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Original Research Article

A Review on Applicability of Banana Waste

Moses G. Nyang'au[1]*, Dr. Eng. Fredrick N. Mutua[1], Prof. Eng. Alex M. Muumbo[1], Dr. Edwin Kamalha[2]
[1]Department of Mechanical and Aerospace Engineering, The Technical University of Kenya
[2]Department of Polymer, Textile and Industrial Engineering Busitema University

***Corresponding Author:** Moses G. Nyang'au
Department of Mechanical and Aerospace Engineering, The Technical University of Kenya

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Abstract: Global warming is major challenge facing mankind globally due to rampant deforestation and emission of greenhouse gases. The pressure on the natural resources has been increasing proportionately with population which needs more food, shelter, textiles, energy and chemicals for day-to-day life. In recent years, research efforts have been made to explore opportunities for utilization of agricultural wastes for enhancement of the circular economy. For instance, considering that Uganda is the largest producer of banana in Africa and the second largest in the world, and that 60% of banana plant is waste, this poses threats and economic opportunities in equal measure in the region. Therefore, efforts to sustainably utilize banana waste are of great importance to reduce their room for decomposition hence greenhouse gas emissions. This review takes stock of the economic opportunities for people in banana growing regions beyond the dining table by exploring sustainable uses of banana wastes as raw materials for fertilizers, textile and bio-fuel. It is here concluded that for realistic conservation of environment, more research is needed on sustainable use of banana waste for briquette production in east Africa which uses cassava starch as binder. Both banana and cassava are widely planted in east Africa but more in Uganda. Use of banana waste and cassava starch in briquette production will ensure reduced global warming, reduced cost of living, creation of new jobs and increased income from the crops.

Keywords: Banana, Waste, Pseudostem, Biochar, Briquettes.

INTRODUCTION

Uganda is the second largest global producer of bananas after India. Locally known as *Matoke*, the East African highland cooking banana (AAA-EA group) is the leading staple food in Uganda(Asada, 2023; Gumisiriza *et al.,* 2019; Yusuf & Inambao, 2020). 9.5 million metric tons are cultivated annually by more than 75% of Ugandan farmers(Oluwole & Onu, 2017). Banana fruit is one of the most liked and traded fruits in the world. It has a calorific value of 67 calories per 100 grams of fruit. (Mohiuddin *et al*., 2014). Over 20 million tons of banana are produced annually in eastern and south Africa. It is stable food in most parts of east Africa sometimes processed into floor, canned slices, jam, jelly, puree, vinegar, wine and beer(Karamura *et al*., 1998; Mohapatra *et al*., 2011). Banana crop bears fruits once in a lifespan. 60% of banana plant is trash rich in cellulose, hemicellulose and natural fiber where 75% of this is pseudo stem(Bhatnagar *et al*., 2023). Consequently, 1 ton of banana produced concurrently generates 100kg of fruit waste, and 4 ton of lignocellulosic waste where 480kg is leaves, 160kg stalk, 440kg skins and 3 tons pseudo stem (Balda *et al.*, 2021; Majumdar & Jagadale, 2023; Wahome *et al*., 2021). Figure 1 is a sample of banana species planted in Uganda.

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Banana fruit for both steaming and ripening

Banana fruit for ripening only

Figure 1: Common banana species grown in Uganda and East Africa

While some of the waste is used as animal feeds, pseudo stem can be used for production of fabrics, quality grade papers, handmade board, hand crafts, pharmaceutical products and pseudo stem based vermicompost (Balda *et al*., 2021; D'SOUZA & D'SOUZA, 2017; Muralikrishna *et al*., 2020; Pillai *et al*., 2024). Furthermore, banana crop waste has huge potential in energy sector for production of biochar, biol-oil, bio-ethanol, food packaging material, nutritional supplements, pulp, paper and clothing industry (Majumdar & Jagadale, 2023).

Unfortunately, majority of banana waste is left to decompose in the fields causing negative environmental impact. This review paper seeks to explore more sustainable uses for banana waste as composite and textile material, bio-fertilizer &chemical and bio-fuels production. Figure 2 shows the various potential applications from banana pseudo stem including fiber production, soft drinks and composite.

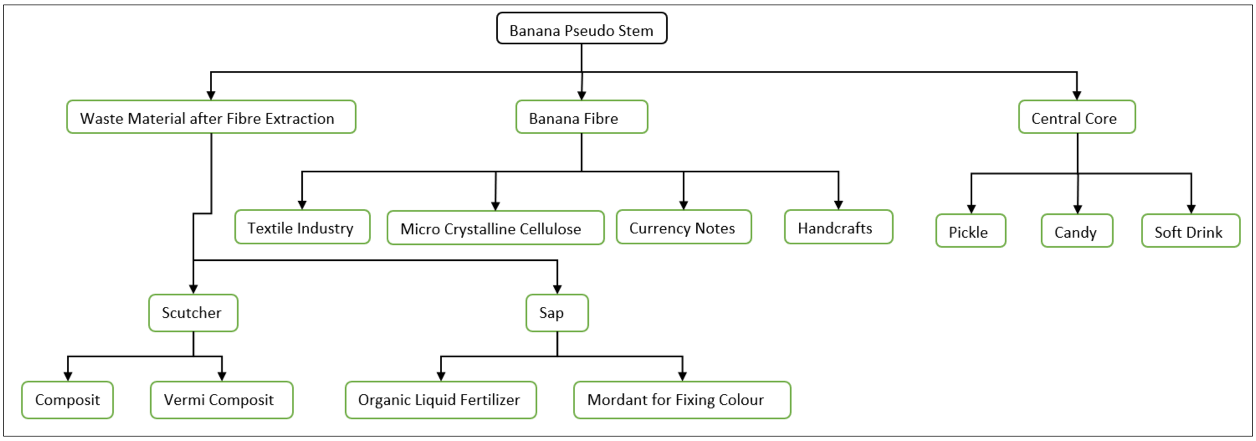

Figure 2: Potential Applications of Components from Banana Pseudo Stem(Padam *et al*., 2014; Subagyo & Chafidz, 2018)

COMPOSITE AND TEXTILE

Banana fibre are cellulosic strands obtained from barrel shaped, group accumulated leaf tail base called pseudo stem. Kavitha *et al*., in a review concluded that banana fibre can suitably be used for paper production, tea bags, currency, shipping cable, and a reinforced polymer composite materials(Kavitha & G, 2021; Subagyo & Chafidz, 2018). In a review on composition and properties of banana fibers, Bhatnagar *et al*., concludes that banana fibers have superior properties such as reinforcement efficiency, strength, durability and resistance to environmental attacks compared to other natural fibers(Bhatnagar *et al*., 2015; Sivaranjana & Arumugaprabu, 2021; W. A *et al*., 2023). NaOH is one of the common chemicals used to extract and pretreat banana fiber in an effective and economical manner whereby a 5% concentration was found to be optimal due to reduction of amorphous components of the fibre(Nguyen & Nguyen, 2022).

Rao *et al*., investigated physical, mechanical and wear properties of banana fiber reinforced composites. Water absorption test was conducted according to ASTM D570-98 standards where it was observed that water uptake increased with increase in fiber loading and soaking duration. Flexural and tensile tests were performed according to ASTM D790 and ASTM D638 standards. Banana reinforced composite had an ultimate tensile strength of (112-115) MPa, an increase of 67% compared to one of pure resin (Laxshaman Rao *et al*., 2021; Prabhakar *et al*., 2022). Chemical composition of banana fibers is shown in table1.

A fully matured banana pseudo stem contains 20-25 layers of flesh sheaths. Badanayak *et al.*, established that mechanical extraction of fibre is preferred to manual methods because its faster and output quality is higher though huge amounts of trash is still generated. It was further noted that large scale commercialization of banana fibre has been constrained by lack of standardized and advanced machinery(Badanayak *et al.*, 2023).

Table 1: Chemical composition of banana fibers(Bhatnagar *et al*., 2015)

Cellulose (%)	60-65
Hemi cellulose (%)	6-19
Lignin (%)	5-10
Pectin (%)	3-5
Ash (%)	1-3
Extractives (%)	3-6

Clothing and textile industries using synthetic fibres are some of the most harmful industries to the environment considering the amount of non-recoverable materials used like water, blends and chemicals. Banana fibres therefore could be suitable alternative due to attractive properties like; being odorless, chemically inert, resistant to high temperatures, fire, water, tension and grease (Balakrishnan *et al.*, 2019; Khan *et al.*, 2022; Provin *et al*., 2024). However, enough studies have not been carried out on softening such fibers for full utilization in the clothing industry though some strides have been made in that front(Balakrishnan *et al*., 2022). When compared with 100% cotton fabric, banana fibre exhibited; 15% higher tensile strength, 18% elongation, 30% higher frictional resistance, 22% superior tear strength, 15% superior air flow and 43% higher yarn quality index(Khan *et al*., 2022).

According to Ramesh *et al*., banana and sisal composite exhibited maximum tensile strength and flexural modulus at ratio of 3:1 by volume(Ramesh *et al*., 2014).Table 2 shows the physical and mechanical properties of banana fibre. Fiber mechanical properties may also vary greatly even from the same plant due to life cycle factors such as; growing conditions, fiber ripeness, fiber extraction methods, transportation and storage conditions(Jordan & Chester, 2017). Improvements of mechanical properties through adhesion of fiber matrix has been done but only through saline and alkali treatments. Gupta *et al*., recommends further physical treatments such as; corona treatment, ultrasound treatment, dielectric barrier discharge and chemical treatment like; benzoylation and acetylation(Gupta *et al.*, 2021).

Table 2: Physical and mechanical properties of banana fibre(Badanayak *et al*., 2023; Jagadeesh *et al*., 2015)

PARAMETER	VALUE	METHOD OF EXTRACTION
Density (g/cm^3)	1.35	Mechanical extraction
		Chemical retting
Length (cm)	10-15	Chemical retting
L/D ratio	150	Chemical retting
Diameter (µm)	50-250	Mechanical extraction
		Chemical retting
Fineness (Tex)	1.67-2	Water retting
Tensile strength (MPa)	600-800	Chemical retting
		Mechanical extraction
Elongation at break (%)	3-9	Chemical retting
		Mechanical extraction
		Anaerobic digestion
Flexural modulus (GPa)	2-5	Mechanical extraction
		Anaerobic digestion
Microfabric angle (°)	10-11	Chemical retting
		Mechanical extraction

Samples of fiber extracted from pseudostem using various extraction methods are shown in figure 3.

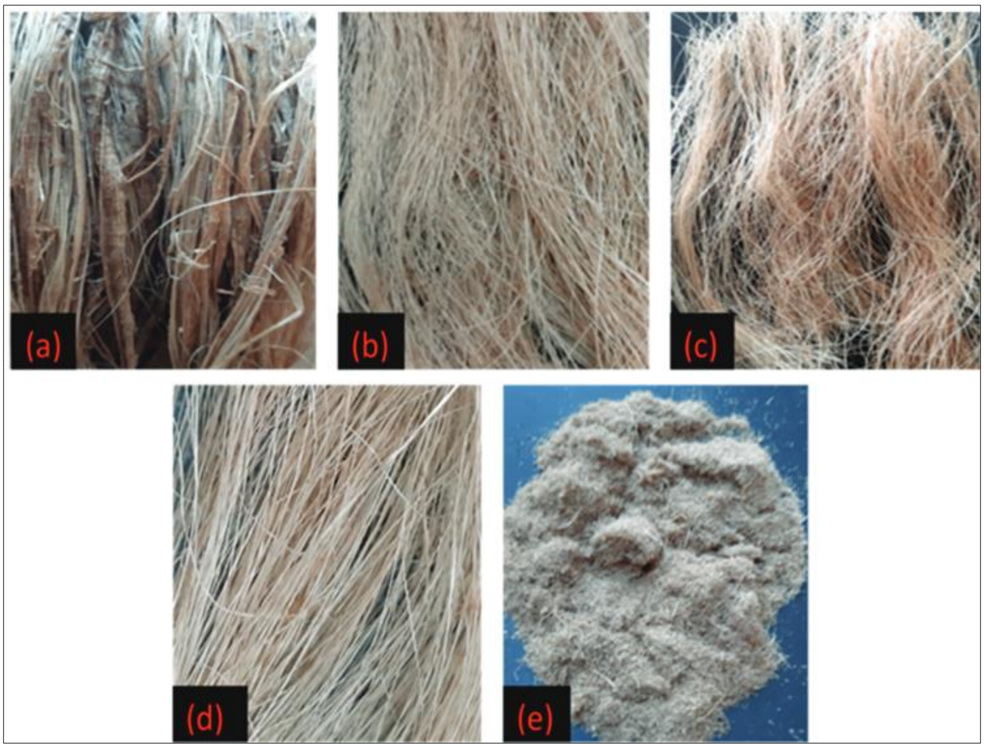

Figure 3: photographic images of; (a)untreated dry banana pseudo-stem(BPS), (b)banana fiber extracted through alkali treatment method, (c)banana fiber extracted through acid treatment method, (d)banana fiber extracted through emulsion treatment method, (e)adhere lignin by-product of emulsion treatment process(Bar *et al.*, 2022)

Consequently, chemical treatment removes odor and bacteria(Bakri *et al.*, 2017). However, there is need to use more sustainable practices such as enzymes in processing these fibers to reduce amounts of chemical wastes that could be released to the environment. As much alkali treatment is the most versatile one, its treatment leads to secondary chemical pollution, usage of huge amounts of water and energy during neutralization(Bar *et al*., 2022). It is an undisputed fact that use of natural fibre particularly agricultural waste like banana fiber helps reduce environmental pollution and energy usage during processing and usage of synthetic fiber(Bordón *et al*., 2022). On the same note, banana fiber and waste plastic composites used by Yaal women group received criticism by environmentalists as that composite was no longer renewable. Recommendations were made to adopt renewable materials in composite production which are friendly to the environment(Conlon *et al.*, 2019).

BIO-FERTILIZER AND CHEMICAL PRODUCTION

Banana peels account for about 18-33% of the whole fruit by mass and is normally considered as waste. It contains potassium, phosphorus, and calcium where potassium is the most important element in fertilizer production at 40% of the banana peel(Hussein *et al*., 2019). Nano-fertilizer is made by crushing banana peels, mixing it with potassium hydroxide, filtration and heating at 70^{o}C with continuous mixing at 300rpm. On the other hand, organic fertilizer is made by decomposition of organic matter(Alzate Acevedo *et al.*, 2021). Organic fertilizers means that nutrients remain in their natural form as opposed to extraction and refinement. These category of fertilizers is commonly used as soil conditioners(Salihin *et al.*, 2020).Castillo *et al*., observes that organic liquid fertilizers and pesticides obtained from banana pseudo stem sap are becoming increasingly popular in boosting crop growth and yield. Full conversion of untapped banana biomass resources is hindered by lack of commercial scale technologies(Castillo *et al*., 2023). In a review, Elkodous *et al*., found out that mineral oil mixed with banana peels produced precursor for synthesis of carbon nanotubes. Banana peel waste was also used to produce highly effective antibacterial graphene oxide (Abd Elkodous *et al*., 2021; Subramaniyan *et al.*, 2018). In addition, Fabusiwa *et al*., found out that banana peels are rich in antioxidants, minerals, phenolic and tryptophan which when converted to serotonin makes humans relaxed and improves mood. They help in management and treatment of people suffering from ulcers, diabetes, high cholesterol, body burns, wounds, constipation, anemia, arthritis and diarrhea(Joy *et al.*, 2022).

Over 40 phenolic compounds have been found in *Musa* species whose composition varies depending on level of maturity, plant variety and crop conditions. Peels of green banana have more tannins compared to ripe ones(Serna-Jimenez *et al*., 2023). Banana peels have proven to be a source of important chemical elements as shown in figure 4 below(Hikal *et al*., 2022).

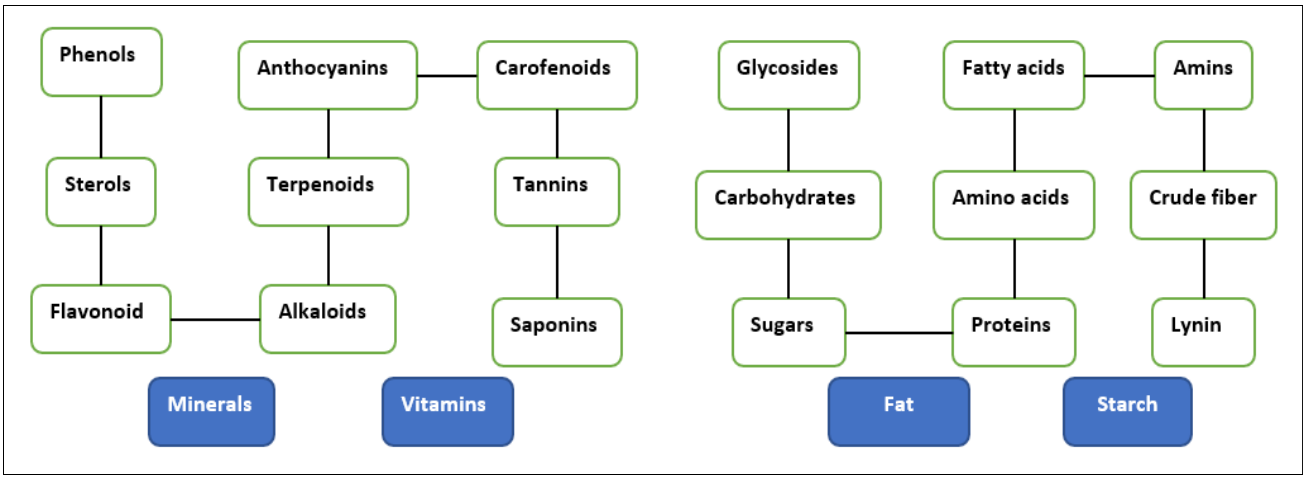

Figure 4: Banana peels phytochemical compositions(Hikal *et al.*, 2022)

BIO-FUELS

Energy consumption is expected to increase from 60% to 75% by 2030 with corresponding increase in greenhouse gases from carbon dioxide emissions and burning of untreated biomass. This necessitates production of biofuels like ethanol due to its renewability, eco-friendliness and local production from agricultural waste such as banana peels(Giwa *et al*., 2023; Sharma & Mishra, 2015). Figure 5 shows production of various kinds of bio-fuels;

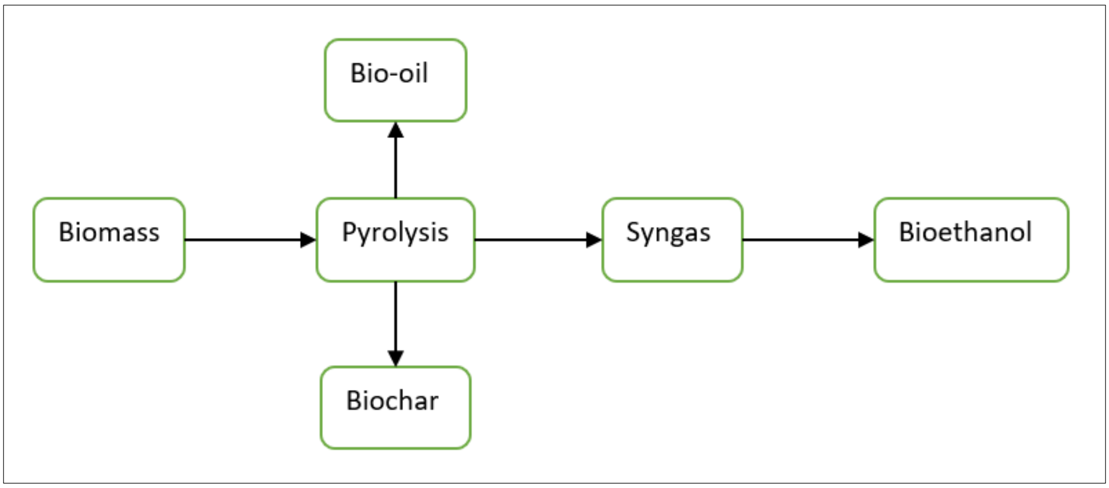

Figure 5: Production of bioethanol from banana plant waste through pyrolysis process(Giwa *et al.*, 2023)

According to Giwa *et al*., the quality of ethanol from banana peels waste is able to replace gasoline without any engine modification though it is commonly used as a gasoline enhancer. (Alshammari *et al*., 2011; Giwa *et al*., 2023). It is produced by addition of dilute sulphuric acid and saccharomyces enzymes at controlled temperature and has a higher oxygen content compared to other biofuels which enhances its combustibility. This biofuel has higher flame velocity, octane value and latent heat compared to gasoline (Devi & Sharma, 2016; Gebregergs *et al*., 2016). In Uganda, anaerobic digestion is the most feasible waste-to-energy technology giving rise to biogas and nutrient rich bio-fertilizer(Gumisiriza *et al*., 2017). Alternatively, producer gas and syngas are produced through gasification, a thermochemical process involving conversion of biomass through temperature partial oxidation whereas bio-oil is produced through fast pyrolysis and commonly used in large stationary engines(Olupot *et al*., 2024; Ruamsook & Thomchick, 2014). Figure 6 shows the various valorization opportunities available from banana waste to energy.

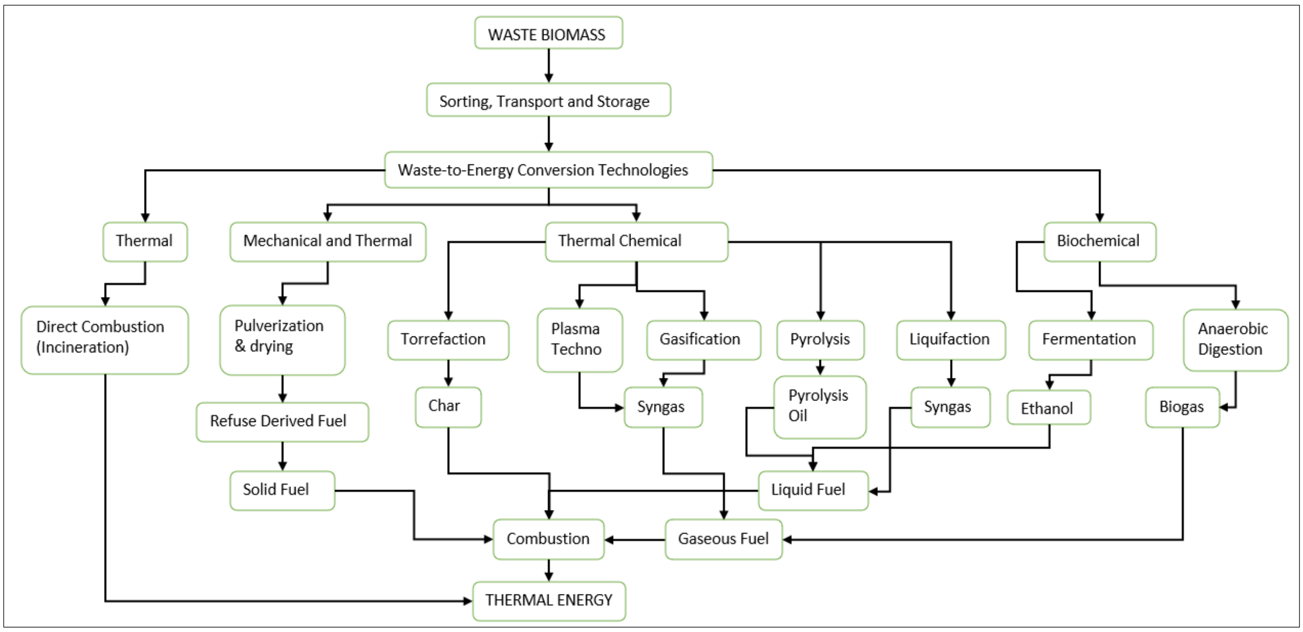

Figure 6: Potential waste to energy valorization technologies for banana waste(Gumisiriza *et al*., 2017)

Meriatna *et al*., established that ash catalysts from banana peels have excellent synthesis performance. Having a high potassium concentration of 78%, banana peel ash is suitable for use as a catalyst in biodiesel production(Meriatna *et al*., 2023). Small scale banana peeling briquettes were made by first drying them for two weeks and burning them halfway to produce char. They were crushed and added to brown soil as a binder. Water was added and then dried in the sun for one day. Due to brown soil, more ash was expected but no performance tests were conducted(Bingh, 2004).

Char refers to the carbon rich product obtained when an organic material is heated at relatively low temperatures in an inert environment. Mythili *et al*., produced char at 400°C from different types of plant and obtained a yield of 29-33%. It was observed that the higher the carbonization temperature, the lower the yield(Mythili & Venkatachalam, 2015). Duangkham *et al*., produced briquettes using rice straw mixed with banana peels in different ratios and (5-6) % (wt./wt.) cassava starch binder. Rice straw/banana peels ratios of 30:70 and 10:90 reached a bulk density of (610-660) kg/m^3 and a compressed density of (768-831) kg/m^3(Duangkham & Thuadaij, 2023). Figure 7 shows material preparation for rice straw/banana peels briquettes.

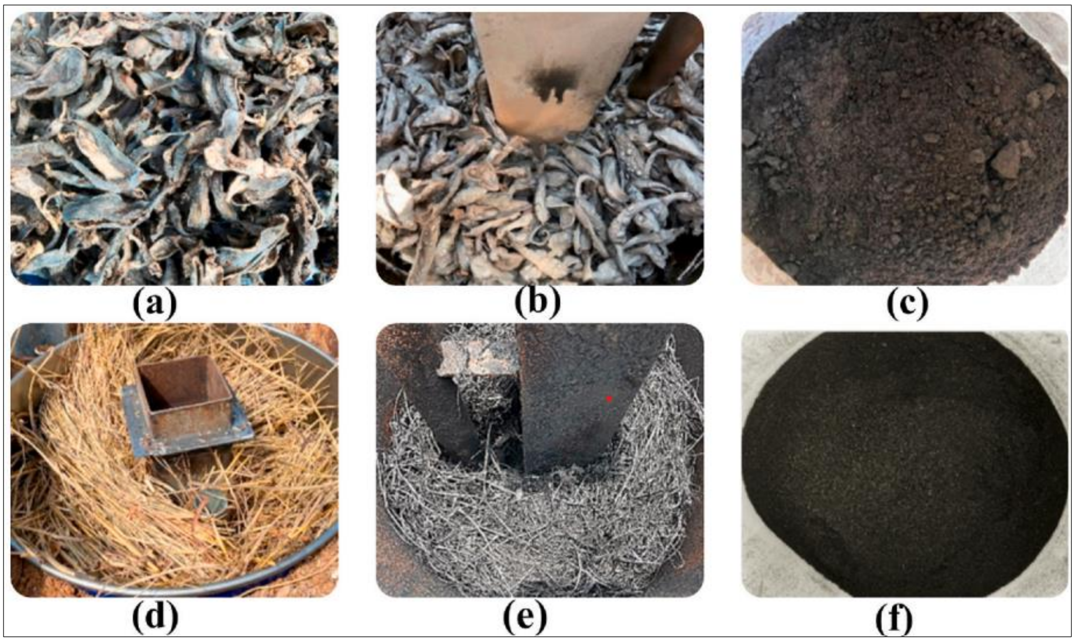

Figure 7: Agricultural residue (a) Dried banana peels (b) Banana peel (c) Fine charcoal from banana peel (d) Dried rice straw (e) Rice straw (f) Fine charcoal from rice straw(Duangkham & Thuadaij, 2023)

Nyakoojo *et al*., developed banana peels/waste glass composite briquettes using cassava starch as binder. The banana peels were first carbonized at 400°C to form biochar where approximately 10kg of biochar was obtained from 80kg of fresh banana peels. It was noted that commercial and industrial use of composite briquettes has been limited by low drop strengths, shatter indices and limited thermal efficiency. Results indicated a reduction in higher heating value and an increase in thermal efficiency with percentage increase of waste glass used(Nyakoojo *et al.*, 2024).

Sellin *et al*., conducted research on production of briquettes from waste banana leaves and pseudo stem. Excess water from pseudo stem was removed by use of hydraulic press, then dried at 60°C to achieve (8-15) % moisture content before the samples were crushed to an average of 2.5mm size. Compaction was conducted at 18MPa for 0.6-1sec. Chemical analysis, high heating value (HHV), thermogravimetric analysis (TGA), differential thermal analysis (TDA) and mechanical compressive strength were conducted. Pseudo stem and banana leaves briquettes presented compressive strength of 15MPa and 5.3MPa respectively(de Oliveira Maiaa *et al*., 2014; Sellin *et al*., 2013).

Ahmad *et al*., produced six samples of briquettes using banana peels, leaves and pseudostem in various ratios. Banana peels acted as binder and base material resulting into a high heating value ranging from 12 to 22 MJ/Kg. Best results were obtained from sample 6 which had higher ratio of banana leaves and pseudo stem. This sample fulfills all standard values recommended in characterization methods as per ISO 17225-1:2020(Ku Ahmad *et al*., 2018). The ratios used in the samples produced are as tabulated in table 3. Similarly, Bot *et al*., prepared banana peels briquettes using cassava starch as binder by drying, carbonizing, crushing and compacting. High calorific value of 16.98KJ/Kg were obtained(Bot *et al*., 2023).

Table 3: Mixing weightage/ratio for briquettes fabrication(Ku Ahmad *et al*., 2018)

Briquette sample	Banana peels	Banana pseudostem	Banana leaves
1	1	1	0
2	1	0	1
3	1	1	1
4	1	2	1
5	1	1	2
6	1	2	2

Wilaipon made banana peel briquettes using molasses as binder in the ratio of 1:0.2 at compact pressures ranging 7-11MPa. Samples made using 7MPa passed both compressive and impact resistance tests(Wilaipon, 2009). A comparison by Maia between banana leaves, pseudostem and rice husks briquettes, prepared at 18MPa for 1 second stay indicated that best features were presented by those made from banana leaves(de Oliveira Maia *et al*., 2018). Similarly, Thulu prepared briquettes from banana peelings using saw dust as binder. The research concluded that the briquettes produced were environmental friendly, and could reduce environmental degradation and health hazards associated with charcoal use(Thulu *et al*., 2016). Waste paper and cassava starch were used as binders in NaOH-treated banana leaves. It was concluded that binder type has an effect on quality and physiochemical properties of briquettes. It was also indicated that paper is a good alternative binder(Bamisaye & Rapheal, 2023).

In research to determine the difference between biochar produced by fast and slow pyrolysis processes, Abdullah *et al*., established that both rate of heating and pyrolysis temperature influence pseudo stem biochar properties. Heating range in slow pyrolysis are (5-20) ^{oC}/min while fast pyrolysis achieves rates exceeding 1000°C/min (Abdullah *et al*., 2023; Rajendiran *et al*., 2023). Banana leaf waste was pyrolyzed at temperatures classified as light (220°C), mild (250°C) and severe (280°C) torrefaction conditions. The study conclusively indicated that banana leaf torrefaction improves combustion performance, reduces emissions, and enhances bioenergy related properties(Alves *et al*., 2022).

Notably, banana waste has binding properties as demonstrated by Nyathi *et al*., Pine saw dust of 6.5% moisture content feedstock was used whereas banana waste from raw fruit, ripe fruit, pseudo stem pith blended and boiled for 1 hour was used as binder. Saw dust binder ratio of 1:4 yielded optimum samples in terms of relaxed density, shatter index and burning properties(Nyathi *et al*., 2022). Table 4 shows results obtained from analysis of pseudo stem biochar samples prepared by both slow and fast pyrolysis.

Table 4: Properties of banana pseudo stem biochar produced at 500°C(Abdullah *et al.*, 2023)

Analysis	Fast Pyrolysis	Slow Pyrolysis
Proximate analysis (db. wt. %)		
Moisture content	11.4	6.1
Volatile matter	28.5	33.2
Ash content	39.3	34.0
Fixed carbon	32.2	32.8

Analysis	**Fast Pyrolysis**	**Slow Pyrolysis**
Elemental analysis (%)		
C	41.28	43.23
H	0.09	0.00
N	28.48	19.96
S	0.00	0.00
O	30.15	36.81
HHV (MJ/Kg)	13.6	23.4
PH	10.11	10.16
BET		
Surface area (m^2/g)	0.638	1.078
Pore volume (cm^3/g)	0.004	0.005

In a similar research, banana peels, clay and waste paper were used as binders to produce bagasse briquettes. Banana peels and clay were recommended in terms of ease of transportation whereas combustion properties and calorific values were best in banana peel binder samples(Sweya *et al*., 2024). Consequently, Ibitoye *et al*., prepared briquettes from carbonized corn cob and banana stalks. It was concluded that carbonization improves thermal (HHV) and water resistance of briquettes manufactured. Higher compaction pressures yields better density, shatter index and water resistance properties whereas smaller particle sizes enhances higher water resistance, compressive strength and shatter properties(Ibitoye *et al*., 2022). Among the binders commonly mentioned in this review is cassava starch. Cassava is an annual root crop thought to have originated from Amazon. It is widely planted in Uganda where 76.4% of farmers cultivate local varieties for home consumption and for sale(Nakabonge *et al*., 2018).

CONCLUSION

Research has demonstrated that banana waste which includes pseudo-stem, banana peels and banana leaves have huge potential for energy production, fiber and bio-fuel production. Consequently, there is need for improvement for material properties through proper selection of binders and ratio optimization specifically in briquette manufacture. Furthermore, low drop strengths, shatter indices and limited thermal efficiency have been cited as the major hindrances from commercial use of composite briquettes. Even as concerted efforts are being made to turn banana waste into economical use, synthetic binders and additives have been discouraged for sustainable environmental integrity.

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