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Research Article

Combustion, Physical, and Mechanical Characterization of Composites Fuel Briquettes from Carbonized Banana Stalk and Corncob

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Abstract. The United States Environmental Protection Agency (EPA) has reported that consumption of fossil fuels and their products has contributed about 65% of the global greenhouse gas emission. Therefore, it is expedient to look for alternative energy sources for an eco-friendly environment. The EPA recommended using biomass energy as a promising stabilization option to alleviate global climate change. This study focused on developing composites fuel briquettes from a blend of carbonized corncob and banana stalk. Carbonization was carried out at 380 ^{o}C, while 60 min was adopted as the residence time. Briquettes were manufactured at different blending ratios (90CC:10BS, 80CC:20BS, 70CC:30BS, 60CC:40BS and 50CC:50BS of corncob: banana stalk, respectively) and compaction pressures (50, 70 and 90 kPa) using gelatinized starch as binder. The manufactured briquettes' calculated and actual calorific values varied between 18.98-22.07 MJ/kg and 20.22-23.12 MJ/kg, respectively, while shatter indices were in the range of 38.22-89.34%. The compressed and relaxed densities of the fuel briquettes were in the range of 0.32-1.39 g/cm^3 and 0.22-1.02 g/cm^3, respectively. The relaxation ratio and water resistance properties varied between 1.11- 2.21 and 11-23 min, respectively. Analyses of the results revealed that compaction pressure, blending ratio, and particle size substantially affect the combustion and physico-mechanical characteristics of the manufactured fuel briquettes. When optimum combustion and physico-mechanical properties are required, a sample made from 90CC:10BS (S1) is recommended for use. The fuel briquettes manufactured in this study possess the required thermal and physico-mechanical properties of solid fuel; therefore, it is recommended for different applications.

Keywords: Briquette, Carbonization, Physico-mechanical property, Thermal property; Corncob, Banana stalk

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1. Introduction

Recent researches have shown that over-utilization of non-renewable energy such as fossil fuels have contributed significantly to the global environmental challenges (Cheol *et al*., 2021; Mcnamee, 2016). This is because fossil fuels are usually burned for energy to be released for different applications. The combustion of fossil fuels leads to the emission of greenhouse gasses, which causes global warming. With an increase in climatic threat, it is not wise to encourage the consumption of energy that contributes to environmental degradation. Therefore, it is essential to seek a renewable and alternative to fossil fuels for healthy living. Generation of biofuel from cellulosic biomass has been identified as a promising option. Biomass is a renewable energy source that exhibits sustainable characteristics and promotes a green environment (Cong, Yao, & Zhao, 2021; Espuelas *et al*., 2020; Lubwama *et al*., 2020; Mitchell *et al*., 2020; Mu, Chilton, & Cant, 2020). Previous studies have revealed that utilization of biomass such as agricultural residues, non-food crops, forest residues, and even algae for biofuel production could reduce global CO_2 emissions (Bhakta, Sarmah, & Dubey, 2020; Supatata, Buates, & Hariyanont, 2017; Thulu, Kachaje, & Mlowa, 2016).

In addressing the global energy crisis, especially in the developing nations where clean, renewable, and sustainable energy is not affordable, decentralized approaches to energy will go a long way. Biofuel production would make a great deal of sense for developing countries

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and remote areas- biomass materials are abundant in developing nations and remote regions (Ibitoye *et al.*, 2021). This is because biomass conversion techniques such as carbonization and densification are promising and favorable options for biofuel production. Carbonization is a thermochemical process where solid biomass is subjected to thermal treatment at a temperature between 350 – 500 ^{o}C in an inert or oxygen-reduced environment (Atan, Nazari, & Azizan, 2018; Brachi *et al.*, 2019; Chen, Peng, & Bi, 2015). Inert gases are employed to create an inert environment, but nitrogen is the commonly used carrier gas to create an inert atmosphere. Densification is the agglomeration of fine particles (different or same particle sizes) by applying pressure into various shapes with or without using a binding agent (Hu *et al.*, 2021; Ibitoye *et al.*, 2021a; Rabiu *et al.*, 2019). Pressure is applied on biomass in a mold so that the particles can articulate together stably for subsequent handling, storage, and transportation. Examples of densification processes are briquetting, pelletizing, bailing, and cubing. The challenges (transport, handling dumping, and burning, etc.) related to biomass utilization can be overcome via densification into solid fuels. Densification improves the fuel properties of the final products. Some of the benefits of biomass agglomeration include an increase in bulk density, improved storage, handling, and flow properties, enhanced homogeneity of blends, reduced dust formation, and improved particle bed heat transfer (Cong *et al.*, 2021; Riva *et al.*, 2021; Yang, Cooke-willis, Song, & Hall, 2021).

Several research efforts have developed solid fuel from biomass feedstock through thermal treatment and densification. Severy *et al.* (2018) carried out torrefaction and briquetting on a pilot-scale plant. Briquettes of high quality and optimal torrefaction conditions were obtained at residence time (RT), moisture content, temperature range of 10 min, < 11%, and 267-275 ^{o}C, respectively. An investigation was conducted on torrefied Tectona grandis in a tubular furnace at 240-300 ^{o}C, 30-60 min, and 2-6 mm torrefaction temperature (TT), RT, and particle size, respectively (Odusote *et al.*, 2019). A reduction in the volatile matter was reported with an increase in fixed carbon and calorific value. Though it was concluded that the fuel met the requirement for energy generation in thermal plants, there was no report on the physico-mechanical properties of the produced fuel.

A torrefaction study on agro-residues (rice straw, corncob, and cassava stalk) of Indonesia origin showed that the blending of feedstock does not significantly influence the product properties (Andini *et al.*, 2018). Fuel pellets were manufactured from food waste (paper cups, vegetable parts, rice, condiments, vegetables, fruit peels, woody chopsticks, noodles, and cooked meat) via hydrothermal carbonization by Zhai *et al.* (2018). Molasses and lime were utilized as binding agents. Carbonization was done at 3 ^{o}C/min heating rate using different temperatures and RT. Molasses only (20%) and a blend of 20% molasses and 5% lime were two binder compositions used for the study. Results revealed that pellets made from blends of molasses and lime exhibited good compressive strength, better resistance to impact forces, and improved density. Song *et al.* (2021) submitted that a briquette of high calorific value and weather resistance could be produced from blends of thermoplastics and wood residues using a unique hot ejection method. A study on the effect of milling size on the pelletization process and pellet quality was conducted using a pilot-scale pellet production route (Pradhan, Mahajani, & Arora, 2021). It was opined that milling sizes greatly influenced pellet quality.

Ganmo is a famous town in Kwara state, Northcentral, Nigeria. Ganmo has a market which people usually go to every five days to sell and buy goods. Due to the town's location and the high level of agricultural activity in the towns and villages surrounding it, the Ganmo market is usually dominated by agricultural products such as guinea corn, yam, maize, sweet potato, plantain, and banana, among other agricultural products. People come from far and near because things are available at a lower price. After the market day, the market area is usually littered with agricultural residues such as banana stalk, cassava peel, corncob, etc. Most time, these residues are disposed by dumping and burning in an open field, and these have constituted a nuisance and environmental threat to the people living in the surrounding.

In view of the foregoing, there is a need to seek a proper waste management method for the residue generated in the Ganmo market and how these residues can be converted into usable products. To the best of the author's knowledge, there is little or no report on the production and characterization of fuel briquettes from blends of carbonized corncob and banana stalk in literature. It is essential to investigate the properties of solid fuel manufactured from blends of this biomass feedstock, especially the physical, mechanical, and thermal properties. Therefore, this study aims to produce and characterize solid fuel briquettes from blends of carbonized corncob and banana stalk as a waste management technique for people living around the Ganmo market. The parameters considered for investigating the combustion properties are higher heating value, ultimate and proximate analyses. The physico-mechanical parameters include particle sizes, density, shatter index, water resistance, relaxation ratio, and compressive strength (Ajimotokan *et al.*, 2019a; Zhai *et al.*, 2018). This research would serve as an alternative to wood charcoal and fossil fuels. It would provide income for the people via employment generation. This study will advance renewable and sustainable energy generation from biomass for different applications. The outcome of this research can be applied in domestic and industrial settings for cooking and heating purposes.

2. Materials and methods

2.1 Materials

The biomasses utilized for this research are agro-residues majorly generated at Jimba-Oja and Ganmo market, Kwara State, Nigeria. Corncob was obtained from the maize processing plant at Jimba-Oja, Kwara state, Nigeria. The banana stalk was collected at Ganmo central market (aftermarket), at Ganmo, Kwara state, Nigeria, while starch was collected from a cassava processing factory at Ganmo, Kwara state, Nigeria. The corncob and banana residues formed about 65% of the agro-residues generated in these areas (Ibitoye, 2018). Therefore, they are selected to be converted into usable products to minimize the environmental problem associated with their disposal.

2.2. Methods

2.2.1. Materials preparation

The corncob and banana stalk were collected and sorted to remove foreign substances such as sand particles and other plant residues. The sorted material was sun-dried for 14 days to reduce the moisture contents. Preliminary characterization (proximate and ultimate analyses and calorific values) was then conducted on each sample. The cassava starch collected was used as a binding agent. The cassava starch powder was gelatinized using boiling water. The water was heated to 100 °C, after which the starch powder was poured and continuously stirred until a uniform starch gel was formed.

2.2.2. Carbonization of biomass samples

Carbonization was carried out in an oxygen-free environment by a continuous flow of nitrogen gas throughout the carbonization process. The banana stalk and corncob feedstock was carbonized using an electric furnace at 380 °C and 60 min residence time. The carbonization temperature was selected based on the reports of Kluska, Ochnio, & Kardas (2020), Liu *et al*. (2018), Sellin *et al*. (2016), and Goulart and Maia (2013). In their study, equilibrium between carbonization char yield and corresponding calorific value was attained at about 380 °C. Also, the TGA reports revealed that about 40-50% biomass feedstock could be recovered at about 380 °C thermochemical conversion temperature. The furnace was preheated up to 100 °C, after which it was loaded with 2 kg of each sample. The furnace attained the maximum carbonization temperature (380 °C), and each sample was allowed to residence at this temperature for 60 min as recommended by Adeleke *et al*. (2019) and Odusote *et al*. (2019). After carbonization, the setup was allowed to cool for about 5-7 min, after which the carbonized sample was collected and transferred into a desiccator for further cooling to room temperature. Figure 1 shows the samples before and after carbonization. The carbonized samples were pulverized to reduce the particle size. Pulverized samples were screened into fines of 1.7-1, 1-0.5, and < 0.5 mm by performing sieve analysis at the Department of Civil Engineering, University of Ilorin, Nigeria. Each fine was kept in a zip lock bag to prevent interaction with the surrounding.

2.2.3. Briquettes formulation and production

Briquettes from carbonized corncob (CC) and banana stalk (BS) were formulated as shown in Table 1. The preliminary characterization of the feedstock revealed that corncob exhibit better fuel properties (fixed carbon, volatile matter, and carbon content) than banana stalks. Therefore, the percentage of corncob in the blends was higher than banana stalk. Each briquette blends consist of 95% biomass feedstock and 5% gelatinized cassava starch as a binder. The percentages of carbonized CC and BS were first of all blended using an electric mixer (Rico, model: YP103KM1511 000056) at 100 rpm for 5 min. Then, the gelatinized starch was added, and the blends were further mixed at 100 rpm for 5 min. These were done to ensure uniformity in the blending of the feedstock and binder. After that, the blended feedstock was poured into the mold for compaction. Compaction was done at room temperature and three different pressures of 50, 70, and 90 kPa using a 1560 kN hydraulic Jack at the Department of Civil Engineering, University of Ilorin, Ilorin, Nigeria. The dwelling time for every briquette manufactured was 2 min. The manufactured briquettes were ejected from the mold, after which they were dried under the sun for 14 days. The dried briquettes were stored at room temperature in an airtight bag for further analysis. Figure 2 shows the samples of manufactured fuel briquettes.

Fig 1. The feedstock samples- (a) raw corncob, (b) carbonized corncob, (c) raw banana stalk, and (d) carbonized banana stalk

Table 1
Briquette formulation

Sample ID	Corncob (%)	Banana stalk (%)	Binder (%)
S1	85.5	9.5	5
S2	76	19	5
S3	66.5	28.5	5
S4	57	38	5
S5	47.5	47.5	5

Fig 2. Samples of briquettes manufactured from a blend of carbonized corncob and banana stalk

2.2.4. Characterization of raw samples and manufactured fuel briquettes

- *Thermal properties*

Proximate analysis: It was conducted to determine the percentages of volatile matter (VM), moisture content (MC), ash content (AC), fixed carbon (FC) of the raw samples as well as the manufactured fuel briquettes in accordance with ASTM standards using a thermogravimetric analyzer (ASTM D7582-15, 2015). The FC was calculated by difference using Equation 1 (Basu, 2013).

$$FC = 100 - (MC + AC + VM)\,\% \quad (1)$$

Ultimate analysis: The elemental compositions of the raw and carbonized samples were determined using a CHNS analyzer in accordance with the ASTM standard (ASTM D5373-16, 2016). The oxygen content was calculated by difference using Equation 2 (Basu, 2013).

$$O = 100 - (C + H + N + S + Ash)\,\% \quad (2)$$

Higher heating value (HHV): The higher heating value was determined experimentally according to ASTM standard using a bomb calorimeter (ASTM D5865-04, 2004). The calculated HHV was estimated from the ultimate analysis results using Equation 3 (Shariff *et al.*, 2016).

$$HHV = 337C + 1442\,(H - O/8) + 93S \quad (3)$$

where C, H, O, and S are carbon, hydrogen, oxygen, and sulphur, respectively.

- *Physico-mechanical properties*

Compressive strength: The crushing strength of the manufactured briquettes was determined using a Universal Testing Machine (Model: FS5080) following the ASTM standard method (ASTM D2166-85, 2008). The compressive strength experiment was conducted twenty-one days after drying. This is to allow the briquettes to attain their maximum strength. The highest stress for each experiment was recorded as the compressive strength of the briquettes. The tests were repeated three times, and the average was reported.

Density: The green (instantly after ejection from the mold) and relaxed (dried) densities of the manufactured briquettes were determined using Equation 4 (Ajimotokan *et al.*, 2019b). The briquettes' mass was measured using an electronic weighing balance, while the volume was calculated by taking the dimension of the briquette using a Vernier caliper. The relaxed density was determined after the briquettes had been sun-dried for two weeks according to ISO standard 3131.

$$Density = \frac{mass}{volume}\,;\ Volume = \pi h(R^2 - r^2) \quad (4)$$

Relaxation ratio: The relaxation ratio was calculated using Equation 5 (Ajimotokan *et al.*, 2019a).

$$Relaxation\ ratio = \frac{compressed\ density}{relaxed\ density} \quad (5)$$

Shattering index: This is the factor the shows the toughness and ability of the briquettes to withstand impact and rubbing load during storage, transportation, and handling of the briquettes. This was determined by dropping briquettes 4 times repeatedly from a height of

1.85 m onto a solid base (Odusote & Muraina, 2017). The portion of the briquette recollected was utilized as an index of briquette mechanical durability. Equation 6 was used to determine the shatter index (Ajimotokan *et al.*, 2019a).

$$Shattering\ index = \frac{weight\ of\ briquette\ in\ plate\ after\ 4\ drops}{the\ initial\ weight\ of\ the\ sample} \times 100\% \qquad (6)$$

Water-resistance capacity: It indicates the hydrophobic nature of the manufactured briquettes. This was estimated as the time taken for the briquettes to break down when submerged in water (Demirbaş, 1999). The water-resistance was determined as the time taken in seconds for the briquettes to collapse in water (Ajimotokan *et al.*, 2019a).

3. Results and Discussion

The combustion, physical and mechanical properties results of the feedstock, and manufacture fuel briquettes are presented and discussed in this section. All experiments are conducted in duplicate, and the averages are reported.

3.1. Sieve analysis

Figure 3 shows the sieve analysis result of the carbonized samples. The particles are highly distributed around < 0.5, 1-0.5, and 1.7-1 mm sieve sizes for both samples. The highest (33.43% with 1.7-1 mm) and the lowest (0.40% with > 1.7-1 mm) particles retained were recorded with corncob and banana stalk, respectively. The particle distribution could be due to the shape and size of the pulverized feedstock. The sieve analysis procedure assumes that feedstock particles are spherical (Gil *et al.*, 2014). The feedstock's irregular shapes and fibrous nature (banana stalk) affect the particle distribution, flowability, and percentage retained on the sieve (Chaloupkova *et al.*, 2016; Gil *et al.*, 2014). However, particle size distribution is greatly dependent on the level of grinding of the samples, oscillating time and method, and the quantity of feedstock used for each analysis (Chaloupkova *et al.*, 2016). Particle sizes of < 0.5, 1-0.5, and 1.7-1 mm were utilized to produce briquettes in large quantity from these samples without conducting more extensive sieve analysis.

3.2. Characterization of the raw and carbonized samples

Table 2 shows the proximate and ultimate analyses and higher heating values (HHV) of the raw and carbonized samples. For the raw samples, MC, AC, VM, FC and HHV was found to vary between 7.70-14.90%, 1.74-5.10%, 71.11-79.10%, 8.89-11.46%, and 10.71-15.18 MJ/kg, respectively. Banana stalk displayed higher MC (14.90%) and AC (5.10%) while corncob gave higher calorific value, VM and FC of 15.18 MJ/kg, 79.10%, and 11.14%, respectively. Higher VM is a sign of the readiness of the sample to ignite during combustion, and greater mass loss might be experienced during carbonization when VM is high (Ajimotokan *et al.*, 2019). The recorded properties show that corncob contained higher energy potential when compared with banana stalk. After carbonization, it was observed that the VM in both samples reduced while FC and the HHV increased significantly. Corncob and banana gave HHV of 23.50 and 17.51 MJ/kg, respectively, while the FC and VM were 55.59 and 36.14% for corncob, and 51.67 and 32.46% for banana stalk, respectively. The reduction in VM could result from devolatilization that occurred during the carbonization process. An increase in FC and HHV resulted from the treatment via the carbonization process. Also, the increase in HHV is traceable to the initial thermal pretreatment via carbonization and the percentage of FC in the samples. This is because the amount of heat released during combustion depends on the amount of carbon available in the feedstock. This observation is in agreement with the report of Ajimotokan *et al.* (2019), Lisseth *et al.* (2021), and Siqueira *et al.* (2021). Kluska *et al.* (2020) carbonized corncob between the temperature range of 300 and 700 °C. At about 380 °C carbonization temperature, they submitted 27.5 MJ/kg, 70 %, and 20.5% for HHV, FC, and VM, respectively. The HHV, FC, and VM obtained in this study are lower than the values reported by Kluska *et al.* (2020). The variation could be a result of the difference in the elemental constituent due to biomass origin and method of carbonization. The results of the elemental analysis revealed that the percentage of carbon (C) increases while oxygen (O) and hydrogen (H) elements decrease after carbonization. The increase in C contents indicated that more C is available for combustion after carbonization, and this could be linked with the increase in the HHV after carbonization. The reduction in the O and H elements would positively influence the carbonized samples' atomic ratio, leading to improved combustion characteristics.

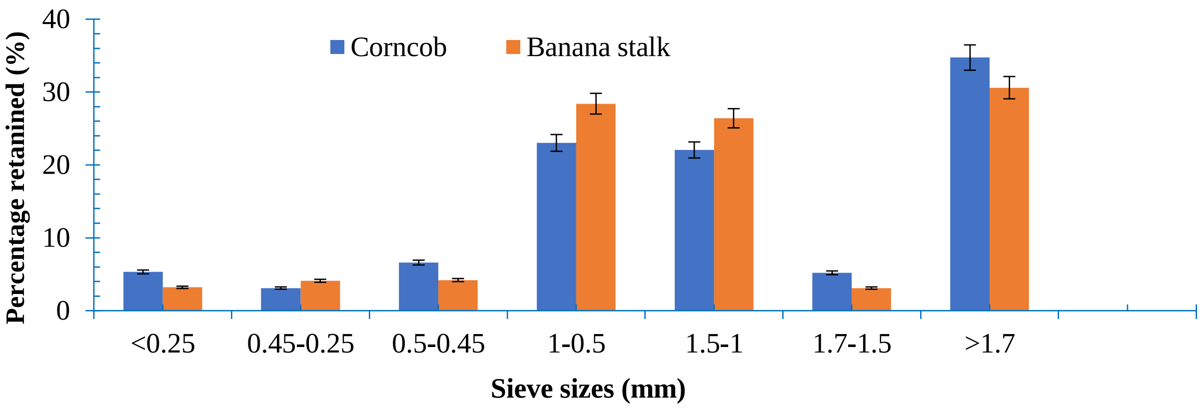

Fig 3. Particle size distribution of the carbonized samples

Table 2
Proximate and ultimate analyses and higher heating value of the raw and carbonized sample

Basis	Fuel properties (%)	Raw		Carbonized	
		Corncob	Banana stalk	Corncob	Banana stalk
As determined	MC	7.70±0.03	14.90±0.01	6.15±0.02	11.43±0.02
	AC	1.74±0.02	5.10±0.02	2.12±0.01	4.44±0.02
	VM	79.10±0.57	71.11±0.60	36.14±0.43	32.46±0.35
	*FC	11.46±0.15	8.89±0.09	55.59±0.12	51.67±0.11
Dry	C	47.78±0.76	41.43±0.34	66.59±0.65	51.22±0.71
	H	5.48±0.01	4.75±0.01	4.34±0.02	4.10±0.02
	S	1.56±0.01	0.81±0.00	0.02±0.00	0.31±0.00
	N	0.12±0.00	1.12±0.00	0.21±0.00	1.32±0.00
	*O	43.32±0.54	46.79±0.49	26.72±0.51	38.61±0.45
	HHV (MJ/kg)	15.18±1.12	10.70±1.11	23.50±1.13	17.51±1.13

**Determined by the difference*

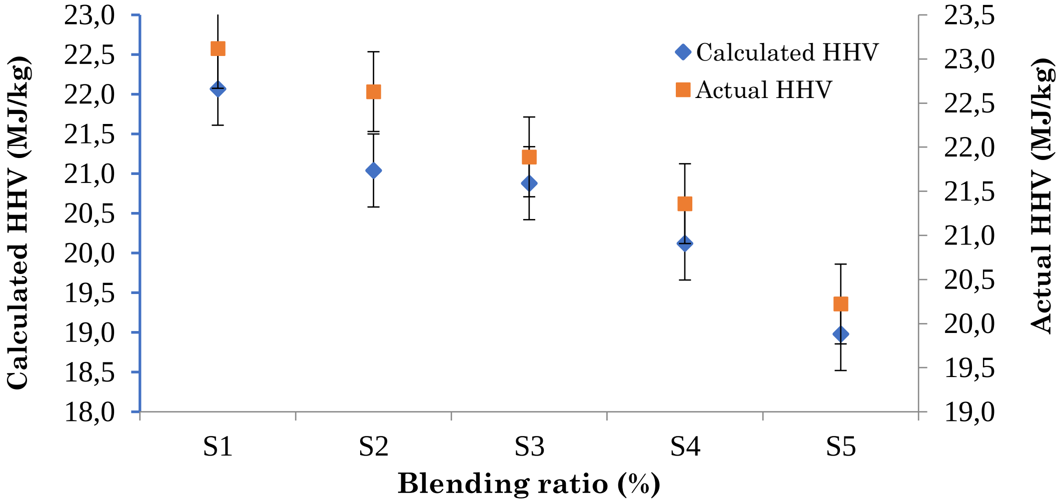

Fig 4. Calculated and actual HHV of the manufactured fuel briquettes at a different blending ratio

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3.3. Thermal property of manufactured fuel briquettes

HHV is the amount of heat released during the combustion of the fuel briquettes. Figure 4 shows the results of HHV of the manufactured briquettes at different blending ratios. The calculated and actual HHV was discovered to be in the range of 18.98-22.07 MJ/kg and 20.22-23.12 MJ/kg, respectively. It could be observed that the actual HHV is higher than the calculated value. This is because the calculated values are based on elemental analysis results which are prone to errors.

However, it is an indication and quick method of estimating heating value without performing the actual experiment. The HHV recorded in this study is higher than the calculated (14.88 MJ/kg) and actual (16.46 MJ/kg) values reported by Shariff *et al.* (2016), and the value (16.54 MJ/kg) reported by Ogunjobi & Lajide (2013). The HHV of S1 was found to be higher than untreated woody biomass (Antwi-Boasiako & Acheampong, 2016), non-woody biomass (Kpalo *et al.*,2020), and a blend of woody and non-woody biomass (Afsal *et al.*, 2020). However, Ajimotokan *et al.* (2019) and Ikubanni *et al.* (2019) reported a higher value of HHV of 24.90 MJ/kg (carbonized *Terminalia ivorensis* and raw *Pinus caribaea*) and 24.50 MJ/kg (Sawdust and Rice husk), respectively. The difference in HHV could be due to the feedstock's nature (combustion characteristics) and the feedstock preparation method. The variation could also be due to the type of thermal treatment method adopted and the difference in the elemental composition of the feedstock. This is because thermal treatment temperature and residence time significantly affect the heating value of the resulting products (Kongto *et al.*, 2021; Ibitoye *et al.*, 2021c). Results revealed that HHV decreases as the percentage of the banana stalk in the blends increases. This could be linked to the characteristics of the raw and carbonized samples. Corncob presents higher FC, which points out the amount of heat released during combustion. It is worthy of note that the corncob contributed majorly to the HHV in the blend. The blending of the two biomasses makes the HHV of the composite fuel briquettes better than the pure banana stalk. However, HHV is lower than briquettes made from pure corncob. Initial carbonization significantly contributed to the improvement in the thermal property of the manufactured briquettes. This is because thermal treatment improves the aromacity and reduces the oxygen-containing (carboxyl, hydroxyl, etc.) functional groups in biomass feedstock, thus an improvement in the energy density after carbonization. Furthermore, the initial carbonization increases the C and reduces H and O contents in the feedstock. The CC bonds in the feedstock are increase after carbonization, while the CO and CH bonds reduces. The percentages of C, H, and O in any fuel determine the energy stored in the fuel. This is because higher O and H with lower C in feedstock results to a reduction in the energy value, as there higher energy stored in CC bond than in CO and CH bonds (Adeleke *et al.*, 2020).

3.4. Proximate and ultimate analyses

The proximate and ultimate analyses of the manufactured fuel briquettes are presented in Table 3. The MC, AC, VM, and FC varied between 4.37-8.42%, 3.11-5.10%, 33.13-36.51%, and 53.35-56.01%, respectively. The results show that sample S1 has the highest VM and FC, while the lowest VM and FC were observed with sample S5. Contrarily, it was discovered that S5 has the highest MC and AC, while S1 displayed the lowest MC and AC. Furthermore, VM and FC decrease as the banana stalk increases in the blend. However, AC increases with an increase in banana stalk in the agglomerate. These observations were traceable to the preliminary characterization results of the feedstock used to produce the briquettes. The feedstock's hydrophilic nature and particle distribution might be responsible for the produced briquettes' porosity and moisture absorption properties. High MC affects the combustion properties of solid fuel because excessive energy would be needed for drying during combustion; thus, MC should be as low as possible. AC is an indication of the percentage of incombustible components of solid fuel. AC significantly affects the heating value and heat transfer during combustion. Hence, high AC affects the combustion characteristics of solid fuel negatively. Therefore, the briquettes manufactured from blends of carbonized corncob and banana stalk would perform efficiently following its AC. FC is the amount of carbon available during combustion for heat to be released, and VM reveals the readiness of the solid fuels to ignite during combustion. The high VM and FC were responsible for the HHV recorded with sample S1 (Figure 4). The highest FC and VM recorded in the briquettes were greater than the carbonized banana stalk, however less than the carbonized corncob. This was because banana stalk has lower FC and VM, and increasing banana stalk would reduce the FC and VM of the fuel briquettes.

Elemental constituents also affect the combustion properties of biofuels. The C, H, S, N, and O of the produced briquettes are in the range of 55.78-61.21%, 4.96-5.14%, 0.00-0.02%, 0.52-0.57%, and 30.00-33.57%, respectively. The ultimate analysis results revealed that C and H decrease as the percentage of banana stalk increase in the agglomerate, while O and N increase with the portion of the banana stalk in the blends. There was no noticeable effect of blending ratio on the S content of the produced briquettes. The results revealed that the blending ratio significantly influenced the ultimate analysis results. Therefore, for optimum performance and to make solid fuel of good energy density, the percentage of the banana stalk in the blends should be as low as possible.

Table 3
Proximate and ultimate analyses of the manufactured fuel briquettes

Basis	Sample ID/ Parameters (%)	S1	S2	S3	S4	S5
As determined	MC	4.37±0.02	5.90±0.03	7.36±0.01	7.43±0.02	8.42±0.01
	AC	3.11±0.01	4.32±0.01	4.55±0.02	4.89±0.02	5.10±0.01
	VM	36.51±0.16	35.22±0.22	34.32±0.14	34.11±0.17	33.13±0.21
	*FC	56.01±0.36	54.56±0.18	53.77±0.16	53.57±0.16	53.35±0.21
Dry	C	61.21±0.04	59.32±0.04	59.11±0.05	57.89±0.10	55.78±0.07
	H	5.14±0.02	5.11±0.01	5.07±0.02	4.99±0.02	4.96±0.01
	S	0.02±0.00	0.02±0.00	0.02±0.00	0.02±0.00	0.02±0.01
	N	0.52±0.00	0.52±0.00	0.55±0.00	0.57±0.00	0.57±0.00
	*O	30.00±0.06	30.71±0.04	30.70±0.08	31.64±0.06	33.57±0.06

*Determined by the difference

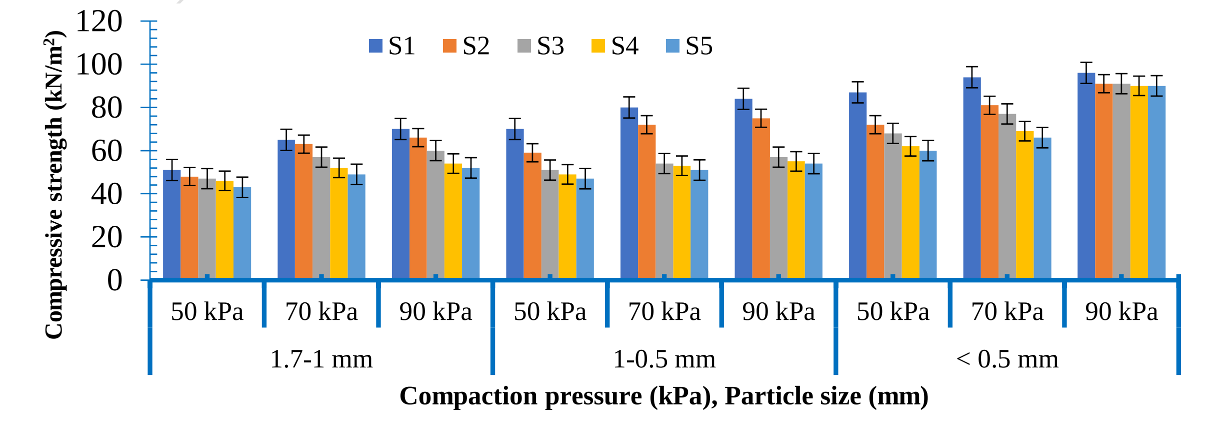

Fig 5. Variation of compressive strength of the manufactured briquettes with blending ratio and compaction pressure

3.5. Physico-mechanical properties

3.5.1. Compressive strength

Cold crushing (compressive) strength reveals the ability of the fuel briquettes to withstand a crushing load. The compressive strength results at different compaction pressure and particle size are shown in Figure 5. The crushing strength of the manufactured fuel briquettes varied between 43-96 kN/m^2. Samples made from 90CC:10BS (S1) and 50CC:50BS (S5) exhibited the highest and lowest compressive strength, respectively. It was observed that particle size and compaction pressure substantially influence the compressive strength properties of the manufactured briquettes. The strength characteristics were found to increase as the particle size decreased. This could result from lower pore spaces between the smaller particles that enhance the inter-molecular bonding of fuel particles. In addition, compressive strength was found to increase as the percentage of the banana stalk in the blend increased. This shows that the banana stalk played a dominant role in improving the strength property of the manufactured fuel briquettes. Furthermore, as the compaction forces increases, compressive strength also increases. Compaction pressure reduced the inter-molecular distance, improving inter-molecular bonding, resulting in better strength properties. The high strength recorded could also be attributed to the binder used to produce the briquettes. The binder enhances the formation of a solid bridge between the feedstock particles, making the atoms and molecules diffuse at the point of contact at elevated pressure. More so, binders improve the adhesion and cohesive forces to hold individual particles together. The adhesion and cohesion forces present at the interface of the feedstock particle and binder form solid bridges that strengthen the composite solid fuel. The observation made in this study agrees with the report of Song *et al.* (2021).

3.5.2. Compressed and relaxed densities

Figures 6 and 7 show the variation of compressed and relaxed densities with compaction pressure and particle size, respectively. The compressed and relaxed densities of the fuel briquettes were in the range of 0.32-1.39 g/cm^3 and 0.22-1.02 g/cm^3, respectively. Samples S1 and S5 present the highest and lowest density, respectively. The compressed density increase as compaction pressure increases. The fuel particles are closely packed at higher compaction pressure- the particle's mass per unit area. Also, particle sizes have a significant influence on compressed density. Compressed density increases as the particle reduce-the smaller the particle, the smaller the porous spaces between the particles. A similar trend was observed with the relaxed density. In general, the relaxed density is lower than the compressed density. This is because the fuel briquettes lose moisture during the drying process. The relaxed density of S1 (1.02 g/cm^3 at 0.09 MPa compaction pressure) is greater than the values reported by Kpalo *et al.* (2020) at ≤7 MPa, Ajimotokan *et al.* 2019b) at 0.065 MPa, and Ikubanni *et al.* (2019). However, Antwi-Boasiako & Acheampong (2016) reported a higher relaxed density at 0.06 MPa. The relaxed density of fuel briquettes greatly depends on the bulk density of the feedstock (Ibitoye, 2018).

3.5.3. Relaxation ratio

From Figure 8, it could be observed that the relaxation ratio varied between 1.11 and 2.21. The highest relaxation ratio was obtained with sample S5 at 90 kPa and 1.7-1 mm compaction pressure and particle size, respectively, while the lowest relaxation ratio was recorded with sample S1 manufactured at 50 kPa compaction pressure and < 0.5 mm particle size. Analyses of the results revealed that the relaxation ratio increase as the densification pressure increases. As particle size decreases, the relaxation ratio was also found to reduce. The lower the relaxation ratio value, the more stable the briquette properties during storage- a small relaxation ratio indicates large volume displacement. This is an essential characteristic for briquettes packaging, transportation, and storage. Therefore, briquettes manufactured from < 0.5 mm particle sizes are more stable than briquettes manufactured from other particle sizes. The values obtained in this study are in line with the report Ajobo (2014), who reported an optimum relaxation ratio of 1.45 using a groundnut shell. Oladeji *et al.* (2016) also reported a relaxation ratio of 1.12 and 1.13 using cornstalk and corncob, respectively. Furthermore, Oladeji (2013) submitted 1.71, 1.44, and 1.17 relaxation ratios for corncob, groundnut shell, and blends of corncob and groundnut shell, respectively. The relaxation ratios presented in these reports are within the range obtained in this study. Although, some briquettes manufactured in this study displayed higher relaxation ratio.

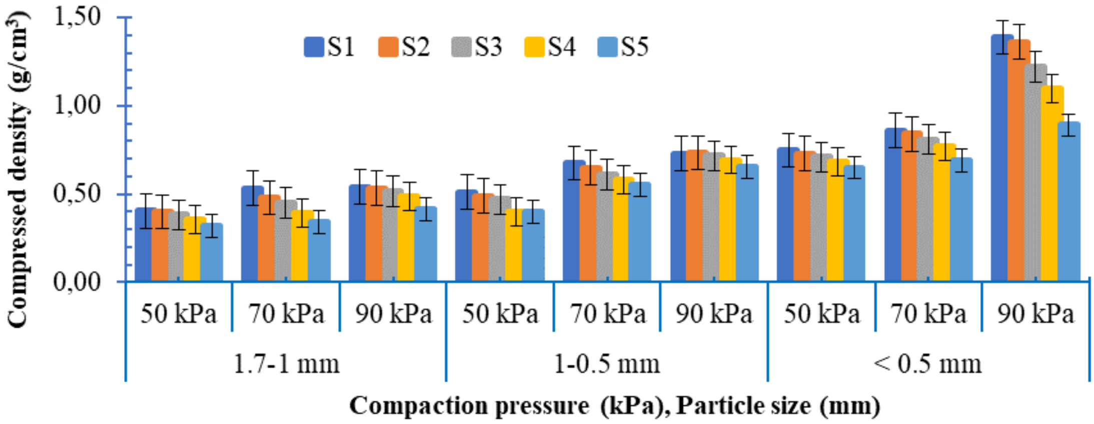

Fig 6. Variation of the compressed density of the manufactured briquettes with blending ratio and compaction pressure

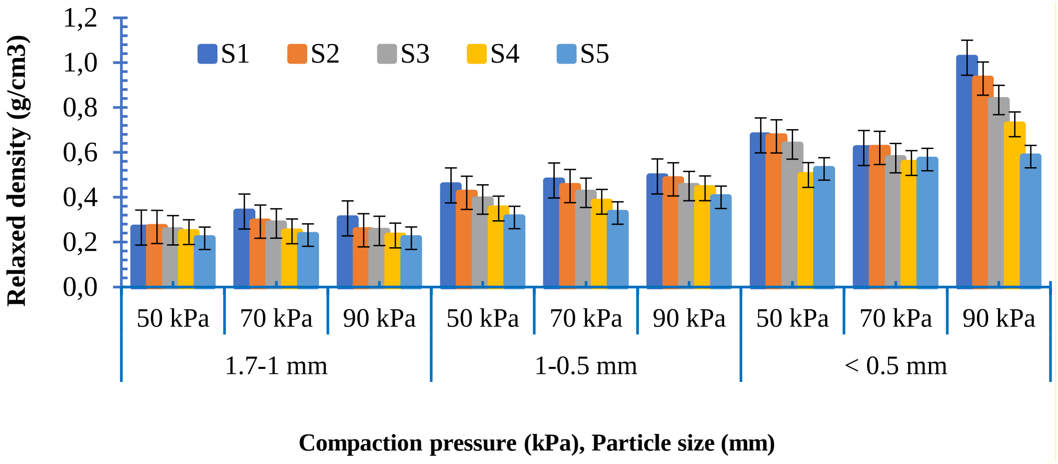

Fig. 7. Variation of the relaxed density of the manufactured briquettes with blending ratio and compaction pressure

3.5.4. Shatter index

The shatter index indicates the durability property and resistance of the manufactured fuel briquettes to impact and rubbing forces. Figure 9 shows the shatter index at different blending ratios and particle sizes. The shatter indices were in the range of 38.22-89.34%. The highest and the lowest shatter index was recorded at 90 kPa (< 0.5 mm particle size) and 50 kPa (1.7-1 mm particle size), respectively. Results show that the shatter index decreases as the proportion of banana stalk increase in the blend. This indicates that corncob performed a prominent role in improving the shatter index of the manufactured fuel briquettes. This could be due to the presence of natural binder and intermolecular arrangement of the corncob particles, which contributed to the resistance of the briquettes to shattering forces (Kluska *et al.*, 2020; Ribas *et al.*, 2013; Takada *et al.*, 2018). A binding agent with a large contact surface area could enhance intermolecular bonding, making briquettes particles interlock, and improving shatter index property. It was observed that samples of the better shattering property displayed excellent compressive strength characteristics (Figure 5). Furthermore, as compaction pressure increases, the shatter index also increases. Conversely, an improvement in the shatter index was noticed as particle size decreased. This is because finer particles are more closely packed with better inter-molecular bonding. In addition, the adhesive forces between finer particles resulting from high compaction force make the particles interlock and bond to one another, enhancing the durability of the produced fuel briquettes. Thermal pretreatment also improves the durability of the fuel briquettes (Ralf *et al.*, 2020). The result of durability was found to be lower than the values reported by Ajimotokan *et al.* (2019b) (99.13% using raw corncob and rice husk), Kpalo *et al.* (2020) (99.08% using Corncob and Oil palm trunk bark), and Antwi-Boasiako & Acheampong (2016) (98.80% using raw *Cylicodiscus gabunensis, Antiaris toxicaria,* and *Ceiba pentandra*). The briquettes made in this study displayed better durability properties than the briquettes produced using sawdust and rice husk, with durability of 81.90% (Ikubanni *et al.*, 2019). The variation in the results could be due to the method of production, type and quantity of binder used, and the type of biomass.

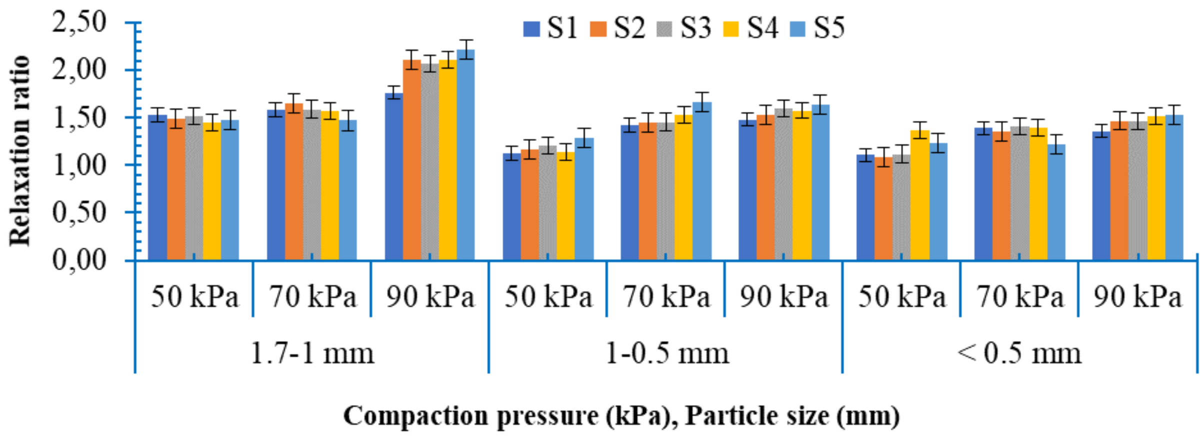

Fig 8 Relaxation ratio of the manufactured briquettes at different blending ratios and particle sizes

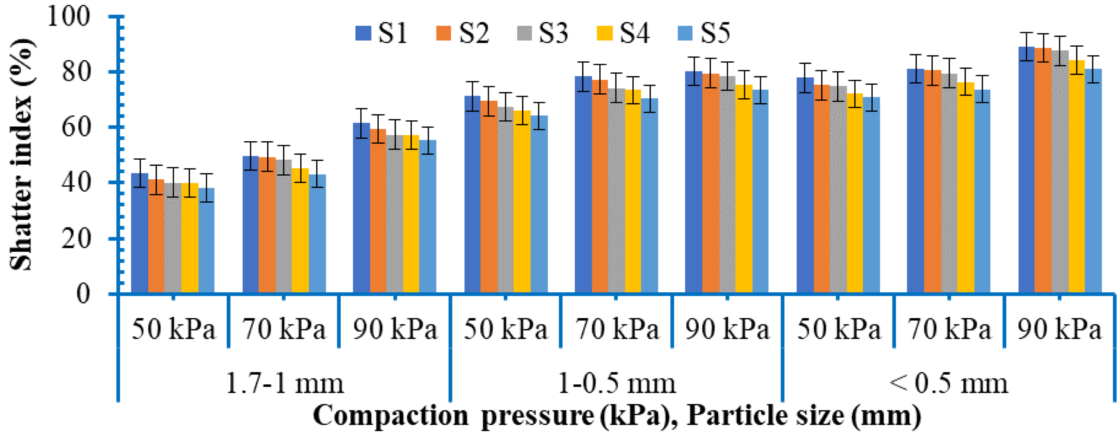

Fig 9. Effect of blending ratio and particle size on shattering index of the manufactured briquettes

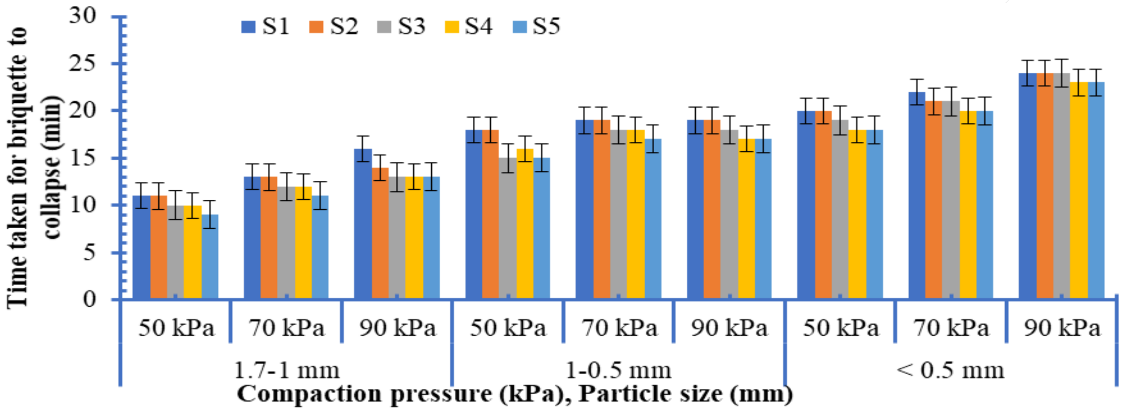

Fig 10 Variation of water resistance capacity of the manufactured briquettes with compaction pressure and blending ratio

3.5.5. Water resistance

Figure 10 shows the variation of water resistance capacity of the manufactured briquettes with compaction pressure and blending ratio. The figure shows the time for the briquettes samples to collapse when immersed in water. Water-resistance results varied between 11 and 23 min. The lowest and highest water resistance was recorded with samples S5 and S1 at 50 and 90 kPa compaction pressure and 1.7-1 and < 0.5 mm particle sizes, respectively. Resistance of the briquettes to water increases as compaction pressure and percentage of the banana stalk in the aggregates increases. Higher compaction pressure reduces the pore spaces between particles, making the briquettes less porous—lesser porosity implies better water resistance. Better water resistance capacity can also be attributed to the initial carbonization of the raw samples. Researches have shown that carbonization improves hydrophobicity (Bhakta *et al.*, 2020; Yang *et al.*, 2021). Furthermore, water resistance increases as briquettes particle size reduction—the finer the particle, the better the water resistance. Finer particles have less pore space which reduces capillary action and rate of water percolation of the produced fuel briquettes (Siqueira *et al.*, 2021). The briquettes manufactured in this study present better water resistance properties than the 16 min report by Ajimotokan *et al.* (2019b) using raw corncob and rice feedstock.

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4. Conclusion

An investigation was carried out on the manufacture of fuel briquettes from carbonized corncob and banana stalks. Combustion, physical and mechanical characterization of the manufactured fuel briquettes was done. It was found that the carbonization process improves the thermal (HHV) and water resistance properties of the manufactured fuel briquettes. The optimum HHV and water resistance were recorded with samples S1 (90CC:10BS). The blending ratio significantly influences the manufactured briquette's proximate analysis and elemental composition. Compaction pressure substantially affects the physico-mechanical properties of the manufactured fuel briquettes. The higher the compaction pressure, the better the density, shatter index, and water resistance properties. As banana stalk increases in the agglomerate, shatter index, density, and water resistance characteristics improve. However, compressive strength decreases as the percentage of the banana stalk in the agglomerate increases. The smaller the particle size, the better the fuel water resistance, compressive strength, and shatter properties. It could be concluded that blending biomass feedstock can help fuel property compensation. For optimum thermal and physico-mechanical properties, 90CC:10BS blend is recommended for use. The fuel manufactured in the study possesses the required thermal and physico-mechanical properties of solid fuel; therefore, it is recommended for different industrial and domestic applications. This research helps to solve the existing environmental problem caused by the uncontrollable dumping of agro-residues generated at the Ganmo market and Jimba-Oja, Kwara State, Nigeria.

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Declarations

Authors' contributions
SE Ibitoye conceptualized and conducted the experiment. TC Jen, RM Mahamood, and ET Akinlabi supervised the research. SE Ibitoye wrote the article. All the authors proofread and approved the final article.

Ethics approval and consent to participate
Not applicable

Research involving human and animal statement
Not applicable

Consent for Publication
The authors approved the consent for publishing the manuscript.

Informed consent
Not applicable

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Availability of data and materials
The data that supports the findings of this study are available within the article.

Code available
Not applicable

Conflict of interests
The authors have no relevant financial and non-financial interests to disclose

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