Cleaner Materials 6 (2022) 100154

Contents lists available at ScienceDirect

Cleaner Materials

journal homepage: www.journals.elsevier.com/cleaner-materials

Potentials of palm kernel shell derivatives: a critical review on waste recovery for environmental sustainability

Ifeanyi Uchegbulam [a,*], Emmanuel Owoichoechi Momoh [b,c], Solomon A. Agan [d]

[a] Production Technology, School of Science Laboratory Technology, University of Port Harcourt, Choba PMB 5323, Nigeria
[b] School of Engineering, University of Aberdeen, King's College, Aberdeen AB24 3UE, UK
[c] School of Built Environment, Engineering and Computing, Leeds Beckett University, Leeds LS1 3HE, UK
[d] Mechanical Engineering, University of Port Harcourt, Choba PMB 5323, Nigeria

ARTICLE INFO

Keywords:
Activated carbon
Carbon footprint
Environment
Palm kernel shell
Sustainability
Waste recovery

ABSTRACT

Huge quantities of Palm Kernel Shell (PKS) are produced as wastes annually due to increase in demand for palm oil. Regardless of the numerous potential derivatives from the waste PKS such as activated carbon, pulverized shells, liquified fumes etc., there still exists the problem of its indiscriminate disposal or incineration without energy recovery thereby creating both economic and environmental concerns. This review is therefore aimed at presenting the state of the art on the numerous applications of PKS as a carbon–neutral, biodegradable, affordable and available residual component of oil palm processing, which if properly maximized will be a value-added precursor to solving the associated disposal and environmental challenges. Findings from most studies demonstrate that PKS has great potentials as a bioabsorbent, abrasive, detoxifier, antibacteria, antifungi and antioxidant material as well as a biofuel for syngas and biodiesel production. Other applications of PKS include reinforcement for polymer and metallic composites and aggregates in construction and ceramics. Industrial uses of PKS in agriculture, oilrefining, healthcare, fashion, glass, drugs and rubber vulcanizate production were also discussed. The suitability of PKS for other engineering applications were also highlighted with recommendation for further exploitation suggested. This review is expected to provide technical data for both scientists and policy makers in environmental sustainability.

Introduction

Global population growth necessitates increased socioeconomic and infrastructural development leading to rapid replacement of rural lifestyle with urbanization, increased depletion of natural resources and the generation of high volume of municipal solid wastes. The need to provide for the basic needs of the swelling population also results in an increase in investments in agriculture in a bid to provide basic commodities such as food crops, natural wool and fibres for textile and timber for construction. Consequently, enormous wastes are generated whose disposal pose several challenges to the environment. A large percentage of these wastes are biomass resulting from the production of food and other agricultural processing activities. These residual components from the increased agricultural activities are characterized by affordability and abundance in huge quantities, thereby making them economically viable to exploit (Momoh et al., 2020).

In both the domestic and industrial sectors, agro-wastes such as poultry bedding/litter, feathers, dung/droppings, and grass cuttings are commonly produced in large quantities from farmyards. According to Obi et al. (2016), up to 80 % of solid wastes (i.e., 998 million tonnes) per annum are generated from farmyards. In another study, about 337,000 tonnes of agricultural waste was generated in Kuwait while the Abu Dhabi Emirates produced up to 1.2 million tonnes of agricultural wastes in 2019. Developing countries present the worst-case scenario: for instance, Nigeria and India produce up to 200 million and 600 million tonnes (respectively) of agricultural wastes annually with most of the wastes burnt openly in the fields as a disposal attempt (Momoh et al., 2022a; Momoh et al., 2022b). These wastes ranges between fruit peels, shells, hulls, seed pods, bagasse, stalks, leaves. barks, roots, sludges, cobs, pulp, straws, brans, and husks, (Adejumo and Adebiyi, 2020; Ioannou et al., 2015) with the oil palm tree generating the largest share of the agro-wastes in the form of fibres from different parts of the tree (Momoh and Osofero, 2019; Momoh et al., 2020; Momoh et al., 2021) and shells from the extraction of palm kernel (Dungani et al., 2018).

* Corresponding author.
E-mail addresses: uche.aberdeen.ac.uk@gmail.com (I. Uchegbulam), e.o.momoh@leedsbeckett.ac.uk (E.O. Momoh).

https://doi.org/10.1016/j.clema.2022.100154
Received 26 April 2022; Received in revised form 18 July 2022; Accepted 19 September 2022
Available online 22 September 2022

Oil Palm (*Elaeis guineensis*) although originated from west Africa, is cultivated in the tropics of Asia, Africa, South and Central America (Sundalian et al., 2021; Momoh and Osofero, 2020). Nigeria was a top producer of oil palm from 1901 up to 1977 when Malaysia began to dominate the industry after decades of intense research and improvement of seedlings from the west African country (Obuka et al., 2018; Otti et al., 2014). Currently, Nigeria and Colombia occupy the 4th position in total palm plantation and oil production behind Indonesia, Malaysia and Thailand who already occupy more than 85 % of the total global palm oil production (Jalani et al., 2016; Sundalian et al., 2021). Fig. 1 presents countries with top global palm oil production in 2021/2022. In Malaysia alone, average rate of palm waste production currently stands at over 100 million tonnes per year with a 5 % annual growth projection. In 2020, the processing of 49 million tonnes of palm oil in Indonesia resulted in about 19.6 million tonnes of waste biomass with associated disposal challenges (Sundalian et al., 2021). A similar study (Jalani et al., 2016) reported up to 49.2 million m^3/year of palm oil mill effluent in Malaysia which requires proper treatment prior to safe disposal into the sea. In Nigeria for example total PKS generated annually is in excess of 2.5 million tonnes with the lack of proper disposal also posing a threat to the environment (Shahbandeh, 2022).

Due to the processing of palm oil from the palm fruits, high volumes of palm kernel shells (PKS) waste are generated which require utilization for diverse applications especially due to their perceived low carbon footprint. Palm kernel shell is the hard covering of the palm kernel left as waste after the processing of palm oil from the mesocarp as well as after the removal of the kernel nut (see Fig. 2). The shells are usually left as waste or burnt openly in an attempt at disposal. Currently, areas of research include (but not limited to) the use of the PKS as a wastewater detoxifier, abrasive in automobile components, reinforcement for metallic and polymeric composites, bioenergy production, additive in drilling fluids, livestock feed as well as construction aggregates. However in the rural areas, the economic attention is focused on the crude palm oil and palm kernel oil from the fruit's mesocarp and kernel respectively while the waste components such as PKS, palm kernel meal, palm oil mill effluent, and various fibres from the palm fruit processing are disposed indiscriminately. Precisely, crude palm oil and palm kernel oil make up to 10 % of the total oil palm products, while 90 % of the palm biomass are wastes which are either dumped arbitrarily (Sabzoi et al., 2016; Dungani et al., 2018) or burnt without any energy recovery (Kim et al., 2014). Therefore, proper waste management is needed to economically harness the wastes while also enhancing environmental conservation.

Research into PKS is fairly abundant but have only focused on certain aspects, while an overview of its application is scarce at the moment. In other words, there is lack of a one-stop-resource document providing an overview of the physical and chemical properties as well as current and potential applications of this agro-waste. It is therefore the aim of this paper to present a summarized state of the art on the applications of PKS as a value-added precursor to environmentally sustainable byproducts at the same time solving disposal problems. We believe that this information will contribute to knowledge that will guide scientists and other stakeholders make informed decisions regarding the ongoing race towards saving the environment through minimizing carbon emissions and promoting cleaner energies. This review has focused on the most recent studies involving PKS with more than 75 % of the studies carried out within the last 5 years. Fig. 3 illustrates the number of studies covered in this review which reveals the growing research interests in PKS. Firstly, the most common methods of characterizing PKS were discussed together with the compilation of its chemical and physical properties from different literatures. This was followed by different applications of PKS, conclusion and recommendations.

Characterization of PKS

Scanning electron microscopy (SEM)

SEM imaging has been used to study the morphology of both untreated and treated PKS. Compared to the dense organic matter in raw PKS (shown in Fig. 4(a) and 4(c)), the effect of chemical stimulation of PKS treatment into activated carbon through disintegration of the lignocellulosic structure is shown in Fig. 4(b) and 4(d). Surface pores and fibres in Fig. 4(b) and (d) are visible after activation of PKS with H_3PO_4 and KOH treatment in the studies of Abdullah et al. (2020) and Ramli and Ghazi, (2020) respectively. Unlike the layered structure of the raw PKS in Fig. 4(a) and (c), the activation process resulted in higher

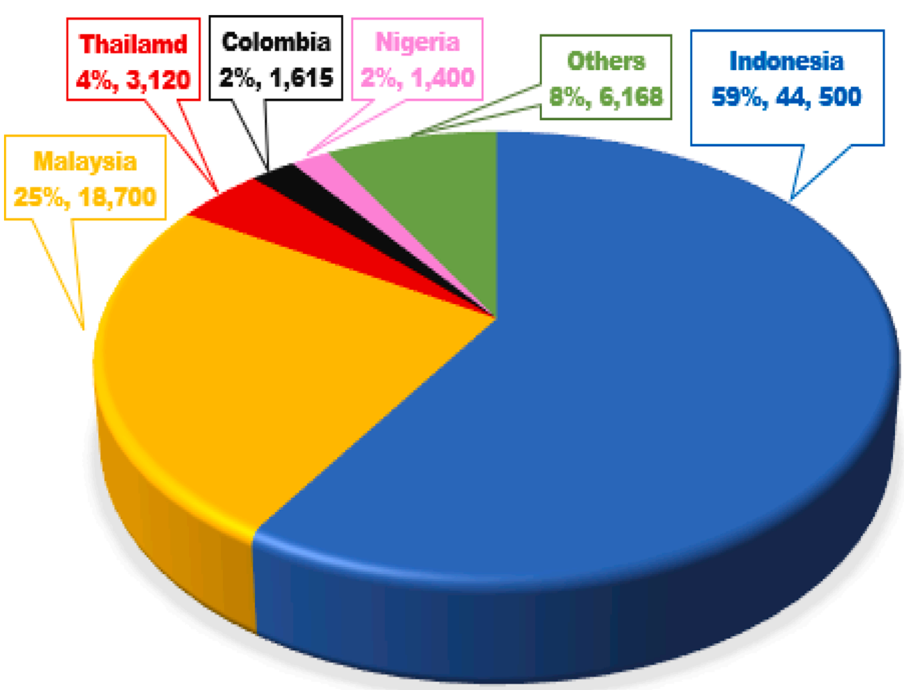

Fig. 1. Top producers of palm oil in thousand metric tonnes in 2021/2022 (Shahbandeh, 2022).

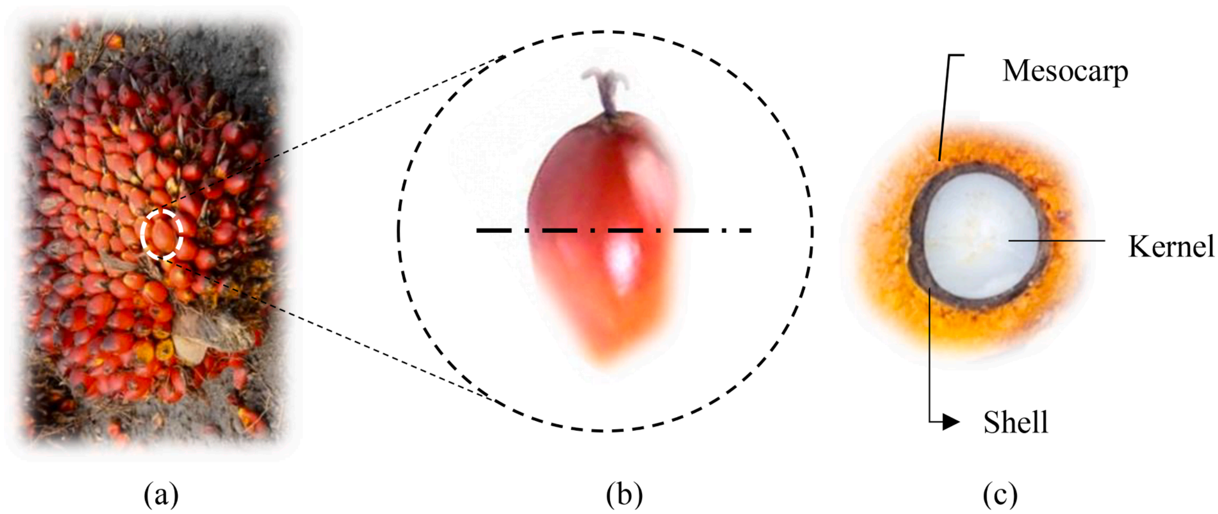

Fig. 2. Photo of (a) oil palm fruit bunch, (b) palm fruit (c) cross section of palm fruit.

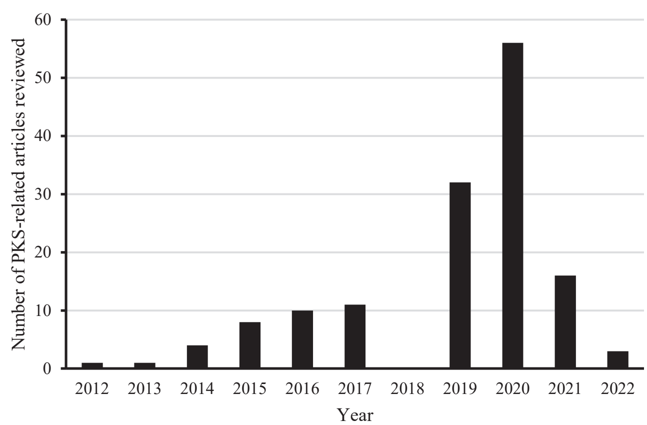

Fig. 3. Number of PKS-related research articles reviewed in this study.

porosity due to the presence of pores within the fibre network thereby resulting in the "honeycomb" structure observed in Fig. 4(d). Chemical activation increases both the surface area and number of active sites which are two favourable parameters for absorption and adhesion of matrices when used as reinforcement. Furthermore, fibres make up to 30 % of the PKS and are responsible for the reinforcing potentials when used in composites (Valášek et al., 2019).

X-Ray diffraction (XRD) analysis

The compositional analysis of PKS provides a background understanding of its chemical configuration. Fig. 5 presents a comparison between XRD crystallinity analysis of raw PKS and activated carbon from PKS. XRD patterns of raw PKS demonstrated the coexistence of carbon and oxygen atoms at peaks of $2\theta = 22^\circ$ and 35° respectively (Fig. 5a). In Fig. 5b, the peaks represent zeolite and phosphorus at $2\theta = 8.8^\circ$ and 44.6° respectively due to the phosphoric acid effect in creating activated carbon from the PKS. Other peaks at $2\theta = 21.0^{\cdot o}$, 26.6°, 50.1°, 59.9° and 68.1° represent the amorphous nature of the activated carbon and is consistent with other studies (Imoisili et al., 2020; Ikubanni et al., 2020; Yeboah et al., 2020, and Jabarullah et al., 2021).

X-Ray fluorescence (XRF) analysis

As an analytical technique, XRF identifies the presence and proportion of elements in a material so that the chemical composition can be established. In the study of Ikubanni et al. (2020), PKS samples for XRF analysis were made by first grinding 20 g of PKS with 0.4 g of stearic acid for 60 s, then pelletizing the powder using 1 g of stearic acid as binder before applying a 2×10^3 KN pressure for 1 h. The XRF analysis on the 2 mm pellets was conducted with X-Ray Spectra generated from a 25 mA and 40 KV current and voltage respectively.

Remarkably, Table 1 presents silica as the major constituent of PKS followed by magnesia, alumina, quicklime, and phosphoric anhydride (P_2O_5). The high silica, magnesia and alumina contents imply potential pozzolanic property which reveals why ash generated from PKS has been studied as a partial replacement for cement in cementitious composites. Furthermore, its availability and affordability together with other properties like relatively high porosity, surface area and strength-to-weight ratio makes the agricultural waste a potential solid biocatalyst (Nwosu-Obieogua, et al., 2022).

Fourier transform infrared spectroscopy (FTIR)

The characteristic absorption bands in FTIR spectra can detect the behaviour and performance of materials to a significant extent by profiling the chemical bonds as molecular fingerprints of the prevalent functional groups present. From the FTIR data in Fig. 6, it is obvious that the raw PKS has abundant peaks thereby demonstrating more functional groups than in the activated carbon spectra. This disappearance and shifts of most peaks in the activated carbon spectra can be attributed to the disappearance of most functional groups due to their chemical and thermal decomposition as well as intermolecular bond breakages during the activation process. The absence of functional groups in the activated carbon spectra indicates that raw PKS are likely to be thermally unstable as their functional groups evaporate in the form of volatile molecules at elevated temperatures.Fig. 7.

Remarkably, a peak appears in the 3434 cm^{-1} wavelength and is consistent in the raw PKS, as well as in the PKS-activated carbon when compared with the commercially obtained activated carbon. This was considered as a stretched vibration from hydroxyl ion (–OH) as a result of absorbed moisture (Rashidi et al., 2020; Ang et al., 2020; Jitjamnong et al., 2020; Abdullah et al., 2020) and hence responsible for the biodegradability of the PKS (Alias et al., 2018). In addition, the FTIR spectra for activated carbons from both PKS and commercial source had four peaks each, therefore implying a comparable quality. Observed differences between their peaks are often asserted to be due to the differences in the nature of the raw material, processing method and chemical configurations.

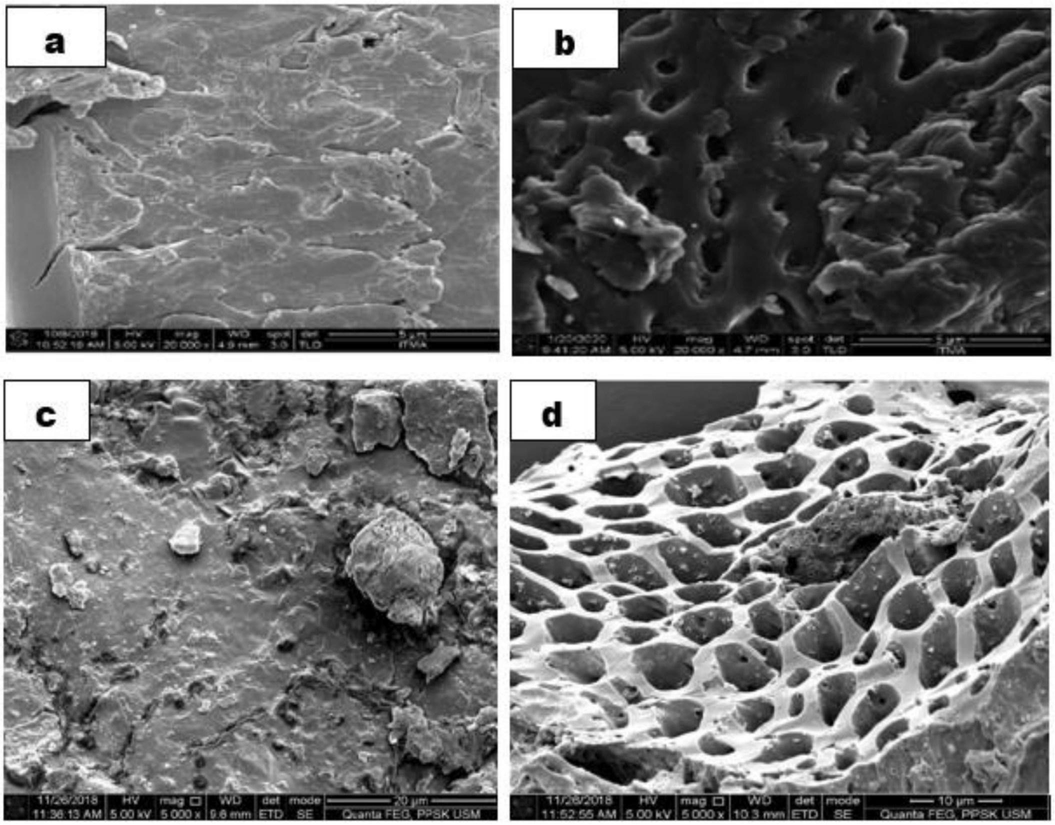

Fig. 4. SEM imaging of: (a), (c) raw PKS and; (b), (d) activated carbon (Abdullah et al. 2020; Ramli and Ghazi, 2020).

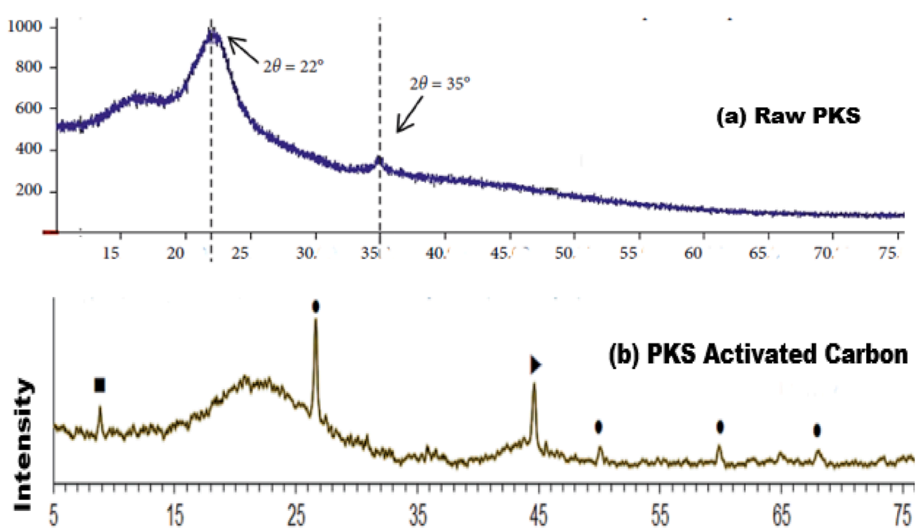

Fig. 5. XRD Crystallinity analysis: (a) raw PKS (Bakar et al. 2019) (b) activated carbon from PKS (Abdullah et al. 2020).

Thermogravimetric analysis

The thermal behaviour of PKS shows that the agricultural waste decomposes under heat in three stages due to its constituents. The first stage occurs at an onset of 30 °C up until 140 °C with weight loss attributed to vaporization of moisture content. The second stage is initiated at 140 °C and lasts up to 435 °C with two distinct derivative thermogravimetric (DTG) peaks. The first peak, $T_1 = 298$ °C marks the onset of the decomposition of hemicellulose while the second peak, $T_2 = 340$ °C indicates the degradation of cellulose. The third stage represents the decomposition of lignin at $T_3 = 560$ °C and its final oxidation into biochar at $T_4 = 610$ °C (Acevedo-Paez et al., 2019).

A summary of some physical and chemical properties of PKS is presented in Table 2. It is noteworthy that there are significant variations between the reported values from different studies. Generally, it is not unusual for plant grown from even the same species to differ significantly in characteristics due to functional grading of plant tissues (Momoh et al., 2022b). Other likely causes of the variation in the properties may include differences in the methodology used to determine the properties. It is important therefore to investigate carefully before adopting reported values available in literature.

Table 1
Percentage chemical composition (by weight) of PKS from XRF analyses.

Compound	Hussain et al. (2019)	Ikubanni et al. (2020)	Edoziuno et al. (2021)	Samotu et al. (2015)	Range
SiO_2	31.50	46.20	55.69	25.1	25–56
MgO	16.90	3.70	4.85	–	4–17
Al_2O_3	16.50	2.30	9.43	7.6	7–17
CaO	10.60	15.10	11.21	12.3	10–15
P_2O_5	10.40	6.00	2.39	–	2–10
SO_3	7.27	–	0.67	1.4	1–7
Cl	2.30	–	–	–	NA
K_2O	1.75	21.20	9.71	15.0	1–21
Fe_2O_3	1.40	3.20	3.32	12.3	1–12
MnO	0.83	0.60	0.72	0.74	0.6–0.8
Cr_2O_3	0.61	–	0.25	0.26	0.2–0.6
Na_2O	–	1.00	1.76	–	1–2
TiO_2	–	0.43	–	0.92	0.4–0.9
NiO	–	–	–	0.2	NA
CuO	–	–	–	1.4	NA
Yb_2O_3	–	–	–	0.9	NA
LOI	–	0.27	–	–	NA

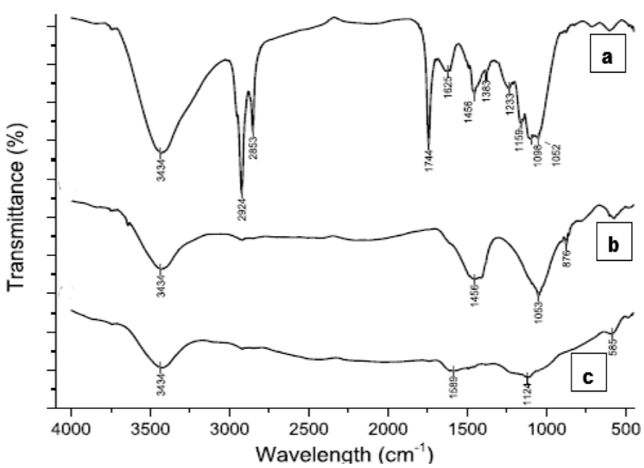

Fig. 6. FTIR spectra of (a) raw PKS (b) activated carbon from PKS (c) activated carbon from a commercial ().
Source Rashidi et al. 2020

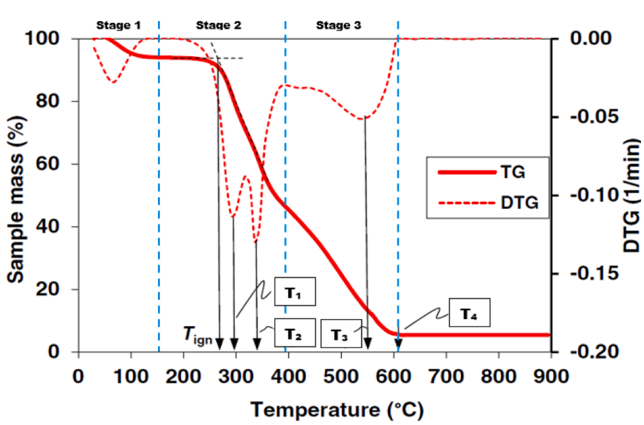

Fig. 7. Thermogravimetric analysis of PKS (Ninduangdee et al. 2015).

Applications of PKS

Several studies have investigated the potentials of PKS as bio-absorbents, biofuels, composite reinforcement, machining abrasives, aggregates in construction, ceramic materials, oil refining as well as applications in biotechnology in the form of antibacteria, antifungi and antioxidants. The following sections present areas where PKS and associated derivatives have been utilized.

Removal of contaminants

Gas recovery

PKS possesses the highest yield potential for activated carbon amongst the other waste biomass hence its conversion into activated carbon. For instance, the study of Nyamful et al. (2020) used H_3PO_4 to obtain activated carbon from PKS and coconut shell with a yield of 26.3 g and 22.9 g respectively. The PKS product possessed selectively higher affinity for components of liquids and gases and has been widely applied in industry as bioabsorbent. For example, to isolate and store hydrogen from a gas stream, PKS-derived biochar was used as a dispersant in a magnesium-based composite in Yeboah et al. (2020). The study reported a 93 % hydrogen storage at an optimal weight fraction of 20 % of the activated carbon. Furthermore, in the study of Shamsudin et al. (2019), activated carbon derived from PKS was used to isolate hydrogen in syngas leaving carbon dioxide residue which resulted in up to an 88.43 % recovery of hydrogen. Also, a binary mixture of PKS and petroleum coke yielded up to 56 % (by weight) activated carbon with optimal absorption of 2.40 mmol/g of carbon dioxide out of solution (Rashidi and Yusup, 2021). The study of Affam (2020) used central composite design to make biochar from traditional steam activation pyrolysis of PKS and for the isolation of colour and the determination of chemical oxygen demand. At optimal conditions of 725 °C and 90 min, 19.39 % fixed carbon was produced while percentage removal of 61.15 % and 32.02 % for colour and chemical oxygen demand were recorded respectively.

Treatment of phenol toxicity

The absorption of phenol during water treatment can been achieved with PKS-based activated carbon precursor which provides a more affordable and environmentally friendly alternative to commercially available activated carbons. Phenol toxicity in wastewater is a major cause of health issues such as kidney dysfunction, cancerous growths, anaemia, and various nervous and mental disorders in humans (Hair-uddin et al., 2019). Aremu et al. (2020) compared the wastewater phenol detoxication between a commercial absorbent and PKS – based activated carbon preparations. Their results showed that the two forms of KOH – activated carbon: activated carbon from PKS and activated carbon from PKS amended with silver nanoparticles had phenol removal efficiencies of 85.64 % and 90.29 % respectively, thereby comparing favourably with commercial absorbents with characteristic removal efficiency of 91.70 %. Fig. 8(a) presents 3D surface response plots of the effects of time and temperature on biodiesel yield, while Fig. 8(b) shows the effect of agitation and pH on phenol removal from wastewater.

Enhancement of used lubricants

In order to reuse lubricating oils, the study of Boadu et al. (2020) harnessed the high adsorption capacity of PKS and coconut shell – based activated carbon to isolate heavy metal contaminants in used oils. The activated carbon made by soaking palm kernel and coconut shells in K_2CO_3 and $NaHCO_3$ at 800 °C for 180 min were successfully used as absorbents to reduce heavy metal contamination in used lubricating oils.

Enhancement of edible oils

Similar to the enhancement of used lubricants through PKS-based activated carbon, organic pollutant and colour treatment of palm oil mill effluent was conducted in the study of Jalani et al. (2016) using PKS – based activated carbon in both batch and continuous methods. Findings from the study showed that at a dosage of 15 % activated carbon and at a treatment duration of 3 days, efficiencies of 75 % and 76 % were achieved for organic pollutant and colour treatment respectively. Interestingly, this application was reported to run up to 8 recycling times

Table 2
Summary of some chemical and physical properties of PKS.

Property	Fuadi et al. (2012)	Okoroigwe et al. (2014)	Ninduangdee et al. (2015)	Ikumapayi and Akinlabi (2018)	Dagwa and Ibhadode (2008)	Yacob et al. (2013)
Chemical properties						
Cellulose (%)	29.7	6.9	33.4	–	–	–
Hemicellulose (%)	47.7	26.1	14.4	–	–	–
Lignin (%)	53.4	53.9	43.3	–	–	–
Ash (%)	1.1	8.7	4.7	–	–	–
Carbon (wt%)	18.7	–	48.1	60.7	63.0	46.2
Oxygen (wt%)	–	–	34.1	38.0	36.0	45.1
Silicon (wt%)	–	–	–	1.0	0.17	5.25
Aluminium (wt%)	–	–	–	0.1	0.43	3.47
Potassium (wt%)	–	–	–	0.1	0.17	–
Physical properties						
Density (g/cm^3)	1.53	0.74	–	–	1.6	–
Moisture (%)	8.0	6.11	–	–	11.2	–
Porosity (%)	3.9	28.0	–	–	6.7	–

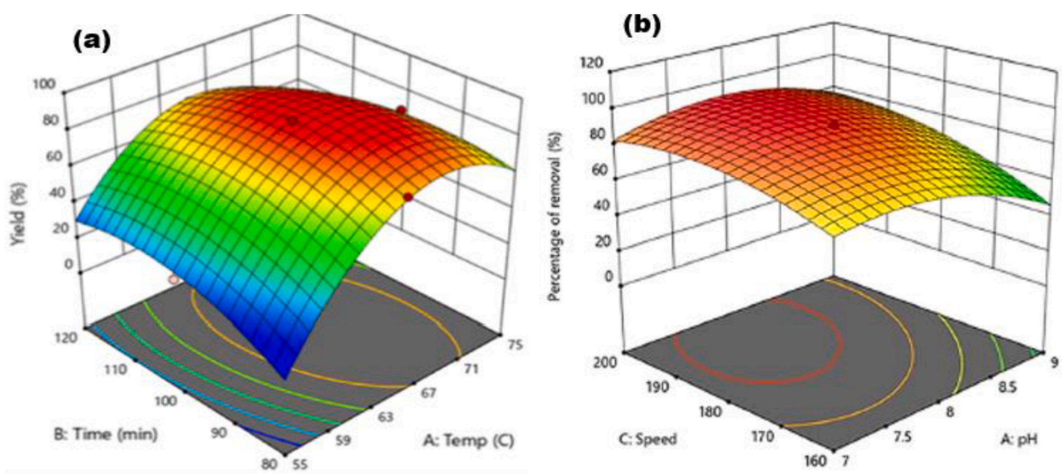

Fig. 8. 3D plots of process parameters on (a) biodiesel yield (Quah et al. 2020) (b) phenol removal (Hairuddin et al. 2019).

before disposal of the activated carbon.

Treatment of wastewater

For wastewater treatment, Mehr et al. (2019), used PKS-based activated carbon to remove chromium (Cr^{6+}) from wastewater. Activated carbon made from calcined PKS was soaked in water containing dissolved equal amounts of KOH and NaOH before being heated and filtered. The biochar was used under different conditions of quantity, time and temperature to optimize its Cr^{6+} absorption capacity. This procedure is similar to the study of Baby et al. (2019) in isolating Cr^{6+}, Pb^{2+}, Cd^{2+} and Zn^{2+} ions in solution. Results from both studies showed that apart from the procedures being eco-friendly, the procedures recorded a maximum adsorption capacity of 125 mg/g of Cr^{6+} in Mehr et al. (2019) while in Baby et al. (2019), adsorptions of 49.55 mg/g, 49.64 mg/g, 43.12 mg/g and 41.72 mg/g of Cr^{6+}, Pb^{2+}, Cd^{2+} and Zn^{2+} respectively were obtained. In another study by Baby and Hussein (2020), phosphoric acid was used to stimulate PKS-based activated carbon which was then used to treat water polluted with heavy metals. Results from the study showed 80 % removal of Zn^{2+} and Cd^{2+} and complete removal of Cr^{6+} and Pb^{2+} from the contaminated water. Similarly, Bakar et al. (2019) studied the performance of PKS (in a quaternized state) as a fluorine ion absorbent with the use of the bio-absorbent for both drinking water and wastewater treatment. Likewise, Fahmi et al. (2019) after obtaining activated carbon from low temperature pyrolysis of PKS reported a high absorption capacity for the bio-absorbent in removing methylene blue dye from its solution.

In the study of Prabu et al. (2020) activated carbon was obtained by firstly impregnating PKS with zero-valent iron nanoparticle and then used to remove cadmium (II) ions from a water environment. The Langmuir saturation absorption capacity recorded in the study was up to 425 mg/g which indicates the potency of PKS for the removal of heavy metal. Hayawin et al. (2020) derived a bioabsorbent system from PKS for reducing the pollutant levels of palm oil mill effluent. The study reported that the colour intensity, biological oxygen demand and chemical oxygen demand in the palm oil mill effluent were further reduced by 6.21 %, 3.52 % and 24.79 % respectively using the PKS-based activated carbon.

Bioabsorbents produced from PKS using 3 M KOH and 10 wt% NaOH as activating agents proved effective for the removal of oil and grease from wastewater (Ramli and Ghazi, 2020) and in the removal of Cu^{2+} as a heavy metal contaminant from wastewater (Asnawi et al., 2019). Similar studies report the use of PKS-based activated carbon to isolate Zn^{2+} ions and crystal violet from wastewater with absorption efficiencies of up to 69.73 % of Zn^{2+} ions and 86.4 % crystal violet respectively (Jitjamnong et al., 2020; Kyi et al., 2020). In the study of Hairuddin et al. (2019), magnetic PKS biochar was used to isolate up to 93.39 % of phenol from wastewater similar to the study of Law et al. (2020) which used bioabsorbents from PKS and Kenaf to recover high purity methane from stranded natural gas. In addition, the later study demonstrated a 94.2 % recovery efficiency of 85 % pure methane from the stranded gas.

Refining of ores

PKS was also used as the reducing agent in a carbothermic reduction supplemented with solar energized system to refine complex $FeTiO_3$ ores (Setiawan et al., 2020). Results show that the different heat procedures offered different microstructural phases out of the ilmenite mineral ore with complete reduction attained in 1 h at 1200 °C. Also, several studies have used PKS under pyrometallurgical process to effectively recover valuable metals from slags. For instance, the study of Alfariz et al. (2020) used PKS charcoal complemented with 10 % Na_2CO_3 as coal replacement to recover nickel and iron from nickel slag. At an optimum condition of 15 % PKS charcoal exposed to 1000 °C in 60 min, 0.103 % of nickel and 3.58 % of iron were recovered from the nickel slag. In a similar study, Usman et al. (2020) beneficiated iron and nickel from ferronickel slag using PKS charcoal. The study demonstrated that under optimal conditions of 15 % PKS charcoal, 60 min time duration, temperature of 1000 °C and in the presence of 10 % NaCl, a yield of 5.98 % of iron and 0.153 % of nickel was practically feasible. Similarly, Nurarani et al. (2020), used PKS charcoal to recover valuable metals from a nickel slag. With a reported optimum of 15 % PKS and 10 % Na_2SO_4 at 1000 °C within 60 min, a recovery of 5.13 % and 0.126 % of iron and nickel were achieved respectively. Furthermore, Suharto et al. (2020) refined Mn_2SiO_4 out of pyrolusite through reduction roasting method with 25 % PKS charcoal. The study investigated the effect of increasing temperature in the recovery of manganese from its ore with a maximum recovery efficiency of 41.28 %.

Carbon molecular sieving of biofuels

Carbon molecular sieves (CMS) using PKS-based porous carbon has been a developed technology in improving biogas performance with regards to the separation of CO_2 from methane. In the study of Masruroh et al. (2021), porous PKS-based CMS oxidized in H_2O_2 and soaked in different amines was used for the capture of CO_2 from biogas. The results from the study show that the monoethanolamine impregnated PKS-based CMS had the highest CO_2 chemisorption of 13.3 mg per gram of biogas. In another CO_2/CH_4 separation study (Ariyanto et al., 2021), a PKS-based CMS was impregnated with deep eutectic solvent enriched with an ammonium salt and hydrogen bond donating alcohols similar to the study of Prasetyo et al. (2020) with a CH_4 purity of more than 95 % for both studies. In another study, Chin et al. (2020a) employed PKS-based activated carbon to prepare Mn and Ce oxides catalysts for NOx retrieval from diesel engine exhaust gas. A NO_x scrubbing efficiency of 74 % at 140 °C was recorded for the Mn/PKS system.

BioGraphitization and battery manufacture

The use of PKS as a precursor to biographite production is a technology that is still underdeveloped. Catalyst impregnation of PKS-based carbon prior to its heat treatment to achieve highly crystalline graphite was studied by both Jabarullah et al. (2021) and Othman et al. (2021). The results from their study show that a biographite of high crystallinity and low defects with d_{002} spacing of 0.3351 nm was realized. This is comparable with a d_{002} spacing of 0.3354 nm of pure graphite but lower than the 0.344 for disordered carbon at 1000 °C and 1400 °C respectively. Han et al. (2020) made heteroatom-doped permeable activated carbon from PKS used in lithium–sulfur batteries.

Use of PKS in construction

Use in concrete

The construction industry has employed as either complete or partial substitutes for binders or aggregates. Several studies have investigated the suitability of PKS as a single substitute (Olanitori and Okusami, 2019; Azunna, 2019; Gibigaye et al., 2017; Yusuf et al., 2018; Oti et al., 2017; Ngagoum et al., 2020), a combination with periwinkle shell (Sulaiman and Olatunde, 2019; Ogundipe et al., 2021), sisal fibre (Ishaya et al., 2019), laterite (Fanijo et al., 2020) as well as in partial replacements of coarse and fine aggregates in concrete. The incorporation of biomass such as PKS have been encouraged in recent times due to increasing depletion of natural construction aggregate from the environment, hence attracting research attention.For example, the ban on beach excavation of terrazzo chippings in India motivated the study of Yalley (2018) which recommended the use of PKS as a fractional substitute of terrazzo chippings in terrazzo floor finish. While the study of Vasudevan and Subramaniam (2020) investigated the possibility of partially replacing cement with PKS in lightweight geopolymer concrete, Razak et al. (2017), combined PKS and fly ash for the partial replacement of the cement. The study of Adewole (2016), used pulverized PKS in Portland cement to make lightweight masonry mortar for wall construction instead of using river sand. The results from the study demonstrated the suitability of crushed PKS as substitutes to river sand in a bid to enhance affordability in construction while also reducing exploitation of natural sand. Danso and Appiah-Agyei, (2021) investigated the effect of different sizes of PKS when used to partially replace coarse aggregate in concrete. Their findings showed that the mechanical properties of the concrete were improved for PKS particle sizes greater than 12 mm.

Odeyemi et al. (2021), used experimental data to formulate models for predicting the depth of chloride ingress into PKS reinforced concrete. Their results showed that PKS increased chloride ingress thereby causing reduction in the compressive strength and an increase in corrosion susceptibility. Furthermore, experimental assessment of porous lightweight PKS concrete showed good performance as grouts (Adeyemi et al., 2017) and as beams (Yusuf et al., 2018). The study also recommended the use of PKS as viable construction material in producing lightweight concrete for use in developing countries. PKS-concrete generally possess densities in the lower band specified by the British Standards for lightweight concrete, hence the recommendation of PKS for lightweight concrete especially in low-cost housing. The use of PKS as a construction aggregate or binder additive is also reported to reduce dependence on limestone used to produce Portland cement thereby reducing carbon emissions.

Use in road pavements

In the study of Olutaiwo and Nnoka (2016), PKS with particle size between 4 and 8 mm were used to substitute 75 % and 100 % coarse aggregates in asphalt concrete for light to heavy traffic roads. The chemical additive used as modifier was zycotherm. Further studies on the effects of particle size of PKS were carried out by Selvam et al. (2020), in which PKS was used as a partial replacement of coarse aggregate in asphalt concrete for low traffic roads. Results from the study showed that the pulverized PKS is suitable for asphalt concrete at a range of 10 – 15 mm particle size and at 5 % weight fraction. PKS and PKS-based nanomaterial were used in the study of Gbadewole et al. (2020) as partial replacement of coarse and fine aggregates in asphalt concretes for highway pavements. Their results showed that 20 % replacement of the coarse and filler aggregates with the PKS and PKS-based nanomaterial offered an optimized air void volume sufficient for bitumen permeation under traffic forces. Similarly, Apeh (2020), recommended 10 % and 50 % replacement of aggregates with PKS for heavy and light traffic roads respectively. Also, Oyedepo et al. (2015), used PKS derivatives as partial replacement of fine and coarse aggregates in asphalt concrete. Their results showed that at 20 % replacements of asphalt aggregates, PKS and crushed PKS had stability values of 2,860 kg and 1,033 kg respectively validating their suitability in various categories of asphaltic concrete road pavements. Likewise, Oyedepo and Olukanni (2015) used PKS and PWS as partial replacement of coarse aggregates in asphalt concrete. Their results showed that 10 % replacements of PKS, PWS and their combined state recorded Marshall Stability values of 3.00 kN, 2.33 kN and 3.22 kN respectively and these values are suitable for light traffic roads.

Use of PKS in soil stabilization

In the improvement of the geotechnical properties of laterite, powdered PKS as well as PKS ash were successfully employed for soil stabilization (Onyelowe and Maduabuchi, 2017; Okonkwo, 2019;

Adeboje et al., 2017). Ayodele and Popoola, (2019) used a blend of PKS and snail shell powder while Arifin and Rahman (2019) used a mixture of PKS ash and cement to stabilize clay soil. In ceramics processing, Kadir et al. (2017) used PKS as a partial replacement of clay component in fired brick. Comparison between 1 and 10 % replacement of clay in fired bricks using PKS, showed that 1 % PKS inclusion in the clay formulation offered the highest compressive strength of 24.61 MPa compared to 19.52 MPa of the control sample. In addition to other appreciable physical properties like porosity and shrinkage of 16.32 % and 0.93 % respectively, PKS inclusion in fired bricks served as both waste recovery and improvement in bricks performance. In road construction, Adeboje et al. (2017) used crushed PKS to stabilize the laterite subgrade. Their results showed that the maximum dry density, soaked California bearing ratio and unconfined compressive strength increased from 1.76 to 1.94 kN/m^2, 24 to 53 kN/m^2 and 46.69 to 127.08 kN/m^2 respectively with corresponding increase in PKS inclusion in the soil from 0 to 12.5 %. Also, the optimum moisture content was noticed to decrease from 14.69 to 12.65 %, hence implying that PKS-stabilized laterite is suitable for road construction.

Combustion and gasification for energy needs

Combustion

Pyrometallurgical distillation of PKS into bio-oil was carried out in the study of Qarizada et al. (2019) in which PKS proved to be a value-added feedstock with a bio-oil yield of 70 % by weight with a heating value of 26 MJ/kg obtained at 120 °C. Similarly, the study of Sanjuan-Acosta et al. (2021) proposed pyrolysis and organosolv as two prospective superstructure optimization routes for PKS conversion to bio-ethanol. Also, Sabzoi et al. (2016) extensively discussed the pyrolytic conversion of PKS into solid char as a potential biofuel. They demonstrated that PKS as a feed for char offers higher heating value and carbon content. Also, Mbada et al. (2016) analyzed the heating values of carbonized PKS which were found close to those of anthracite and bituminous coals but higher than conventional lignin and peat. These outcomes reveal the potentials of PKS as environmentally friendly substitute to fuels from fossil origin.

Pouya et al. (2016), efficiently produced aromatic hydrocarbons using Fe/HBeta catalytic pyrolysis of palm kernel shell waste. Patrick et al. (2020), compared the kinetics of catalytic and noncatalytic breakdown of PKS. Their results show that the catalyst (H_2SO_4 treated coal bottom ash), increased the rate of breakdown by reducing the activation energy to between 145.7242 and 142.1033 kJ mol^{-1} based on the two kinetic models used. In another comparison, Tumsa et al. (2019), compared burnout rate, efficiency and nitrogen dioxide emissions of PKS combustion and bituminous coal at different oxidizing conditions. Their results show that PKS combustion had a lower burnout efficiency and 32.3 % less nitrogen monoxide emission than Sebuku coal. Also, the PKS valorization exhibited an improved burnout rate as well as 16.5 % less nitrogen monoxide emission under oxy-fuel than air-fired condition. Also, Ahmad et al. (2020b), studied the thermal dehydration of PKS using microwave radiation as a pretreatment. Optimum results of the torrefied PKS were obtained at an optimal microwave power and temperature of 450 W and 270 °C respectively. The influence of reaction parameters like temperature, time, rate of agitation, pH of the reaction medium was also studied.

The influence of duration and temperature on the anerobic decomposition of PKS with respect to biochar yield was investigated in the study of Hasan et al. (2019). A similar study by Dirgantara et al. (2020), investigated energy yield instead. The optimal decomposition conditions reported were at a temperature and time of 400 °C and 30 min respectively with a biochar yield of 43.13 %. Similarly, (Hasan et al., 2019) at 275 °C and 20 min obtained an energy yield of 87 %. However, the yields reduced for both studies as the optimal conditions were increased.

Gasification

The environmental issues accruing from the rapidly depleting fossil fuel has generated much attraction towards renewable energy sources such as biofuels. PKS is among the agro-wastes that has demonstrated huge potentials to solving the current energy problems in terms of both economy and environmental sustainability. Key areas of eco-friendly waste conversion are gasification and combustion of biomass. In the study of Suheria and Kuprianov (2015), the fluidized bed combustion of PKS co-fired with palm fruit bunch as a secondary fuel was carried out. Combustion efficiency of up to 99 % was recorded with the incorporation of the secondary fuel thereby reducing the nitrogen monoxide emission by 35 %. As a carbon-rich biomass, air gasification of PKS was performed in the study of Dechapanya et al. (2020) to produce syngas. A NiO/CaO catalyst supplemented with biochar from mangosteen and durian peel residues was used to remove the tar produced which in turn increased the syngas yield efficiency. Also, Rezk et al. (2019) used an optimization algorithm to improve syngas yield from PKS. With specified optimal conditions of particle size, weight of coal bottom ash, CaO/biomass ratio and temperature, a syngas yield of 65.44 % was obtained.

Several studies have validated computational modelling using data from experimental results. For instance, Shahbaz et al. (2017) used Aspen Plus® modelling tool to simulate syngas production during PKS steam gasification with the simulation results in good agreement with experimental outcomes. Also, the study of Acevedo-Paez et al. (2019), used the same Aspen Plus® tool to model and simulate the PKS gasification for making hydrogen. Results predicted a maximum yield of 109 g H_2 per kg of PKS at the least steam/biomass ratio at 950 °C. Their findings with 0.135 mean square error against the benchmark of 0.282 demonstrates a good fit between the simulated prediction and the experimental results. Furthermore, on the use of Aspen Plus®, Putro et al. (2020) made syngas (carbon monoxide and hydrogen) from PKS with their results forecasting 2.6–2.7 Nm^3 of syngas per kg of PKS. Thoharudin et al. (2020) used computational fluid dynamics to investigate the pyrolysis of PKS. Both simulated and experimental thermal breakdown in the fluidized bed reactor revealed that loading rate and operating temperature are key determinants of tar yield with maximum yield of 60.5 % at 500 °C.

Co-gasification

This is another means of waste conversion into useful energy where two or more solid wastes are converted to a gaseous fuel. For instance, good blends for co-gasification of PKS with other energy sources such as PKS with bituminous coal for syngas (Thiagarajan et al., 2019), PKS with Mukah Balingian coal for tar, biochar and gas production (Ahmad et al., 2020a) and PKS with polystyrene (Basha and Sulaiman, 2020) have been investigated. The blend ratio was a predominant factor in the study of Thiagarajan et al. (2019) while fixed bed reactor pretreatment was the focus in the study of Ahmad et al. (2020a). The impact of polystyrene content was emphasized in the study of Basha and Sulaiman, (2020) for the effective thermal conversion of feedstock into useful energy.

Catalytic production of biodiesel

In the study of Abdullah et al. (2020), activated carbon from PKS was used as transesterification–esterification nanocatalysts for the conversion of waste cooking oil to biodiesel. Similarly, Quah et al. (2020) used same PKS biochar infused with Fe_3O_4 to obtain a magnetic and sulfonated catalyst for transesterification of used cooking oil into biodiesel. Comparatively, a maximum biodiesel yield and methanol-oil molar ratio of 95 % and 12:1 respectively were obtained at 80 °C within 240 min (Abdullah et al., 2020) while an optimum of 90.2 % biodiesel yield and 13:1 methanol-oil molar ratio at 65 °C in 102 min were reported in another study (Quah et al., 2020). Kim et al. (2014) conducted a fluidized bed catalytic pyrolysis of PKS with their results suggesting huge potentials of oil for biodiesel and petrochemical refinery. In another study (Farabi et al., 2019), sulphonated PKS and bamboo biomass were used to synthesize biocatalysts for biodiesel production from palm fatty acid distillate. The biodiesel yield obtained by employing the PKS and bamboo biomass catalysts were 95 % and 94.2 % respectively at 65 °C and at a methanol-palm fatty acid distillate molar ratio of 15:1 within 60 min.

PKS as reinforcement in composites

Use in polymer composites

An area of numerous applications of PKS derivatives is as reinforcement for composites. The suitability of PKS as a reinforcement in PKS-LDPE composite was investigated in the studies of Inegbedion et al. (2021) and Nafu et al. (2020). Results investigating the effect of PKS weight fraction in the study of Inegbedion et al. (2021), showed an improvement of 76.06 % in stiffness, 55.07 % in ductility, 53.86 % in tensile strength and 24.33 % in hardness at 50 %, 10 %, 40 % and 50 % of PKS inclusion in the composite respectively. While studying the effect of PKS particle sizes, Nafu et al. (2020), recorded maximum results in compressive stress of 0.75 MPa, flexural stress of 0.44 MPa, density of 0.852 g/cm^3, and stiffness of 1754 MPa at 1 mm, 5 mm, 3 mm and 5 mm respectively. In the study of Husna et al. (2019), effect of weight fraction of PKS as well as pre-treatment with sodium bicarbonate was investigated using PKS as reinforcement in recycled high-density polyethylene matrix. Optimal results showed that, 30 % PKS fraction increased the stiffness by about 44.44 % and 22.22 % in the sodium bicarbonate treated and untreated conditions respectively. However, the 10 % PKS inclusion reduced the composite tensile strength by 13.04 % and 28.26 % in the treated and untreated conditions respectively.

PKS treated with 2 wt% of 3-aminopropyltriethoxysilane was compared with the untreated samples and both were used as fillers in a polypropylene matrix biocomposite in the studies of Lin et al. (2016) and Omar et al. (2015). The treated PKS reinforcement showed superior properties. For instance, in Lin et al. (2016), at 10 % PKS loading, the tensile strength increased by 17.24 % and 3.45 % for the silane treated and untreated PKS respectively with flexural strengths by 19.57 % and 15.22 % accordingly. However, reduced ductility and moisture resistance were observed in all weight fractions studied. Similarly, in Omar et al. (2015), though the inclusion of PKS into the composite reduced the degree of crystallinity from 34.8 % to 31.7 %, yet silane treatment of the PKS made a significant improvement in the thermal stability by up to 37.6 % crystallinity at almost the same melting point of about 163 °C.

Alias et al. (2018), made a biocomposite with PKS ash reinforced in a polyvinyl alcohol matrix. Results showed that at 30 % weight fraction of PKS in the composite, the stiffness increased from about 95 to 330 MPa with about 21.62 % rise in biodegradability at 40 % PKS. However, at 10 % PKS reinforcement, the tensile strength decreased from 33 MPa to 11.5 MPa while the ductility dropped from 340 to 75 %. Sahari and Maleque (2016), used PKS as a reinforcement in unsaturated polyester matrix composite. Optimal weight fraction of PKS at 30 % displayed a tensile modulus of 8.5 GPa showing 1.18 times higher than the unreinforced polymer). Valášek et al. (2019) used PKS to increase shear strength in epoxy composite while Oladele et al. (2020), made a hybrid of PKS-cassava peel particles as reinforcement in epoxy composite leading to increased stiffness, higher flexural strength and improved wear resistance. In the study of Habrová et al. (2020), PKS was used to reduce the aging effect of epoxy resins products. The developed PKS-epoxy composite had a tensile strength only about 3 % greater than the unfilled epoxy resin material. This result demonstrates how the use of PKS as an industrial waste can be used to achieve both composite reinforcement as well as polymeric ageing recovery.

For polymeric composites used in building construction, Nicholas et al. (2020) used H_3PO_4-activated carbon from PKS filled with *n*-octadecane to form a nanocomposite for thermal energy accumulation. Chin et al. (2020b), produced a composite of activated carbon from PKS impregnated with paraffin. This PKS activated carbon-paraffin composite was further used to make concrete panels for thermal energy storage systems. Results showed that the composite had good thermal delay, as well as chemical and phase change stabilities in service. Likewise, Achukwu et al. (2015) used alkali treated PKS to reinforce an epoxy composite resulting in improved mechanical properties and water absorption.

Use of PKS in metal composites

In metal matrix composites, PKS ash was used as a composite reinforcement embedded in A345 alloy (Ezema and Aigbodion, 2020), AA6063 (Edoziuno et al., 2020), Al-Mg-Si (Oyedeji et al., 2021) and Al-7 %Si-0.3 %Mg (Ezema et al., 2020) matrices. The results presented by Ezema and Aigbodion (2020a) demonstrated that incorporation of PKS reinforcement in the composites improved its seawater corrosion resistance with corrosion current densities of 1.35×10^{-3} and 2.35×10^{-3} A/cm^2 respectively (the higher the corrosion current density, the higher the corrosion susceptibility). Also, in the study of Ezema et al. (2020), optimum results were recorded at 30 °C with reported fatigue strengths of 125 MPa and 146 MPa for the alloy and PKS reinforced composite respectively. Also, the reported densities of 2.64, 2.62 and 2.55 g/cm^3 at 0, 2.5 and 15 wt% of PKS show how increasing PKS weight fraction increases weightlessness of the PKS-A6063 composite. A similar study reported increase in porosities of 1.50 %, 1.84 % and 3.81 % at 0, 2.5 and 15 wt% of PKS respectively in the PKS-A6063 composite (Edoziuno et al., 2020). Similarly, Oyedeji et al. (2021) reinforced Al-Mg-Si using PKS and recorded 37.4 %, 44.4 % and 252.03 % increments in impact strength, hardness, and modulus of rupture respectively.

Other application of PKS

Abrasives for cutting and machining tools

Afolalu et al. (2018) developed a cutting tool from recycled steel with the incorporation of PKS as the carbon replacement. The results obtained demonstrated good hardness and wear endurance during machining applications. The studies of Ishola et al. (2017) and Mgbemena et al. (2014) separately used PKS as asbestos replacement in brake pads with results demonstrating potential suitability. In their results, the PKS brake pads had thermal decomposition temperature and wear rate of 634.87 °C and 0.006 μm/minute respectively compared to the 583.57 °C and 0.004/minute of the commercial brake pads. This showed that the PKS abrasive has better thermal stability but moderate wear rate. Similarly, Sa'ad et al. (2021) used a combination of pulverized PKS and coconut shell as abrasives. The abrasive was embedded in a polyester resin matrix to make sandpaper. At a sieve size of 420 μm, 150 °C and 120 g of PKS and coconut shell in the polyester matrix, the sandpaper recorded wear rates of 1.88 and 2.22 mg/m respectively. The composite demonstrated stable mechanical and physical properties suitable for grinding and polishing purposes.

Oil and gas refinery

In the oil and gas industry, PKS was used in the study of Ayodele and Adewale (2020) to solve loss circulation and stuck pipe problems during drilling. The results recommended the exploitation of PKS as an alternative local and cost-effective additive to the imported loss circulation materials. Also, Mamudu et al. (2021) used PKS to synthesize zeolite through liquid phase molecular transport method. The spongy and absorbent zeolite crystals were found suitable in fluid catalytic cracking unit for petroleum refineries. In a similar application (Jun et al., 2020), activated carbon from PKS was used to make zeolite-Fe/activated carbon and Fe/activated carbon systems for refining palm oil mill effluent. Their results showed that the two absorbents were effective such that at 4 g/L of zeolite-Fe/activated carbon, 67.2 % COD and 83.1 % colour were removed while Fe/activated carbon system removed 65.6 % COD and 86.8 % colour at 5 g/L.

Application of PKS in agriculture

In the enhancement of soil fertility, Dominguez et al. (2020), used biochar from PKS infiltrated with NH_4NO_3 and KH_2PO_4 to improve crop yield as well as climatic change control. Analysis on the leachate showed that the PKS biochar was a superior release agent than the conventional fertilizer release agent. In palm oil processing, Hidayu et al. (2019) used $ZnCl_2$ to stimulate activated carbon from PKS used to absorb β-carotene from crude palm oil. Results showed 69 % removal efficiency of β-carotene from the crude palm oil. In animal husbandry, feedstock was made from PKS (Ohanaka et al., 2021). They made a good blend of PKS with pig dung and bamboo chips to formulate activated charcoal recommended as livestock feed additive.

Carburization heat treatment

Salawu et al. (2019) used crushed PKS and eggshell in the ratio of 7:3 as a source of graphite during heat treatment of grey cast iron in a muffle furnace. The carburization process at 900 °C produced protective layer of graphite films on the cast iron which increased both the hardness value and wear resistance of the resulting cast iron. Similarly, Umunakwe et al. (2017) used PKS and coconut shell in their separate and combined states as carburizers in heat treatment of low carbon steels. At solutionizing and tempering temperatures of 950 °C and 450 °C respectively, an ultimate tensile strength of about 1200 MPa and case hardness of about 55 HRA were recorded at a carburizer ratio of 1:4 of PKS and coconut shell.

Healthcare

To solve plaque and teeth discoloration, Syamsurizal et al. (2019) compared the absorption capacity of a commercial charcoal to activated carbon from PKS. Findings showed that the PKS derivative was twice better even under pH changes. Similarly, Lestari et al. (2019), made a powdered deodorant preparation from activated carbon from PKS for sweat absorption. Results from this formulation showed that the PKS powder was both high in storage stability and effectiveness for sweat absorption from the skin than when compared with a conventional deodorant roll-on.

Biotechnological applications of PKS

The biodegradable antibacterial, antifungal, antioxidant and anti-inflammatory properties of PKS have been established due to its high phenolic content when pyrolyzed (Sundalian et al., 2021). Practically, several studies obtained pyroligneous acid from pyrolyzed PKS while fumes from pyrolyzed PKS and empty fruit bunches were condensed into liquid smoke in (Rabiu et al., 2020; Mahmud et al., 2019; Sulong et al., 2020; Ni'mah et al., 2019). Optimal conditions of 375 g PKS with 125 g empty bunches had a yield of 266 ml of liquid smoke at 500 °C. Due to the high phenol content of the fractionated pyroligneous acid or liquified smoke, the products were recommended as a fungicide, antioxidant, and bactericide for nitric oxide inhibition and against odor development in latex. Bio-oil from pyrolyzed PKS was studied in Chan et al. (2017) through hydrothermal liquefaction of PKS between subcritical and supercritical water and yielded biofuel with higher heating values of up to 16 MJ/Kg. In bioimaging, the study of Ang et al. (2020) produced UV-radiation-stimulated multicolor luminescent carbon nanoparticles (known as carbon dots) by passing PKS through microwave irradiation. Results showed that a carbon dot yield of up to 44 % was possible. This highly affordable and available PKS as a raw material proved to be non-toxic to bacterial cellular imaging and detection as well as removal of heavy metals like Cu^{2+} from contaminated media.

Glass, drugs, and rubber vulcanizate production

In separate studies, reformed sol–gel technique was used to make up to 54.35 % and 56.65 % silica nanoparticles from PKS ash (Imoisili et al., 2019; Imoisili et al., 2020). These nanoparticles were recommended for glass and drug manufacturing while solving waste disposal challenges. For making rubber, Malomo et al. (2020) used H_3PO_4 and KOH in chemical activation of carbon from PKS used in combination of carbon black to make natural rubber vulcanizates. In a separate investigation, Abbas et al. (2019) used 100 µm PKS biochar particles to reduce the tear strength of the rubber vulcanizates.

Fashion design

In a way of diversifying the material base in costume jewelry, the study of Quaye et al. (2016) exploited the affordable, available and aesthetic features of PKS. This is an emerging potential area of utilization of PKS which should be sought after.

Conclusion

The state of the art on the numerous applications of PKS as an affordable and eco-friendly material has been discussed and presented. Associated advantages such as carbon-neutrality, biodegradability, affordability and availability of this agricultural waste was also discussed with the aim of drawing attention to its potentials at domestic and industrial applications. Characterizations discussed included XRD for crystallographic mineral composition of PKS, XRF aimed at identifying the presence and abundance of resident elements, SEM for morphological changes, FTIR for identifying resident functional groups and TGA/DTA for thermal behaviour. Although there is significant variation between the reported values from literature, it is not unusual for plant parts even from the same species to differ significantly in characteristics due to functional grading of tissues. It is therefore important to investigate carefully before adopting reported values available in literature. Overall, the findings reveal various properties of PKS that favour its application as a bioabsorbent and detoxifier in wastewater and gas streams, antibacteria, antifungi, antioxidants, healthcare, fashion, glass manufacture, abrasives, syngas, biodiesel and rubber vulcanization. Information from this review can be used by scientists and policy makers in research and decision-making towards the sourcing of renewable energy as well as the pursuit of sustainability.

Recommendation

It is recommended that PKS be further investigated for medical applications where their absorptive capacities to isolate toxins and undigested minerals in the urinary, respiratory and circulatory systems can be utilized. In jewelry-making and in skincare, continued effort in cosmetics to utilize the absorptive potencies of activated carbon used in clearing out toxins and clogged particles from skin pores is also recommended.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors of this review hereby acknowledge all authors whose publications were cited. No funding or sponsorship was received for this work.

References

Abbas, K., Ghazali, A.M.M., Ong, S.K., 2019. The effect of particle size of palm kernel shell on the mechanical properties and physical properties of filled natural rubber vulcanizates. Mater. Today Proc. 19, 1599–1607. https://doi.org/10.1016/j.matpr.2019.11.188.

Abdullah, R.F., Rashid, U., Taufiq-Yap, Y.H., Ibrahim, M.L., Ngamcharussrivichai, C., Azam, M., 2020. Synthesis of bifunctional nanocatalyst from waste palm kernel shell and its application for biodiesel production. Royal Soc. Chem. 10, 27183–27193. https://doi.org/10.1039/d0ra04306k.

Acevedo-Paez, J., Duran, J.M., Posso, F., Arenas, E., 2019. Hydrogen production from palm kernel shell: Kinetic modeling and simulation. Int. J. Hydrogen Energy. https://doi.org/10.1016/j.ijhydene.2019.10.146.

Achukwu, E.O., Barnabas, A.M., Mamman, A. and Uzochukwu, M.I., (2015). Fabrication of palm kernel shell epoxy composites and study of their mechanical properties. *Nigerian J. Mater. Sci. Eng. 6*(1), 32-38. View Article.

Adeboje, A., Kupolati, W., Sadiku, E., Ndambuki, J., Kambole, C., Ogunleye, O., 2017. Stabilization of lateritic soil with pulverized palm kernel shell (PPKS) for road construction. Afr. J. Sci. Technol. Innov. Dev. 9 (1), 55–60. https://doi.org/10.1080/20421338.2016.1262100.

Adejumo, I.O., Adebiyi, O.A., (2020). Agricultural Solid Wastes: Causes, Effects, and Effective Management. Chapter 10, In: Saleh, H.M., *Strategies of Sustainable Solid Waste Management.IntechOpen.* doi:10.5772/intechopen.93601.

Adewole, K.K., 2016. Development of palm kernel shell lightweight masonry mortar. Int. J. Struct. Constr. Eng. 10 (9), 1241–1244. https://doi.org/10.5281/zenodo.1130537.

Adeyemi, A.O., Anifowose, M.A., Adebara, S.A., Olawuyi, M.Y., Amototo, I.O., (2017). Effect of Palm Kernel Shell (PKS) as aggregate in concrete with varying water cement ratio. *Int. Conf. Sci. Eng. Environ. Technol. 2*(8), 55-62. View Article.

Affam, A.C., 2020. Conventional steam activation for conversion of oil palm kernel shell biomass into activated carbon via biochar product. Glob. J. Environ. Sci. Manage. 6 (1), 15–30. https://doi.org/10.22034/gjesm.2020.01.02.

Afolalu, S.A., Abioye, A.A., Idirisu, J., Okokpujie, I.P., 2018. Abrasion wear of cutting tool developed from recycled steel using palm kernel shell as carbon additive. Prog. Ind. Ecol. – Int. J. 12 (1), 206–218. https://doi.org/10.1504/PIE.2018.10014662.

Ahmad, R., Ishak, M.A.M., Kasim, N.N., Ismail, K., 2020a. Effect on product yield and tar composition through co-gasification of pretreated palm kernel shell and mukah balingian coal. IOP Conf. Ser. Mater. Sci. Eng. 864 https://doi.org/10.1088/1757-899X/864/1/012210.

Ahmad, R., Ishak, M.A.M., Kasim, N.N., Ismail, K., 2020b. Torrefaction of palm kernel shell using conventional and microwave irradiation pretreatment. IOP Conf. Ser.: Earth Environ. Sci. 476 https://doi.org/10.1088/1755-1315/476/1/012073.

Alfariz, M.D., Mayangsari, W., Prasetyo, A.B., Maksum, A., Prasetyo, T., Ulum, R.M., Soedarsono, J.W., 2020. Effect of Sodium Carbonate (Na_2CO_3) additives and palm kernel shell charcoal to increase nickel and iron content from ferronickel slag using the pyrometallurgical method. AIP Conf. Proc. 2255 https://doi.org/10.1063/5.0014052.

Alias, N.F., Ismail, H., Ab Wahab, M.K., Ragunathan, S., Ardhyananta, H., Ting, S.S., 2018. Development of new material based on polyvinyl alcohol/palm kernel shell powder biocomposites. Adv. Environ. Stud. 2 (2), 98–107. https://doi.org/10.36959/742/208.

Ang, W.L., Mee, C.A.L.B., Sambudi, N.S., Mohammad, A.W., Leo, C.P., Mahmoudi, E., Ba-Abbad, M., Benamor, A., 2020. Microwave–assisted conversion of palm kernel shell biomass waste to photoluminescent carbon dots. Sci. Rep. 10 https://doi.org/10.1038/s41598-020-78322-1.

Apeh, O.A.S., 2020. Assessment of palm kernel shells as partial replacement of coarse aggregates in highway pavements. Int. J. Eng. Manage. 4 (2), 25–29. https://doi.org/10.11648/j.ijem.20200402.12.

Aremu, M.O., Arinkoola, A.O., Olowonyo, I.A., Salam, K.K., 2020. Improved phenol sequestration from aqueous solution using silver nanoparticle modified Palm Kernel Shell Activated Carbon. Heliyon 6. https://doi.org/10.1016/j.heliyon.2020.e04492.

Arifin, Y.F., Rahman, G., 2019. Stabilization of soft soil with cement and palm kernel shell ash admixture. Web Conf. 280 https://doi.org/10.1051/matecconf /201928004011.

Ariyanto, T., Masruroh, K., Pambayun, G.Y.S., Mukti, N.I.F., Cahyono, R.B., Prasetya, A., Prasetyo, I., 2021. Improving the separation of CO_2/CH_4 using impregnation of deep eutectic solvents on porous carbon. ACS Omega 6, 19194–19201. https://doi.org/10.1021/acsomega.1c02545.

Asnawi, T.M., Husin, H., Adisalamun, A., Rinaldi, W., Zaki, M., Hasfita, F., 2019. Activated carbons from palm kernels shells prepared by physical and chemical activation for copper removal from aqueous solution. Mater. Sci. Eng. 543 https://doi.org/10.1088/1757-899X/543/1/012096.

Ayodele, E., Adewale, D., (2020). Experimental characterization of palm kernel shell as wellbore strengthening material for depleted and loss circulation zones. *Society of Petroleum Engineers*, (pp. 1-22). Lagos. doi:10.2118/203633-MS.

Ayodele, F.O., Popoola, O.O., 2019. Potential of Snail shell and palm kernel shell powders in improving engineering properties of clay. J. Appl. Sci. Environ. Manage. 23 (8), 1437–1444. https://doi.org/10.4314/jasem.v23i8.5.

Azunna, S.U., 2019. Compressive strength of concrete with palm kernel shell as a partial replacement for coarse aggregate. SN Appl. Sci. 1 (342), 1–10. https://doi.org/10.1007/s42452-019-0334-6.

Baby, R., Hussein, M.Z., 2020. Ecofriendly approach for treatment of heavy-metal-contaminated water using activated carbon of kernel shell of oil palm. Materials 13. https://doi.org/10.3390/ma13112627.

Baby, R., Saifullah, B., Hussein, M.Z., 2019. Palm Kernel Shell as an effective adsorbent for the treatment of heavy metal contaminated water. Sci. Rep. 9 (18955), 1–11. https://doi.org/10.1038/s41598-019-55099-6.

Bakar, A.H.A., Abdullah, L.C., Zahri, N.A.M., Alkhatib, M., 2019. Column efficiency of fluoride removal using Quaternized Palm Kernel Shell (QPKS). Int. J. Chem. Eng. 1–13 https://doi.org/10.1155/2019/5743590.

Basha, M.H., Sulaiman, S.A., 2020. Air co-gasification of palm kernel shell and polystyrene: effect of different polystyrene content. IOP Conf. Ser. Mater. Sci. Eng. 863 https://doi.org/10.1088/1757-899X/863/1/012023.

Boadu, K.O., Joel, O.F., Essumang, D.K., Evbuomwan, B.O., 2020. Adsorption of heavy metals contaminants in used lubricating oil using palm kernel and coconut shells activated carbons. Am. J. Chem. Eng. 8 (1), 11–18. https://doi.org/10.11648/j.ajche.20200801.13.

Chan, Y.H., Quitain, A.T., Yusup, S., Uemura, Y., Sasaki, M., Kida, T., 2017. Liquefaction of palm kernel shell in sub- and supercritical water for bio-oil production. J. Energy Inst. 1–12 https://doi.org/10.1016/j.joei.2017.05.009.

Chin, T.Y., Yakub, I., Hin, T.Y., 2020b. Evaluation of catalysts derived from palm kernel shell carbon in a passive NOx removal from a diesel engine exhaust. Emission Control Sci. Technol. https://doi.org/10.1007/s40825-020-00164-0.

Chin, C.O., Yang, X., Paul, S.C., Susilawati, Wong, L.S., Kong, S.Y., 2020a. Development of thermal energy storage lightweight concrete using paraffin-oil palm kernel shell-activated carbon composite. J. Cleaner Prod. 261 https://doi.org/10.1016/j.jclepro.2020.121227.

Dagwa, I.M., Ibhadode, A.O., 2008. Some physical and mechanical properties of palm kernel shell (PKS). Botswana J. Technol. 17 (2) https://doi.org/10.4314/bjt.v17i2.52206.

Danso, H., Appiah-Agyei, F., 2021. Size variation of palm kernel shells as replacement of coarse aggregate for lightweight concrete production. Open J. Civ. Eng. 11, 153–165. https://doi.org/10.4236/ojce.2021.111010.

Dechapanya, W., Rattanahirun, S., Khamwichit, A., 2020. Syngas production from palm kernel shells with enhanced tar removal using biochar from agricultural residues. Front. Energy Res. 8 (157) https://doi.org/10.3389/fenrg.2020.00157.

Dirgantara, M., Karelius, Cahyana, B.T., Suastika, K.G., Akbar, A.R.M., 2020. Effect of temperature and residence time torrefaction palm kernel shell on the calorific value and energy yield. J. Phys. Conf. Ser. 1428 https://doi.org/10.1088/1742-6596/1428/1/012010.

Dominguez, E.L., Uttran, A., Loh, S.K., Manero, M., Upperton, R., Tanimu, M.I., Bachmann, R.T., 2020. Characterisation of industrially produced oil palm kernel shell biochar and its potential as slow release nitrogen-phosphate fertilizer and carbon sink. Mater. Today Proc. https://doi.org/10.1016/j.matpr.2020.05.143.

Dungani, R., Aditiawati, P., Aprilia, S., Yuniarti, K., Karliati, T., Suwandhi, I., Sumardi, I., (2018). Biomaterial from Oil Palm Waste: Properties, Characterization and Applications. Chapter 3, In: Waisundara, V. , (Ed.). Palm Oil. IntechOpen. doi:10.5772/intechopen.76412.

Edoziuno, F.O., Adediran, A.A., Odoni, B.U., Utu, O.G., Olayanju, A., 2020. Physico-chemical and morphological evaluation of palm kernel shell particulate reinforced aluminium matrix composites. Mater. Today Proc. https://doi.org/10.1016/j.matpr.2020.03.641.

Ezema, I.C., Aigbodion, V.S., 2020. Explicit microstructural evolution and electrochemical performance of value added palm kernel shell ash nanoparticle/A356 alloy composite. Materialwiss. Werkstofftech 51, 324–329. https://doi.org/10.1002/mawe.201900071.

Ezema, I.C., Aigbodion, V.S., Okonkwo, E.G., Obayi, C.S., 2020. Fatigue properties of value-added composite from Al-Si-Mg/palm kernel shell ash nanoparticles. Int. J. Adv. Manuf. Technol. https://doi.org/10.1007/s00170-020-05268-z.

Fahmi, A.G., Abidin, Z., Kusmana, C., Kharisma, D., Prajaputra, D., Rahmawati, W.R., 2019. Preparation and characterization of activated carbon from palm kernel shell at low temperature as an adsorbent for methylene blue. Earth Environ. Sci. 399 https://doi.org/10.1088/1755-1315/399/1/012015.

Fanijo, E., Babafemi, A.J., Arowojolu, O., 2020. Performance of laterized concrete made with palm kernel shell as replacement for coarse aggregate. Constr. Build. Mater. 2020 https://doi.org/10.1016/j.conbuildmat.2020.118829.

Farabi, M.S.A., Ibrahim, M.L., Rashid, U., Taufiq-Yap, Y.H., 2019. Esterification of palm fatty acid distillate using sulfonated carbon-based catalyst derived from palm kernel shell and bamboo. Energy Convers. Manage. 181, 562–570. https://doi.org/10.1016/j.enconman.2018.12.033.

Fuadi, N.A.B, Ibrahim, A.S., Ismail K.N. Review study for activated carbon from palm shell used for the treatment of wastewater. *J. Purity Util. React. Environment,* 1, 252-266.

Gbadewole, O.A., Alayaki, F.M., Adekunle, A.A., Dada, P.O., 2020. Evaluation of palm kernel shell and its nano-variant as aggregates in asphalt concrete. Egypt. Int. J. Eng. Sci. Technol. 32, 43–48. https://doi.org/10.21608/eijest.2021.48247.1024.

Gibigaye, M., Godonou, G.F., Katte, R., Degan, G., 2017. Structured mixture proportioning for oil palm kernel shell concrete. Case Stud. Constr. Mater. 6, 219–224. https://doi.org/10.1016/j.cscm.2017.04.004.

Habrová, K., Valášek, P., Müller, M., 2020. The effect of aging on the decrease in tensile strength of composites with palm oil kernel shell powder. Solid State Phenom. 305, 18–22. https://doi.org/10.4028/www.scientific.net/SSP.305.18.

Hairuddin, M.N., Mubarak, N.M., Khalid, M., Abdullah, E.C., Walvekar, R., Karri, R.R., 2019. Magnetic palm kernel biochar potential route for phenol removal from wastewater. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-019-06524-w.

Han, X., Guo, X., Xu, M., Pang, H., Ma, Y., 2020. Clean utilization of palm kernel shell: sustainable and naturally heteroatom-doped porous activated carbon for lithium–sulfur batteries. Rare Met. https://doi.org/10.1007/s12598-020-01439-9.

Hasan, M.H.M., Bachmann, R.T., Loh, S.K., Manroshan, S., Ong, S.K., 2019. Effect of pyrolysis temperature and time on properties of palm kernel shell-based biochar. IOP Conf. Ser. Mater. Sci. Eng. 548 https://doi.org/10.1088/1757-899X/548/1/012020.

Hayawin, Z.N., Ibrahim, M.F., Faizah, J.N., Ropandi, M., Astimar, A.A., Noorshamsiana, A.W., Abd-Aziz, S., 2020. Palm oil mill final discharge treatment by a continuous adsorption system using oil palm kernel shell activated carbon produced from two-in-one carbonization activation reactor system. J. Water Process Eng. 36 https://doi.org/10.1016/j.jwpe.2020.101262.

Hidayu, A.R., Sukor, M.Z., Mohammad, N.F., Elham, O.S.J., Azri, N.I., Azhar, M.A.I., Jalil, M.J., 2019. Preparation of activated carbon from palm kernel shell by chemical activation and its application for β-carotene adsorption in crude palm oil. J. Phys. Conf. Ser. 1349 https://doi.org/10.1088/1742-6596/1349/1/012103.

Husna, N., Lim, B.Y., Voon, C.H., Teh, P.L., 2019. Properties of eco-friendly composites: palm kernel shell treated with sodium bicarbonate filled recycled high-density polyethylene. Mater. Sci Eng. 701 https://doi.org/10.1088/1757-899X/701/1/012035.

Hussain, M., Tufa, L.D., Yusup, S., Zabiri, H., 2019. Thermochemical behavior and characterization of palm kernel shell via TGA/DTG technique. Mater. Today Proc. 16, 1901–1908. https://doi.org/10.1016/j.matpr.2019.06.067.

Ikubanni, P.P., Oki, M., Adeleke, A.A., Adediran, A.A., Adesina, O.S., 2020. Influence of temperature on the chemical compositions and microstructural changes of ash formed from palm kernel shell. Results in Engineering 8. https://doi.org/10.1016/j.rineng.2020.100173.

Ikumapayi, O.M., Akinlabi, E.T., 2018. Composition, characteristics and socioeconomic benefits of palm kernel shell exploitation-an overview. J. Environ. Sci. Technol 11 (6), 1–13.

Imoisili, P.E., Ukoba, K.O., Jen, T., (2019). Green technology extraction and characterisation of silica nanoparticles from palm kernel shell ash via sol–gel. *J. Mater. Res. Technol.* 10.1016/j.jmrt.2019.10.059.

Imoisili, P.E., Ukoba, K.O., Jen, T., 2020. Synthesis and characterization of amorphous mesoporous silica from palm kernel shell ash. Bol. Soc. Esp. Ceram. Vidrio 59, 159–164. https://doi.org/10.1016/j.bsecv.2019.09.006.

Inegbedion, F., Igbonazobi, I.C., Imasuen, A.O., Inetianbor, C.O., 2021. Characterization of low-density polyethylene waste filled with palm kernel shell. Int. J. Eng. Technol. Manage. Res. 8 (4), 71–78. https://doi.org/10.29121/ijetmr.v8.i4.2021.918.

Ioannou, Z., Kavvadias, V., Karasavvidis, C., (2015). Recycling of Agricultural Wastes: Treatment and uses. Chapter 1, In: Foster, C.N., Agricultural Wastes: Characteristics, Types and Management. Nova Science Publishers, Inc. USA. View eBook.

Ishaya, A.A., Anowai, S.I., Yahaya, A.M., Williams, F.N., Emeka, O.B., 2019. Performance of sisal fiber in manually crushed palm kernel shell concrete. Sci. Res. J. 7 (5), 36–45. https://doi.org/10.31364/SCIRJ/v7.i5.2019.P0519651.

Ishola, M.T., Oladimeji, O.O., Paul, K.O., 2017. Development of ecofriendly automobile brake pad using different grade sizes of palm kernel shell powder. Curr. J. Appl. Sci. Technol. 23 (2), 1–14. https://doi.org/10.9734/CJAST/2017/35766.

Jabarullah, N.H., Kamal, A.S., Othman, R., (2021). A modification of palm waste lignocellulosic materials into biographite using iron and nickel catalyst. *Processes*, 9 (1079). doi:10.3390/pr9061079.

Jalani, N.F., Aziz, A.A., Wahab, N.A., Hassan, W.H.W., Zainal, N.H., 2016. Application of palm kernel shell activated carbon for the removal of pollutant and color in palm oil mill effluent treatment. J. Earth Environ. Health Sci. 2, 15–20. https://doi.org/10.4103/2423-7752.181802.

Jitjamnong, J., Luengnaruemitchai, A., Kongrit, N., Kasetsomboon, N., Khantikulanon, N., 2020. Efficiency of zinc ions (II) adsorption using activated carbon from palm kernel shell. Earth Environ. Sci. 463 https://doi.org/10.1088/1755-1315/463/1/012069.

Jun, K.C., Raman, A.A.A., Buthiyappan, A., 2020. Treatment of oil refinery effluent using bioadsorbent developed from activated palm kernel shell and zeolite. Royal Soc. Chem. Adv. 10, 24079–24094. https://doi.org/10.1039/d0ra03307c.

Kadir, A.A., Sarani, N.A., Kadir, S.A., 2017. Incorporation of palm kernel shell into fired clay brick. MATEC Web Conf. 1–7 https://doi.org/10.1051/matecconf/201710301017.

Kim, S.W., Koo, S.O., Lee, D.H., 2014. Catalytic pyrolysis of palm kernel shell waste in a fluidized bed. Bioresour. Technol. 167, 425–432. https://doi.org/10.1016/j.biortech.2014.06.050.

Kyi, P.P., Quansah, J.O., Lee, C., Moon, J., Park, S., 2020. The removal of crystal violet from textile wastewater using palm kernel shell-derived biochar. Appl. Sci. 10 (2251) https://doi.org/10.3390/app10072251.

Law, L.C., Abdullah, A., Idris, I., Othman, M.R., 2020. Effect of pressure equalization on methane enrichment from stranded natural gas using PSA with amorphous Kenaf and microporous palm kernel shell adsorbents. Int. J. Energy Res. 44, 6555–6566. https://doi.org/10.1002/er.5388.

Lestari, U., Farid, F., Fudholi, A., 2019. Formulation and effectivity test of deodorant from activated charcoal of palm shell as excessive sweat adsorbent on body. Asian J. Pharm. Clin. Res. 12 (10), 193–196. https://doi.org/10.22159/ajpcr.2019.v12i10.33490.

Lin, O.H., Yee, T.G., Azza, N,A.N.N., Safwan, M.M., Villagracia, A.R., Mern, C.K. and Abdullah, M.M.A., (2016). Utilization of Modified Palm Kernel Shell for Biocomposites Production. *Key Engineering Materials, 700*, 60-69. doi:10.4028/www.scientific.net/KEM.700.60.

Mahmud, K.N., Hashim, N.M., Ani, F.N., Zakaria, Z.A., 2019. Antioxidants, toxicity, and nitric oxide inhibition properties of pyroligneous acid from palm kernel shell biomass. Waste Biomass Valorization. https://doi.org/10.1007/s12649-019-00857-w.

Malomo, D., Olasupo, A.D., Adesigbin, A.M., Egharevba, O., Adewuyi, S.O., Odubunmi, J.O., Idemmudia, L., 2020. Studies on the physicochemical and physico-mechanical properties of activated palm kernel shell blended with carbon black filled NR vulcanizates. J. Eng. Technol. 5 (1), 95–101. https://doi.org/10.46792/fuoyejet.v5i1.478.

Mamudu, A., Emetere, M., Ishola, F., Lawal, D., 2021. The production of zeolite Y catalyst from palm kernel shell for fluid catalytic cracking unit. Int. J. Chem. Eng. 1–8 https://doi.org/10.1155/2021/8871228.

Masruroh, K., Cahyono, R.B., Prasetyo, I., Ariyanto, T., 2021. The effect of amine types on breakthrough separation of methane on biogas. Int. J. Renewable Energy Dev. 10 (2), 249–255. https://doi.org/10.14710/ijred.2021.33514.

Mbada, N.I., Atanda, P.O., Apobiede, O., Abioye, A.A., Ugbaja, M.I., Alabi, A.S., 2016. Performance evaluation of suitability of carbonized palm kernel shell (PKS) as a veritable alternative to coal and charcoal in solid fuel fired furnaces. Int. J. Metall. Eng. 5 (1), 15–20. https://doi.org/10.5923/j.ijmee.20160501.03.

Mehr, M.R., Fekri, M.H., Omidali, F., Eftekhari, N., Akbari-adergani, B., 2019. Removal of Chromium (VI) from wastewater by palm kernel shell-based on a green method. J. Chem. Health Risks 9 (1), 75–86. https://doi.org/10.22034/jchr.2019.584177.1012.

Mgbemena, C.O., Mgbemena, C.E., Okwu, M.O., (2014). Thermal stability of pulverized palm kernel shell (PKS) based friction lining material locally developed from spent waste. *ChemXpress, 5*(4), 115-122. View Article.

Momoh, E.O., Osofero, A.I., Menshykov, O., (2021). Bond behaviour of oil palm broom fibres in concrete for eco-friendly construction. *Proc. Inst. Civ. Eng. – Constr. Mater.* 174(1), 47-64. https://doi.org/10.1680/jcoma.19.00097.

Momoh, E.O., Osofero, A.I., 2019. Behaviour of oil palm broom fibres (OPBF) reinforced concrete. Constr. Build. Mater. 221, 745–761. https://doi.org/10.1016/j.conbuildmat.2019.06.118.

Momoh, E.O., Osofero, A.I., Martinez-Felipe, A., Hamzah, F., 2020. Physico-mechanical behaviour of Oil Palm Broom Fibres (OPBF) as eco-friendly building material. J. Build. Eng. 30, 101208 https://doi.org/10.1016/j.jobe.2020.101208.

Momoh, E.O., Osofero, A.I., 2020. Recent developments in the application of oil palm fibers in cement composites. Front. Struct. Civ. Eng. 14, 94–108. https://doi.org/10.1007/s11709-019-0576-9.

Momoh, E.O., Osofero, A.I., Menshykov, O., 2022a. Enhancing the behaviour of broom-strands reinforced concrete using hose-clamps. Mater. Today Proc. https://doi.org/10.1016/j.matpr.2022.03.187 in press.

Momoh, E.O., Osofero, A.I., Menshykov, O., 2022b. Behaviour of clamp-enhanced palm tendons reinforced concrete. Constr. Build. Mater. 341, 127824 https://doi.org/10.1016/j.conbuildmat.2022.127824.

Nafu, Y.R., Mofor, W.K., Ngaaje, N.N., 2020. Influence of mechanical and physical properties of palm nut shell- plastic composite. Int. J. Eng. Sci. Technol. 4 (6), 30–38. https://doi.org/10.29121/IJOEST.v4.i6.2020.128.

Ngagoum, S.G., Fokwa, D., Tchemou, G., Maxime, E., 2020. Study of physico-mechanical properties of concretes based on palm kernel shells originating from the locality of Haut Nkam in Cameroon. J. Civ. Eng. Constr. Technol. 11 (1), 13–27. https://doi.org/10.5897/JCECT2019.0525.

Ni'mah, L., Setiawan, M.F., Prabowo, S.P., 2019. Utilization of waste palm kernel shells and empty palm oil bunches as raw material production of liquid smoke. Earth Environ. Sci. 366, 1–9. https://doi.org/10.1088/1755-1315/366/1/012032.

Nicholas, A.F., Hussein, M.Z., Zainal, Z., Khadiran, T., 2020. The effect of surface area on the properties of shape–stabilized phase change material prepared using palm kernel shell activated carbon. Sci. Rep. 10 https://doi.org/10.1038/s41598-020-72019-1.

Ninduangdee, P., Kuprianov, V.I., Cha, E.Y., Kaewrath, R., Youngyuen, P., Atthawethworawuth, W., 2015. Thermogravimetric studies of oil palm empty fruit bunch and palm kernel shell: TG/DTG analysis and modeling. Energy Procedia 79, 453–458. https://doi.org/10.1016/j.egypro.2015.11.518.

Nurarani, Usman, S.N.M., Prasetyo, A.B., Maksum, A., Prasetyo, T., Ulum, R.M. and Soedarsono, J.W., (2020). Increasing nickel from nickel slag with Na_2SO_4 additives and palm kernel shell charcoal reductors using the pyrometallurgical method. *AIP Conf. Proc. 2255*. doi:10.1063/5.0014050.

Nwosu-Obieogua, K., Agu, C.M., Dzarma, G.W., Awele, A.M., Nkemakolam, A., 2022. Microwave-assisted carbon-based sulphonated melon seed peel catalyst development for the optimization of neem seed oil epoxidation using response surface methodology. Clean. Mater. 4 https://doi.org/10.1016/j.clema.2022.100069.

Nyamful, A., Nyogbe, E.K., Mohammed, L., Zainudeen, M.N., Darkwa, S.A., Phiri, I., Mohammed, M., Ko, J.M., 2020. Processing and characterization of activated carbon from coconut shell and palm kernel shell waste By H3po4 activation. Ghana J. Sci. 61 (2), 91–104. https://doi.org/10.4314/gjs.v61i2.9.

Obi, F.O., Ugwuishiwu, B.O., Nwakaire, J.N., 2016. Agricultural waste concept, generation, utilization and management. Nigerian J. Technol. 35 (4), 957–964. https://doi.org/10.4314/njt.v35i4.34.

Obuka, N.S.P. Onyechi, P.C. and Okoli, N.C., (2018). Palm oil biomass waste a renewable energy resource for power generation. *Saudi J Eng. Technol. 3*(12), 680-691. doi.org/10.21276/sjeat.2018.3.12.2f.

Odeyemi, S.O., Odeyemi, O.T., Adeniyi, A.G., Giwa, Z.T., Salami, A.K., Adesina, A., 2021. Prediction of chloride ingress for palm kernel shell concrete. Res. Eng. Struct. Mater. 7 (1), 35–49. https://doi.org/10.17515/resm2020.226st0921.

Ogundipe, K.E., Ogunbayo, B.F., Olofinnade, O.M., Amusan, L.M., Aigbavboa, C.O., 2021. Affordable housing issue: experimental investigation on properties of eco-friendly lightweight concrete produced from incorporating periwinkle and palm kernel shells. Results Eng. 9 https://doi.org/10.1016/j.rineng.2020.100193.

Ohanaka, A.U.C., Ukonu, E.C., Ogbuewu, I.P., Etuk, I.F., Okoli, I.C., (2021). *Int. J. Agric. Rural Dev. 24*(1), 5711-5719. View Article.

Okonkwo, U.N., 2019. Critical state of compacted lateritic soil and palm kernel shell ash for earth embankments. In: Proceedings of the Institution of Civil Engineers – Ground Improvement. https://doi.org/10.1680/jgrim.19.00005.

Okoroigwe, E.C., Christopher, M.S., Pascal, D.K., 2014. Characterization of palm kernel shell for materials reinforcement and water treatment. J. Chem. Eng. Mater. Sci. 5 (1), 1–6. https://doi.org/10.5897/jcems2014.0172.

Oladele, I.O., Ibrahim, I.O., Adediran, A.A., Akinwekomi, A.D., Adetula, Y.V., Olayanju, T.M.A., 2020. Modified palm kernel shell fiber/particulate cassava peel hybrid reinforced epoxy composites. Results Mater. 5, 1–7. https://doi.org/10.1016/j.rinma.2019.100053.

Olanitori, L.M., Okusami, J.I., 2019. Comparative strength analysis of normal weight and palm kernel shell reinforced concrete beams for sustainable development. Eur. J. Sustain. Dev. 8 (2), 346–357. https://doi.org/10.14207/ejsd.2019.v8n2p346.

Olutaiwo, A.O., Nnoka, C.C., 2016. Study of the performance of graded Palm Kernel Shells (PKS) as partial replacement for coarse aggregates in hot mix asphalt (HMA) binder course with zycotherm chemical additive. J. Mech. Civ. Eng. 13 (5), 99–109. https://doi.org/10.9790/1684-13050399109.

Omar, M.S.M., Lin, O.H., Akil, H.M., Azza, N.A.N.N., Safwan, M.M., Sofiah, M.K.A., 2015. Thermal properties of polypropylene/palm kernel shell biocomposites: effects of amino silane (APTES). Mater. Sci. Forum 803, 250–254. https://doi.org/10.4028/www.scientific.net/MSF.803.250.

Onyelowe, K.C., Maduabuchi, M.N., 2017. Waste management and application of waste micro-sized palm kernel shell ash (MSPKSA) in the stabilization of engineering soil. Int. J. Waste Resour. 7 (2), 1–3. https://doi.org/10.4172/2252-5211.1000277.

Othman, R., Kamal, A.S., Jabarullah, N.H., 2021. The effect of changing graphitization temperature toward bio-graphite from Palm Kernel Shell. Production Eng. Arch. 27 (2), 124–129. https://doi.org/10.30657/pea.2021.27.16.

Oti, O.P., Nwaigwe, K.N. and Okereke, N.A.A., (2017). Assessment of palm kernel shell as a composite aggregate in concrete. *Agric. Eng. Int. 19*(2), 34-41. View Article.

Otti, V.I, Ifeanyichukwu, H.I., Nwaorum, F.C., Ogbuagu, F.U. (2014). Sustainable oil palm waste management in engineerint development. *Civ. Environ. Res.* 6(5), 121-125. View Article..

Oyedeji, E.O., Dauda, M., Yaro, S.A., Abdulwahab, M., 2021. The effect of palm kernel shell ash reinforcement on microstructure and mechanical properties of Al-Mg-Si metal-matrix composites. J. Mech. Eng. Sci. 1–8. https://doi.org/10.1177/09544062211014535.

Oyedepo, O.J., Olukanni, E.O., 2015. Experimental investigation of the performance of palm kernel shell and periwinkle shell as partial replacement for coarse aggregate in asphaltic concrete. J. Build. Mater. Struct. 2015 (2), 33–40. https://doi.org/10.34118/jbms.v2i2.18.

Oyedepo, O.J., Olanitori, L.M., Olukanni, E.O., 2015. Investigation of palm kernel shell as partial replacement for aggregate in asphaltic concrete. Malaysian J. Civ. Eng. 27 (2), 223–234. https://doi.org/10.11113/mjce.v27.15921.

Patrick, D.O., Yusup, S., Osman, N.B., Zabiri, H., Uemura, Y., Shahbaz, M., 2020. Thermogravimetric kinetics of catalytic and non-catalytic pyrolytic conversion of palm kernel shell with acid treated coal bottom ash. IOP Conf. Ser. Mater. Sci. Eng. 736 https://doi.org/10.1088/1757-899X/736/4/042029.

Pouya, S.R., Shafaghat, H., Wan, M.A., 2016. Aromatic hydrocarbon production by catalytic pyrolysis of palm kernel shell waste using a Bi-functional Fe/HBeta catalyst: effect of lignin derived phenolics on zeolite deactivation. Green Chem. 18 (6), 1684–1693. https://doi.org/10.1039/C5GC01935D.

Prabu, D., Kumar, P.S., Varsha, M., Sathish, S., Anand, K.V., Mercy, J., Tiwari, A., 2020. Potential of nanoscale size zero valent iron nanoparticles impregnated activated carbon prepared from palm kernel shell for cadmium removal to. Int. J. Environ. Anal. Chem. https://doi.org/10.1080/03067319.2020.1828387.

Prasetyo, I., Mukti, N.I.F., Cahyono, R.B., Prasetya, A., Ariyanto, T., 2020. Nanoporous carbon prepared from palm kernel shell for CO_2/CH_4 separation. Waste Biomass Valorization. https://doi.org/10.1007/s12649-020-01006-4.

Putro, F.A., Pranolo, S.H., Waluyo, J., Setyawan, A., 2020. Thermodynamic study of palm kernel shell gasification for aggregate heating in an asphalt mixing plant. Int. J. Renew. Energy Dev. 9 (2), 311–317. https://doi.org/10.14710/ijred.9.2.311-317.

Qarizada, D., Mohammadian, E., Alis, A.B., Yusof, S.M., Dollah, A., Rahimi, H.A., Nazari, A.S., Azizi, M., 2019. Thermo distillation and characterization of bio oil from fast pyrolysis of palm kernel shell (PKS). Key Eng. Mater. 797, 359–364. https://doi.org/10.4028/www.scientific.net/KEM.797.359.

Quah, R.V., Tan, Y.H., Mubarak, N.M., Kansedo, J., Khalid, M., Abdullah, E.C., Abdullah, M.O., 2020. Magnetic biochar derived from waste palm kernel shell for biodiesel production via sulfonation. Waste Manage. 118, 626–636. https://doi.org/10.1016/j.wasman.2020.09.016.

Quaye, H.A., Agyeman, K.K., Tachie-Mensah, J., (2016). Application of Palm Kernel Shells in Costume Jewellery. *Int. J. Innov. Res. Dev. 5*(1), 193-201. View Article.

Rabiu, Z., Hamzah, M.A.A., Hasham, R., Zakaria, Z.A., et al., 2020. Characterization and antiinflammatory properties of fractionated pyroligneous acid from palm kernel shell. Environ. Sci. Pollut. Res. 1–9 https://doi.org/10.1007/s11356-020-09209-x.

Ramli, A.N., Ghazi, R.M., 2020. Removal of oil and grease in wastewater using palm kernel shell activated carbon. Earth Environ. Sci. 549 https://doi.org/10.1088/1755-1315/549/1/012064.

Rashidi, N.A., Yusup, S., 2021. Co-valorization of delayed petroleum coke – palm kernel shell for activated carbon production. J. Hazard. Mater. 403 https://doi.org/10.1016/j.jhazmat.2020.123876.

Rashidi, N.A., Bokhari, A., Yusup, S., 2020. Evaluation of kinetics and mechanism properties of CO_2 adsorption onto the palm kernel shell activated carbon. Environ. Sci. Pollut. Res. 1–13 https://doi.org/10.1007/s11356-020-08823-z.

Razak, R.A., Abdullah, M.M.A., Yahya, Z., Jian, A.Z. and Nasri, A., (2017). Performance of fly ash based geopolymer incorporating palm kernel shell for lightweight concrete. *AIP Conf. Proc.* 020223-1-020223-5. doi:10.1063/1.5002417.

Rezk, H., Nassef, A.M., Inayat, A., Sayed, E.T., Shahbaz, M., Olabi, A.G., 2019. Improving the environmental impact of palm kernel shell through maximizing its production of hydrogen and syngas using advanced artificial intelligence. Sci. Total Environ. 658, 1150–1160. https://doi.org/10.1016/j.scitotenv.2018.12.284.

Sa'ad, H., Omoleyomi, B.D., Alhassan, E.A., Ariyo, E.O., Abadunmi, T., 2021. Mechanical performance of abrasive sandpaper made with palm kernel shells and coconut shells. J. Mech. Behav. Mater. 30, 28–37. https://doi.org/10.1515/jmbm-2021-0004.

Sabzoi, N., Siddhartha, S., Saadia, A., Brahim, S.A., Muhammad, A.S., 2016. A critical analysis on palm kernel shell from oil palm industry as a feedstock for solid char production. Rev. Chem. Eng. 32 (5), 489–505. https://doi.org/10.1515/revce-2015-0062.

Sahari, J., Maleque, M.A., 2016. Mechanical properties of oil palm shell composites. Int. J. Polym. Sci. 1–7 https://doi.org/10.1155/2016/7457506.

Salawu, E.W., Ajayi, O.O., Inegbenebor, A., Akinlabi, S., Akinlabi, E., 2019. Influence of pulverized palm kernel and egg shell additives on the hardness, coefficient of friction and microstructure of grey cast iron material for advance applications. Results Eng. 3 https://doi.org/10.1016/j.rineng.2019.100025.

Samotu, I.A., Dauda, M., Anafi, F.O., Obada, D.O., (2015). Suitability of recycled polyethylene/palm kernel shell-iron filings composite for automobile application. *Tribol. Ind. 37*(2), 142-153. View Article.

Sanjuan-Acosta, M.J., Tobón-Manjarres, K.M., Sánchez-Tuirán, E., Ojeda-Delgado, K.A., González-Delgado, A.D., 2021. An optimization approach based on superstructures for bioethanol production from African Palm Kernel Shells. Polish J. Environ. Stud. 30 (3), 2293–2300. https://doi.org/10.15244/pjoes/127554.

Selvam, S., Dhirde, M., Gharat, R., Shelar, V. and Gondhali, R., (2020). Effect of partial replacement and sizes of palm kernel shells on asphalt concrete. *Int. J. Creative Res. Thoughts, 8*(7), 4891-4897. View Article.

Setiawan, A., Shaw, M., Torpy, A., Pownceby, M.I., Harjanto, S., Rhamdhani, M.A., (2020). Solar Carbothermic Reduction of Ilmenite Using Palm Kernel Shell Biomass. *JOM: the journal of the Minerals, Metals & Materials Society*. doi:10.1007/s11837-020-04297-z.

Shahbandeh, M., 2022. "Leading producers of palm oil worldwide from 2021/2022". On line: <https://www.statista.com/statistics/856231/palm-oil-top-global-producers/>.Accessed: 25/03/2022.

Shahbaz, M., Yusup, S., Inayat, A., Ammar, M., Patrick, D.O., Pratama, A., Naqvi, S.R., 2017. Syngas production from steam gasification of Palm kernel shell with subsequent CO_2 Capturing using CaO sorbent: an Aspen plus modelling. Energy Fuels 1–22. https://doi.org/10.1021/acs.energyfuels.7b02670.

Shamsudin, I.K., Abdullah, A., Idris, I., Gobi, S., Othman, M.R., 2019. Hydrogen purification from binary syngas by PSA with pressure equalization using microporous palm kernel shell activated carbon. Fuel 253, 722–730. https://doi.org/10.1016/j.fuel.2019.05.029.

Suharto, N.F., Shofi, A., Sudibyo, Milandia, A., Rismananda, M.H., 2020. Analysis of the effect of temperature on the reduction roasting process of Lampung manganese ore using palm kernel shell charcoal. IOP Conf. Ser.: Earth Environ. Sci. 483 https://doi.org/10.1088/1755-1315/483/1/012012.

Suheria, P., Kuprianov, V.I., 2015. Co-firing of oil palm empty fruit bunch and kernel shell in a fluidized-bed combustor: optimization of operating variables. Energy Procedia 79, 956–962. https://doi.org/10.1016/j.egypro.2015.11.593.

Sulaiman, A.O., Olatunde, O.A., (2019). Study on the use of palm kernel shell and periwinkle shell as coarse aggregates in concrete. *Int. J. Eng. Appl. Sci. Technol 4*(3), 454-460. View Article.

Sulong, R.S.R., Zulkifli, S.E., Hasham, R., Zakaria, Z.A., 2020. Characterization of pyroligneous acid produced from microwave-assisted treatment of palm kernel shell. J. Phys. Conf. Ser. https://doi.org/10.1088/1742-6596/1444/1/012005.

Sundalian, M., Larissa, D., Suprijana, O.O., 2021. Contents and utilization of palm oil fruit waste. Biointerface Res. Appl. Chem. 11 (3), 10148–10160. https://doi.org/10.33263/BRIAC113.1014810160.

Syamsurizal, Uce, L., Nurhasanah, (2019). Formulation of toothpaste activated charcoal from palm shell (Elaeis guineensis Jacg) as teeth whitening for nicotine addicts. *Int. J. Pharm. Sci. Rev. Res. 58*(1), 9-12. View Article.

Thiagarajan, J., Srividhya, P.K., Balasubramanian, P., 2019. Thermochemical behaviors and co-gasification kinetics of palm kernel shells with bituminous coal. Biomass Convers. Biorefin. https://doi.org/10.1007/s13399-019-00450-0.

Thoharudin, Yi-Shun, C., Shu-San, H., 2020. Numerical studies on fast pyrolysis of palm kernel shell in a fluidized bed reactor. IOP Conf. Ser. Mater. Sci. Eng. 874 https://doi.org/10.1088/1757-899X/874/1/012033.

Tumsa, T.Z., Chae, T.Y., Yang, W., Paneru, M., Maier, J., 2019. Experimental study on combustion of torrefied palm kernel shell (PKS) in oxy-fuel environment. Int. J. Energy Res. 1–9 https://doi.org/10.1002/er.4792.

Umunakwe, R., Okoye, O.C., Madueke, C.I., Komolafe, D.O., (2017). Effects of carburization with palm kernel shell/coconut shell mixture on the tensile properties and case hardness of low carbon steel. *J. Eng. Technol.* 2(1), 2579-0617. 10.46792/fuoyejet.v2i1.83.

Usman, S.N.M., Nurarani, S.A., Prasetyo, A.B., Maksum, A., Prasetyo, T., Ulum, R.M., Soedarsono, J.W., 2020. The effect of NaCl addition and biomass palm kernel shell charcoal with different ratio on pyrometallurgical process of a wasted ferronickel slag. AIP Conf. Proc. 2255 https://doi.org/10.1063/5.0014049.

Valášek, P., Habrová, K., Müller, M., 2019. Experimental description of aging of palm oil kernel shell powder/epoxy composite. Mater. Sci. Eng. 617 https://doi.org/10.1088/1757-899X/617/1/012009.

Vasudevan, G., Subramaniam, M., 2020. Mechanical properties and sustainability of Palm Kernel Shell Powder (PKSP) as a partial replacement of cement. Mater. Sci. Eng. 897, 1088/1757-899X/897/1/012011.

Yacob, A.R., Wahab, N., Suhaimi, N.H., Mustajab, M.K.A.A., 2013. Microwave induced carbon from waste palm kernel shell activated by phosphoric acid. Int. J. Eng. Technol. 5 (2), 214.

Yalley, P.P. (2018). Use of Palm Kernel shells as a partial replacement of chippings in terrazzo floor finish. *Int. J. Civ. Eng. Res. 9*(1), 35-47. View Article.

Yeboah, M.L., Li, X., Zhou, S., 2020. Facile fabrication of biochar from palm kernel shell waste and its novel application to magnesium-based materials for hydrogen storage. Materials 13 (625). https://doi.org/10.3390/ma13030625.

Yusuf, I.T., Babatunde, Y.O., Abdullah, A., 2018. Investigation on the flexural strength of palm kernel shell concrete for structural applications. Malaysian J. Civ. Eng. 30 (2), 269–281. https://doi.org/10.11113/mjce.v30.16029.