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REGENERATION OF DEGRADED TRANSFORMER OIL USING PALM KERNEL SHELL ACTIVATED CARBON AS ADSORBENT

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Abstract: Transformer oil plays a critical role in insulation and cooling within power transformers, but degradation due to thermal, chemical, and electrical stresses reduces its efficiency and reliability. Conventional adsorbents such as fuller's earth and activated alumina are expensive and non-renewable, prompting the investigation of sustainable alternatives. This study investigates the regeneration of degraded transformer oil using palm kernel shell synthesized adsorbent. The ground palm kernel shell was chemically activated with sodium bicarbonate, and carbonized at 800 °C. The performance of the regeneration process was assessed at varied temperature (60, 80 and 100 °C) at constant time of 30 min, and contact time (30, 45 and 60 min) at constant temperature of 80 °C. The results show that the synthesized adsorbent exhibited desired properties including neutral pH (7.0), low moisture content (1.139 %), moderate ash content (20.42 %), and high pore volume (0.537 cm^3). The results show that the optimal regeneration condition of 80 °C and contact time of 60 min resulted to a dielectric breakdown voltage of 24.0 kV, total acid number of 2.24 mgKOH/g and viscosity of 9.64 cP. With these results, 46.78 % dielectric breakdown voltage, 46.78 % total acid number, and 13 % viscosity recovery, respectively of the degraded transformer oil were achieved. The results demonstrate that palm kernel shells synthesized adsorbent provides an efficient, potential cheap, and environmentally friendly solution for transformer oil regeneration, while promoting sustainable waste utilization.

Keywords: Transformer oil, regeneration, palm kernel shell, activated carbon, adsorbent, sustainability

1.0 Introduction

Power transformers are essential components of electrical power systems, enabling voltage transformation and efficient energy transmission. Transformer oil serves as both coolant and insulator in power transfers given their high dielectric strength, thermal stability, and chemical resistance. However, prolonged operation leads to oil degradation through oxidation, moisture accumulation, and sludge formation, resulting in reduced dielectric strength and increased risk of transformer failure. Based on this, there is a need to remove these contaminants reducing the performance of transformer oil to enhance its efficiency. Transformer oil regeneration restores the dielectric and chemical properties of aged or degraded transformer oil, thereby extending the operational life of both the oil and the transformer. This regeneration process is crucial for maintaining transformer efficiency and reliability while minimizing environmental impact (Audibert, 2006). The contaminants can be removed through the physical, chemical and physio-chemical methods (Hasanpour, 2021). The physical methods involve filtration, vacuum dehydration / degassing, and centrifugation. The methods remove contaminants such as moisture, gases and particulate matter from oil without altering its chemical composition (Hasanpour, 2021). The chemical methods of restoring transformer oil quality include acid-base refining, hydrogenation and vacuum pyrolysis. These methods are employed to restore the quality of degraded transformer oils by removing contaminants such as acids, oxidation products and sludge. The chemical reactions involved convert harmful substances into removable compounds, thereby enhancing the insulating properties and extending the service life of transformer oil (Garifulli et al, 2020; Hassanpour, 2021; Abdul & Kadhum). The physicochemical methods of regenerating transformer oils include coagulation and adsorption using solid adsorbents such as fuller's earth, activated alumina, silica gel and activated carbon. These methods involve combining physical and chemical processes to remove contaminants and restore the oil's original properties. They are particularly effective in eliminating dissolved impurities, oxidation products and moisture that degrades oil performance over time (Hassanpour, 2021; saffidine et al, 2021; Jay, 2024; Ghadiri, 2025).

Conventionally, mineral-based adsorbents such as fuller's earth and bentonite have been employed for the transformer oil purification. These materials, though effective, are expensive, non-renewable, and environmentally challenging to dispose of. Consequently, research has shifted toward agro-waste-derived adsorbents such as coconut shells, rice husks, date pits, and palm kernel shells, probably due to their high carbon content, porous structure, large surface area. The agro-waste synthesized adsorbents are projected to offer cost-effective and sustainable alternatives to the synthetic adsorbents. The palm kernel shell is a by-product of palm oil processing. This agro-waste material contains 45 - 50 % carbon, it is abundant in palm-producing regions, and being considered as a potential raw material source for activated carbon production due to its high carbon content. The methods used in

Some researchers have investigated the potential use of palm kernel shells as adsorbent in the regeneration or reclamation of degraded transformer oil. Thus, Sulaiman et al. (2012) studied the use of activated carbon produced from waste date-pit as an adsorbent for transformer oil regeneration. The regenerated transformer oil exhibited significant improvement in properties such as viscosity, interfacial tension and breakdown voltage. The neutralization index decreased by 68 % approaching acceptable standards. Ghani et al (2015) carried out an analysis on the performance of palm shell activated carbon as an alternative adsorbent for the reclamation of used transformer oil. The palm kernel shell activated carbon was compared with conventional adsorbent like fuller's earth and bentonite. After five times running of the regeneration process and testing, it was observed that palm kernel adsorbent out performed fuller's earth in the reduction of oxidation by-products by 27.6 % and also break down voltage was enhanced by 57.14 % while fuller's earth and bentonite enhanced break down voltage by 43.75 % and 52.63 % respectively. Boadu et al (2020), carried out a study, on the adsorption of heavy metals contaminants in used lubricating oil using coconut shell and palm kernel shell activated carbon. From this study, it was found that palm kernel and coconut shells are adsorbents with high adsorption capacity. These Palm kernel and coconut shell activated carbon were good adsorbent for the adsorption of magnesium, cadmium and chromium, but were not very good adsorbent for copper and iron.

The current work was focused on synthesizing an adsorbent from palm kernel shells and assessing the effect of temperature and contact time in the regeneration of degraded transformer oil using physicochemical method. The properties such as pH, moisture content, ash content, and pore volume, functional groups, and surface morphology of the palm kernel shells were analysed. The physicochemical characteristics such as the moisture content, total acid number, viscosity and dieletric breakdown voltage of both degraded and regenerated transformer oil were analysed.

2.0 Materials and Methods

2.1 Materials

2.1.1.Sample collection:

A 5 L sample of degraded transformer oil was obtained from a distribution transformer at the Bayelsa State Electricity Board (BSEB) maintenance facility located in Nembe Local Government Area, Bayelsa State, Nigeria. The oil was extracted from retired 500 kVA distribution transformers that had been operational for a period of 12 yr.

Also, 18 kg of palm kernel shell (PKS) was collected from a palm oil refinery situated at Elipokwuodu, Rupokwu, Rivers state, Nigeria.

The equipment used were Fourier Transform Infra-red spectrometer (Digilab Excalibur FTS 3000 series), Scanning Electron Microscope (JSM-7610F), 500µm test sieve, centrifuge (MYFUGE C1012), gasoline powered grinding machine, electronic weighing balance (Kerro series P5C), muffle furnace (Select-Horn), 500ml measuring cylinder, desktop constant temperature drying oven (DNP-9022A), ostwald viscometer, 85-2 magnetic stirrer with temperature control, burettes, beakers and conical flasks. The reagents used were sodium bicarbonate ($NaHCO_3$), acetic acid, and hydrochloric acid. All reagents were of analytical grade and were purchased from Bernaco Enterprise, Nigeria.

2.2 Methods

2.2.1 Pretreatment of Palm Kernel Shell

The palm kernel shell obtained was thoroughly washed severally with tap water to remove specks of dirt and clouds of dust, and sun dried for five days (Figure 1). The dried samples were pulverized based on ASTM-D2862-(2016) (Standard Test Method for Particle Size Distribution of Granular Activated Carbon). The powdered samples were then sieved with 500 µm mesh to obtain a fine powder of uniform particle size. This was then kept in an air-tight container for further analyses.

2.2.2 Chemical Activation and Carbonization of palm kernel shell

The palm kernel shell activated carbon (PKSAC) were prepared following the method prescribed by ASTM-D2862 (2016) and Boadu et al.(2018). A 30 g of the powdered palm kernel shell was soaked with 1 M solution of $NaHCO_3$. The mixture (palm kernel shell and $NaHCO_3$ solution) was left at room temperature for 3 h until it was saturated. The mixture was filtered and then activated for 40 min at a carbonization temperature of 800 °C using the Select Horn muffle furnace.

Figure 1. Washed palm kernel shell

The palm kernel shell activated carbon produced was washed with 0.5 M acetic acid solution to neutralize it. The produced activated carbon was also rinsed using distilled water to bring the pH within a range of 6 - 7. The activated carbon obtained was then sieved using a 500 µm (0.5 mm) sieve, and dried in the oven for 1 h after which it was stored in an airtight container (Figure 2).

Figure 2. Activated and carbonized palm kernel shell

The physicochemical properties (moisture, ash, pH, pore volume) of the adsorbent were analyzed.

2.2.2 Regeneration of degraded transformer oil

The oil sample was pretreated by gravity filtration using a Whatman No. 6 quantitative filter paper with a pore size of 3 microns. A 50 mL of the pretreated degraded transformer oil was placed in a beaker and then 0.5 g of the prepared palm kernel shell activated carbon was added to it and mixed properly. A 85-2 magnetic stirrer and hot plate were used to homogenize the mixture at temperatures of 80 ºC, 100 ºC and 60 ºC, respectively, stirring speed of 750 rpm for 30 min. The different samples of oil obtained at the different temperatures were analysed and then the temperature that yielded the best regenerated oil sample was kept constant and the contact time was varied at 30 mins, 40 mins and 60 min, respectively.

2.2.3 Analysis of the degraded and regenerated transformer oil

1. Moisture Content Test

The moisture content of the degraded transformer oil was determined by centrifuging 20 mL degraded transformer oil using a MYFUGE C1012 centrifuge. The water in the samples settled at the bottom and was aspirated using a syringe. The moisture content was determined using Equation 1, according to Abdullah et al. (2022).

$$\frac{\text{Volume of water}}{\text{Volume of sample centrifuged}} \quad (1)$$

2. Acid Number Test (Total Acid Number, TAN)

The acid number or acid value of the degraded transformer oil was obtained using an acid-base titration technique. A 10 mL of ethyl alcohol (ethanol) and 1 mL of phenolphthalein were mixed with 1g of the oil sample. The solution was titrated against 0.94 M KOH solution until a faint pink color was obtained (Nur et al., 2022). The acid value or acid number was determined using Equation 2

$$\text{Acid Number}\left(\frac{mgKOH}{g\ oil}\right)=\frac{MW_{KOH}\times C_{KOH}\times V_{KOH}}{m_{oil}} \qquad (2)$$

Where; MW_{KOH} = Molecular weight of KOH, C_{KOH} = Concentration of KOH, V_{KOH} = volume of KOH used for titration, m_{oil} = mass of the oil.

3. Dielectric Breakdown Voltage (BDV) Test

The dielectric breakdown voltage of the degraded transformer oil was determined using a portable BDV test set equipped with spherical brass electrodes spaced 2.5 mm apart. Approximately 400 mL of the oil sample was poured into the test cell, and a steadily increasing AC voltage was applied at a rate of 2 kV/s until breakdown occurred. The procedure was repeated six times, and the average of the six breakdown readings was taken as the BDV value, expressed in kilovolts (kV) (IEC, 2018).

4. Viscosity Test (Ostwald Viscometer Method)

To calculate the viscosity of the degraded transformer oil, the density of the oil was first evaluated using a specific gravity bottle. The empty bottle was first weighed and the value was recorded. It was filled with the degraded transformer oil, weighed and the reading recorded. Afterwards, the bottle was cleaned, filled with distilled water, weighed again and the value was also recorded. Then the density of the oil was calculated using Equation 3.

$$\rho_s=\frac{W_3-W_1}{W_2-W_1} \qquad (3)$$

Where;ρ_s = Density of the sample; W_3 = Weight of the specific gravity bottle + oil; W_2 = Weight of the specific gravity bottle + water; W_1 = Weight of the specific gravity bottle.

The dynamic viscosity of the transformer oil was then determined using an OStwald glass viscometer. Approximately 10 mL of water was added to the viscometer tube and allowed to fall under gravity at room temperature and the time taken for it fall was recorded. Then the oil sample was introduced into the viscometer tube, the time taken for the oil to flow between two calibrated marks was recorded using a stopwatch (Savi et al, 2020). The dynamic viscosity (μ) was obtained using Equation 4

$$\mu_s=\frac{\rho_s-T_2}{\rho_w-T_1} \qquad (4)$$

Where; μ_s = Viscosity of the sample; ρ_s = Density of the sample; T_2 = Time taken for the oil to fall in the viscometer; ρ_w = Density of water ; andT_1 = Time taken for water to fall in the viscometer

3.0 Results and Discussion

The results from the experimental investigations are systematically presented as follows;

3.1 Characterization of the palm kernel shell activated carbon

3.1.1 Determining the physicochemical properties of palm kernel shell activated carbon

The physicochemical properties of the palm kernel shell activated carbon including moisture content, ash content, pore volume and pH were determined. The results obtained are presented in Table 1. The results show that the pH, moisture content, ash content and pore volume of the palm kernel shells were 7, 1.14 %, 20.4 % and 0.54 cm^3/g, respectively. The palm kernel shell activated carbon exhibited a pH of 7.0, indicating a neutral surface. This suggests that the adsorbent has a balanced chemical nature without strong acidic or basic active sites, making it suitable for transformer oil regeneration without altering the composition of the oil. The neutral pH also reflects good surface stability and minimal reactivity. This result is consistent with that presented by Boadu (2020), who reported a pH range of 6.8 - 7.2 for palm kernel shell activated carbon. Typical PKS pH range between 6.5 - 7.5. The close agreement confirms the adsorbent produced has similar surface characteristics and suitability for adsorption process.

Table 1. Physicochemical characteristics of produced PKS

S/N	Parameter	Value

1.	pH	7
2.	Moisture content	1.14 %
3.	Ash content	20.4 %
4.	Pore volume	0.54 cm^3/g

The ash content of the palm kernel shell activated carbon of 20.4 %, indicates a relatively high amount of inorganic matter. The high ash content may reduce adsorption efficiency by occupying pore spaces and active sites on the carbon surface. However, it can also suggest the presence of stable mineral constituents that contribute to the structural strength of the adsorbent. The result obtained is slightly higher than that reported by Boadu (2020). This can suggest that there is potential for further optimization of the carbonization or activation process.

The moisture content, defined as the presence of water in small quantities, plays a critical role in determining product quality. As presented in Table 1, the moisture content of the palm kernel shell activated carbon was 1.14 %, signifying a low level of retained water relative to the 20.42 % value reported by Boadu (2020). The low moisture content of the activated carbon produced indicates a good drying and thermal stability which enhances adsorption efficiency. It should be noted that chemically activated carbons are prone to atmospheric moisture absorption upon exposure, which can result in elevated moisture levels (Verla *et al.*, 2012).

The pore volume characterizes the internal structure and adsorption capacity of activated carbons, directly influencing their efficiency in toxin removal (Odisu et al., 2019). From Table 1, the pore volume of the palm kernel shell activated carbon was 0.54 cm^3. Its high microporosity suggests suitability for liquid-phase adsorption and pollution control applications (Kalderis et al., 2008).

3.1.2 Determining the functional groups of palm kernel shell activated carbon

The chemically activated carbon produced from palm kernel shells was characterized using Fourier Transform Infrared (FTIR) spectroscopy to identify its surface functional groups. The FTIR spectrum of the palm kernel shell activated carbon is presented in Figure 2. Most of the observed peaks in the activated carbon spectrum fall within specific wave number ranges corresponding to various functional groups such as C–H stretching, N–O stretching, C=O stretching, C–F stretching, O–H stretching, N–H stretching, N=C=S stretching, C–H bending, C–O stretching, C=C bending, and O–H bending. In the 3500 - 4000 cm^{-1} range, the peaks present showed O-H Stretching vibration which indicated the presence of the alcohol functional group. 3000 - 3500 cm^{-1} range showed O-H, N-H and C-H stretching vibrations, and this indicted the presence of alcohols, aliphatic primary amine, alkyne and carboxylic acid functional groups.

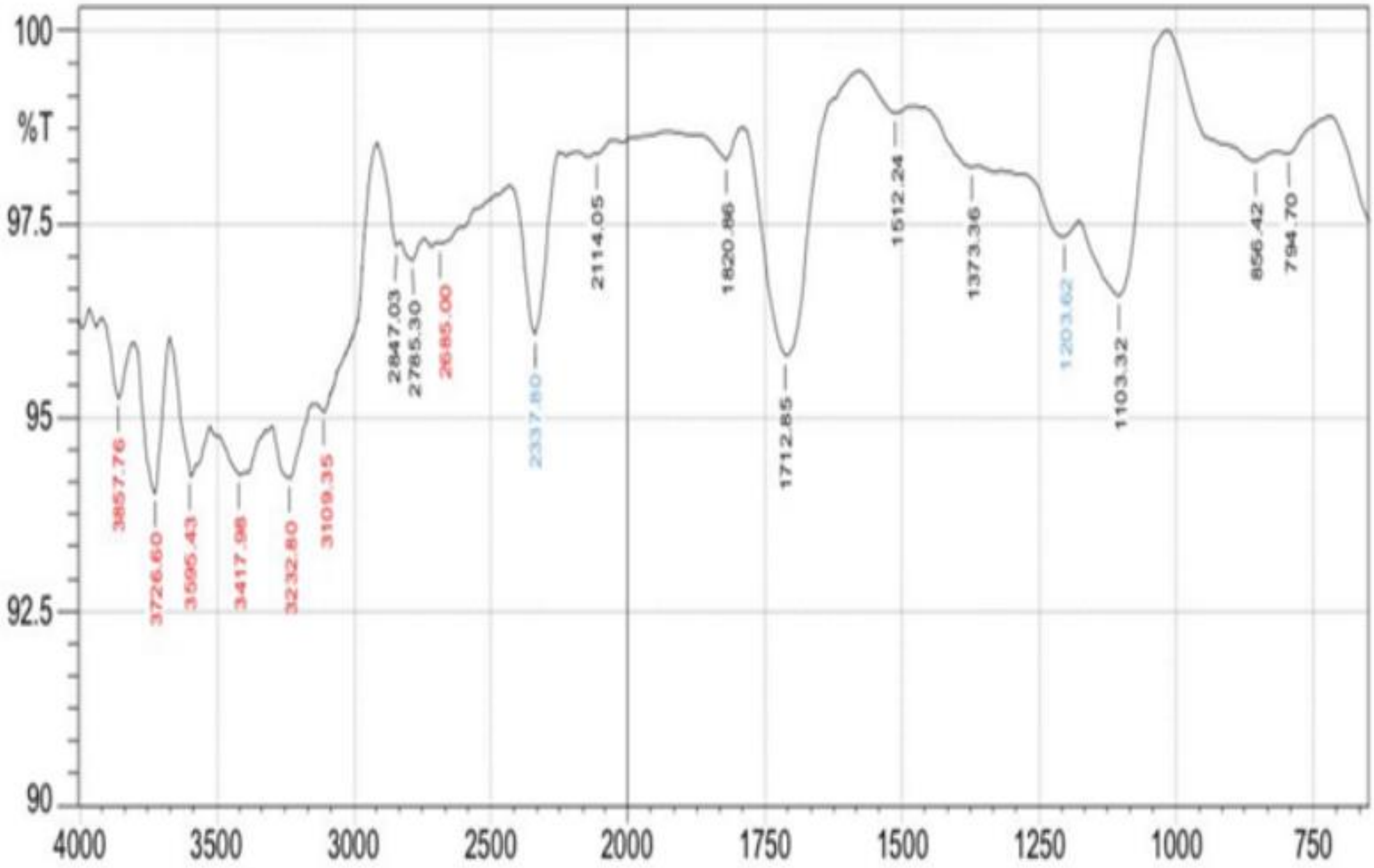

Figure 3. FTIR Spectra of Palm Kernel Shell

2500 – 3000 cm^{-1} range, peaks were attributed to C–H, O–H, and N–H stretching vibrations. Peaks between 2000 – 2500 cm^{-1} were associated with C≡C and N=C=S stretching, while those in the 1750–2000 cm^{-1} range corresponded to C–H bending, indicative of aromatic compounds. Similarly, peaks observed between 1500 – 1750 cm^{-1} were linked to N–O and C=O stretching vibrations, representing nitro and carboxylic acid functional groups, respectively.

The transmittance peaks in the 1200 – 1500 cm^{-1} range revealed the presence of alcohols, phenols, and fluoro compounds with O–H bending and C–F stretching vibrations. Peaks between 1000–1250 cm^{-1} indicated the coexistence of fluoro compounds and aliphatic ethers, corresponding to C–F and C–O stretching vibrations. The lowest transmittance peak, found between 750–1000 cm^{-1}, was attributed to C=C bending.

Overall, the FTIR spectrum of the palm kernel shell activated carbon (PKSAC) displayed ten well-defined peaks, each representing distinct surface functional groups. The variation and distribution of these peaks confirm the unique chemical characteristics and adsorption properties of the activated carbon derived from palm kernel shells (Osman et al., 2017).

3.1.3 Investigating the surface morphology of palm kernel shell activated carbon

Figure 4, represents the SEM image at 80 µm magnification showing the surface morphology of chemically activated carbon derived from palm kernel shells. The figure reveals the presence of pores on the surface following the carbonization process. This observation indicates that carbonization facilitated the decomposition and release of volatile organic matter from the palm kernel shells, leaving behind non-volatile components that were converted into activated carbon with pores of various shapes and sizes. Furthermore, the SEM image shows that the activation stage resulted in a well-developed external surface with visible pores, confirming a highly porous structure. The pores appear irregular in shape and are unevenly distributed across the carbon surface. The pretreatment of the palm kernel shells resulted in a cleaner and more uniform

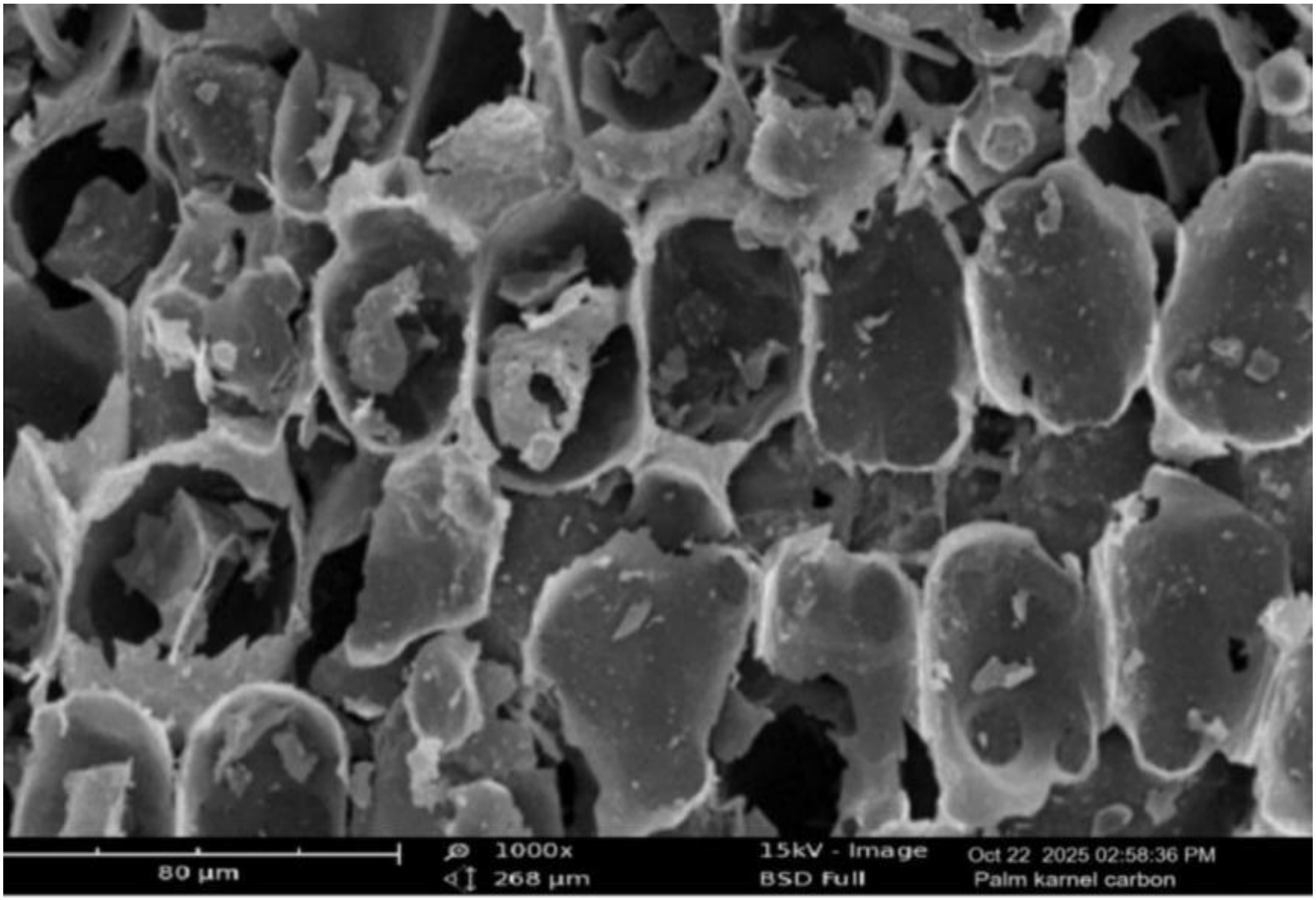

Figure 4. Scanning Electron Microscopy of Palm Kernel Shell

material. The pretreatment improved the overall appearance and purity of the palm kernel shell. This also ensured that the lignocelluosic structure of the shell was retained. The results also showed that pretreatment yielded a fine and homogeneous particle size. This uniformity achieved enables even heat distribution during carbonization and enhanced surface exposure for adsorption sites. This physical change also contributed to better contact between the adsorbent and the degraded transformer oil during regeneration. The similarity between the pretreatment results and those of Boadu (2020) further validates the reliability of the pretreatment approach adopted.

3.2 Analysis of the degraded transformer oil

This was conducted to determine the quality of the degraded transformer prior to regeneration, and this would serve as a baseline to assess the performance of the regeneration process. The moisture content, total acid number (TAN), viscosity and the dielectric breakdown (B/D) voltage were analysed using the methods described earlier in section 2. The results obtained are presented in Table 2, and these show that the moisture content, TAN, viscosity and dielectric B/D voltage of the degraded transformer oil were 15000 ppm, 4.21 mgKOH/g, 9.19 cP, and 7.8 kV, respectively. The moisture content of 15,000 ppm of the degraded transformer oil shows excessive water contamination, which critically weakens its dielectric strength and promotes acid formation. Moisture intrusion, often resulting from leaks, inadequate sealing, or condensation during load variations, has been identified as the primary cause of rapid transformer oil deterioration (Eze and Oghene, 2022). The TAN of 4.21 mgKOH/g of the degraded transformer oil shows an extensive oxidative degradation induced by long-term service and thermal stress. The elevated acidity is attributed to the generation of organic acids, sludge, and other oxidation products, which promote corrosion of transformer windings and impair dielectric performance. The result is consistent with the findings of Okoh and Okechukwu (2020), who observed significant oxidative deterioration in transformer oils with TAN values exceeding 1.0 mgKOH/g. The dynamic viscosity of 9.19 cP of the degraded transformer oil is an indicative of oxidation, polymerization, and accumulation of insoluble degradation products, which diminish oil fluidity (Adeosun et al., 2021). Such viscosity elevation can impede oil circulation and cooling within the transformer, fostering localized thermal stress. These findings confirm that the oil has undergone considerable thermal-oxidative degradation during service. The dielectric breakdown voltage of the degraded transformer oil was measured at 7.8 kV, indicating a significantly reduced insulating strength. This low breakdown voltage suggests contamination by moisture, dissolved gases, and particulate matter, which collectively deteriorate the oil's dielectric integrity. The poor dielectric performance confirms advanced degradation, as the presence of water and oxidation by-products promotes premature electrical discharge under stress conditions (Oladimeji et al., 2019). Comparing the results of the moisture content, TAN, viscosity and dielectric B/D voltage with the specifications for a typical fresh transformer oil of moisture content (<35 ppm), TAN (<0.003), viscosity (8.0 ± 0.5 cP), and dielectric B/D voltage (>30 kV), respectively, showed that the transformer oil (sample) was out of the range specified and hence, degraded.

Table 2. Physicochemical characteristics of degraded transformer oils

SN	Parameter	Degraded transformer oil	Typical transformer oil (Reference)	
1	Moisture content (ppm)	15000	< 35	IEC (2014)
2	TAN, mgKOH/g	4.21	< 0.003	IEC (2003)
3	Viscosity, cP	9.19	8.0 ± 0.5	ASTM D445
4	Dielectric B/D voltage, kV	7.8	> 30 (tested over a 2.5 mm gap)	IEC (2018)

3.3 The regeneration of degraded transformer oil

3.3.1 Investigating the effect of temperature on the performance of regeneration of degraded transformer oil

The regeneration of the degraded transformer oil using palm kernel shell activated carbon was carried out at varied temperature (60, 80 and 100 ^{o}C) and a constant time of 30 min to investigate the effect of temperature on the process. The results obtained are presented in Table 3. The result shows that the the highest dielectric breakdown voltage (23.8 kV), and the lowest (19.3 kV) were obtained at 100 ºC and 60 ºC, respectively. Thus, the breakdown voltage increased progressively with temperature. This increase indicates that the dielectric strength of the oil improved with temperature. This enhancement can be attributed to the removal of moisture, dissolved gases, and polar contaminants that weaken the insulating property of transformer oil. At higher temperatures, the adsorption rate of the activated carbon improved due to greater molecular motion, which enhances contaminant diffusion and binding to the adsorbent surface. The results obtained confirm that higher temperature enhances regeneration efficiency. This agrees with the findings of Ghani et al. (2015), who reported that increased regeneration temperature improves dielectric strength and reduces acid content by enhancing contaminant removal during adsorption. Comparing the dielectric B/D voltage obtained at the various temperatures of the regeneration process, showed that there was improvement in dielectric B/D recovery from 147.4 % to 205.13 %, although, the transformer oil failed to regain its original dielectric B/D voltage as the values were below the standard of > 30 kV specified by IEC (2018).

Table 3. Performance of the regeneration process at varied temperature and constant time of 30 min.

SN	Temperature (ºC)	Dielectric breakdown voltage (kV)	Viscosity (cP)	Total acid number (mgKOH/g)
1	60	19.3	8.56	3.68
2	80	20.8	7.96	3.16
3	100	23.8	8.15	2.63

The viscosity slightly decreased from 8.56 cP to 7.96 cP between 60 °C and 80 °C, followed by a minor increase to 8.15 cP at 100 °C. The initial reduction suggests that the breakdown of large molecular species occurred during adsorption, while the subsequent increase may be due to thermal effects or the concentration of heavier fractions. Comparing the viscosity at the various temperatures showed that the viscosity of ~8.0 cP obtained at 80 ºC with the 9.19 cP of the degraded transformer oil prior to regeneration gave a viscosity recovery of 13.38 %. Similarly, the viscosity corresponds to the 8.0 ± 0.5 cP specified by the IEC (2018). This shows that the regeneration process was effective in restoring the viscosity of the degraded transformer oil.

The total acid number decreased from 3.68 mgKOH/g at 60 °C to 2.63 mgKOH/g at 100 °C. This reduction signifies that higher regeneration temperatures promote more effective removal of acidic oxidation products, sludge, and polar impurities. The decrease in acidity is essential for preventing further oil degradation and improvement in dielectric recovery. Comparing these results with the total acid number (TAN) of 4.21 mgKOH/g of the degraded transformer oil shows 12.59 % to 37.53 % removal of the acidic substances in the transformer oil. But, the TAN of the regenerated transformer oil is still high based on the < 0.003 mgKOH/g specified by IEC (2003). With this further regeneration process may be required to bring down the TAN of the regenerated transformer to meet the specification requirement.

3.3.2 Investigating the effect of contact time on the performance of regeneration of degraded transformer oil

The influence of contact time on the regeneration process was investigated at a constant temperature of 80 °C and constant stirring speed. The breakdown voltage rose from 20.8 kV at 30 min to 24.0 kV at 60 min, indicating that longer contact time allows more complete adsorption of impurities and moisture that compromise insulation performance. This corresponds to a regeneration efficiency of 166.9 - 207.7 % with respect to the degraded transformer oil. The improvement suggests that sufficient time is required for effective interaction between the adsorbent surface and the contaminants present in the oil. Although, there is an improvement in regenerating the degraded transformer oil at varied contact time (30, 45, and 60 min) and constant temperature (80 ºC), the highest dielectric breakdown voltage (24 kV) is below > 30 kV specified by IEC (2018), and this means that the dielectric breakdown voltage of the degraded transformer oil was not restored, and there is a need to explore longer contact time.

Table 4. Performance of the regeneration process at varied constant time and constant temperature of 80 ºC

S/N	Contact time (min)	Dielectric breakdown voltage (kV)	Viscosity (cP)	Total acid number (mgKOH/g)
1	30	20.8	7.96	3.16
2	45	23.4	8.06	2.81
3	60	24.0	9.64	2.24

The viscosity increased slightly from 7.96 cP at 30 min to 9.64 cP at 60 min. This increase may be associated with mild oxidation effects at prolonged contact time or minor retention of high-molecular-weight fractions during the regeneration process. These trends align with the work of Ghani et al. (2015), who also observed that extended contact time enhances regeneration efficiency by increasing the extent of adsorption. The best viscosity is ~8.0 cP obtained after 30 min as shown by comparing this result with 8.0 ± 0.5 cP specification according to ASTM D445. With this, over 13 % performance efficiency was obtained in restoring the viscosity of the degraded transformer oil.

The acid number decreased from 3.158 mgKOH/g to 2.244 mgKOH/g with increasing contact time. This demonstrates that prolonged exposure enhances the adsorption of acidic and polar compounds, resulting in cleaner and more stable oil. With this result, the highest viscosity regeneration efficiency of 46.78 % of the degraded transformer oil was achieved after 60 min. The gradual reduction in acid value confirms the continued removal of oxidation by-products over time.

4.0 Conclusion

The current study has demonstrated that the properties such as dielectric break/down voltage, viscosity, and total acid number of the degraded transformer oil can be improved through a regeneration process involving varying temperature and contact time. From the results obtained, the most effective regeneration condition for the treatment of the degraded transformer oil was achieved at 80 °C and 60 min contact time due to improved dielectric breakdown voltage (20.8 kV),visocity (9.64 cP), and total acid number (2.24 mgKOH/g). The results confirms that palm kernel shell-based activated carbon is a strong adsorbent and effective in restoring degraded oil properties. Thus the produced adsorbent is a viable, eco-friendly, and cost-effective for transformer oil regeneration. It has the potential to restores critical physicochemical properties, extends transformer lifespan, and reduces environmental impact by utilizing agricultural waste. This approach aligns with sustainable development goals and offers practical benefits for power systems, particularly in developing regions with limited access to costly adsorbents.

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