava starch binders were prepared by mixing 30 g, 50 g, 70 g, and 90 g of wheat flour and cassava flour in water and boiling them to obtain a uniform starch binder. The combination of binder and biochar was compressed at a pressure of ≤ 7 MPa into cylindrical briquettes of 0.05-m diameter and 0.05-m height [4].

2.3 Design of experiments

A general factorial multi-level categorical experimental design method was used in this study to investigate the effects and interactions of the agricultural type, binder type, and binder amount on responses of physical properties and calorific values. Physical properties of the developed carbonized briquettes were determined using an Eltra Thermostep Thermogravimetric analyzer according to the ASTM E1131-08 standard. An IKA C 2000 bomb calorimeter was used to determine calorific values following the ASTM D5865-13

Table 1 Biochemical and physical properties of agricultural raw materials used in this study

Property	Groundnut shells	Bagasse	Rice husks	Coffee husks
Biochemical				
Lignin	21.2[a]	22.6[b]	21.5[c]	19.5[c]
Hemi-cellulose	23.5[a]	20.8[b]	15.7[c]	24.5[c]
Cellulose	34.5[a]	46.2[b]	34.3[c]	42.2[c]
Physical				
Ash content	3.8[d]	2.5[d]	18.1[e]	5.9[e]
Moisture content	9.2[d]	22.5[d]	11.3[e]	13.0[e]
Volatile matter	67.7[d]	62.7[d]	56.4[e]	65.4[e]
Fixed carbon	19.3[d]	12.2[d]	14.2[e]	15.7[e]

[a] Source Ref. [26]

[b] Source Ref. [27]

[c] Source Ref. [28]

[d] Source Ref. [4]

[e] Source Ref. [5]

standard procedure. Design-Expert Version 12.0.8 was used in this study. Effects of the variables and interactions between the factors on the responses were determined using the effects model shown in Eq. 1 [25].

$$y_{ijk=}\mu+\tau_i+\beta_j+(\tau\beta)_{ij}+\epsilon_{ijk}\begin{cases} i=1,2,\ldots,a\\ j=1,2,\ldots,b\\ k=1,2,\ldots,c\end{cases} \tag{1}$$

where μ is the overall mean effect, τ_i is the effect of the ith level of the row factor A, β_j is the effect of the jth level of the column factor B, $(\tau\beta)_{ij}$ is the effect of the interaction between τ_i and β_j, and ϵ_{ijk} is a random error component [25].

In the first experiment, two categorical factors, namely, specific carbonized agricultural residue and cassava starch binder, were used. Carbonized agricultural residues were maintained at four levels corresponding to each specific agricultural residue, namely, groundnut shells, bagasse, rice husks, and coffee husks. Cassava starch binder amount was investigated at two levels, namely, 30 g (minimum level) and 50 g (maximum level). Binder contents of 30 and 50 g were selected for use in this study because they produced briquettes with good cohesion between binder and agricultural residue biochar. Amounts lower than 30 g and amounts higher than 50 g did not provide cohesion between binder and agricultural residue biochar. Cassava starch was used because it has widely been used as binder for briquette development [4–6]. The reason for this trend is that addition of water and heat to starch granules causes swelling, which results in the formation of intermolecular hydrogen bonds between the amylose and amylopectin components of starch, followed by the loss of the individual crystalline structure of the two components. This leads to the formation of a viscous solution that undergoes retrogradation during cooling or storage. The viscosity of hydrated starch increases its shear and tensile strengths and gives it the ability to occupy void spaces present within and between biomass particles, thus forming solid bridges that increase in strength during air cooling and storage [9]. Twenty-four fully randomized with 3 repetitions were carried out to determine responses which were specific physical properties, namely, fixed carbon, ash content, volatile matter, and moisture content. In the second experiment a two-factor interaction design model using 16 randomized runs was used to determine the corresponding calorific values for carbonized groundnut shell, bagasse, rice husk, and coffee husk briquettes developed with cassava starch binder. A two-factor interaction design model was used to study both effects and interactions.

In order to investigate the effect of the binder type and increasing binder, a third experimental setup was used involving both wheat and cassava starch binders at 30 g, 50 g, 70 g, and 90 g amounts in developing briquettes using carbonized groundnut shell and bagasse agricultural residues. A two-factor interaction design model was set up using 48 randomized runs to determine physical properties. The factors involved included agricultural residues at 2 levels, namely, groundnut shells (minimum) and bagasse (maximum), binder type at 2 levels, namely, cassava starch binder (minimum) and wheat starch binder (maximum), and binder amount at 4 levels. Thirty-two randomized runs were used in a two-factor interaction design model to determine corresponding calorific values involving agricultural residues, binder type, and binder amount as factors.

3 Results and discussion

3.1 Effects and interactions for physical properties for agricultural residue briquettes developed with cassava starch binder

From the results shown in Table 2, it was observed that fixed carbon responses ranged from 30.3 to 53.6% which implies that the ratio of maximum to minimum responses is 1.76898. Responses for volatile matter ranged from 17.7 to 35.7% implying a ratio of 2.01695 for maximum to minimum volatile matter values. Ash content responses ranged from 9.9 to 40.8%, and responses for moisture content ranged from 0.8 to 9.5% with maximum to minimum ratios of 4.12121 and 12.0101, respectively. Therefore, the response results for the physical properties do not require any transformation to be applied to them as their ratios are less than 10 except for moisture content. This implies that the residuals were normal, and therefore, there was no need for transformation. The moisture content value of 0.8% was observed for briquettes developed from groundnut shells with 30 g of cassava starch binder. This value is considered an outlier in the data given that the other samples for similar briquettes had moisture contents of 7.9% and 8.3% (see Fig. 1). The moisture content (%) and volatile matter (%) results show that the developed briquettes are suitable for cooking applications because fewer amounts of energy are required in the evaporation phase and ignition with lower smoke levels during combustion of the developed briquettes is enhanced [29, 30]. The fixed carbon results are in line with expected results because of the carbonization process which causes moisture and volatiles to be expelled [4, 5, 31].

Analysis of variance results for the specific physical responses for briquettes developed with cassava starch binder are shown in Table 3. The statistical models for the physical property responses of fixed carbon, ash content, volatile matter, and moisture content are all significant since $p < 0.05$. Also, model F values of 20.36 (fixed carbon), 28.50 (ash content), and 19.11 (volatile matter) indicate a 0.01% chance that an F value this large could occur due to noise [25]. Moisture content F value of 4.83 indicates a 0.74% chance that an F value this large could occur due to noise. The lack-of-fit F value of 0.24 implies that the lack of fit is not

Table 2 Physical property responses for different agricultural residues and cassava starch binder amounts

Std	Run	Factor 1 A: agricultural residue type	Factor 2 B: cassava starch binder (g)	Response 1: fixed carbon (%)	Response 2: ash content (%)	Response 3: volatile matter (%)	Response 4: moisture content (%)
23	1	Rice husks	50	37.1	36.4	20.3	6.2
1	2	Groundnut shells	30	50	10.1	32	7.9
5	3	Groundnut shells	50	49.4	22.8	20.9	7
17	4	Groundnut shells	30	48.7	17.4	25.6	8.3
21	5	Groundnut shells	50	43.6	26.3	23.1	7
3	6	Rice husks	30	36.8	39.7	17.7	5.8
13	7	Groundnut shells	50	53.6	10.5	28.4	7.5
9	8	Groundnut shells	30	52.4	21.3	25.4	0.79
18	9	Bagasse	30	50.3	10	33.5	6.2
12	10	Coffee husks	30	45.7	15.5	29.4	9.4
16	11	Coffee husks	50	44.5	15	31	9.5
4	12	Coffee husks	30	47.1	14.4	29.4	9.1
7	13	Rice husks	50	37.6	36.8	19.3	6.3
24	14	Coffee husks	50	43.5	16.6	30.8	9.1
2	15	Bagasse	30	49.1	12.7	32.1	6.1
11	16	Rice husks	30	34.2	39.5	20	6.3
20	17	Coffee husks	30	46.3	15.3	29.9	8.5
10	18	Bagasse	30	48.9	13.2	31.9	6.1
6	19	Bagasse	50	49.8	10.2	33.4	6.6
15	20	Rice husks	50	37.6	36.8	19.5	6.2
14	21	Bagasse	50	47.3	10.6	35.7	6.5
22	22	Bagasse	50	49.2	9.9	34.3	6.6
19	23	Rice husks	30	30.3	40.8	23	5.9
8	24	Coffee husks	50	41.4	17.2	32.1	9.2

significant relative to the pure error. There is a 86.83% chance that a lack-of-fit *F* value this large could occur due to noise. Therefore, a non-significant lack of fit is good as the intention is for the model to fit. A careful review of the data in Table 3 shows that run 8 (standard 9) with a recorded moisture content of 0.79 could be the most logical cause for this ANOVA statistic for moisture content. This point was highlighted and ignored in future models to attain normality of moisture content responses (see Fig. 1). Whereas the models for all physical properties were significant, the only significant term is factor A which corresponds to the carbonized agricultural residues used in the development of the carbonized briquettes. This implies that the cassava starch binder had a minimal impact on the resulting briquette physical property when compared with the main parent agricultural residue. Carbonization destroys hydroxyl groups which is advantageous in promoting ignition of the developed briquette as a result of reduced moisture content levels [12]. The positive influence of binders in combination with carbonized agricultural residues has been reported as affecting physical properties in previous studies [4]. This study indicates that small binder increments of the same binder material do not have a significant role in physical properties of the developed briquettes. Carbonization of agricultural residues plays a much more dominant role on the resulting physical properties of the developed briquette. This result should be expected because on a mass balance basis, 1000 g of agricultural residue was mixed with 30 g and 50 g of cassava starch binder. Cassava starch binder was therefore less than 5% of the total mass of developed briquette even after the endothermic evaporation process already took place during the initial carbonization processes of the agricultural residues [12]. Fit statistics results for physical property responses for the briquettes developed with cassava starch binder only are shown in Table 4. In all physical property cases, the predicted R^2 is in reasonable agreement with the adjusted R^2 as their difference is less than 0.2. Adequate precision values for fixed carbon (12.15), ash content (14.1), volatile matter (11.6), and moisture content (5.6) are all greater than 4. Since adequate precision measures the ratio of signal to noise, then the statistical models generated for all physical properties can be used to navigate the design space.

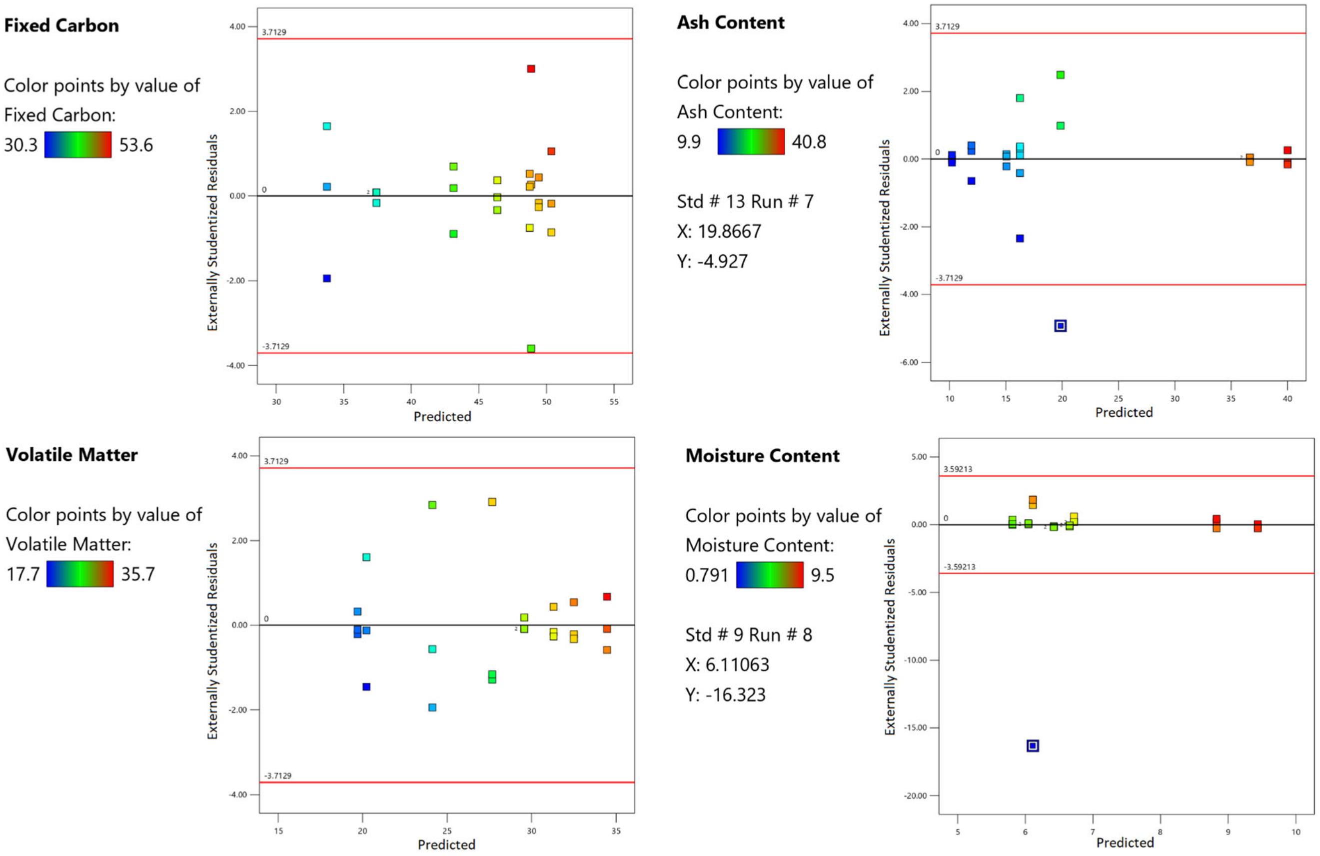

Fig. 1 Externally studentized residuals vs. predicted for physical properties of briquettes developed with cassava starch binder

Two-factor interaction plots for physical properties with factors carbonized agricultural residue type and 30 g and 50 g cassava binder starch for fixed carbon, ash content, and volatile matter are shown in Fig. 2. Main effects for moisture content are also shown in Fig. 2d. These plots are necessary for determining the effects caused by interaction of factors carbonized agricultural residue type (A) and cassava binder amount (B), i.e., effect AB. The general observation from Fig. 2 is that the dominant factor in determining the physical property content in the developed briquette was the carbonized agricultural residue raw material that was used and not an increase in cassava starch binder from 30 to 50 g. These results agree very well with the ANOVA results in Table 3 where for all overall effects AB, non-significant *p* values were calculated. The impact of non-significant cassava starch binder affects the overall effect AB even though effect A (carbonized agricultural residue type) is significant.

An increase in binder amount to 50 g of cassava starch binder resulted in a decrease in fixed carbon (%) for carbonized groundnut shell, coffee husk, and bagasse briquettes (see Fig. 2a). Only in rice husk briquettes was a marked increase in fixed carbon (%) observed. Rice husk briquettes had an overall lower fixed carbon (%) compared with all the other developed briquettes. The minimal differences in fixed carbon (%) noted for groundnut shell and bagasse briquettes support the developed significant models shown in the ANOVA results (see Table 3) that showed that carbonized agricultural residues were the significant term in the model and not varying binder quantities because the differences in binder amount are extremely small at 20 g and the overall amounts of binder used were also very small. Ash content (%) results were clearly affected by the carbonized agricultural residue used for briquette development. All changes in ash content as a result of increasing binder amount were within the standard error of measurement. Volatile matter (%) showed a significant decrease when cassava starch binder increased from 30 to 50 g. This result is expected due to the substitution of carbonized agricultural residue with cassava starch binder, thus reducing on their quantities in the developed briquette. Bagasse and coffee husk briquettes showed an increase in volatile matter (%) for a similar increment in cassava starch binder. Rice husk briquettes had the lowest amount of volatile matter (%) of all the briquettes developed. Volatile matter (%) is explained by the expulsion of volatile matter during pyrolysis and combustion of organic matter which results in the removal of heteroatoms [31]. This result is also dependent on combustion characteristics during the carbonization of specific agricultural residue [4–6, 30]. The plot of main effects shown in Fig. 2d shows no change in moisture content for all of the developed agricultural residue briquettes irrespective of both

Table 3 Analysis of Variance results for physical property responses for developed briquettes using cassava starch binder only

Source	Sum of squares	df	Mean square	*F* value	*p* value	
Response 1: fixed carbon						
Model	797.86	7	113.98	20.36	< 0.0001	Significant
A-agricultural residue	757.97	3	252.66	45.12	< 0.0001	
B-cassava starch binder	1.13	1	1.13	0.2012	0.6598	
AB	38.76	3	12.92	2.31	0.1154	
Pure error	89.59	16	5.60			
Cor total	887.45	23				
Response 2: ash content						
Model	2654.75	7	379.25	28.50	< 0.0001	Significant
A-agricultural residue	2611.98	3	870.66	65.43	< 0.0001	
B-cassava starch binder	0.0267	1	0.0267	0.0020	0.9648	
AB	42.75	3	14.25	1.07	0.3893	
Pure error	212.91	16	13.31			
Cor total	2867.66	23				
Response 3: volatile matter						
Model	651.69	7	93.10	19.11	< 0.0001	Significant
A-agricultural residue	622.22	3	207.41	42.57	< 0.0001	
B-cassava starch binder	0.0504	1	0.0504	0.0103	0.9202	
AB	29.41	3	9.80	2.01	0.1528	
Pure error	77.95	16	4.87			
Cor total	729.64	23				
Response 4: moisture content						
Model	38.80	4	9.70	4.83	0.0074	Significant
A-agricultural residue	36.58	3	12.19	6.07	0.0045	
B-cassava starch binder	2.23	1	2.23	1.11	0.3057	
Residual	38.16	19	2.01			
Lack of fit	1.63	3	0.5442	0.2384	0.8683	Not significant
Pure error	36.53	16	2.28			
Cor total	76.96	23				

the agricultural residue type and the increment from 30 to 50 g of cassava starch binder. Overall moisture content was highest for coffee husk briquettes. However, low levels of moisture content reported for all briquettes developed are explained by weight loss during thermal degradation of the agricultural residue during the carbonization process [30].

In Fig. 1, outliers in the plots of externally studentized residuals vs. residuals were clearly observed for plots for ash content (%) and moisture content (%). These outliers in the data set affect calculations of overall standard deviations and residuals for the data set results. By scrutinizing the outlier data points shown in Fig. 1 from the measured experimental

Table 4 Fit statistics results for physical property responses for briquettes developed with cassava starch binder only

	Fixed carbon	Ash content	Volatile matter	Moisture content
Std Dev	2.37	3.65	2.21	1.42
Mean	44.77	20.79	27.45	7.00
C.V.%	5.29	17.54	8.04	20.23
R^2	0.8990	0.9258	0.8932	0.5042
Adjusted R^2	0.8549	0.8933	0.8464	0.3998
Predicted R^2	0.7729	0.8330	0.7596	0.2089
Adeq precision	12.1504	14.1337	11.5874	5.6052

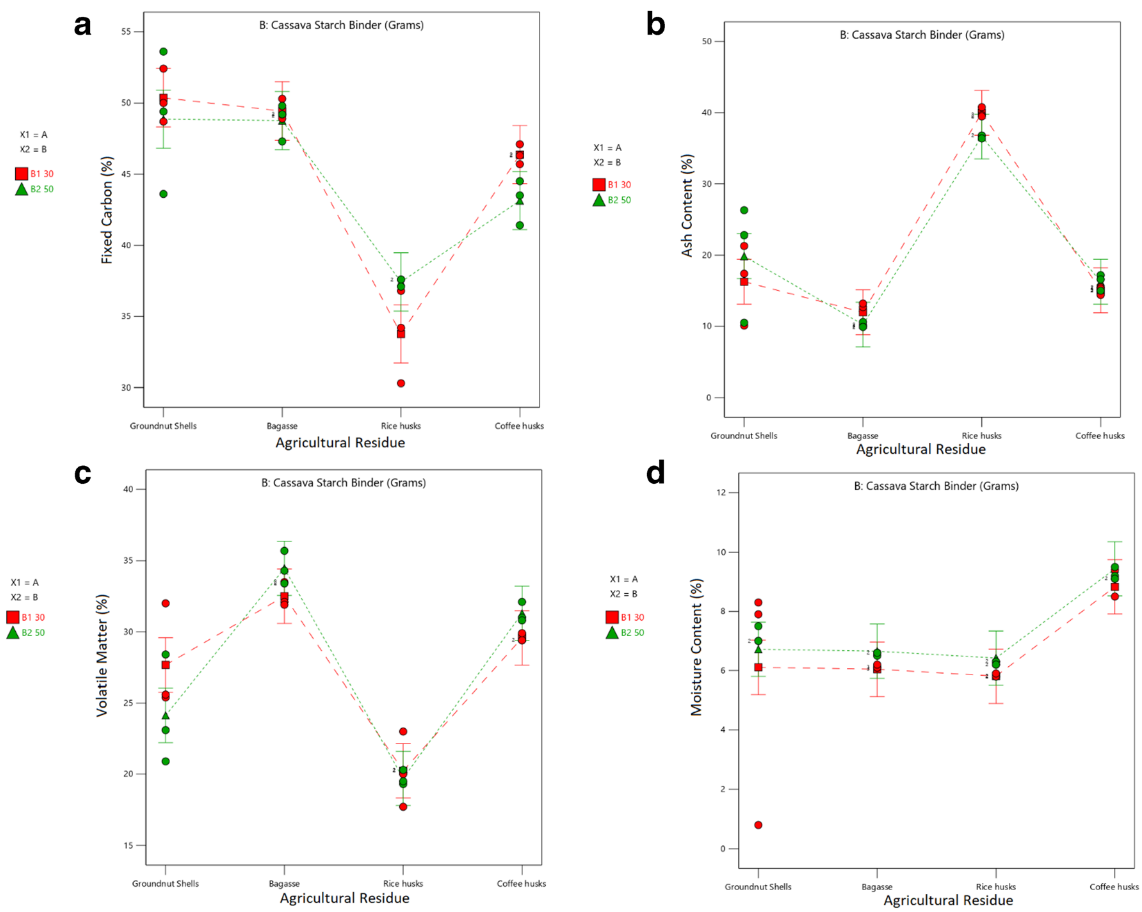

Fig. 2 Two-factor interaction plots for factors agricultural residue type and 30 g and 50 g cassava binder starch for **a** fixed carbon, **b** ash content, and **c** volatile matter. Main effects for **d** moisture content are also shown

results for physical property responses (see Table 2), the outlier results were most likely measurement errors. Highlighted outlier data points were subsequently ignored, and the output responses of ash content (%) and moisture content (%) were re-analyzed [32]. Re-analysis of responses of ash content and moisture content showed that the models were still significant with $p < 0.05$. However, in both cases, the effect AB was also significant ($p = 0.0010$ for ash content (%); $p = 0.0018$ for moisture content (%)). Modified plots of externally studentized residuals and the resulting effect-interaction plots for ash content and moisture content are shown in Fig. 3. The results of moisture content (%) interaction effects in Fig. 3 are completely different from the results shown in Fig. 2d when the 0.79% result of moisture content was ignored. Ignoring these data points led to a non-orthogonality in the design. However, this leads to much better fit of the remaining measured results for both ash content (%) and moisture content (%) in the modified results shown in Fig. 3. When cassava starch binder was increased from 30 to 50 g, the moisture content (%) in groundnut shell briquettes showed a clear reduction. Moisture content (%) increased in both bagasse and rice husk briquettes as cassava starch binder was increased from 30 to 50 g. The overall low levels of moisture content in the developed briquettes are due to destruction of hydroxyl groups during the carbonization of the agricultural raw material residues [12]. Rice husk briquettes had the highest ash content (%). High ash content in rice husk briquettes is due to the formation of SiO_2 inherently present in rice husks and formation of silica ash and the strengthening of silica–carbon bonds [30, 31]. Briquettes developed with high ash content are expected to exhibit lower calorific values due to increased thermal resistance to heat transfer within the developed briquette [4, 6]. Combustibility of rice husk briquettes is decreased because of high ash content (%) [7, 33].

3.2 Effects and interactions for physical properties for groundnut shell briquettes and bagasse briquettes developed with cassava and wheat starch binders

The third experimental design intended to determine the interaction effects of the different types of binder (wheat starch binder and cassava starch binder), binder amounts (30 g, 50 g, 70 g, and 90 g), and agricultural residue type (groundnut shells and bagasse) on the resulting developed carbonized briquette. Results of physical property responses, namely, fixed carbon (%), volatile matter (%), moisture content (%),

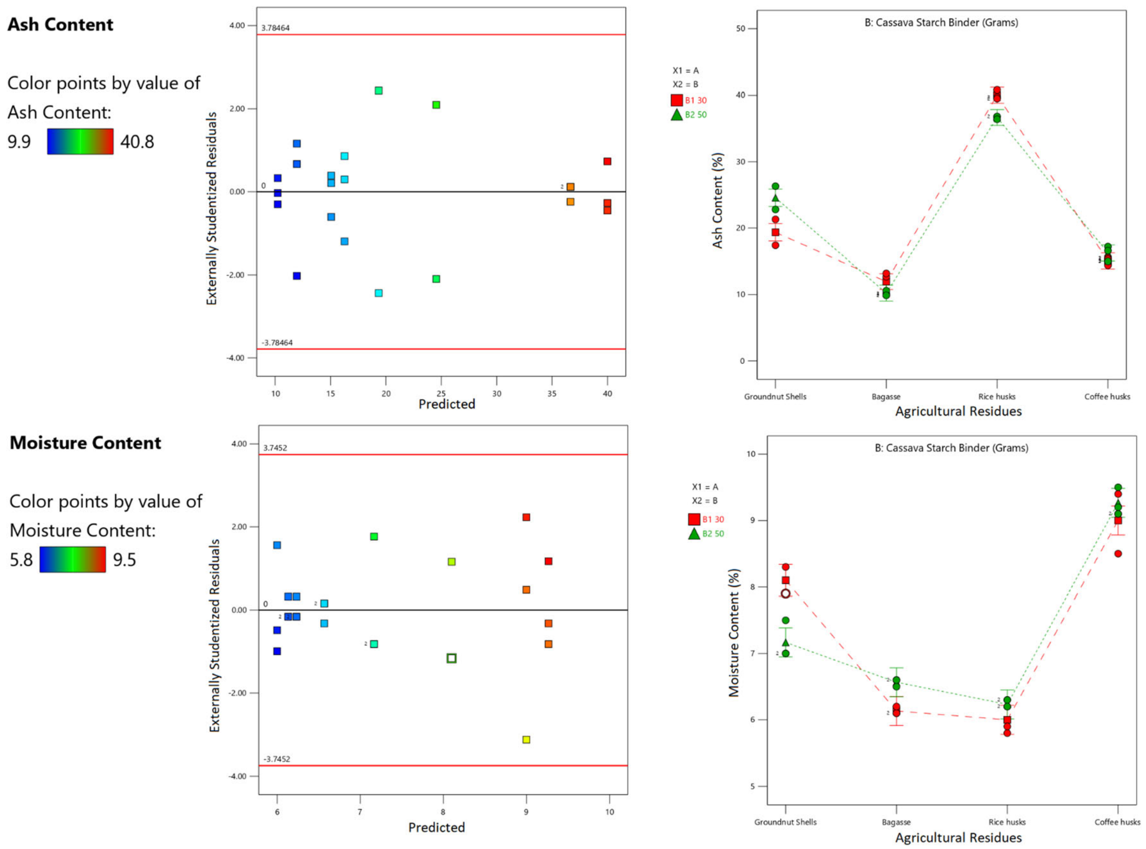

Fig. 3 Modified externally studentized residuals vs. predicted and resulting interaction plots for ash content and moisture content with factors agricultural residues and cassava starch binder at 30 g and 50 g

and ash content (%), are shown in Table 5. The main effects and interactions are clearly seen in the half-normal probability plots for factors agricultural residues (effect A), binder type (effect B), and binder amount (effect C). Interactions AB, BC, AC, and ABC are also indicated for all physical properties of the developed briquettes (see Fig. 4). ANOVA results for physical properties for factors agricultural residues (groundnut shells and bagasse), binder type (wheat and cassava starch), and binder amount (30 g, 50 g, 70 g, and 90 g) are shown in Table 6. The model *F* values of 12.54 (fixed carbon), 10.72 (volatile matter), 15.49 (moisture content), and 18.07 (ash content) imply that the statistical models for each physical property are significant with a 0.01% chance that *F* values that large could occur due to noise. Fit statistics results for physical property responses for groundnut shell and bagasse briquettes developed with cassava starch binder and wheat starch binder are shown in Table 7. In all physical property cases, the difference between predicted R^2 and adjusted R^2 is less than 0.2. Also, the adequate precision statistics which measures signal-to-noise ratio was greater than 4 which was desirable and meant that the models in each case were sufficient to navigate the design space.

Interactions of groundnut shell and bagasse agricultural residues, wheat and cassava starch binders, and different binder amounts on the resulting physical properties are shown in Figs. 5, 6, 7, 8, 9, and 10. Interaction plots for factors agricultural residue type (groundnut shells and bagasse) and 30 g cassava and wheat starch binder types for (a) fixed carbon, (b) volatile matter, (c) moisture content, and (d) ash content are shown in Fig. 5. Figure 6 shows interaction plots for factors agricultural residue type (groundnut shells and bagasse) and 90 g cassava and wheat starch binder types for (a) fixed carbon, (b) volatile matter, (c) moisture content, and (d) ash content. From Figs. 5 and 6, it was observed that the physical properties were dependent on the agricultural residue used in the development of the carbonized groundnut shell and bagasse briquettes. Carbonization of agricultural residues reduces the volatile combustion phase and prolongs char combustion [34]. This affects fixed carbon (%), which is generally higher for carbonized briquettes when compared with non-carbonized briquettes [4]. Binder type differences, i.e., wheat starch and cassava starch binders, were seen to have a significant impact on fixed carbon (%), volatile matter (%), and moisture content (%) for groundnut shell briquettes with 30 g of binder (see Fig. 5) [9, 35]. This is explained by the differing levels of phosphorus in cassava and wheat flour which affect amylose

Table 5 Physical property responses for different factors including the agricultural residue, binder type, and binder amounts for developed carbonized bagasse and groundnut shell briquettes

Std	Run	Factor 1 A: agricultural residue type	Factor 2 B: binder type	Factor 3 C: binder amount (g)	Response 1: fixed carbon (%)	Response 2: volatile matter (%)	Response 3: moisture content (%)	Response 4: ash content (%)
14	1	Bagasse	Cassava starch binder	90	48.5	32.3	7.2	11.9
37	2	Groundnut shells	Cassava starch binder	50	49.4	20.9	7	22.9
42	3	Bagasse	Cassava starch binder	70	49.1	33.6	7	10.4
10	4	Bagasse	Cassava starch binder	70	47.7	32.7	6.7	12.9
13	5	Groundnut shells	Cassava starch binder	90	49.5	20.4	7.3	22.8
8	6	Bagasse	Wheat starch binder	50	51.6	30.5	6.5	11.4
39	7	Groundnut shells	Wheat starch binder	50	55.7	17.2	7.3	19.8
44	8	Bagasse	Wheat starch binder	70	47.4	30.5	6.7	15.4
1	9	Groundnut shells	Cassava starch binder	30	50.2	32	7.9	10.1
25	10	Groundnut shells	Cassava starch binder	70	51.9	22.6	7.9	17.5
18	11	Bagasse	Cassava starch binder	30	50.3	33.5	6.2	10
47	12	Groundnut shells	Wheat starch binder	90	53	21.6	7	18.4
26	13	Bagasse	Cassava starch binder	70	48.3	34.8	7	9.9
12	14	Bagasse	Wheat starch binder	70	49.2	31.3	6.9	12.6
36	15	Bagasse	Wheat starch binder	30	50.2	31.4	7.3	11.1
38	16	Bagasse	Cassava starch binder	50	49.8	33.4	6.6	10.2
35	17	Groundnut shells	Wheat starch binder	30	53.4	15.9	6.9	23.9
15	18	Groundnut shells	Wheat starch binder	90	50.5	23.9	7.1	18.6
2	19	Bagasse	Cassava starch binder	30	49.1	32.1	6.1	12.7
9	20	Groundnut shells	Cassava starch binder	70	52	21.8	7.9	18.3
45	21	Groundnut shells	Cassava starch binder	90	50.1	24	7.6	18.3
33	22	Groundnut shells	Cassava starch binder	30	48.7	25.6	8.3	17.4
31	23	Groundnut shells	Wheat starch binder	90	49.7	23.2	6.8	20.3
5	24	Groundnut shells	Cassava starch binder	50	43.6	23.1	7	26.3
22	25	Bagasse	Cassava starch binder	50	47.3	35.7	6.5	10.6
34	26	Bagasse	Cassava starch binder	30	48.9	31.9	6.1	13.2
4	27	Bagasse	Wheat starch binder	30	51.2	29.7	6.9	12.2
30	28	Bagasse	Cassava starch binder	90	32.4	23.7	5.5	38.5
48	29	Bagasse	Wheat starch binder	90	44	35.7	8.2	12.1
23	30	Groundnut shells	Wheat starch binder	50	55.2	24.8	7.4	12.5
24	31	Bagasse	Wheat starch binder	50	50.5	30.6	6.6	12.2

Table 5 (continued)

Std	Run	Factor 1 A: agricultural residue type	Factor 2 B: binder type	Factor 3 C: binder amount (g)	Response 1: fixed carbon (%)	Response 2: volatile matter (%)	Response 3: moisture content (%)	Response 4: ash content (%)
19	32	Groundnut shells	Wheat starch binder	30	54.3	15.2	6.9	23.7
32	33	Bagasse	Wheat starch binder	90	44.6	34	7.9	13.5
17	34	Groundnut shells	Cassava starch binder	30	52.4	25.4	0.791	21.3
43	35	Groundnut shells	Wheat starch binder	70	54.4	17.7	7	20.9
20	36	Bagasse	Wheat starch binder	30	49.9	30.4	6.8	12.8
40	37	Bagasse	Wheat starch binder	50	49.6	32.7	6.9	10.8
7	38	Groundnut shells	Wheat starch binder	50	54.3	28	7.4	10.4
28	39	Bagasse	Wheat starch binder	70	48.7	31.8	7.2	12.2
6	40	Bagasse	Cassava starch binder	50	49.2	34.3	6.6	9.9
21	41	Groundnut shells	Cassava starch binder	50	53.6	28.4	7.5	28.4
27	42	Groundnut shells	Wheat starch binder	70	54.3	16.3	6.9	22.4
11	43	Groundnut shells	Wheat starch binder	70	51.9	20.9	7	20.2
16	44	Bagasse	Wheat starch binder	90	46.7	31.7	7.4	14.2
29	45	Groundnut shells	Cassava starch binder	90	49.7	20.4	7.2	22.8
46	46	Bagasse	Cassava starch binder	90	49.6	32	7	11.3
41	47	Groundnut shells	Cassava starch binder	70	51.5	21.2	7.8	19.5
3	48	Groundnut shells	Wheat starch binder	30	54	25.6	7.4	13

development on resulting starch binders that affect resistance to heat and shear forces [36, 37]. A significant difference in fixed carbon (%), volatile matter (%), and moisture content (%) was observed for bagasse briquettes when 90 g of cassava and wheat starch binders was used. Interaction plots for factors agricultural residue type (groundnut shells and bagasse) and different amounts of wheat starch binder for (a) fixed carbon, (b) volatile matter, (c) moisture content, and (d) ash content are shown in Fig. 7. Interaction plots for physical properties with factors agricultural residue type (groundnut shells and bagasse) and different amounts of cassava starch binder for (a) fixed carbon, (b) volatile matter, (c) moisture content, and (d) ash content are shown in Fig. 8. The results show that the agricultural residue type has a greater effect on the resulting physical properties of developed groundnut shell and bagasse briquettes when compared with binder amount. However, binder amount had a specific significant effect for case-specific briquettes. Fixed carbon (%) and ash content (%) generally decreased with increasing binder amount from 30 to 90 g of wheat starch binder for both groundnut shell and bagasse briquettes. An opposite trend was observed for volatile matter (%) (see Fig. 7). The opposite trends in the behavior of fixed carbon (%) and volatile matter (%) are expected. An increase in wheat starch binder implies that the amount of carbonaceous matter in the developed briquette is reduced which explains the reduced fixed carbon results. Wheat starch binder amounts had limited significance on moisture content (%) for both groundnut shell and bagasse briquettes. Only for 90 g of wheat starch binder was a significant increase in moisture content observed. An increase in cassava starch binder from 30 to 90 g showed a significant impact in physical properties of groundnut shell briquettes. Aransiola et al. [10] noted that the binder type and binder concentrations had a significant impact on moisture content (%). The agricultural residue type had a clear effect on the interaction between the residue type

Table 6 Analysis of variance for physical properties for factors agricultural residues (groundnut shells and bagasse), binder type (wheat and cassava starch), and binder amount (30 g, 50 g, 70 g, and 90 g)

Source	Sum of squares	df	Mean square	*F* value	*p* value	
Response 1: fixed carbon						
Model	265.03	15	17.67	12.54	< 0.0001	Significant
A-agricultural residues	135.76	1	135.76	96.38	< 0.0001	
B-binder type	16.20	1	16.20	11.50	0.0020	
C-binder amount	55.65	3	18.55	13.17	< 0.0001	
AB	21.35	1	21.35	15.16	0.0005	
AC	6.42	3	2.14	1.52	0.2297	
BC	25.10	3	8.37	5.94	0.0026	
ABC	5.75	3	1.92	1.36	0.2735	
Pure error	42.26	30	1.41			
Cor total	307.29	45				
Response 2: volatile matter						
Model	1396.94	15	93.13	10.72	< 0.0001	Significant
A-agricultural residues	1142.70	1	1142.70	131.48	< 0.0001	
B-binder type	42.56	1	42.56	4.90	0.0341	
C-binder amount	26.42	3	8.81	1.01	0.3996	
AB	13.87	1	13.87	1.60	0.2156	
AC	29.30	3	9.77	1.12	0.3541	
BC	108.92	3	36.31	4.18	0.0133	
ABC	33.17	3	11.06	1.27	0.3005	
Pure error	278.11	32	8.69			
Cor total	1675.05	47				
Response 3: moisture content						
Model	10.38	15	0.6919	15.49	< 0.0001	Significant
A-agricultural residues	2.13	1	2.13	47.73	< 0.0001	
B-binder type	0.0228	1	0.0228	0.5108	0.4803	
C-binder amount	0.8315	3	0.2772	6.21	0.0021	
AB	2.47	1	2.47	55.37	< 0.0001	
AC	2.40	3	0.8003	17.92	< 0.0001	
BC	0.6755	3	0.2252	5.04	0.0060	
ABC	1.45	3	0.4835	10.82	< 0.0001	
Pure error	1.34	30	0.0447			
Cor total	11.72	45				
Response 4: ash content						
Model	1068.34	15	71.22	18.07	< 0.0001	Significant
A-agricultural residues	790.46	1	790.46	200.53	< 0.0001	
B-binder type	2.01	1	2.01	0.5111	0.4804	
C-binder amount	8.89	3	2.96	0.7520	0.5301	
AB	31.25	1	31.25	7.93	0.0087	
AC	8.41	3	2.80	0.7116	0.5530	
BC	103.73	3	34.58	8.77	0.0003	
ABC	114.53	3	38.18	9.69	0.0001	
Pure error	114.31	29	3.94			
Cor total	1182.65	44				

and the binder amount (see Fig. 8). In Figs. 9 and 10, interaction plots for factors of different binder amounts and binder types are shown for the physical properties of the developed briquettes. The results showed that

Table 7 Fit statistics results for physical property responses for groundnut shell and bagasse briquettes developed with cassava starch binder and wheat starch binder

	Fixed carbon	Volatile matter	Moisture content	Ash content
Std Dev	1.19	2.95	0.2113	1.99
Mean	50.46	27.22	7.10	16.00
C.V.%	2.35	10.83	2.97	12.41
R^2	0.8625	0.8340	0.8857	0.9033
Adjusted R^2	0.7937	0.7561	0.8285	0.8533
Predicted R^2	0.6369	0.6264	0.7278	0.7710
Adeq precision	14.2388	9.4984	15.7782	13.2054

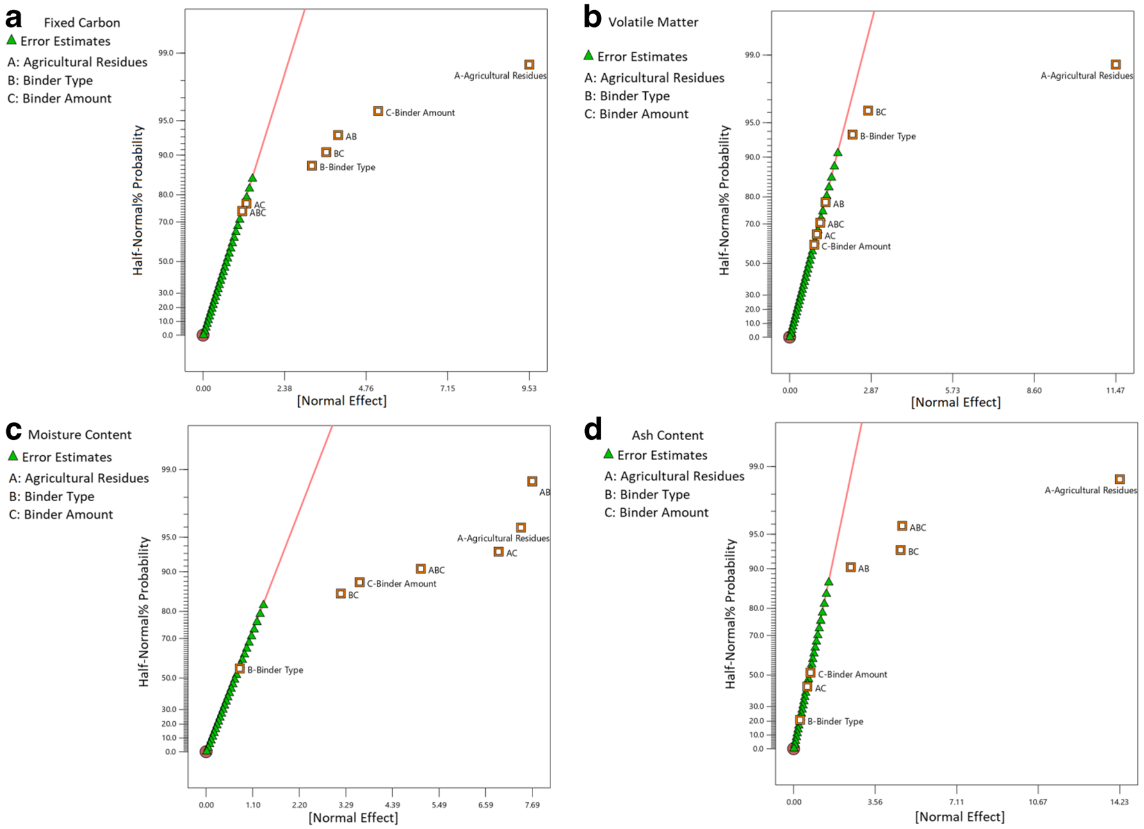

Fig. 4 Half-normal probability plots for factors agricultural residues (groundnut shells and bagasse), binder type (wheat and cassava starch), and binder amount (30 g, 50 g, 70 g, and 90 g)

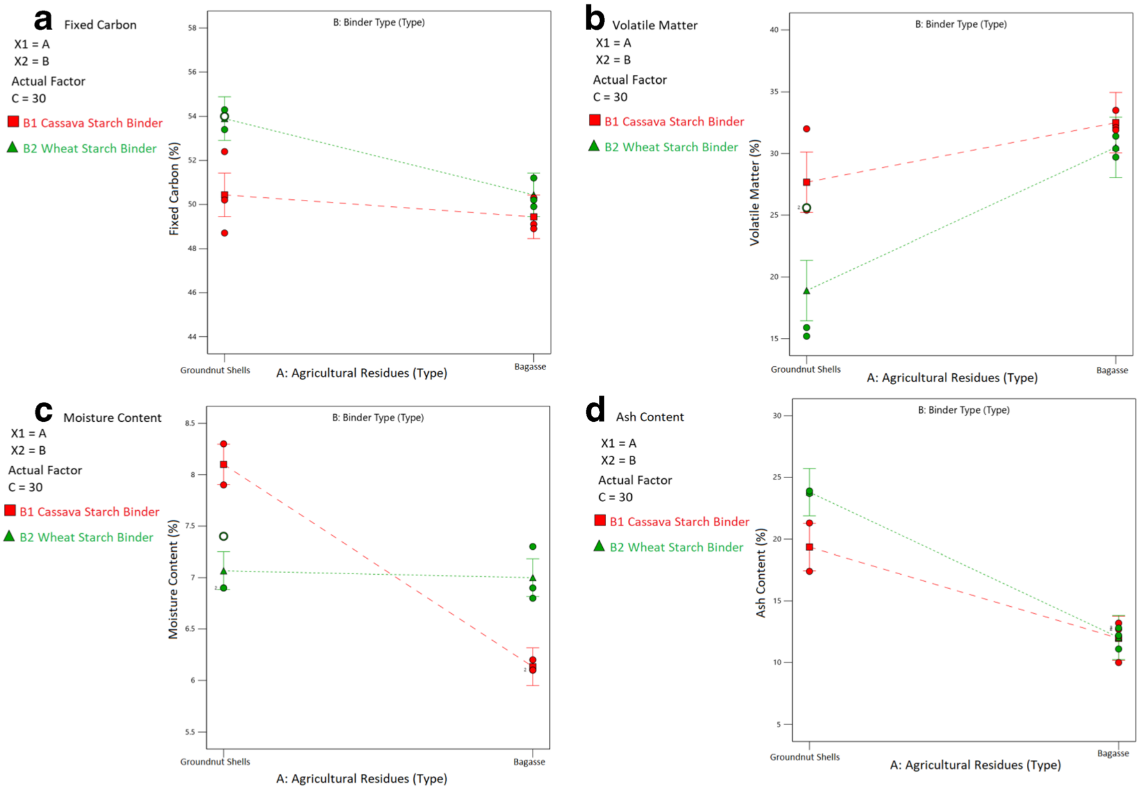

Fig. 5 Interaction plots for factors agricultural residue type (groundnut shells and bagasse) and 30 g cassava and wheat starch binder types for **a** fixed carbon, **b** volatile matter, **c** moisture content, and **d** ash content

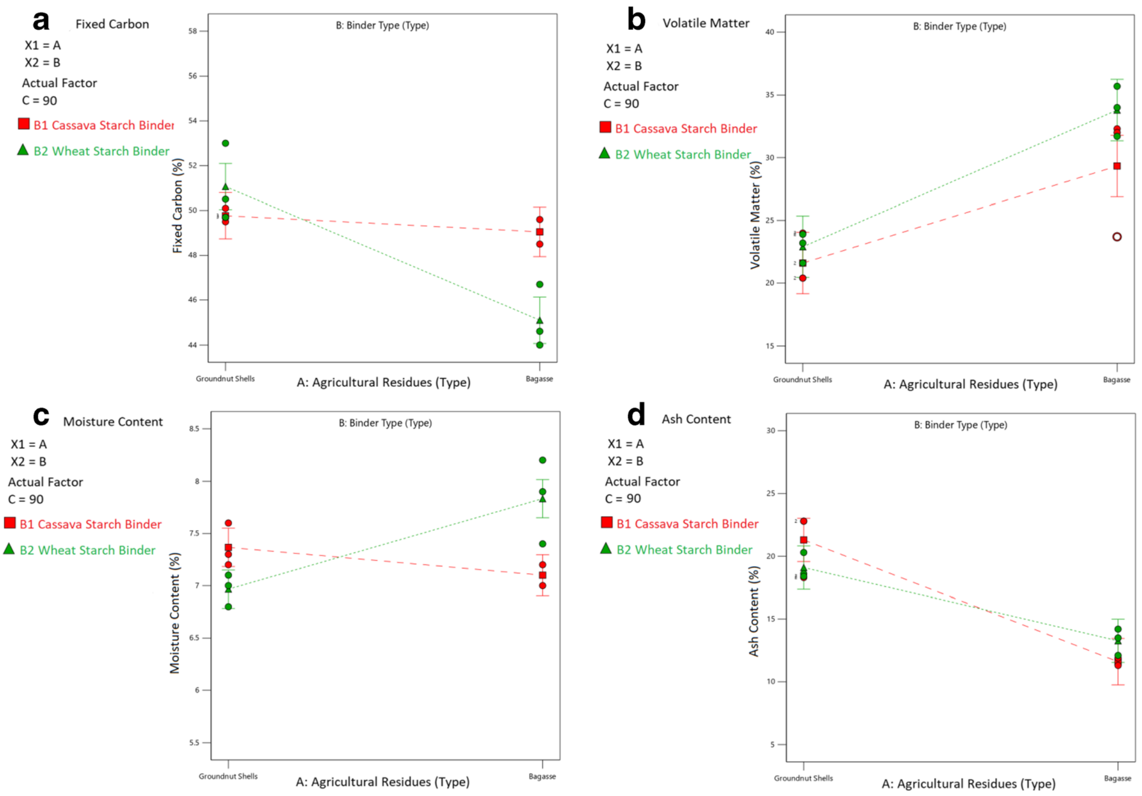

Fig. 6 Interaction plots for factors agricultural residue type (groundnut shells and bagasse) and 90 g cassava and wheat starch binder types for **a** fixed carbon, **b** volatile matter, **c** moisture content, and **d** ash content

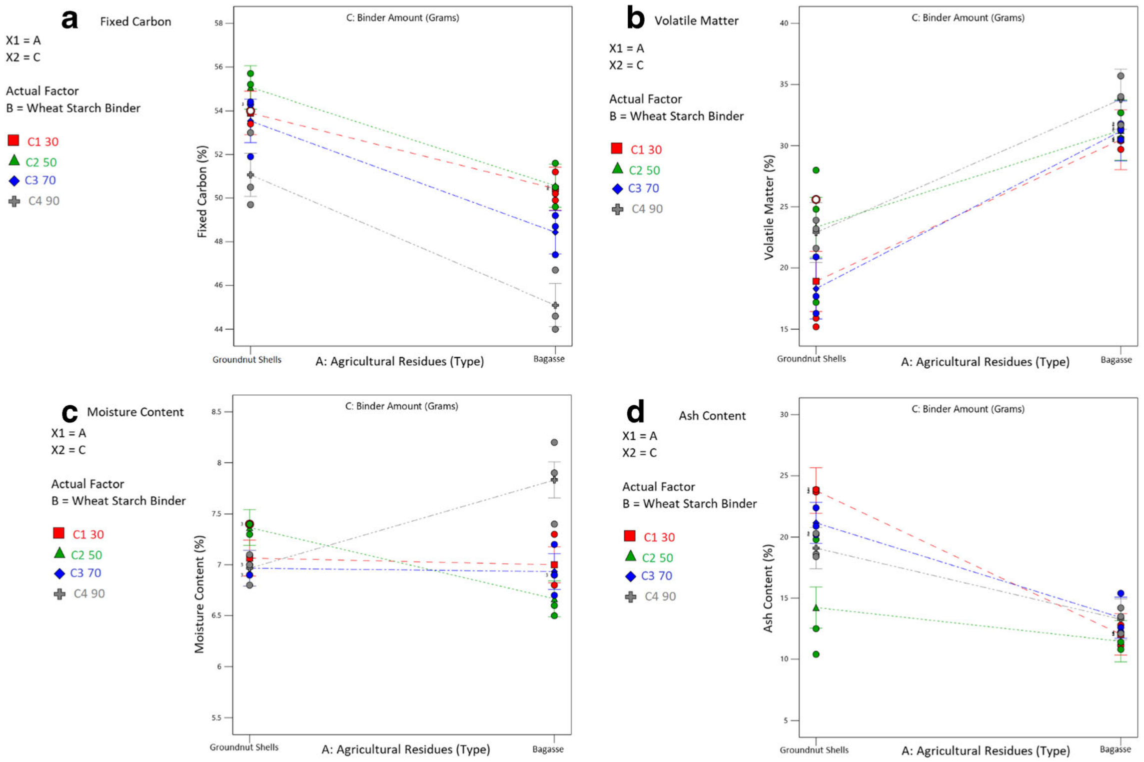

Fig. 7 Interaction plots for factors agricultural residue type (groundnut shells and bagasse) and different amounts of wheat starch binder for **a** fixed carbon, **b** volatile matter, **c** moisture content, and **d** ash content

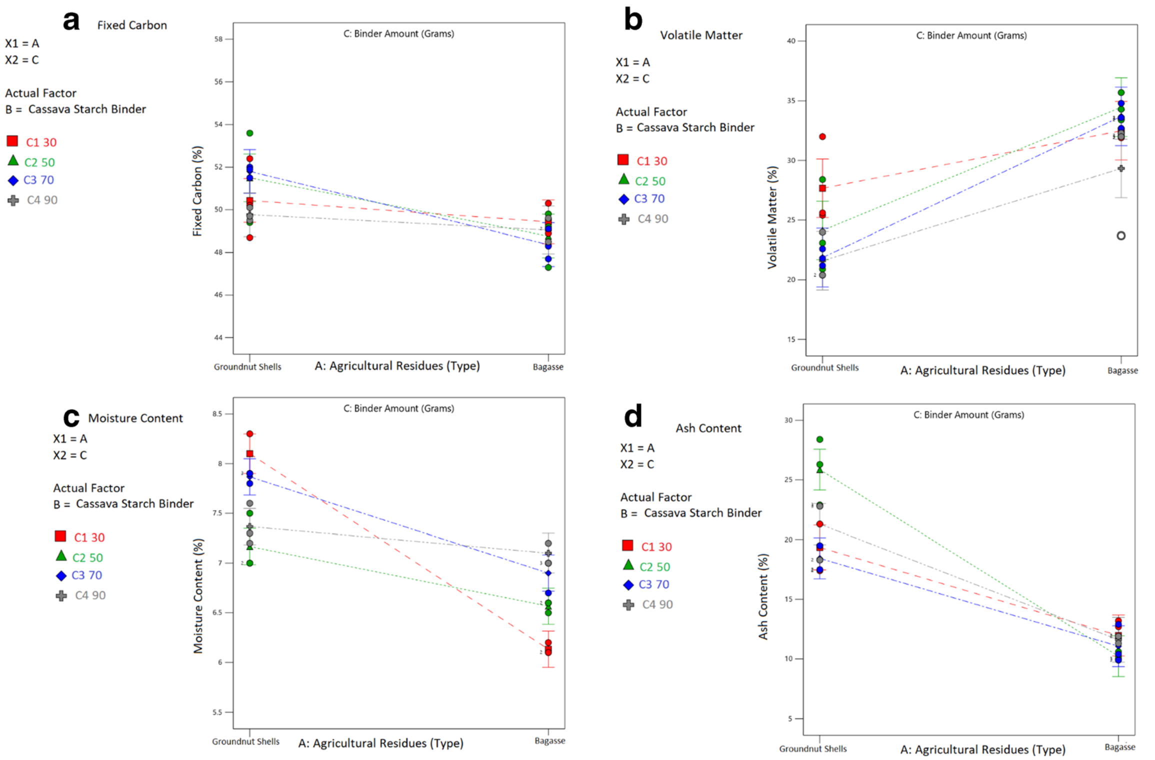

Fig. 8 Interaction plots for factors agricultural residue type (groundnut shells and bagasse) and different amounts of cassava starch binder for **a** fixed carbon, **b** volatile matter, **c** moisture content, and **d** ash content

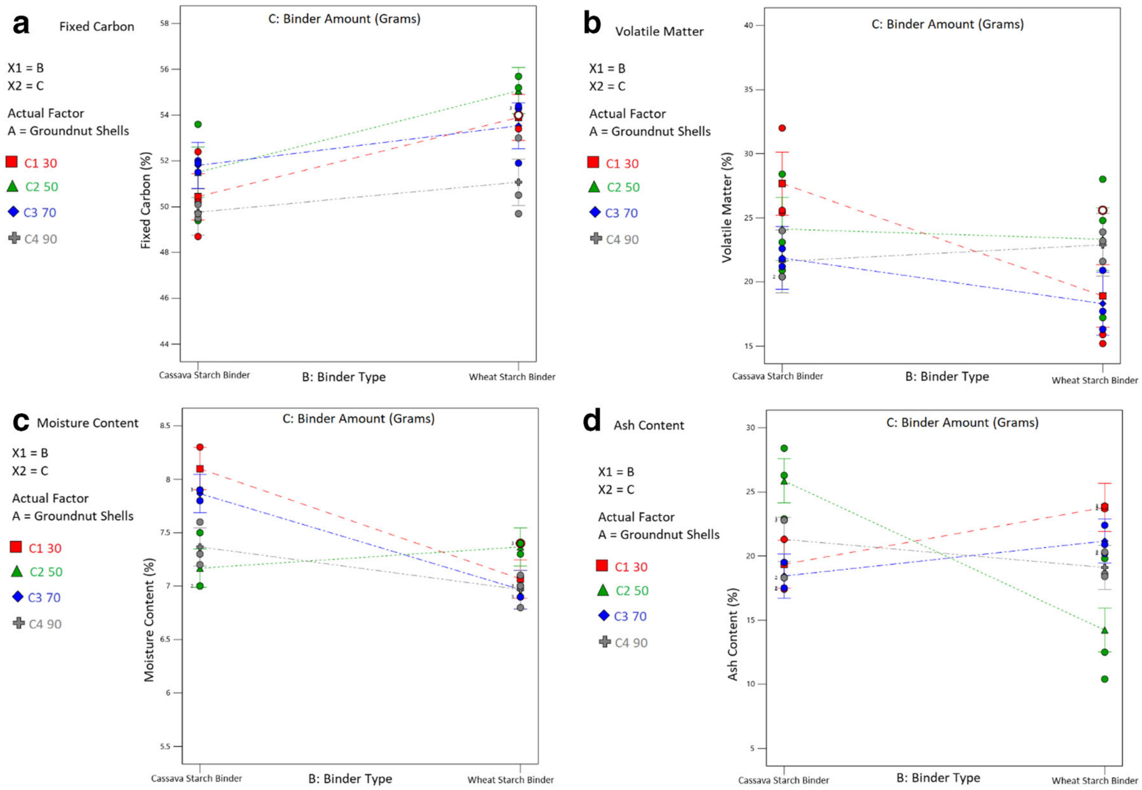

Fig. 9 Interaction plots for factors different binder amounts and cassava and wheat starch binders in groundnut shell briquettes for **a** fixed carbon, **b** volatile matter, **c** moisture content, and **d** ash content

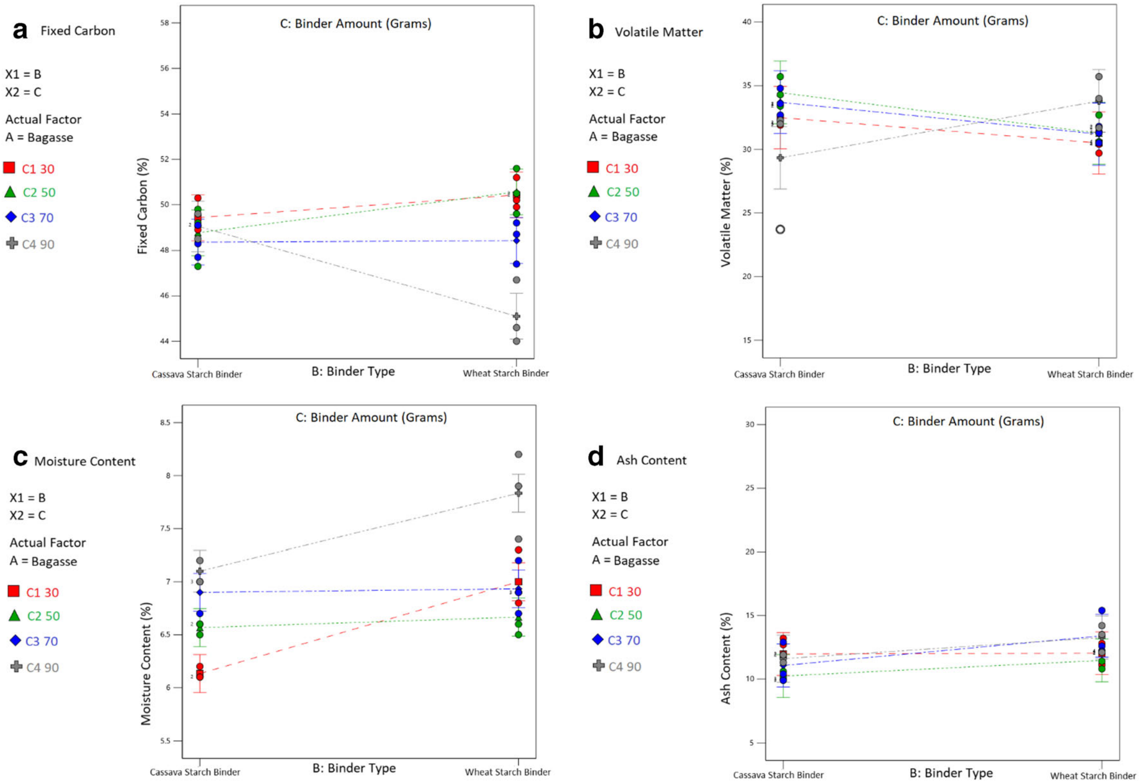

Fig. 10 Interaction plots for factors different binder amounts and cassava and wheat starch binders in bagasse briquettes for **a** fixed carbon, **b** volatile matter, **c** moisture content, and **d** ash content

binder amount had a significantly higher effect on physical properties of groundnut shell briquettes (see Fig. 9) and bagasse briquettes (see Fig. 10) when compared with the actual starch binder type.

Table 8 Calorific values for 30 and 50 g of cassava starch binder in developed carbonized agricultural residue briquettes

Std	Run	Factor 1 A: agricultural residue type	Factor 2 B: cassava starch binder (g)	Response 1: calorific value (MJ/kg)
3	1	Rice husks	30	16.6
6	2	Bagasse	50	23.3
11	3	Rice husks	30	16.6
15	4	Rice husks	50	16.4
14	5	Bagasse	50	23.1
16	6	Coffee husks	50	22.1
9	7	Groundnut shells	30	23.9
1	8	Groundnut shells	30	21.7
5	9	Groundnut shells	50	20.4
13	10	Groundnut shells	50	20.6
12	11	Coffee husks	30	23.1
8	12	Coffee husks	50	22
2	13	Bagasse	30	23.3
4	14	Coffee husks	30	23
10	15	Bagasse	30	23.1
7	16	Rice husks	50	16.4

3.3 Interactions of the agricultural residue type and binder on the calorific value of briquettes

The effect of the agricultural residue type, binder type, and binder amount and their interactions on calorific values of developed briquettes is shown in Fig. 11. Experimental run results when cassava starch binder was used and when both cassava and wheat starch binders were used are shown in Tables 8 and 9, respectively. An increase in cassava starch binder from 30 to 90 g showed a significant reduction in the calorific value of groundnut shell briquettes. Lower amounts of phosphorus in cassava starch binder affect resistance to heat which explains this result [36, 37]. Calorific values for all of the other briquettes were not affected by an increase in cassava starch binder from 30 to 90 g. Calorific values of groundnut shell and bagasse briquettes were observed to be significantly affected by the agricultural residue type. Yank et al. [7] also noted that the binder type used in briquette development significantly affected physical and performance properties of the developed briquettes. Changes in cassava and wheat starch binder amounts from 30 to 90 g did not significantly affect heating values of developed groundnut shell and bagasse briquettes.

4 Conclusion

In this study, a general factorial multi-level categorical experimental design method was used to investigate the effects and interactions of the agricultural type, binder type, and binder

Table 9 Calorific values for varying amounts of wheat and cassava starch binders in carbonized bagasse and groundnut shell briquettes

Std	Run	Factor 1 A: agricultural residue type	Factor 2 B: binder type	Factor 3 C: binder amount (g)	Response 1: calorific value (MJ/kg)
32	1	Bagasse	Wheat starch binder	90	21
22	2	Bagasse	Cassava starch binder	50	23.3
24	3	Bagasse	Wheat starch binder	50	23.2
17	4	Groundnut shells	Cassava starch binder	30	23.9
6	5	Bagasse	Cassava starch binder	50	23.1
1	6	Groundnut shells	Cassava starch binder	30	21.7
20	7	Bagasse	Wheat starch binder	30	21.7
21	8	Groundnut shells	Cassava starch binder	50	20.4
2	9	Bagasse	Cassava starch binder	30	23.3
12	10	Bagasse	Wheat starch binder	70	23
19	11	Groundnut shells	Wheat starch binder	30	22.7
7	12	Groundnut shells	Wheat starch binder	50	22.6
26	13	Bagasse	Cassava starch binder	70	22.7
10	14	Bagasse	Cassava starch binder	70	23.1
31	15	Groundnut shells	Wheat starch binder	90	22.5
29	16	Groundnut shells	Cassava starch binder	90	22.1
30	17	Bagasse	Cassava starch binder	90	22.2
28	18	Bagasse	Wheat starch binder	70	21.9
15	19	Groundnut shells	Wheat starch binder	90	23
18	20	Bagasse	Cassava starch binder	30	23.1
5	21	Groundnut shells	Cassava starch binder	50	20.6
9	22	Groundnut shells	Cassava starch binder	70	21.8
16	23	Bagasse	Wheat starch binder	90	21.7
27	24	Groundnut shells	Wheat starch binder	70	22.7
3	25	Groundnut shells	Wheat starch binder	30	22.5
8	26	Bagasse	Wheat starch binder	50	22.2
13	27	Groundnut shells	Cassava starch binder	90	21.3
14	28	Bagasse	Cassava starch binder	90	22.2
25	29	Groundnut shells	Cassava starch binder	70	21.6
23	30	Groundnut shells	Wheat starch binder	50	23.7
11	31	Groundnut shells	Wheat starch binder	70	22.4
4	32	Bagasse	Wheat starch binder	30	23.2

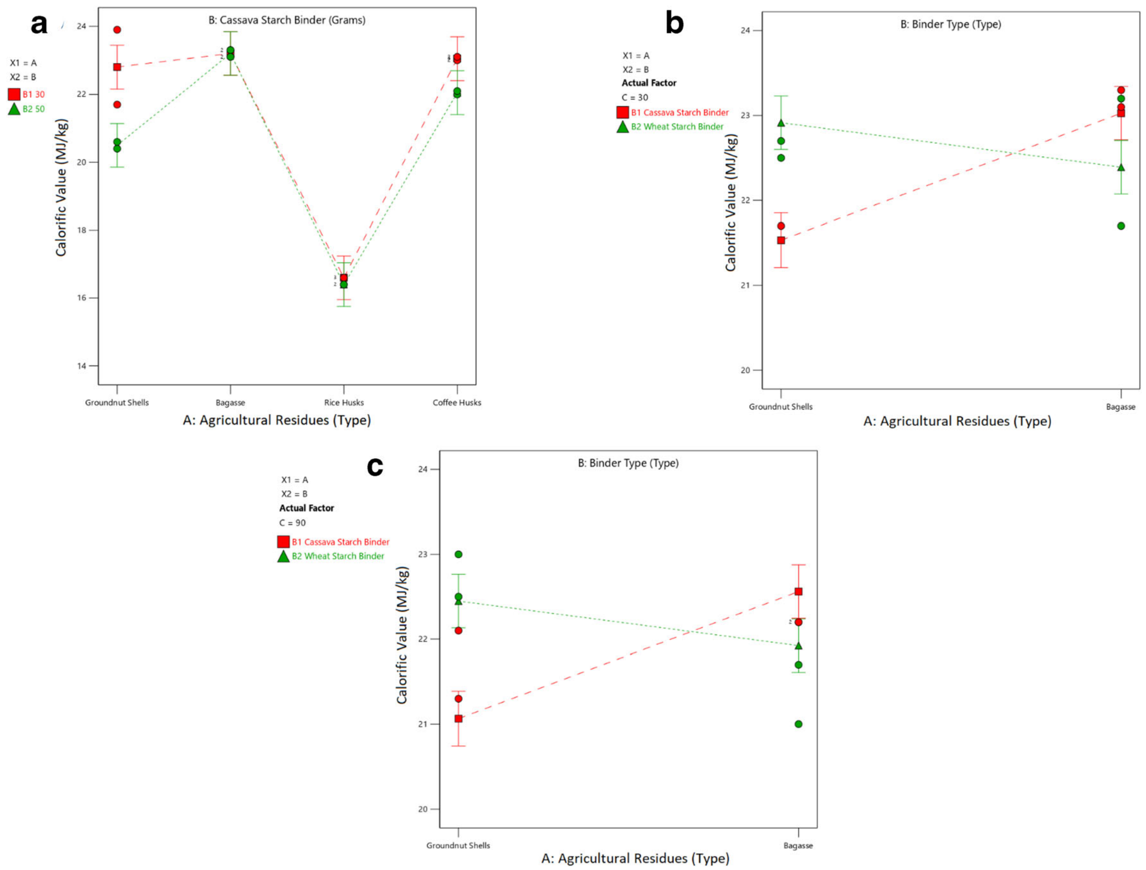

Fig. 11 Interaction plots for the calorific value for factors agricultural residue and cassava starch binder (**a**) and agricultural residues and binder type for 30 g (**b**) and 90 g (**c**) of cassava and wheat starch binders

amount on responses of physical properties and calorific values. Multiple factors are responsible for the properties of developed briquettes. The effect of the agricultural residue type in determining resulting properties of developed briquettes is seldom elucidated. Physical properties of the developed carbonized briquettes were determined using an Eltra Thermostep Thermogravimetric analyzer. An IKA C 2000 bomb calorimeter was used to determine calorific values. The highest calorific values of 23.9 MJ/kg and 23.3 MJ/kg were obtained for groundnut shell and bagasse biochar briquettes, respectively, when only 30 g of cassava starch binder was used. Design-Expert Version 12.0.8 was used to determine the effects and interactions. This approach was used to enable us to determine the interactions between the agricultural type and the binder type as well as binder amount and the effects of these factors on physical properties and calorific values of the developed carbonized briquettes. Briquettes were developed using carbonized groundnut shells, sugarcane bagasse, rice husks, and coffee husks. Statistically significant models ($p < 0.05$) were obtained for the physical property responses of fixed carbon, ash content, volatile matter, and moisture content and calorific values for the developed briquettes. In experiments where only cassava starch binder (30 g and 50 g) was used, it was observed that the carbonized agricultural residues used in the development of the carbonized briquettes played a more significant role in the resulting physical property. Increasing the cassava starch binder from 30 to 50 g in binding the carbonized agricultural residue had a minimal impact on the resulting briquette physical property. In experiments where cassava starch binder and wheat starch binder were used, it was clear that the physical property of the developed briquette was affected significantly by the carbonized agricultural residue used as well as the binder type. The effect of varying binder amounts was within the margin of error. Calorific values of groundnut shell and bagasse briquettes were observed to be significantly affected by the agricultural residue type. Changes in cassava and wheat starch binder amounts from 30 to 90 g did not significantly affect heating values of developed groundnut shell and bagasse briquettes.

Author contributions Michael Lubwama and Vianney Andrew Yiga were responsible for execution of experiments. Michael Lubwama, Vianney Andrew Yiga, and Harriet Nalubega Lubwama were responsible for analysis of data, writing, and technical editing during the preparation of this manuscript.

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