SUSTAINABLE ENERGY TRANSITION IN JIGAWA STATE: EVALUATING BIOMASS BRIQUETTES AN ALTERNATIVE TO FIREWOOD.

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ABSTRACT

Energy demand for daily life activities has been increasing globally, this demand posed threats to environment and nature in generally. In underdeveloped countries, numbers of people that solely depends on firewood for energy source are continuously increase, this resulting in severe environmental challenges. Most of this countries are agrarians, they produced million tons of biomass residues but unfortunately, they does not used these residue in a sustainable way or they tend to disposed it directly. In this study, a sustainable way of using biomass residues was highlighted. A biomass briquetting procedure was introduced as a sustainable way of handling various biomass residues. A biomass briquetting in the method of converting biomass residues (such as agro-waste residue, wood residues, municipal waste residues, and animal waste) into eco-friendly fuels. Biomass briquettes are classified based on the raw materials used and type of binding agents. Biomass briquettes is presented as a renewable source of energy as well as sustainable way of disposing wastes. The major production procedure of biomass briquettes involve sourcing of raw materials, drying, size reduction, binders addition, and densification. The key performance indicators for biomass briquettes are level of moisture content, ash content and calorific values. Additionally, a study was conducted for the assessing the availability of agro-waste biomass in Jigawa State, Nigeria. Major crops, theirs residues and annual production in year 2023 was analysed and presented. Millet husk, rice straw, sorghum straw and husk for making briquettes were highlighted. The study presented an opportunities and highlighted level of awareness of biomass briquette in Jigawa State.

Keywords: *Biomass Briquettes, Agro-wastes Residues, Jigawa State*

1. INTRODUCTION

Biomass is known be one of the excellent alternative source of energy. Biomass is the one of the source of renewable source of energy with fixed amount of carbon, importantly for meeting various fuel requirement. Biomass is essential more environmental friendly than many sources of energy such as coal, which can be produce from organic sources, such as agricultural residue, wood, and other organic waste from industries [1, 2]. Biomass can be converted to fuel directly through combustion processes, unlike other renewable sources, those require complex processes. However, due to some limitations such as low bulk and energy density, high moisture content, causing storage, handling and transportation costs high, as such is not recommended as a sources of energy *in natura* [2, 3]. Another complexities with sources of biomass is their periodic; agricultural residues, such as millet straw, sorghum straw, and wheat straw are usually produce and harvested 3-4 months in a year, while coppiced crops can only be harvested in the winter months[4]. In order to achieve solid biofuels with desirable characteristics such as hardness, higher energy density and resistance, biomass densification is recommended. The biomass densification process produce the biofuel in the form of pallets, briquettes or cubes [5, 6].

There are several studies conducted in Nigeria to use the sample of Nigeria's coal plus biomass to produce bio-coal briquette that will be used in industries. The studies utilized different briquetting processes and considered some parameters such as particle size, briquetting pressure, biomass composition etc. One of the studies concentrated on the effect of elephant grass as a composition of bio-coal briquette, with the concentration of biomass of 20-30%. The result showed an improved cooking efficiency, burning rate, and smoke emission[7].

Briquetting is the method of producing energy concentrated fuel with high density by converting low bulk density biomass [8]. The quality of briquettes depends on the size, surface area, and production parameters such as pressure, compressibility, temperature, and binder used [9, 10]. Bonding of biomass materials is achieved using different pressure percentages and binders (e.g. lignin) [11, 12]. The use of biomass briquettes in the form of solid biofuel has gained significance in developed, developing and underdeveloped countries [8, 13-15]. In Africa, countries like Nigeria, South Africa, Ghana, Madagascar, and Cameroon use biomass briquetting system on a small scale[16]. However, biomass briquettes is not yet fully spread and implement as alternative source of energy, this is because of the number of factors such as adequate technologies, briquettes market and availability of materials used other than waste[17].

Energy is one of the most important need that rapidly transform different sectors such as industries, transportation, commerce, and domestic etc. Nigeria's population grows rapidly hence the energy demand has increased. The unreliable nature of the energy industry coupled with constant increase in tariffs cost is a popular trend that made it necessary for most of the populace to adopt unsustainable sources of energy [18].

Jigawa State population is estimated to be about 7,763,488 by National Population Commission (NPC) hence energy challenge increases with the nature population which made it necessary for the rural as well as urban people to continue exploiting fuel wood as primary source of heating and cooking. This trend has so many negative impacts to the environment such as deforestation, soil degradation, biodiversity loss and climate change[19].

2. TYPES OF BIOMASS BRIQUETTES

Biomass briquettes can be categories based on the raw materials as well as types of binding agents used as shown in Figure 1[20]. Biomass briquettes could be binderless, made from material that have high concentration of natural lignin, this type of biomass material could easily bind under excessive temperature and pressure. Biomass briquettes could made by adding binder into the raw materials, such binding include lignin, starch, and clay to increase cohesion and durability[21].

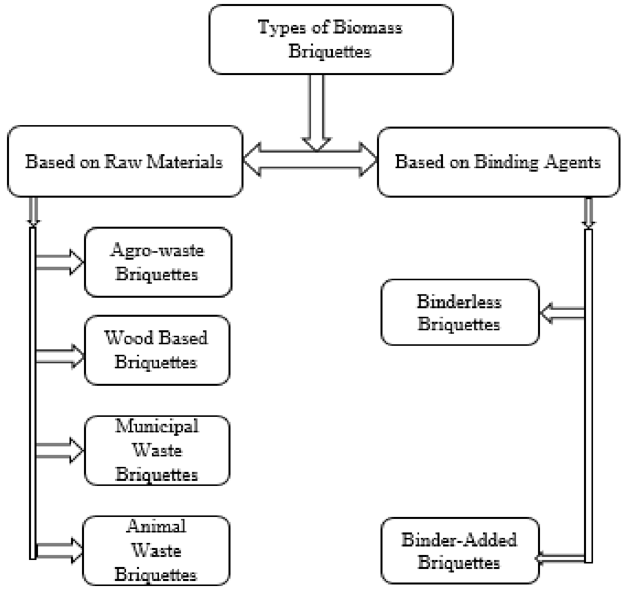

Figure 1. Types of Biomass Briquette Flowchart

2.1 Agricultural Residue Briquettes.

Agricultural residues are residual product of crop harvesting and processing. Agricultural residue briquettes are categories of biomass briquettes produced from crop residues such as millet husks, millet stalks, rice husk, rice stalks, wheat straws, sorghum straws and stalks, maize husks and cobs, corn stalks, coconut shell, groundnut shells and straws, and sugarcane bagasse[22]. These residues are rich in materials such as lignin, and cellulose, making them optimal for briquetting[23]. These residues are excessive in agricultural zones and are often burned or disposed, leading to environmental pollutions. Converting these residues into briquettes present a sustainable alternative source of energy, while mitigating environmental hazards. Agricultural residues briquettes exhibits excellent fuel properties, including high calorific values ranging from 15-20MJ/kg, lower moisture content (15%), lower ash content, and high density (1.0 to 1.4g/cm^3) for easy compaction and transportation[24]. Agro-residue briquettes present cost-effective alternative source of energy, especially in an agrarian regions where the raw materials are hugely available[25].

2.2 Wood-Based Briquettes

Wood-based briquettes are kind of biomass briquettes produce from wood waste[26]. This include bark, sawdust, shavings, wood chips and others waste-product from forestry operation[27]. Wood-derived biomass is one of suitable residues for making briquettes because of the available and level of energy efficient. Briquettes made from wood-based residues typically have a calorific value of 16 to 20 MJ/kg, lower moisture content of less than 15%, and high density from 1.0 to 1.4 g/cm$^{3.}$ The level of ash content usually varies by type of wood, hard wood produces less ash[28, 29].

2.3 Municipal-Waste Briquettes

Municipal-waste briquettes are another kind of biomass briquettes produced from constituents of domestic solid waste (DSW)[30]. These waste include food waste (leftover food, organic kitchen waste, and other compostable waste), paper and cupboard (waste paper and packaging materials), organic yard debris, and other biodegradable waste[31]. Domestic solid waste usually have high binders component (such as lignin) making them appropriate for briquetting[32]. Depending of the type of waste, municipal-waste briquettes have high calorific value ranging from 12 to 18MJ/kg, a lower moisture content, and high density (1.0-1.4 g/cm^3), as well as variable ash content. Producing briquettes from municipal-waste provide a safer way of waste management while address energy challenges especially in urban areas[33, 34].

2.4 Animal Waste Briquettes.

Animal waste briquettes is another kind of biomass briquettes produce from dried animal dung including cow chips, guano, poultry litter, excrement, goat droppings, and other animals manure[35, 36]. These raw materials are usually produce in abundance especially in agrarian regions, and are often underused. Key performance properties of animal waste briquettes include a calorific value range from 10-15 MJ/kg, low moisture content (>15%), high density ranging from 1.0 to 1.3 g/cm^3, and a variable ash content[37]. Using animal waste for making briquettes is another means of mitigating environmental pollution while providing safer and cheaper alternative source of fuel[38].

3. PRODUCTION PROCESS

The manufacturing procedure of biomass briquettes primarily involves sourcing and converting the raw materials (agro-waste residues, solid waste, wood-waste, and animal waste) into solid, compact and eco-friendly fuel briquettes[39]. The manufacturing procedure conventionally involves sourcing, drying, binding, densification, briquetting, cooling, and packaging as shown in Figure 2[40]. Drying process involves spreading the biomass in an open place under direct sunlight, or using mechanical dryers, which faster and easy to control level of dryness. Size reduction is the breaking down of the biomass into smaller and homogeneous particles using industrial shredders and hammer mill for easy compression. Binders could add when need or where necessary, in order to improve cohesion as well as durability. Binder can be a natural (such as lignin) or synthetic (such as clay). Densification referred to as compression of the processed biomass into solid briquettes by applying high pressure as well as temperature [22, 41-43]. In briquetting process, biomass are injected into briquetting machine, a pressure ranging from 50 to 150 MPa, and temperature from 90ºC to 200^{O}C are applied to produce a solid briquettes of desired size and shapes. Briquettes are ventilated at room temperature stabilize[44].

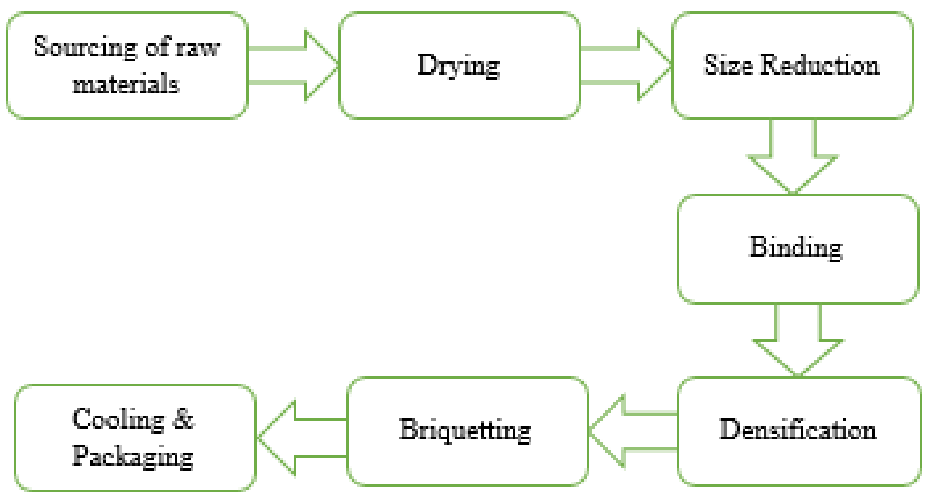

Figure 2. Briquette manufacturing procedure.

4. PROSPECT OF BIOMASS BRIQUETTE IN JIGAWA STATE

With the present energy crisis, environmental problems, Jigawa state should leverage the potential of biomass residues produce yearly to solve the domestic energy demand and reduce risk to the environment as well as revenue generation through biomass briquette production. There are existing policies by Jigawa State government to harness the potential youths in the State. The state's population is mostly youths that aged between 0-19 years, which account for 60% of the entire population. Various initiatives were made to provide opportunities and create jobs and revenue through capacity building trainings, agricultural practices, and technology adoption.

A sustainable and affordable alternative source of heating and cooking to households is an area of investment in order to effectively harness the youth potential in the state. This will be an effective approach for the government to achieve its expectation in the youths. According to research conducted in our previous paper, adoption of biomass briquette as a substitute to firewood in Jigawa state may be hindered by the following factors:

I. Financial and availability factor: initial investment in every technology is the main concern regardless of its life cycle. Most of the respondents to the questionnaire were willing to transit to biomass briquette if and only if it will be readily available and cheaper than firewood. To make it realistic, private investors have to be engaged for the continual and actualizing the cost other than only governments and non-governmental organizations.

Table 1. Primary sources used by respondents and awareness of environmental impact.

	North Central		North East		North West					
Variables	Freq	%	Freq	%	Freq	%	DF	χ^2-value	p-value	% Mean
Gender(sex)										
Male	86	86	76	76	89	89	2	6.78	0.034	84
Female	14	14	24	24	11	11				16
Age										
18-25	3	3	11	11	7	7	4	14.78	0.0052	7
26-45	87	87	78	78	69	69				78
>45	10	10	11	11	24	24				15
Level of education										
Non-formal	0	0	5	5	0	0	6	22.16	0.0011	1
Primary	7	7	0	0	4	4				4
Secondary	31	31	23	23	18	18				24
Tertiary	62	62	72	72	78	78				71
Household size										
1-5	61	61	49	49	44	44	4	8.55	0.0733	51
6-10	26	26	37	37	33	33				32
>10	13	13	14	14	23	23				17
Occupation										
Farming	45	45	57	57	55	55	6	7.45	0.1139	52
Self-employed	25	25	11	11	18	18				18
Employee	30	30	32	32	27	27				30
Unemployed	0	0	0	0	0	0				0

II .Socio-cultural Factors: the acceptance of any technology or energy source is the awareness of its benefit. According to the respondents, there is lack of awareness and perception to stop using firewood. There is a need for awareness campaign to inform people about the negative effect of deforestation and potential benefit of adopting biomass briquette as substitute.

III .Technological Factor: This is the whole concept of briquette production ranging from resource data, research, and standards for production. In Nigeria the main centers affiliated to the energy commission of Nigeria are Sokoto energy research center and the national center for energy research and development. They are responsible for research and manpower development in sustainable alternative energy in Nigeria[7].

IV. Government Policy: there is need for poly enforcement amongst the people for successful implementation of the scheme.

Table 2. Awareness and perception of respondents about biomass briquettes

	North Central		North East		North West					
Variables	Freq	%	Freq	%	Freq	%	DF	χ^2-value	p-value	%Mean
Had you heard of biomass briquettes before this survey?										

Yes	31	31	23	23	18	18	2	4.71	0.0947	24
No	69	69	77	77	82	82				76
Do you believe biomass briquettes could be a suitable alternative to firewood?										
Yes	63	63	81	81	69	69	4	9.70	0.0458	71
No	11	11	8	8	13	13				10.67
Maybe	26	26	11	11	18	18				18.33
Willingness to transition										
Yes	97	97	91	91	79	79	4	17.76	0.00138	89
No	0	0	3	3	5	5				2.67
Maybe	3	3	6	6	16	16				8.33
What would encourage you to switch to biomass briquettes?										
Lower cost than firewood	26	26	34	34	18	18	6	12.91	0.0445	26
Easy availability	5	5	9	9	4	4				6
More efficient than firewood	13	13	5	5	11	11				9.67
Environmental benefits	56	56	52	52	67	67				58.33
Others	0	0	0	0	0	0				0
Would you be interested in learning how to make biomass briquettes if training were provided?										
Yes	93	93	86	86	97	97	4	12.37	0.0148	92
No	0	0	4	4	0	0				1.33
Maybe	7	7	10	10	3	3				6.67

4.1 Residue availability and their Sources in Jigawa State, Nigeria

The biomass residue can be quantify by agricultural crops production, agro-industrial residues and their residues coefficient [45-47].

Table 3. Crops, theirs residues and annual production in year 2023

Crop	Residue	Year 2023 Production Average (ton)	Average Area Harvested (ha)

Millet	• Stalk • Husk	593,440	190,746
Sorghum	• Straw • Husk	418,812	167,524
Wheat	• Straw • Husk[P]	604,818	150,606
Rice	• Straw • Husk	120,869	163,700
Maize	• Cob • Straw • Husk	129,456	104,902
Groundnut	• Shell • Straw	105,673	100,24
Sesame	• Husk • Straw	103,000	135,000

A crops and their potential biomass residues produced in Jigawa State, taking year 2023 average production and area harvested is shown in Table 3. The residues can be divided into two categories: Farm residue and agro-industrial residues. Farm residues are residues which usually remain in the in the farm field after harvesting, thus are millets straws, sorghum straws, maize straws, wheat straws, rice straws, groundnut straws and sesame straws. These residue account to more than 80% of the unused residues as feedstock for briquetting in Nigeria [47]. Moreover, these residues are practically used as an animal feed, and manure. The agro-industrial residues are produced during the production of the crops, thus residues include millet husks, sorghum husks, wheat husks, rice husks, maize cobs, maize husks, groundnut shells, and sesame husks. Practically, farm residues and agro-industrial residues are used for briquetting, because of their properties such as homogeneous in nature and contain lowest moisture (usually below 15%) [10].

The residues such as millets straws, sorghum straws, maize straws, wheat straws, rice straws, rice husk, maize husks, and sesame straws are residues that are generated in larger quantities with lowest moisture content in Nigeria. A case study for assessing the availability of these residues and adaptability of biomass briquetting machine was conducted in Jigawa State.

4.1.1 Millets straws and husks

Millet is the most common crop cultivated in Jigawa State with annual harvested area of 359.37k ha. and total production valued at $73.49M. Due to this, millet straws and husks are produced in abundance. Only small amount of these residue are utilized and directly burned as a sources of fuel, as such there is need to implement efficient methods of converting these residues into valuable sources of energy, and alternatively sources of revenue to the state [48]. Researchers study the combustion properties of millets straws and husks for the purpose of producing high-quality briquettes [49-51], the study shows that, millet straws and husks have high volatile matter with lower ash and moisture content, these indicate that millet straws and husks are suitable sources of renewable energy. Another study [52] used millet husk and gum Arabic as binder to produced briquette, different particle sizes such as 0.3, 0.4 and 0.6, and compaction pressures of 10, 15 and 20 were studied using proximate and ultimate analysis, the results showed that briquette produced had high volatile matter of 76 %, low ash content of 6.5 %, and 0.3% of sulphur content, their results suggested that the briquette made from millet husk and gum Arabic is within the suitable range for domestic used.

4.1.2 Sorghum straw and husks

Another most common crop cultivated in Jigawa State is sorghum with 337.09K ha area harvested annually[53, 54]. Sorghum straw and husk are major byproducts sorghum which can effectively transformed into solid biofuel for domestic use due to theirs low moisture and high volatile matter properties[55]. To assess the potential of sorghum straw, a combustion characteristic study was conducted by [55, 56], different testing techniques were employed to study proximate parameters including volatile matter, ash and water content. Briquette were formed using different compositions of sorghum panicle and millet straw while comparing with different briquettes made from different materials such as pongamia–tamarind, it was found that briquette made from sorghum panicle-millet straw has better calorific value with good fuel properties, such that they produce excellent heating value[55]. As such, biomass briquettes made from sorghum and millet agro wastes are good sources of solid biofuels.

4.1.3 Rice straws

Another hugely available agro wastes in Jigawa State are rice straw and husk, this is due to state favorable weather and huge land for year-round farming. According to state authority (FADAMA), Jigawa state has about 1.9 million hectare cultivable land for rice farming. Unfortunately, only small portion of these agro wastes are put into used for various purposes such as animal feeds, poultry feeds, and direct burning for energy source. Rice straw and husk could be processed to produced solid biofuel via briquetting process, thus, could serves as sustainable source of energy. For instance, Yank et al.[57] studied the physical properties of rice husk briquette, a manual press capable of generating 4.2 MPa pressure was fabricated and used to produce the briquettes. Calorific value, moisture content, compressive strength, and durability were tested while using different binders (cassava wastewater, okra stem gum). The briquettes produced with cassava wastewater as binder, recorded a density of 441.18 kg $m^{-3,}$ while briquettes produced with rice dust recorded a great durability (91.9%), and compaction of 2.54kN. Narzary et al. [58] investigate the production of a rice straw briquettes produce with three different binder (starch, paper, and taro starch). Theirs study showed that rice straw briquettes discharge lower CO to the environment than direct burning of straws, whereas, burning rate surged with different binder level. Based on the available literatures and experimental works, a rice husk and rice briquettes presents an interesting substitute to the fuel wood, so as to tackle environmental issues such as deforestation.

5. KEY PERFORMANCE INDICATORS FOR AGRO-WASTE BIOMASS BRIQUETTES.

The energy value of briquette depends on solely on the physical and chemical compositions of the raw materials used[41]. There are main key performance indicators to be considered when selection for agro-waste biomass for the production of briquettes; thus include level of ash content; moisture content, and calorific value. Ash content is amount (in percentage) of non-combustible elements present in the biomass sample. A lower ash content means that higher heating value[59]. The appropriate amount of moisture content of agro-waste biomass briquette should be in the range of 5-10% [60] while another study by [61] on the impact of moisture content on the rice husk briquette, different percentage of the moisture content (12, 14, and 16%) where analyzed, briquette made with moisture content of 14% had optimum density requirement with heating value of 17.688 MJ/Kg. The table 2 below present thermochemical properties of various agro-waste biomass.

Crop	Residue	Calorific value(MJ/Kg)	Ash content (%)	Moisture content (%)	Ref
Millet	• Husk	15.27	6.5 %	8.20	[52]
Sorghum	• Straw	24.3	5.6	6.7	[56]
Rice	• Straw	16.08	17.0	7.5	[57]
Maize	• Straw	15.40	5.4	N/A	[62]
Groundnut	• Husk	25.03	24.18	2.43	
Wheat	• Straw	N/A	9.2	9.6	[63]

6. CONCLUSION

Biomass briquette present an opportunities for safer and cleaner source of energy, which could be alternative to firewood. In this study, biomass briquettes was deeply discussed. Biomass briquetting is the process of converting biomass residues into fuel source. Biomass briquettes can be categories based on the raw materials as well as kind of binders. Types of biomass briquettes based on raw materials are agro-waste briquettes, wood-based briquettes, solid waste briquettes and animal manure. Biomass briquettes can be manufacture using binders or binderless. Addition of binder could increase the durability and cohesion of briquettes. A manufacturing process of biomass briquettes involves sourcing of raw materials, drying, and binder addition and densification process. Moreover, prospects of biomass briquettes in Jigawa State, Nigeria was study. The study showed various crops residues that are hugely available in Jigawa State. Additional, level of awareness of biomass briquette in Jigawa State was presented.

7. ACKNOWLEDGEMENT

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REFERENCES

[1] T. Bridgwater, "Biomass for energy," *Journal of the Science of Food and Agriculture,* vol. 86, no. 12, pp. 1755-1768, 2006.
[2] H. M. P. Marreiro, R. S. Peruchi, R. M. B. P. Lopes, S. L. F. Andersen, S. A. Eliziário, and P. Rotella Junior, "Empirical Studies on Biomass Briquette Production: A Literature Review," *Energies,* vol. 14, no. 24, p. 8320, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/24/8320.
[3] F. F. Felfli, J. D. Rocha, D. Filippetto, C. A. Luengo, and W. A. Pippo, "Biomass briquetting and its perspectives in Brazil," *Biomass and bioenergy,* vol. 35, no. 1, pp. 236-242, 2011.
[4] M. Mardikis and E. Alexopoulou, "BIO-ENERGY CHAINS FROM PERENNIAL CROPS IN SOUTH EUROPE," 2002.
[5] T. Wongsiriamnuay and N. Tippayawong, "Effect of densification parameters on the properties of maize residue pellets," *Biosystems Engineering,* vol. 139, pp. 111-120, 2015.
[6] P. Grover and S. Mishra, *Biomass briquetting: technology and practices*. Food and Agriculture Organization of the United Nations Bangkok, Thailand, 1996.
[7] A. S. Aliyu, J. O. Dada, and I. K. Adam, "Current status and future prospects of renewable energy in Nigeria," *Renewable and sustainable energy reviews,* vol. 48, pp. 336-346, 2015.
[8] T. H. Mwampamba, M. Owen, and M. Pigaht, "Opportunities, challenges and way forward for the charcoal briquette industry in Sub-Saharan Africa," *Energy for Sustainable Development,* vol. 17, no. 2, pp. 158-170, 2013/04/01/ 2013, doi: https://doi.org/10.1016/j.esd.2012.10.006.
[9] A. Trubetskaya *et al.*, "Characterization of woodstove briquettes from torrefied biomass and coal," *Energy,* vol. 171, pp. 853-865, 2019.
[10] C. J. L. G. Navalta, K. G. C. Banaag, O. R. Von Adrian, A. W. Go, L. K. Cabatingan, and Y.-H. Ju, "Solid fuel from Co-briquetting of sugarcane bagasse and rice bran," *Renewable Energy,* vol. 147, pp. 1941-1958, 2020.
[11] M. O. Okwu and O. D. Samuel, "Adapted hyacinth briquetting machine for mass production of briquettes," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects,* vol. 40, no. 23, pp. 2853-2866, 2018.
[12] S. Khlifi, M. Lajili, S. Belghith, S. Mezlini, F. Tabet, and M. Jeguirim, "Briquettes production from olive mill waste under optimal temperature and pressure conditions: Physico-chemical and mechanical characterizations," *Energies,* vol. 13, no. 5, p. 1214, 2020.
[13] L. Agbemabiese, J. Nkomo, and Y. Sokona, "Enabling innovations in energy access: An African perspective," *Energy Policy,* vol. 47, pp. 38-47, 2012/06/01/ 2012, doi: https://doi.org/10.1016/j.enpol.2012.03.051.

[14] L. S. Angulo-Mosquera, A. A. Alvarado-Alvarado, M. J. Rivas-Arrieta, C. R. Cattaneo, E. R. Rene, and O. García-Depraect, "Production of solid biofuels from organic waste in developing countries: A review from sustainability and economic feasibility perspectives," *Science of The Total Environment*, vol. 795, p. 148816, 2021/11/15/ 2021, doi: https://doi.org/10.1016/j.scitotenv.2021.148816.

[15] A. P. D. Baltrocchi, N. Ferronato, I. J. Calle Mendoza, M. A. Gorritty Portillo, F. Romagnoli, and V. Torretta, "Socio-economic analysis of waste-based briquettes production and consumption in Bolivia," *Sustainable Production and Consumption*, vol. 37, pp. 191-201, 2023/05/01/ 2023, doi: https://doi.org/10.1016/j.spc.2023.03.004.

[16] O. F. Obi, "Effect of briquetting temperature on the properties of biomass briquettes," *African Journal of Science, Technology, Innovation and Development*, vol. 7, no. 6, pp. 386-394, 2015, doi: doi:10.1080/20421338.2015.1096508.

[17] S. Yu, V. Lew, W. Ma, Z. Bao, and J. L. Hao, "Unlocking key factors affecting utilization of biomass briquettes in Africa through SWOT and analytic hierarchy process: A case of Madagascar," *Fuel*, vol. 323, p. 124298, 2022/09/01/ 2022, doi: https://doi.org/10.1016/j.fuel.2022.124298.

[18] S. Richards, "Physical testing of fuel briquettes," *Fuel processing technology*, vol. 25, no. 2, pp. 89-100, 1990.

[19] S. Yaman, M. Şahan, H. Haykiri-açma, K. Şeşen, and S. Küçükbayrak, "Production of fuel briquettes from olive refuse and paper mill waste," *Fuel Processing Technology*, vol. 68, no. 1, pp. 23-31, 2000.

[20] J. Chaney, "Combustion characteristics of biomass briquettes," University of Nottingham Nottingham, UK, 2010.

[21] S. Bhattacharya, M. A. Leon, and M. M. Rahman, "A study on improved biomass briquetting," *Energy for sustainable development*, vol. 6, no. 2, pp. 67-71, 2002.

[22] R. Shuma and D. M. Madyira, "Production of loose biomass briquettes from agricultural and forestry residues," *Procedia Manufacturing*, vol. 7, pp. 98-105, 2017.

[23] O. F. Obi, R. Pecenka, and M. J. Clifford, "A review of biomass briquette binders and quality parameters," *Energies*, vol. 15, no. 7, p. 2426, 2022.

[24] A. Tamilvanan, "Preparation of biomass briquettes using various agro-residues and waste papers," 2013.

[25] R. Singh, "Equilibrium moisture content of biomass briquettes," *Biomass and Bioenergy*, vol. 26, no. 3, pp. 251-253, 2004.

[26] N. Ferronato, I. J. C. Mendoza, M. A. G. Portillo, F. Conti, and V. Torretta, "Are waste-based briquettes alternative fuels in developing countries? A critical review," *Energy for Sustainable Development*, vol. 68, pp. 220-241, 2022.

[27] C. Antwi-Boasiako and B. Acheampong, "Strength properties and calorific values of sawdust-briquettes as wood-residue energy generation source from tropical hardwoods of different densities," *Biomass and Bioenergy*, vol. 85, pp. 144-152, 2016.

[28] O. A. Sotannde, A. b. Oluyege, and G. a. Abah, "Physical and combustion properties of charcoal briquettes from neem wood residues," *International Agrophysics*, vol. 24, no. 2, pp. 189-194, 2010.

[29] K. Sahoo, S. Alanya-Rosenbaum, R. Bergman, D. Abbas, and E. Bilek, "Environmental and economic assessment of portable systems: Production of wood-briquettes and torrefied-briquettes to generate heat and electricity," *Fuels*, vol. 2, no. 3, pp. 345-366, 2021.

[30] J. Prasityousil and A. Muenjina, "Properties of solid fuel briquettes produced from rejected material of municipal waste composting," *Procedia Environmental Sciences*, vol. 17, pp. 603-610, 2013.

[31] P. Križan *et al.*, "Briquetting of municipal solid waste by different technologies in order to evaluate its quality and properties," *Agronomy Research*, vol. 9, pp. 115-123, 2011.

[32] A. R. D. Romallosa and E. Kraft, "Feasibility of biomass briquette production from municipal waste streams by integrating the informal sector in the Philippines," *Resources*, vol. 6, no. 1, p. 12, 2017.

[33] I. E. Onukak, I. A. Mohammed-Dabo, A. O. Ameh, S. I. Okoduwa, and O. O. Fasanya, "Production and characterization of biomass briquettes from tannery solid waste," *Recycling*, vol. 2, no. 4, p. 17, 2017.

[34] J. Gug, D. Cacciola, and M. J. Sobkowicz, "Processing and properties of a solid energy fuel from municipal solid waste (MSW) and recycled plastics," *Waste Management*, vol. 35, pp. 283-292, 2015.

[35] R. Peamsuwan, "The Production and Properties of Fuel Briquettes from Animal and Agricultural Bio-Waste to Renewable Energy Source in Rural Community," *Journal of Renewable Energy and Smart Grid Technology*, vol. 16, no. 2, pp. 56-67, 2021.

[36] M. I. Said, "Characteristics of by-product and animal waste: A review," *Large Animal Review*, vol. 25, no. 6, pp. 243-250, 2019.

[37] T. Athaillah, H. Husin, and M. R. Aulia, "Briquettes from a Mixture of Cow Menure, Rice Husks and Wood Dust as Alternative Fuel," *Journal of Ecological Engineering,* vol. 25, no. 2, 2024.

[38] N. F. Noorrahman, A. Sandriya, and P. Paulini, "Utilization of Livestock Waste (Cow Manure) and Household Waste (Waste Cooking Oil) as Briquettes to Substitute Alternative Fuels," *Jurnal Sain Peternakan Indonesia,* vol. 19, no. 2, pp. 90-95, 2024.

[39] M. A. Brand, R. C. Jacinto, R. Antunes, and A. B. da Cunha, "Production of briquettes as a tool to optimize the use of waste from rice cultivation and industrial processing," *Renewable energy,* vol. 111, pp. 116-123, 2017.

[40] P. D. C. Sanchez, M. M. T. Aspe, and K. N. Sindol, "An overview on the production of bio-briquettes from agricultural wastes: methods, processes, and quality," *Journal of Agricultural and Food Engineering,* vol. 1, p. 0036, 2022.

[41] G. Zhang, Y. Sun, and Y. Xu, "Review of briquette binders and briquetting mechanism," *Renewable and Sustainable Energy Reviews,* vol. 82, pp. 477-487, 2018.

[42] M. Sawadogo, S. T. Tanoh, S. Sidibé, N. Kpai, and I. Tankoano, "Cleaner production in Burkina Faso: Case study of fuel briquettes made from cashew industry waste," *Journal of cleaner production,* vol. 195, pp. 1047-1056, 2018.

[43] B. G. de Oliveira Maiaa, O. Souzab, C. Marangonib, D. Hotzaa, A. P. N. de Oliveiraa, and N. Sellinb, "Production and characterization of fuel briquettes from banana leaves waste," *CHEMICAL ENGINEERING,* vol. 37, 2014.

[44] E. C. De Souza *et al.*, "Briquette production as a sustainable alternative for waste management in the tannin extraction industry," *Environmental Science and Pollution Research,* vol. 30, no. 7, pp. 18078-18090, 2023.

[45] F. Kemausuor, A. Kamp, S. T. Thomsen, E. C. Bensah, and H. Østergård, "Assessment of biomass residue availability and bioenergy yields in Ghana," *Resources, Conservation and Recycling,* vol. 86, pp. 28-37, 2014/05/01/ 2014, doi: https://doi.org/10.1016/j.resconrec.2014.01.007.

[46] C. G. Ozoegwu, C. Eze, C. O. Onwosi, C. A. Mgbemene, and P. A. Ozor, "Biomass and bioenergy potential of cassava waste in Nigeria: Estimations based partly on rural-level garri processing case studies," *Renewable and Sustainable Energy Reviews,* vol. 72, pp. 625-638, 2017/05/01/ 2017, doi: https://doi.org/10.1016/j.rser.2017.01.031.

[47] S. O. Jekayinfa and V. Scholz, "Potential Availability of Energetically Usable Crop Residues in Nigeria," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects,* vol. 31, no. 8, pp. 687-697, 2009/03/23 2009, doi: 10.1080/15567030701750549.

[48] A. Radich, "United State Energy Information Administration.“," *Biodiesel Performance, Costs, and Use,* 2004.

[49] A. Hammajam, Z. Ismarrubie, and S. Sapuan, "Millet husk fiber filled high density polyethylene composites and its potential properties," *International Journal of Engineering and Technical Research (IJETR), ISSN,* pp. 2321-0869, 2014.

[50] D. SENCHI and C. ELINGE, "Combustion Profile of Fuel Briquettes Produced From Millet Stalk with Charcoal as Blend," 2020.

[51] J. S. Tumuluru, C. T. Wright, J. R. Hess, and K. L. Kenney, "A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application," *Biofuels, Bioproducts and Biorefining,* vol. 5, no. 6, pp. 683-707, 2011, doi: https://doi.org/10.1002/bbb.324.

[52] A. Kuhe, A. V. Terhemba, and H. Iortyer, "Biomass valorization for energy applications: A preliminary study on millet husk," *Heliyon,* vol. 7, no. 8, p. e07802, 2021/08/01/ 2021, doi: https://doi.org/10.1016/j.heliyon.2021.e07802.

[53] A. Y. Kamara, O. Oyinbo, H. A. Ajeigbe, E. O. Idowu, and C. Ojiewo, "Sustainable intensification technologies and farm performance: evidence from smallholder sorghum farmers in Nigeria," *International Journal of Agricultural Sustainability,* vol. 21, no. 1, p. 2270233, 2023/12/31 2023, doi: 10.1080/14735903.2023.2270233.

[54] F. FAOSTAT, "Food and agriculture organization of the United Nations," *Statistical database,* 2013.

[55] S. Velusamy, A. Subbaiyan, and R. S. Thangam, "Combustion characteristics of briquette fuels from sorghum panicle–pearl millets using cassava starch binder," *Environmental Science and Pollution Research,* vol. 28, pp. 21471-21485, 2021.

[56] J. O. Ajikashile, M.-J. Alhnidi, G. K. Parku, A. Funke, and A. Kruse, "A study on the fast pyrolysis of millet and sorghum straws sourced from arid and semi-arid regions of Nigeria in a twin-screw mixing reactor," *Materials Science for Energy Technologies,* vol. 6, pp. 388-398, 2023/01/01/ 2023, doi: https://doi.org/10.1016/j.mset.2023.03.007.

[57] A. Yank, M. Ngadi, and R. Kok, "Physical properties of rice husk and bran briquettes under low pressure densification for rural applications," *Biomass and Bioenergy*, vol. 84, pp. 22-30, 2016/01/01/ 2016, doi: https://doi.org/10.1016/j.biombioe.2015.09.015.

[58] A. Narzary, J. Brahma, and A. K. Das, "Utilization of waste rice straw for charcoal briquette production using three different binder," *Cleaner Energy Systems*, vol. 5, p. 100072, 2023/08/01/ 2023, doi: https://doi.org/10.1016/j.cles.2023.100072.

[59] J. Sjaak van Loo, "The handbook of biomass combustion and co-firing," ed: Routledge: London, UK, 2008.

[60] N. Kaliyan and R. V. Morey, "Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass," *Bioresource Technology*, vol. 101, no. 3, pp. 1082-1090, 2010/02/01/ 2010, doi: https://doi.org/10.1016/j.biortech.2009.08.064.

[61] A. A. H. Saeed *et al.*, "Moisture Content Impact on Properties of Briquette Produced from Rice Husk Waste," *Sustainability*, vol. 13, no. 6, p. 3069, 2021. [Online]. Available: https://www.mdpi.com/2071-1050/13/6/3069.

[62] M. Križan, K. Krištof, M. Angelovič, J. Jobbágy, and O. Urbanovičová, "Energy potential of densified biomass from maize straw in form of pellets and briquettes," 2018.

[63] A. Funke, D. Richter, A. Niebel, N. Dahmen, and J. Sauer, "Fast Pyrolysis of Biomass Residues in a Twin-screw Mixing Reactor," (in eng), *J Vis Exp*, no. 115, Sep 9 2016, doi: 10.3791/54395.