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EVALUATION OF PHYSICO-MECHANICAL CHARACTERISTICS OF BIOMASS BRIQUETTES FROM MIXING OF WATER HYACINTH PLANTS AND SESAME STALKS

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ABSTRACT: This study aims to produce and determine the characterization of biomass briquettes derived from water hyacinth plants and sesame stalks, using starch as a binding agent. Eight biomass mixtures were formulated by varying the proportions of water hyacinth plant and sesame stalks, while maintaining a constant 10% starch content as a binding agent. The ratios of water hyacinth plants to sesame stalks ranged from 80:10 to 10:80 across treatments one to eight. Each mixture was processed into briquettes using a screw press briquetting machine. The resulting briquettes were air-dried for 20 days in a ventilated environment before being tested. Physico-mechanical properties assessed included density, shatter resistance, dimensional stability, and compressive strength. Results indicated that increasing the proportion of sesame stalks significantly enhanced briquette performance across all measured parameters. The highest values of briquette density, shatter resistance, dimensional stability, and compressive strength were 1137.51 kg/m³, 98.43%, 99.19%, and 6.27 MPa, respectively, and were recorded in treatment 8, which contained 10% water hyacinth and 80% sesame stalks. This study demonstrates a sustainable approach to managing water hyacinth by blending it with sesame stalks to produce environmentally friendly biomass briquettes. This method not only contributes to the reduction of invasive aquatic plants but also promotes the utilization of agricultural waste in clean energy production.

Keywords: Biomass briquettes, water hyacinth, sesame stalks, agricultural residues, renewable energy.

INTRODUCTION

Researchers have increasingly focused on diversifying energy sources over the past few years. Globally, many individuals are turning to alternative energy options either to reduce their utility expenses or to secure a stable energy supply for daily needs. Studies indicate that as both population and economic activities continue to grow, global energy demand is expected to rise accordingly (Balogun *et al.*, 2021). Choosing an energy source usually depends on several factors, including its cost, availability, performance efficiency, and environmental impact. Over the past few decades, global energy production has seen an increase of approximately 2.5% (Li *et al.*, 2022). Although significant progress has been made in energy technologies, fossil fuels such as oil, coal, and natural gas continue to play a dominant role, particularly in powering transportation and generating electricity (Zheng & Suh, 2019) However, their extensive use has led to serious environmental issues, including greenhouse gas emissions, air and water pollution, ocean acidification, and climate change. As a result, there is increasing emphasis on transitioning to renewable energy sources to achieve a low-carbon future. The growing scarcity and rising costs of non-renewable energy sources, along with their environmental consequences such as greenhouse gas emissions, have intensified global interest in renewable energy alternatives (Ajimotokan *et al.*, 2019). Among these alternatives, biomass has emerged as a sustainable and viable energy source. It consists primarily of organic materials derived from plants and animals, which can serve as substitutes for fossil fuels (Fajobi *et al.*, 2023). Biomass is recognized as one of the most significant

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contributors to global energy supply (Adegoke *et al*., 2021). Data from the Egyptian Ministry of Environment indicate that agricultural residues account for the largest share, approximately 30% of the total solid waste generated in Egypt, with an estimated annual volume of around 30 million tons (Zaki et al., 2013). Water hyacinth was introduced to Egypt in the 19th century for its ornamental flowers. However, it soon began to proliferate extensively across water bodies. Then it started to spread rapidly and uncontrolled, eventually leading to adverse effects, as it began forming thick layers over water surfaces, disrupting aquatic ecosystems (Gaurav *et al*., 2020). Globally, water hyacinth is recognized as one of the most invasive aquatic plants, affecting over 70 countries (Nega *et al*., 2022). Water hyacinth is widely regarded as an invasive species due to its harmful environmental effects. It disrupts aquatic ecosystems by forming dense mats that block sunlight and reduce oxygen levels in the water, leading to a decline in biodiversity (Singh *et al*., 2021). Globally, the production of sesame plants reached approximately 5.47 million tons in 2014, with Africa contributing about 51% (2.79 million tons) and the Nile Basin countries contributing about 33% (1.8 million tons) of the total sesame production (El-Sayed *et al*., 2023). Al-Behera governorate, where sesame is widely cultivated, contributes significantly to the total residue production (Zahran, 2022). Improper disposal of sesame stalks poses environmental risks. Leaving them in fields leads to soil degradation, and burning them, a common practice, releases pollutants that harm air quality and contribute to climate change (El-Sayed *et al.,* 2018, and Khairy *et al*., 2024). Agricultural residues can be converted into green energy using cost-effective methods, such as anaerobic digestion, gasification, pyrolysis, and fermentation, each producing different forms of energy (Binod *et al*., 2010). Despite challenges like low bulk density and high moisture content, modern techniques like pyrolysis and briquetting help improve biomass handling and storage (Anupam *et al*., 2016). Briquette fuel offers several advantages over raw biomass. It is renewable, has a higher calorific value, produces significantly less ash than coal, and burns more efficiently (Ifa *et al*., 2020). In both rural and urban areas, briquettes serve multiple domestic and industrial functions, such as food preparation, steam production, oil extraction, and tile manufacturing (Kpalo *et al*., 2020). Key factors in selecting raw materials include moisture content, ash level, flowability, and particle size. For optimal grinding and drying performance, the moisture content is preferably maintained between 10% and 15% (Abdoli *et al*., 2018). Numerous studies have examined the physical, chemical, and energy properties of biomass briquettes in Egypt and globally (Bot *et al*., 2021). This study aimed to benefit from water hyacinth by blending it with sesame stalks to produce environmentally friendly biofuel briquettes.

MATERIALS AND METHODS

1. Material Collection and Preprocessing

The present study was conducted at the Laboratory of the Agricultural and Biosystems Engineering Department, Faculty of Agriculture, Menoufia University, from July to December 2024. Briquettes were produced using water hyacinth and sesame stalks, and starch as a binding agent. The water hyacinth was collected from the Shibin El Kom River in Menoufia Governorate, Egypt. In contrast, the sesame stalks were collected from private farms located in Beheira Governorate, Egypt, as illustrated in Figure 1.

Experimental residues used

Chopped residues

Water hyacinth

Sesame stalks

Fig. 1: Preparation of agricultural residues

Upon collection, the initial moisture content of water hyacinth and sesame stalks was 90% and 15% (wet basis), respectively. The biomass residues were dried under sunlight until their moisture content dropped below 12% (w.b.), with efforts made to keep it within the 10–12% range during briquetting to achieve dense and high-quality briquettes (Elsisi *et al*., 2023). The drying process was conducted over a period of 6 days, during which the biomass was turned twice daily to ensure uniform exposure and prevent mold formation. Moisture content was monitored daily using representative samples. The average moisture content of the water hyacinth biomass decreased progressively over the six days of sun drying. By the sixth day, the biomass had reached a final moisture content of 10–12%, which is considered suitable for briquetting applications. The initial fresh weight of the collected biomass was approximately 50 kg, which was reduced to around 5.5–6 kg after complete drying.

2. Chopping process of agricultural residues

The dried residues were ground into fine particles using a hammer mill (ELEKTRIM SLINIK MOTOR 013835) equipped with a 4 mm screen, preparing them for the briquetting process. Eight different sample mixtures were formulated using varying ratios of Water Hyacinth (W) and Sesame Stalks (S), and starch. Each mixture was blended by weight according to the proportions listed in Table 1, with starch added at 10% of the total mixture weight to act as a binder. Mixing played a crucial role in enhancing particle adhesion, which supported the successful formation of briquettes. The physicochemical properties of the chopped residues, as identified in previous research, are presented in Table 2.

Table 1: Mixing material composition of Water Hyacinth (W) and Sesame Stalks (S).

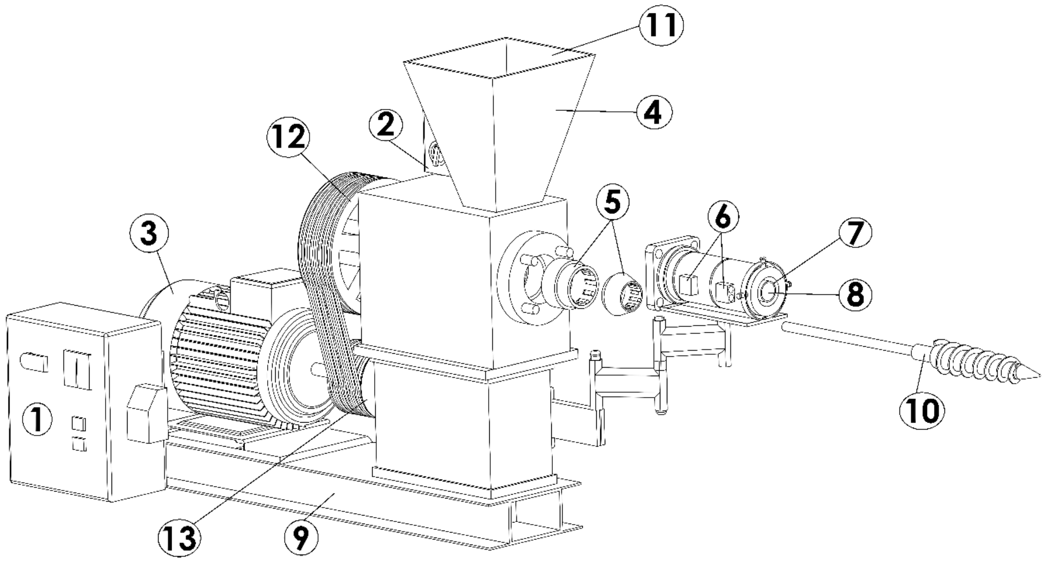
Treatment	Water Hyacinth (%)	Sesame Stalks (%)	Binding material (Starch) (%)
T_1	80	10	10
T_2	70	20	10
T_3	60	30	10
T_4	50	40	10
T_5	40	50	10
T_6	30	60	10
T_7	20	70	10
T_8	10	80	10

Table 2: Physical characterization of water hyacinth (W) and sesame stalks (S)

Analysis	Bulk density kg/m3	HHV (MJ/kg, dry basis)	Lignin %	Hemi celluloses %	Cellulose %	References
Water hyacinth	226	17.39	6.1	27.9	26.5	(Wauton and William 2019)
Sesame stalks	293.54	18.05	18.55	17.49	63.96	(Khairy *et al.*, 2024)

3. Briquette production process

Laboratory-scale briquetting was carried out using a Shimada Type SPMM-850 KS screw press, functioning under controlled temperature and pressure conditions. This equipment is capable of producing up to 400 kg per hour and is powered by a 30 kW electric motor. It includes two ceramic heating bands rated at 3 kW each. The system runs on a standard three-phase electrical supply of 220/380 Volts at 50 Hz, as shown in Figure 2. Prior to briquetting, the die was preheated to approximately 140 °C. The briquetting process involved compressing 3 kg of residue for 1 minute at a temperature of 170 °C and a pressure of 70 MPa, followed by a cooling period of 10 minutes.



1,2 – Control panel 3 – Motor 4 – Hopper 5- Compression molds 6 – Heater 7- Die 8 – Outlet birquettes 9 – Base 10 - screw 11 – Inlet chopped 12-Pulley 13 – Pellet

Fig. 2: Detailed view of the conical screw briquetting system.

The chopped residues, mixed according to the proportions in Table 1, were manually loaded into the hopper, and the feeding process was repeated periodically throughout the operation. The produced briquettes had a cylindrical form, measuring 50 mm across, and included a central opening of 10 mm in diameter. The outer surface was slightly carbonized due to the heating system. The central hole enhances porosity and oxygen flow, improving combustion efficiency. The stages involved in the briquetting process are illustrated in Figure 3. After production, the briquettes were air-dried for 20 days in a well-ventilated and secure area before their fuel properties were analyzed.

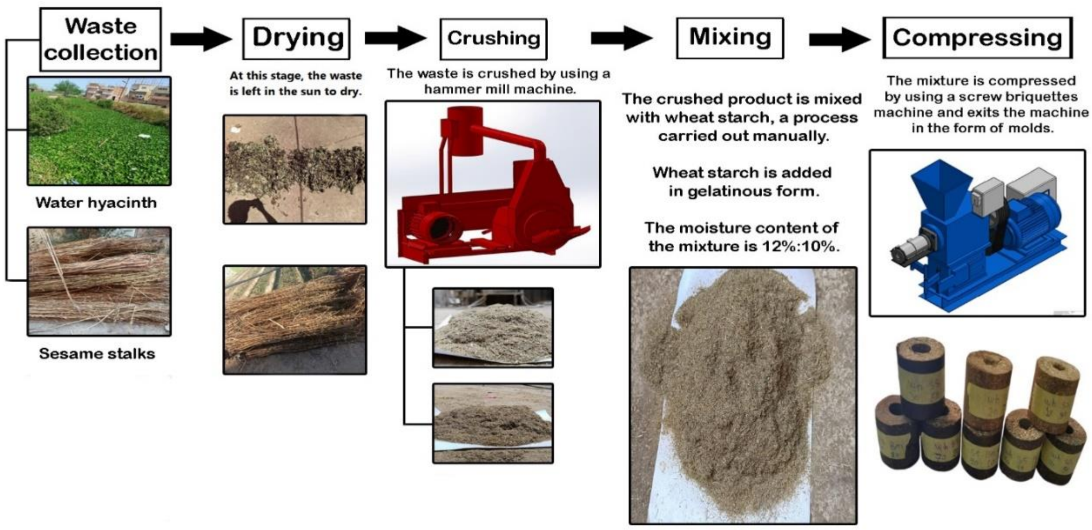


Fig. 3: Briquette production stages.

4. Assessment of physical and mechanical attributes of biomass briquettes

4.1. Dimensional stability

To assess whether the briquette's dimensions changed over time due to stress relaxation, the method described by Jiao *et al.* (2020) was applied. The diameter and height of each briquette were measured immediately after removal from the die and then monitored daily until the measurements stabilized. The dimensional stability of the briquettes was calculated using equation 1 .

$$\mathrm{DS} = 100 - \left(\frac{\mathrm{v_t} - \mathrm{v_0}}{\mathrm{v_0}} \times 100\right) \quad (1)$$

Where:

DS is dimensional stability (%), v_t is the volume of the briquette after volume stabilization (20 days), cm^3 and $\mathrm{v_0}$ is the initial volume of the briquette after molding, cm^3

4.2 Density

Upon drying the briquettes, their weight was then recorded. Given that the briquettes had a cylindrical form, their volumes were derived from their height and diameter. The relaxed bulk density of the briquettes was calculated using equation 2, which involves mass and volume, as suggested by Mandal *et al.* (2019).

$$\rho = \frac{M}{\pi H(r_o^2 - r_i^2)} \quad (2)$$

Where:

ρ is relaxed density $(\mathrm{kg/m^3})$, M is briquette mass (kg), π is a mathematical constant (3.14), H is briquette height (m) and $\mathrm{r_o}$ and $\mathrm{r_i}$ were the outer and inner radius of the briquette (m).

4.3. Shatter resistance

The durability of the briquettes was evaluated through their shatter resistance, which reflects the proportion of material that remained unbroken after impact (Kpalo *et al.*, 2020). To assess its resistance to impact, a dried briquette was repeatedly dropped five times from a height of 2 meters onto a concrete surface. After measuring the leftover mass, the shatter resistance was calculated using Equation 3, in accordance with the procedure outlined by Adu-Poku *et al.* (2022).

$$SR = 100 - \left(\frac{(W_1 - W_2)}{W_1} \times 100\right) \quad (3)$$

Where:

SR is the shatter resistance (%) and $\mathrm{W_1}$ and $\mathrm{W_2}$ are the weights of the briquette before and after shattering (cm), respectively

4.4. Compressive strength

The compressive strength of the briquettes was assessed using a universal testing machine (H-500KN, Shimadzu) featuring a load cell with a capacity of 500 kN, operating at a cross-head speed of 1mm/min. The briquette was positioned between the machine's plates and subjected to consistent loading until failure occurred, as shown in Figures 4 (a, b, and c). This can be calculated from the following equation 4 (Navalta *et al.,* 2020).

$$\sigma_C = \frac{F_C}{A} \quad (4)$$

Where:

σc is Compressive strength, $\mathrm{N/mm^2}$, Fc is the fracture force of the specimen, N, A is the cross-sectional area $(\pi(r_0^2 - r_i^2)$ of the briquette, $\mathrm{mm^2}$.

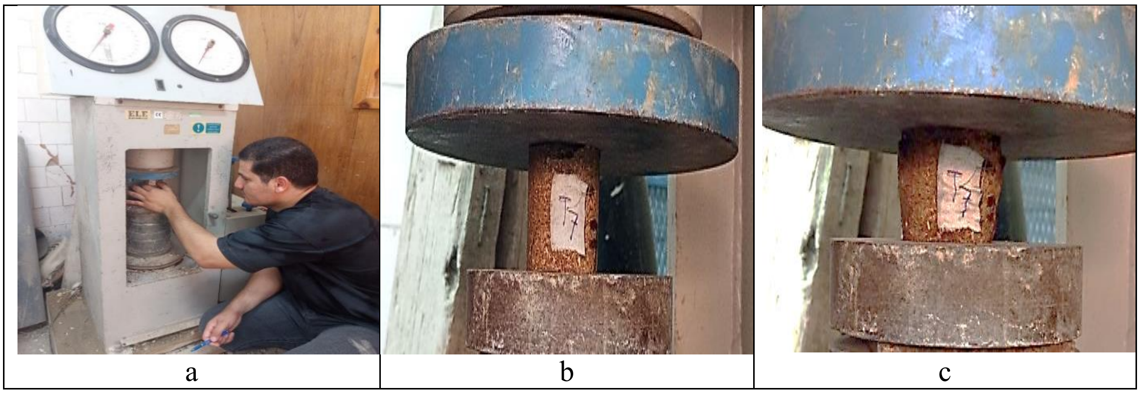


Fig. 4: (a) Universal testing machine (b) biomass briquette before compression (c) biomass briquette after compression

5. Statistical analysis

The effects on the dependent variables were assessed across biomass blends with eight distinct mixing proportions using multivariate ANOVA analysis to evaluate their influence on all measured properties. The results were presented as the mean values derived from three repetitions, accompanied by the standard deviation. The significance of the diverse factors associated with the samples was examined using Duncan's method at $P < 0.05$, employing the SPSS software (SPSS 22). It was represented by various lowercase letters within the data table.

RESULTS AND DISCUSSIONS

1. Evaluation of the properties of the produced briquettes

The produced briquettes were arranged in a flat place and left to air dry for 20 days in a sealed environment with adequate ventilation, as shown in Figure 5. After the drying period, their properties were evaluated, including density, shatter resistance, dimensional stability, and compressive strength.

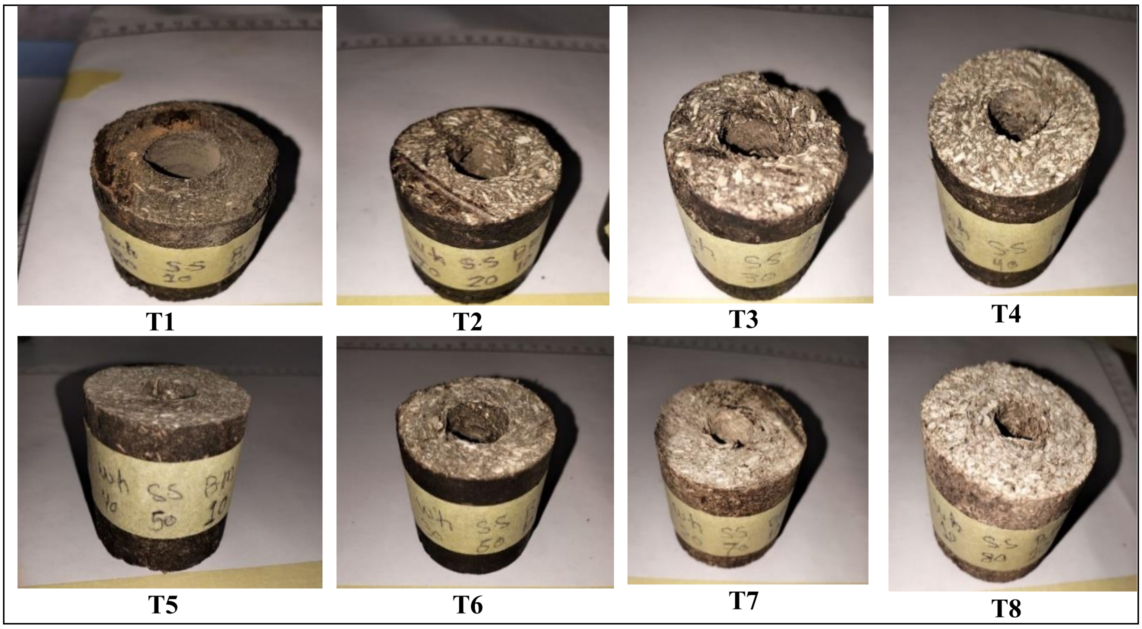


Fig. 5: Briquettes made from agricultural residue mixtures (water hyacinth (W), sesame stalks (S), and starch) using a screw press.

1.1. Dimensional stability

Dimensional stability is a key performance indicator in the production and application of biofuel briquettes, as it determines the briquettes' ability to retain their shape and size during storage, handling, and combustion. This property is significantly influenced by several factors, which include moisture content, compressive strength, biomass type, particle size, binder usage, and storage conditions (Demisu and Muluye, 2023). The data presented in Table 3 and Figure 6 demonstrate the influence of chopped residue mixing on the dimensional stability of the briquettes produced .Treatments showed an increase in dimensional stability; the T_1 briquette had a low dimensional stability of 98.37%, while the T_8 briquette had the highest dimensional stability of 99.19%. Statistical analysis of the experimental data on dimensional stability indicated that the treatment T_8 was statistically significant for the produced briquettes, while the treatment T_1 was not statistically significant. This improvement suggests enhanced internal bonding and moisture redistribution over time. These findings are consistent with those of Kaliyan and Morey (2009), who reported that densification parameters such as compression stress and moisture content significantly affect the strength and dimensional stability of biomass briquettes.

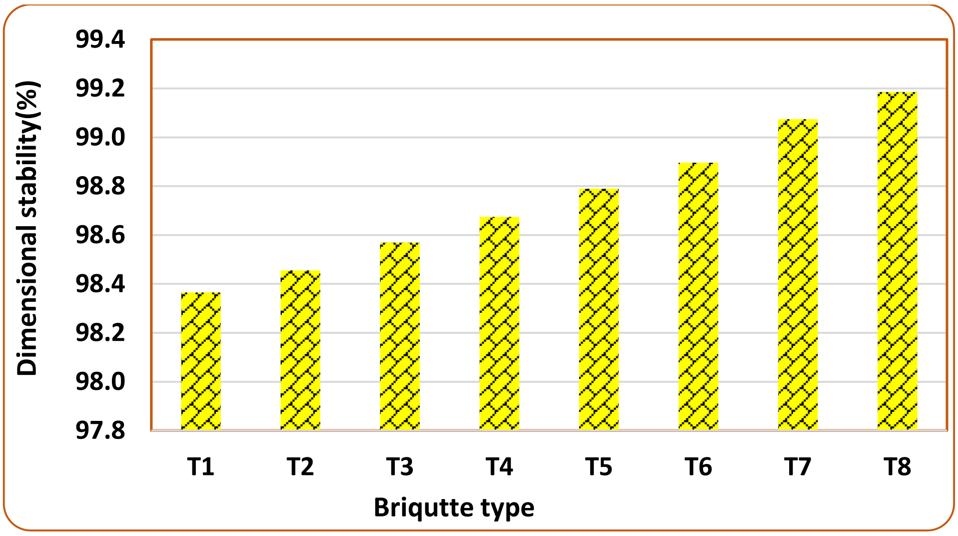


Fig. 6: The dimensional stability of biomass briquettes made of mixing water hyacinth, sesame stalks, and starch as a binder at treatments T_1 to T_8

Table 3: Mean values and standard deviations of physical and mechanical properties of the briquettes made of water hyacinth, sesame stalks, and starch as a binder.

Treatment	Dimensional stability (%)	Density (kgm^{-3})	Shatter resistance (%)	Compressive strength (Mpa)
T_1	98.37 ± 0.070^h	779.08±0.020^h	87.74±0.040^h	2.14±0.106^h
T_2	98.46 ± 0.030^g	857.23±0.021^g	89.32±0.031^g	2.64±0.060^g
T_3	98.57 ± 0.068^f	890.40±0.030^f	91.76±0.038^f	3.21±0.040^f
T_4	98.67 ± 0.040^e	990.39±0.040^e	92.31±0.035^e	3.73±0.086^e
T_5	98.79 ± 0.050^d	1047.45±0.045^d	93.68±0.015^d	4.28±0.070^d
T_6	98.90 ± 0.040^c	1080.13±0.035^c	95.05±0.031^c	5.01±0.040^c
T_7	99.07 ± 0.050^b	1107.21±0.040^b	96.65±0.020^b	5.71±0.060^b
T_8	99.19± 0.030^a	1137.51±0.035^a	98.43±0.035^a	6.27±0.056^a

Data are presented as the mean ± SD of 3 determinations.

1.2. Density

The density of fuel briquettes is a crucial physical property. Higher density implies a higher energy-to-volume ratio, significantly influencing handling, transportation, energy content, ignition, and burning characteristics (Ramírez *et al*., 2022; Adeleke *et al*., 2022). However, as density increases, porosity decreases, limiting air movement and lowering the combustion rate (Okot *et al*., 2019). The density values of the biomass briquettes treatments are presented in Table 3 and Figure 7. The data show that treatment T_1 recorded the lowest density value (779.08 kg/m³), while treatment T_8 recorded the highest density value (1137.51 kg/m³). When the increase in the fraction of sesame stalks ranged from 10% to 80% for samples T_1 and T_8, respectively, the corresponding increase in the briquette density was 31.5%. This indicates that increasing the proportion of sesame stalks enhances briquette density. The fibrous and fine particle structure of sesame stalks likely contributes to better compaction and inter-particle bonding during briquetting. These findings align with Yunusa *et al*. (2023), who reported that biomass type and particle size significantly influence briquette density, with finer and more fibrous materials yielding higher compaction and density. Statistical analysis of briquettes treatment data revealed that treatment T8 was statistically significant, indicating a clear improvement in density compared to other treatments. In contrast, treatment T_1 did not show a statistically significant difference. The remaining treatments showed slight variations, suggesting that the proportion of sesame stalks plays a dominant role in determining briquette density.

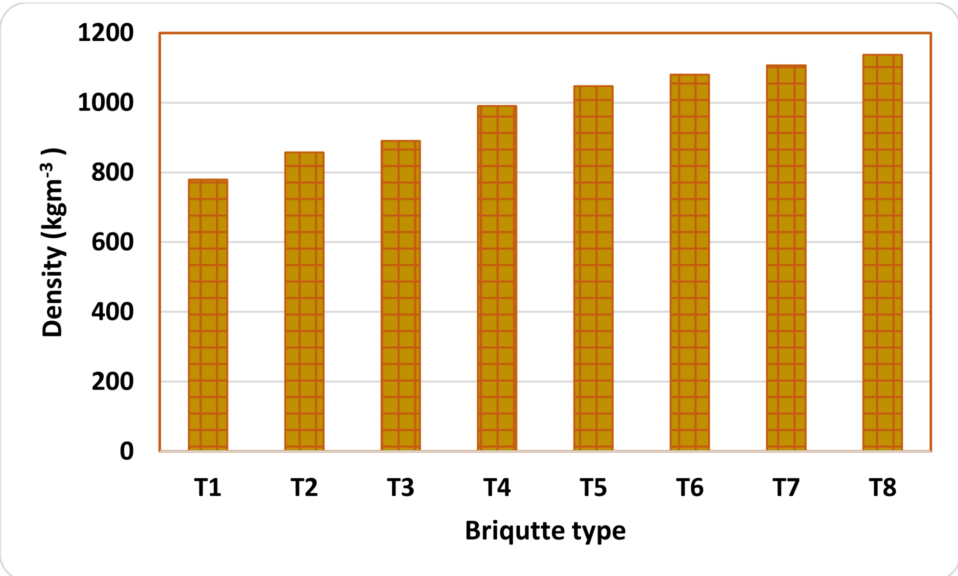


Fig. 7: The density of biomass briquettes made of mixing water hyacinth, sesame stalks and starch as a binder at treatments T_1 to T_8

1.3. Shatter resistance

The data presented in Table 3 and Figure 8 demonstrate the influence of chopped residue mixing on the shatter resistance of briquettes produced. According to Table 3 and Figure 8, the T_8 briquette had the highest shatter index, measuring 98.43%. The T_7 briquette came in second, with a score of 96.65%. While the briquettes showed a lower shatter index of 87.74 % for the T_1 briquette. The composition utilized in T_8 had a statistically significant impact on briquette strength, as demonstrated by statistical analysis that verified T_8 was considerably different from the other treatments. T_1, on the other hand, did not exhibit any notable variations, suggesting that its efficacy was not different from that of other treatments with lesser performance. Only minor alterations were observed in the remaining treatments at T_2 to T_7, indicating a trend towards progressive improvement rather than sudden changes. This trend can be attributed to the increasing proportion of lignocellulosic material in the mix, which enhances inter-particle bonding and reduces internal voids. The fibrous nature of the secondary biomass likely contributed to better compaction and cohesion during the briquetting process. These findings are consistent with those of Oliveira Maia *et al.* (2014), who reported that biomass with higher lignin content and lower moisture levels tends to produce briquettes with superior mechanical properties. Additionally, Waheed *et al.* (2023) emphasized that incorporating structurally dense biomass improves the mechanical strength of briquettes, which corresponds with the observed improvements in mixture.

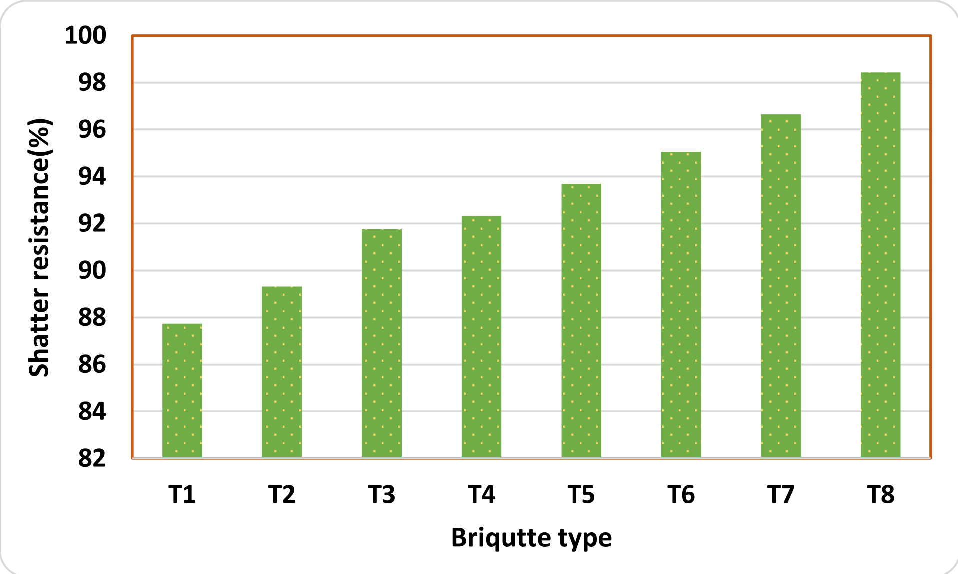


Fig. 8: The shatter resistance of biomass briquettes made of mixing water hyacinth, sesame stalks, and starch as a binder at treatments T_1 to T_8

1.4. Compressive strength

Compressive strength is the maximum crushing force that briquettes can withstand before failure (Marreiro *et al.*, 2021). Data in Table 3 and Figure 9 illustrate the impact of mixing chopped residues on the compressive strength of biomass briquettes. The compressive strength values of briquettes varied significantly across treatments. Treatment T_8 recorded the highest compressive strength (6.27 Mpa), while T_1 had the lowest (2.14 Mpa), indicating a nearly threefold increase. Statistical analysis (ANOVA) revealed that T8 was significantly different from other treatments at $p < 0.05$, suggesting that the composition in T_8 had a substantial effect on briquette strength. This improvement is likely due to the higher proportion of woody biomass, represented by sesame stalks, which are known for their fibrous and dense structure. These findings align with Lavie *et al.* (2025), who found that woody residues enhance briquette strength due to their compactness and low moisture content. Similarly, Ali *et al.* (2024) emphasized the role of lignocellulosic materials in improving the mechanical properties of biomass briquettes.

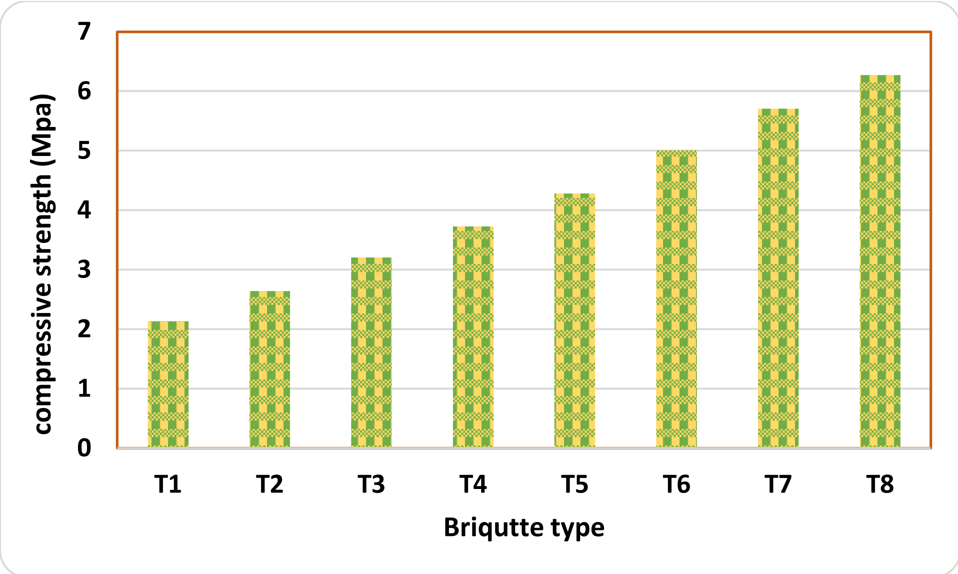


Fig. 9: The compressive strength of biomass briquettes made of mixing water hyacinth, sesame stalks, and starch as a binder at treatments T_1 to T_8

CONCLUSION

The findings of this study confirm the effectiveness of utilizing agricultural residues and aquatic plant, water hyacinth and sesame stalks, respectively for the production of biomass briquettes using starch as a binder. Among the eight tested formulations, treatment eight, which contained 10% water hyacinth and 80% sesame stalks, consistently outperformed the others across all evaluated parameters. It achieved the highest dimensional stability (99.19%), density (1137.51 kg/m^3), shatter resistance (98.43%), and compressive strength (6.27 MPa), indicating superior structural integrity and potential for combustion. These results highlight the crucial role of sesame stalks in improving briquette quality, owing to their fibrous nature and low moisture content. The study demonstrates that combining aquatic and agricultural residues not only provides a sustainable solution for biomass waste management but also contributes to the development of renewable energy sources suitable for domestic and industrial applications. This approach aligns with global efforts to reduce reliance on fossil fuels and mitigate environmental impacts. Future research should explore the combustion behavior, emission profiles, and economic feasibility of scaling up production, as well as the integration of other types of residues to optimize briquette performance further.

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تقييم الخصائص الفيزيائية ـالميكانيكية لقوالب الوقود الحيوي من خليط نباتات ورد النيل وسيقان السمسم

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الملخص العربي

تهدف هذه الدراسة إلى إنتاج وتقييم خصائص قوالب الوقود الحيوي من خلط مخلفات ورد النيل وسيقان السمسم، مع اضافة النشا كمادة رابطة. تم إعداد ثماني معاملات من خلال تغيير نسب خلط ورد النيل وسيقان السمسم، مع الحفاظ على نسبة ثابتة من النشا تبلغ ١٠%. كانت نسب خلط سيقان السمسم مع ورد النيل هي ١٠, ٢٠, ٣٠, ٤٠ , ٥٠, ٦٠, ٧٠ و٨٠ % من وزن العينة (٣ كجم). تم كبس كل معاملة لإنتاج قوالب باستخدام مكبس حلزوني. جُففت القوالب الناتجة في الهواء لمدة ٢٠ يومًا في بيئة جيدة التهوية قبل اختبارها. شملت الخصائص الفيزيائية والميكانيكية التي تم تقييمها على الكثافة، ومقاومة الكسر، وثبات الابعاد، ومقاومة الضغط. أظهرت النتائج أن زيادة نسبة سيقان السمسم حسّنت أداء القوالب بشكل ملحوظ في جميع الخواص المقاسة. وكانت أعلى قيم لثبات الابعاد، الكثافة، مقاومة الكسر ومقاومة الضغط عند ٩٩,١٩%، ١١٣٧,٥١ كجم/م³، و٩٨,٤٣%، و٦,٢٧ ميجا باسكال على التوالي، وذلك في المعاملة الثامنة التي احتوت على ١٠% من مخلف ورد النيل و٨٠% من سيقان السمسم و ١٠% من النشا كمادة رابطة، بينما اظهرت النتائج ان اقل قيم لثبات الابعاد، الكثافة، مقاومة الكسر، ومقاومة الضغط كانت ٩٨,٣٧% ،٧٧٩,٠٨ كجم/م³، و٨٧,٧٤%، و٢,١٤ ميجا باسكال على التوالي، وذلك في المعاملة الاولى التي احتوت على ٨٠% من مخلف ورد النيل و١٠% من سيقان السمسم و ١٠% من النشا كمادة رابطة. توضح هذه الدراسة امكانية استخدام نبات ورد النيل من خلال خلطه مع مخلفات زراعية ذات قيمة حرارية عالية مثل سيقان السمسم لإنتاج قوالب وقود حيوي.

الكلمات المفتاحية: قوالب الكتلة الحيوية؛ ورد النيل؛ سيقان السمسم؛ المخلفات الزراعية؛ الطاقة المتجددة.