COMPARATIVE ASSESSMENT OF RICE HUSK AND PALM KERNEL SHELL PROPERTIES FOR SUSTAINABLE BIOENERGY APPLICATIONS

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Abstract. Following the growing global pressure in the need to have a sustainable and affordable energy this has triggered the need to explore biomass residues as renewable feedstocks. Rice husk (RH) and palm kernel shell (PKS) are two common agro-wastes that are promising in their applications as an energy source and a material. In this review, the compositional, proximate, ultimate, and higher heating value (HHV) properties of these are critically assessed based on the recent reports (2018 to 2024). Moderate lignin content, high ash and comparatively low HHV characterize RH, which is suited to combustion and briquetting but ash treatment is an issue. On the other hand, PKS has greater lignin and HHV, less ash, and more desirable carbon content that makes it a better feedstock to thermochemical conversion pathways, including pyrolysis, gasification, and activated carbon generation. What is novel in this review is a direct comparative evaluation of RH and PKS with systematically harmonized data, with a discussion of their implications to the development of advanced energy systems and carbon materials. It is suggested that hybrid briquettes, carbon-based electrode materials of PKS and RH mixtures, and AI-guided conversion pathway optimization be the focus of future research.
Keywords: *agricultural waste, rice husk, palm kernel shell, briquettes, proximate analysis, ultimate analysis*

Introduction

The pressing necessity to move toward a use of renewable energy sources rather than fossil fuels has developed the concern of biomass-generated fuels and carbon-based products. Biomass can be regarded as carbon-neutral and locally accessible, which lowers greenhouse gas emissions and increases energy security (IEA, 2023; Demirbas, 2008). Rice husks (RH) and palm kernel shell (PKS) are biomass residues that are especially abundant in the regions that yield rice and palm-oil like Nigeria, Malaysia, and Indonesia (Gani et al., 2024; Onokwai et al., 2022). Rice husk constitutes approximately 20 percent of rice milling by-products, and the production in the world is more than 150 million tonnes each year (Srinivasan et al., 2024). Palm kernel shell is a by-product of palm oil processing, and its amount is equally large, yet it is not fully used even though it has higher energy density (Ninduangdee, 2015). When these wastes are not handled adequately, they are a source of environmental problems, including land pollution, methane emission, and the risks of burning these wastes in the air (Sebastine

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et al., 2023). Earlier reviews examined general biomass characteristics (Kahar et al., 2022; Vassilev et al., 2021), and not many studies have compared RH and PKS in a systematic manner according to harmonized physicochemical data. Moreover, the role of these fundamental features on the suitability in next-generation applications, such as carbonized electrodes to power batteries, adsorbent to treat pollution, and hybrid bio-composites has received limited attention (Alonge and Obayopo, 2023; Acevedo et al., 2018). This review fills this gap by: (1) Summarization of recent compositional, proximate and ultimate analyses of RH and PKS; (2) Their HHV and thermochemical conversion potential were compared; (3) Speaking about applications to sustainable bioenergy and high-technology use of carbon materials; (4) Suggesting an outlay of the way forward on the use paths in the future, especially in the low-cost and decentralized energy storage and electrification of rural areas.

Compositional analysis

Rice Husk (RH)

Table 1 below indicated that Rice husk (RH) has a composition of 28–36% cellulose, 20-32% hemicellulose, and 18-26% lignin, depending on growth conditions, processing methods and geographical origin (Sebastine et al., 2023; Onokwai et al., 2022). The intermediate cellulose fraction serves to release energy during combustion, and the hemicellulose serves to degrade at low temperature of about 200-300 °C (Srinivasan et al., 2024). That is why RH briquettes are relatively easy to ignite. Nevertheless, an excessive amount of silica in the ash (up to 20%), contributes to a decrease in the overall calorific efficiency of RH and may cause slagging and fouling during combustion (Kaniapan et al., 2021). The lignin content (18-20%) is smaller than that of woody biomass but lignin increases the structural rigidity and yields of char during pyrolysis. Accordingly, the RH should be used in fast ignition (such as domestic cooking briquettes) but not in long-duration burning or yielding char.

***Table 1**. Compositional analysis of rice husk.*

Cellulose (%)	Hemicellulose (%)	Lignin (%)	References
36.56	20.12	19.44	Onokwai et al. (2022)
28.5	25.49	25.68	-
33.4- 35	20.99-25	18.25-20	Srinivasan et al. (2024)
33.00	20.35	18.1	Kaniapan et al. (2021)
32.67	31.68	18.18	Sebastine et al. (2023)
30.12	23.33	26.2	-

Palm Kernel Shell

Table 2 below revealed that Palm kernel shell (PKS) has much greater lignin contents (43- 53%) than RH, and less hemicellulose contents (6-26%). Lignin is a slow-decomposing biomass that releases stable char and elevates the heating values (HHV) above 400 °C, as it is full of aromatic compounds (Onokwai et al., 2022). That is why PKS is more stable to heat and has better potential to produce activated carbon, gasify, and process electrodes. The lignin is also high, which contributes to the mechanical durability of briquettes, thus making PKS-based briquettes denser and more resistant to degradation during storage and manipulation (Ninduangdee, 2015). Unlike RH, PKS does not result in a lot of problematic ash, and is therefore preferred in industrial boilers and co-firing.

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***Table 2**. Compositional analysis of Palm Kernel Shell.*

Cellulose (%)	Hemicellulose (%)	Lignin (%)	References
28.92	25.01	45.41	Onokwai et al. (2022)
45.69	6.41	47.9	Gani et al. (2024)
20.8	22.7	50.7	Kaniapan et al. (2021)
33.4	14.4	46.3	Ninduangdee (2015)
20.7-35.64	21.39- 47.7	42.97-53.4	Srinivasan et al. (2024)

Proximate analysis

Rice Husk

The volatility of RH is comprised of volatile matter (VM) at 61-81 percent, ash at 6-23 percent, and fixed carbon (FC) at 5-20 percent (Emmanuel et al., 2023; Martinez et al., 2021). High VM causes RH to be easily combustible and the high ash content is a major operational problem as indicated in *Table 3*. As an example, Martinez et al. (2021) documented VM of 72.7% and ash of 22.3% and Emmanuel et al. (2023) 6.1% ash and 20.2 % FC. Such variability may be attributed to cultivation and milling. Notably, low FC and high ash impede efficiency of energy recovery during a thermochemical process. Therefore, RH is suited best in low-ash demanding processes such as briquetting, or co-firing with low-ash biomass.

***Table 3**. Proximate analysis of rice husk.*

M.C (%)	V.M (%)	A.C (%)	F.C (%)	References
8.61	72.69	22.37	4.94	Martinez Cera et al. (2021)
9.72	80.66	9.68	9.66	Arranz et al. (2021)
7.0	68.12	12.19	17.91	El-Sayed (2019)
3.96	69.74	6.10	20.21	Emmanuel et al. (2023)
5.88	63.92	22.90	13.18	Ndecky et al. (2022)
9.12	61.90	15.0	17.89	Fauzan (2018)

Palm Kernel Shell

It was revealed that PKS exhibits more desirable proximate properties, i.e., volatile matter 67-76 %, fixed carbon 14-27 %, and ash 0.06-8 % (Alonge and Obayopo, 2023; Osei Bonsu et al., 2020) as presented in *Table 4*. It is exceptionally low ash (0.06% in certain cases) and therefore burns cleanly without much clinker formation which is a significant benefit in industry. The large fixed carbon ratio (20-27%) shows a great possibility of producing char and biochar, which is essential in energy storage as electrode material. Compared to RH, a low ash and high FC content in PKS makes it clearly a better feedstock in a pyrolysis and gasification system.

***Table 4**. Proximate analysis of palm kernel shell.*

M.C (%)	V.M (%)	A.C (%)	F.C (%)	References
1.08	71.80	0.06	27.07	Osei Bonsu et al. (2020)
10.75	75.81	3.79	20.40	Fuad (2020)
6.00	73.40	5.80	14.00	-
7.52	69.37	2.67	20.46	Acevedo et al. (2018)
8.31	67.52	8.11	16.06	Alonge and Obayopo (2023)

Ultimate analysis

Rice Husk

The final RH analysis in *Table 5* indicates that, it contains 34-41 percent of carbon, 4-6 percent of hydrogen, 0.3-1.3 percent of nitrogen, and 38-53 percent of oxygen (El-Sayed, 2019). The HHV is low and the oxygen is high that decrease the HHV, in

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comparison, to PKS. Moreover, the existence of traces of nitrogen and sulfur can cause the emissions of NOx and SOx during the combustion unless they are controlled (Fauzan et al., 2018). Nevertheless, the elevated oxygen content increases reactivity, which means that RH is applicable in the fast pyrolysis and gasification processes where oxygenated volatiles enhance flame stability.

***Table 5**. Ultimate analysis of rice husk.*

Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulphur (%)	Oxygen	References
34.60	4.28	0.30	0.05	38.37	Martinez Cera et al. (2021)
40.80	5.99	0.50	0.064	49.78	-
39.87	5.92	1.33	0.48	52.45	El-Sayed (2019)
40.87	5.59	0.45	0.00	53.09	Fauzan (2018)

Palm Kernel Shell

Table 6 indicated that PKS has more carbon (41-49%) and hydrogen (5-7 %), and oxygen, as a rule, is 42-46 % (Osei Bonsu et al., 2020). The increased C/H ratio provides PKS with increased calorific strength and char forming efficiency. Both nitrogen and sulfur are less than 1% and therefore, PKS is a low-emission biomass relative to coal and other residues. Such profile is very appealing to make PKS significant in energy production, as well as, biochar in soil amendment, carbon sequestration, and electrochemical equipment.

***Table 6**. Ultimate analysis of palm kernel shell.*

Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulphur (%)	Oxygen	References
48.90	7.00	1.02	0.22	42.86	Osei Bonsu et al. (2020)
48.37	5.86	0.60	0.10	45.07	-
46.05	5.14	0.62	0.14	45.40	Acevedo et al. (2018)
41.25	5.08	1.24	0.17	44.15	Alonge and Obayopo (2023)

Higher Heating Value (HHV)

Rice Husk

HHV of RH is 14-18 MJ/kg (Emmanuel et al., 2023; Arranz et al., 2021). The variation is due primarily to the ash content and oxygen level. As an example, high ash was associated with low HHV of 14.16 MJ/kg (quoted by Emmanuel et al., 2023) and 18.14 MJ/kg (quoted by Arranz et al., 2021) under optimum milling conditions, as presented in *Table 7*. The values are low compared to woody biomass (~20 MJ/kg), but given the existence of ash management systems, RH can be used as domestic fuel and briquetting.

***Table 7**. Higher Heating Values (HHV) of rice husk in MJ/Kg.*

HHV(MJ/Kg)	References
15.30	Martinez Cera et al. (2021)
18.14	Arranz et al. (2021)
16.63	Onokwai et al. (2022)
14.16	Emmanuel et al. (2023)
14.63	Ndecky et al. (2022)
14.70	Kaniapan et al. (2021)
14.39	El-Sayed (2019)

Palm Kernel Shell

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Table 8 indicated that PKS has always recorded higher HHV (16-22 MJ/kg), that beats or surpasses most sources of woody biomass (Kaniapan et al., 2021; Osei Bonsu et al., 2020). The maximum of 21.65 MJ/kg has been reported (Onokwai et al., 2022), which highlights the fact that PKS is a high-quality bioenergy feedstock. The fact that PKS is a perfect target in industrial co-firing, gasification, and export-grade pellets of biomass and RH is a better fit in small scale, localized energy is proved by the fact that the HH is high.

***Table 8**. Higher Heating Values (HHV) of palm kernel shell in MJ/Kg.*

HHV(MJ/Kg)	References
20.27	Osei Bonsu et al. (2020)
17.88	Fuad (2020)
18.84	-
18.96	Acevedo et al. (2018)
15.94	Alonge and Obayopo (2023)
21.65	Onokwai et al. (2022)
20.73	Kaniapan et al. (2021)

New uses and novelty of this review

The findings of this review highlight several emerging applications of rice husk (RH) and palm kernel shell (PKS) beyond their conventional use as biomass fuels. PKS is particularly suitable for co-firing in thermal plants due to its higher energy density, lower ash content, and greater lignin and fixed carbon contents, whereas RH is more suitable for small-scale briquetting because of its relatively high volatile matter and ease of ignition. Furthermore, PKS-derived char shows promising potential for the production of activated carbon and carbon-based electrodes for energy storage applications, while RH-derived silica-carbon composites could be utilized as adsorbent materials for pollution control and as potential materials for supercapacitor applications. The blending of RH and PKS may also provide complementary properties by combining the favorable ignition characteristics of RH with the higher energy density and char-forming potential of PKS. The novelty of this review lies in its direct comparison of the compositional, proximate, ultimate, and higher heating value (HHV) characteristics of RH and PKS using harmonized datasets from recent studies. More importantly, the review connects these physicochemical characteristics with emerging applications in sustainable bioenergy, electrochemical energy storage, and environmental remediation, thereby providing a clearer framework for selecting suitable utilization pathways for these agricultural residues.

Future recommendations

Future research should focus on improving the utilization of RH and PKS through advanced conversion technologies, optimized biomass blending, and the development of high-value carbon materials. Artificial intelligence and machine-learning approaches could be investigated to predict optimum RH-PKS blending ratios and conversion conditions based on their compositional, proximate, ultimate, and energy characteristics. Further experimental studies are also recommended to evaluate hybrid RH-PKS briquettes in terms of ignition performance, combustion stability, mechanical durability, emissions, and calorific value. In addition, PKS-derived biochar should be further investigated as a carbonized electrode material for batteries and supercapacitors,

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particularly for low-cost and decentralized energy-storage applications, while RH-derived silica-carbon composites should be explored as economical adsorbents for heavy-metal and other pollutant removal. Future studies should also examine the technical, economic, and environmental feasibility of these applications at larger scales. Finally, appropriate policy incentives and institutional support for biomass valorisation should be strengthened in rice- and palm-producing regions to encourage the conversion of agricultural residues into sustainable energy and value-added materials.

Conclusion

Rice husk (RH) and palm kernel shell (PKS) are abundant biomass wastes with strong potential for sustainable energy production and the development of value-added products. The comparative assessment in this review demonstrates that the two biomass resources possess different but complementary physicochemical and energy characteristics. RH is characterized by relatively high volatile matter and reactivity, which support easy ignition and its potential application in briquetting and small-scale energy production. However, its relatively high ash and silica contents may reduce calorific efficiency and contribute to operational problems such as slagging and fouling during combustion. In contrast, PKS generally exhibits higher lignin and fixed carbon contents, lower ash content, and higher heating value (HHV), making it a more suitable feedstock for thermochemical conversion processes such as pyrolysis, gasification, and industrial co-firing. These differences demonstrate that the selection of RH or PKS for energy applications should consider their compositional, proximate, ultimate, and heating-value characteristics.

Beyond conventional energy production, both RH and PKS also offer considerable opportunities for the development of advanced carbon-based and environmental materials. The higher lignin and carbon characteristics of PKS indicate its potential for producing biochar, activated carbon, and carbonized materials for energy-storage applications, while the silica-rich characteristics of RH provide opportunities for developing silica-carbon composites and adsorbent materials. Furthermore, blending RH and PKS could potentially combine the favorable ignition characteristics of RH with the higher energy density and char-forming properties of PKS. Overall, the comparative findings of this review provide a basis for selecting appropriate utilization pathways for these agricultural residues and demonstrate their potential contribution to waste valorisation, sustainable bioenergy, environmental remediation, and decentralized energy systems. Further experimental investigations, optimization of RH-PKS blending ratios, development of carbonized materials, and evaluation of large-scale technical and economic feasibility are therefore necessary to support their effective utilization in future sustainable energy and material applications..

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Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

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