**Sustainable Reclamation of Spent Transformer Oil Using Bentonite and Palm Kernel Shell: A Review**

**Abstract**

Transformer oil plays a crucial role in ensuring the operational reliability of power transformers by providing electrical insulation and facilitating thermal management. Nevertheless, its deterioration owing to thermal, oxidative, and electrical stresses results in the emergence of contaminants, including sludge, acids, moisture, and dissolved gases, which subsequently undermine performance and present environmental hazards. Traditional treatment methodologies, although effective, frequently produce hazardous waste and incur substantial operational expenditures. This review explores the sustainable reclamation of spent transformer oil utilising various adsorbents, with a focus on bentonite clay and palm kernel shell due to their natural abundance, effectiveness, and sustainability. The investigation assesses the transformer oil composition and degradation products, the efficacy of various adsorbents, the activation methods, and the regeneration strategies. Modified bentonite, physically and chemically treated, exhibits superior adsorption efficiency. Similarly, palm kernel shell (PKS), recognised as a lignocellulosic agro-waste, demonstrates increased adsorption capacities for polar compounds due to its porous structure and carbon content. Integrated reclamation protocols encompassing heating, agitation, centrifugation, and adsorption methodologies effectively restore spent oil to a quality approaching its original state. Properties of transformer oil, such as dielectric strength, viscosity, acid number, moisture content, flash point, and fire point, improve after reclamation. The findings reinforce the viability of employing these cost-effective, environmentally benign adsorbents for sustainable transformer oil reclamation, offering a scalable solution suitable for industrial implementation.

**Keywords:** Transformer oil, degradation, reclamation, Bentonite clay, Palm kernel shell (PKS) and Adsorption.

1. **Introduction**

Transformer oil is a major insulating liquid for transformers obtained by fractional distillation of crude petroleum (Lyutikova et al., 2022; Raj et al., 2020) and further treatment (hydrotreating, addition of catalyst, high temperature and pressure) to remove impurities and obtain the most desirable properties to make it suitable as an insulating and cooling liquid (Park et al., 2017). As shown by Sai et al. (2020), the degradation of transformer oil takes place because of a chemical reaction. When the transformer oil is exposed to oxygen, heat, core, and coil components, a chemical reaction occurs, initiating the oxidation process as soon as the device is powered on (Thiviyanathan et al., 2022). Acids and polar molecules are created as the oxidation process goes on, and eventually, sludge forms (Guan et al., 2018). This sludge will subsequently contaminate heat transfer surfaces at the tank/radiators and the core/coil, reducing the system's capacity to transfer heat (Safiddine et al., 2017). This leads to an extension of the working temperatures, which in turn accelerates the oil degradation. Oil performance decreases at the same time the properties change. In these circumstances, oil has to be treated or changed. It is therefore desirable to process or recover oil due to economic and environmental considerations.

Reclamation is an economically viable strategy since it decreases the need to dispose of waste oils in landfills and the need to purchase new oils (Parekh et al., 2022), which is not necessary given the rising cost of petroleum-derived oils. The primary goal of reclamation is to regenerate transformer oil by removing impurities (Duraisamy et al., 2022). The reclamation process entails removing impurities and degradation byproducts from used transformer oils using a chemical or adsorbent (Duraisamy et al., 2022; Sarathkumar & Srinivasan, 2022). The ability to restore waste transformer oil characteristics to levels comparable to those of new transformer oil is the primary benefit of the reclamation process (Ghani et al., 2018; Duraisamy et al., 2022). Recent research has demonstrated that reclamation effectively reduces the quantities of unwanted molecular species present in in-service transformer oils, such as sludge, acids, ketones, other polar species, and water produced during oil deterioration. Raymon and Karthik (2015) studied the reclamation of aged transformer oil with activated bentonite and the enhancement of the reclaimed and fresh transformer oils with antioxidants. Safiddine et al. (2017) researched transformer oil reclamation by combining several strategies enhanced by the use of four adsorbents. Similarly, Ghani et al. (2018) reviewed the reclamation technologies for service-aged transformer insulating oils. All of these studies support the value of employing adsorbents and validate the path of research aimed at enhancing transformer oil regeneration using sustainable materials. One of the most sought-after physical adsorbents for the reclamation/regeneration of spent transformer oils is palm kernel shell activated carbon (Ukwu et al., 2016; Ezechukwu et al., 2025**;** Erhimona et al., 2023), which is both inexpensive and eco-friendly. Numerous research studies have been conducted to discover and characterise viable adsorbents for industrial applications, with strong adsorption potential and acceptable regeneration capacity being two of the most crucial attributes of a suitable adsorbent (De Gisi et al., 2016).

This study critically reviews the reclamation of transformer oil with various adsorbents, with a focus on bentonite clay and palm kernel shell due to their natural abundance, effectiveness, and sustainability.

1. **Transformer Oil**

Transformer oil, sometimes referred to as insulating oil, is a unique kind of oil that is stable at high temperatures and has exceptional electrical insulating qualities (Mehta et al., 2016). Oil-filled electrical power transformers use transformer oil to dissipate heat, prevent arcing and corona discharge, and for insulation. Due to their complete submersion in the oil, the transformer's core and windings are also preserved by using transformer oil. The insulating oil capacity to stop the oxidation of the paper insulation, formed of cellulose, is another crucial characteristic. Transformer oil minimises oxidation by acting as a barrier between the cellulose and ambient oxygen, preventing direct contact.

Transformer oil performs two vital roles: it acts as a heat transfer medium and an electrical insulator (Weesmaa et al., 2014). In order to preserve the integrity of the insulation system and stop electrical discharge between live parts and ground, high dielectric strength is crucial (Ghassemi et al., 2011). The good thermal conductivity also guarantees effective heat dissipation from the transformer windings and core, controlling operating temperatures and averting thermal deterioration. Additionally, transformer oil is essential for suppressing arcs that might form during faults or operational disruptions.

**2.1 Types of Transformer Oil and Their Composition**

Refined mineral oil consists of a blend of naphthenic, paraffinic, and aromatic hydrocarbons (Jacob et al., 2020). For the carbon distribution classification of transformer oil, naphthenic base oils usually have less than 50% paraffinic carbon atoms, while paraffinic base oils have a concentration exceeding 56%. This classification is important because it affects the properties, which in turn influence the performance of transformers in insulation and cooling (Gao et al., 2025). There are two main types of transformer oil used in transformers (Rathna et al., 2017), as shown in Table 1

**Table 1**: Types of Transformer Oil and Their Descriptions

| Types | Description | Chemical Structure |
| --- | --- | --- |
| Paraffin-Based Transformer Oil | This kind of transformer oil contains a high amount of n-paraffine (Rathna et al, 2017). They are not easily oxidised, the sludge is insoluble and impedes the transformer cooling system, it has a high pour point, the rate of deterioration of electrical properties is high, and it has a high cost (Pahlavanpoura and Habibollahi, 2019). The paraffinic structure has a linear or branched group of molecules (Jacob et al., 2020). | Chemical structure of Paraffin (Jacob et al., 2020) |
| Naphtha-Based Transformer Oil | This is a type of transformer oil that includes very low n-paraffine (Rathna et al, 2017). They are easily oxidised, the sludge is more soluble and does not impede the transformer cooling system, it has a low pour point, the rate of deterioration of electrical properties is low, and it has a low cost (Pahlavanpoura and Habibollahi, 2019). They are also referred to as cycloalkanes and often have ring structures. | Chemical structure of Naphtha (Rizk and Trinh, 2014) |

Table 2 highlights the mass fraction (%) of the cycloalkyl and paraffin groups in the oil.

**Table 2:** Composition of paraffin‐based oils and naphthenic‐based oils (Gao et al., 2025)

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Composition** | **Paraffin Base Oil (%)** | **Naphthenic Base Oil (%)** |
| 1 | Paraffinic hydrocarbons | 93 | 14.7 |
| 2 | Naphthenic hydrocarbons | 6.7 | 76.6 |
| 3 | Aromatics | 0.3 | 8.6 |

The International Electrotechnical Commission (IEC) and the International Organisation for Standardisation provide a standard approach and acceptable limits for physical, chemical, and electrical properties measurements as seen in Table 3. According to Safiddine et al. (2017), the overall characteristics of used transformer oil are shown in Table 3.

**Table 3:** Characteristics of the used transformer oil (Atanasova‑Höhlein, 2021; Safiddine et al., 2017)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Test | Test Standard | Unit | Acceptable limit a | Value b |
| acid number TAN | IEC 62021 | mg KOH/g | < 0.01 | 0.384 |
| water content | IEC 60814 | ppm. | < 30 | 35.4 |
| dissipation factor at @50 Hz, 90°C | IEC 60247 | — | < 0.005 | 0.253 |
| permittivity (90°C), εr | IEC 60247 | — | — | 2.17 |
| resistivity (90°C) | IEC 60247 | GΩ m | — | 0.986 |
| dielectric breakdown voltage | IEC 60156 | kV | > 30 | 33.4 |
| kinematic viscosity at 40°C | ISO 3104 | mm²/s | < 12 | 7.77 |
| Density | ISO 3675 | g/ml | < 0.9 | 0.875 |
| colour factor | ISO 2049 | — | > 0.5 | 6.9 |

a Acceptable limit of transformer oil according to Atanasova‑Höhlein 2021

b Measured Values of used transformer oil according to Safiddine et al. (2017)

**2.2 Common Contaminants and Degradation Products**

Over transformer operational life, the insulating oil is exposed to thermal, electrical, and environmental stresses that cause it to degrade, resulting in the formation of a variety of contaminants and byproducts that impair the oil ability to insulate and cool (N’cho et al., 2016; Rafiq et al., 2020). Table 4 lists the main contaminants that are frequently found in spent transformer oil, along with their sources, the impact on transformer performance, and references to related literature.

**Table 4:** Common Contaminants and Degradation Products in Spent Transformer Oil

| Contaminant / Degradation Product | Source | Effect on Transformer Oil | References |
| --- | --- | --- | --- |
| Moisture (Water) | Leaks, condensation, and cellulose insulation degradation | It increases oxidation, decreases dielectric strength, and encourages the production of acid and sludge. | (Abdi et al., 2020; Dmitriev et al., 2019) |
| Oxidation Products (Acids) | Reaction of oil with oxygen under heat and electrical stress | It lowers insulating performance, corrodes metal components, increases acidity, and aids in the production of sludge. | (Duraisamy et al., 2022; Meshkatoddini & Abbospour, 2008) |
| Sludge and Sediment | Oxidation of oil and paper insulation | It increases operational temperature, blocks cooling ducts, and hastens transformer ageing. | (Baba et al., 2018) |
| Dissolved Gases (e.g., H₂, CH₄, C₂H₂) | Thermal and electrical decomposition of oil/insulation | It reduces dielectric integrity, shows defect kind and severity, and is used for dissolved gas analysis (DGA). | (H. He & Xu, 2012) |
| Furanic Compounds (e.g., 2-Furfural) | Degradation of insulation made of cellulose | It helps determine the life expectancy of transformers by indicating the ageing of the insulation. | (Abd El-Aal et al., 2019; Verma et al., 2005) |
| Particulate Matter (carbon, metal debris) | Byproducts associated with ageing, arcing, and mechanical wear | It reduces dielectric strength and serves as an oxidation process catalyst. | (Karthikeyan et al., 2024) |

1. **Activation and Composition of Adsorbents**
   1. **Activation of Adsorbents**

Activated carbon (AC) can be prepared through physical and chemical methods. By physical activation, AC is obtained after two steps: the first is carbonization, which is the pyrolysis of carbonaceous materials at high temperature (500 - 1000 oC) in an inert atmosphere to eliminate maximum amounts of oxygen and hydrogen elements; the second is the thermal activation at the same temperature in the presence of an oxidizing gas such as steam, carbon dioxide or both. Chemical activation involves impregnation of raw materials with such chemicals as H3PO4, KOH, NaOH, or ZnCl2, etc. (Hoa et al., 2017; Hidayu et al., 2019). These chemicals are dehydrating agents that can influence the pyrolytic decomposition and retard the formation of tars during the carbonisation process, thereby increasing the yield of AC (Hoa et al., 2017).

Taher et al. (2017) stated some modification methods used to improve the adsorption capability of natural bentonite, which include acid activation, thermal activation, cold plasma treatment and pillarization. Bentonite modification by the combination method of thermal and acid activation is a simple modification procedure that is applicable to enhance the surface properties of the bentonite sample prior to use as adsorbent materials (Taher et al., 2017). According to Taher et al. (2017), thermal activation was conducted by heating the sample using a muffle furnace at 400 °C for 3 h then cooled and stored in a desiccator for one night. The acid activation was performed using H2SO4 0.1 M, with a bentonite to acid ratio of 1:5 (g mL-1) (Taher et al., 2017). Okoroigwe et al. (2013) suggested that optimum quality will be obtained by carbonising the charred shells at 500°C for 20 min after cessation of fumes and quenching the shells in an alkaline water medium. In addition, drying the shells and pulverising them to the desired grain sizes and activating the pulverised shells at 800°C for 15 min in an alkaline steam medium would enhance the quality. It has been noted that effectiveness in impurity removal is a function of the material and the method of production (Okoroigwe et al., 2013). Hidayu et al. (2019) carried out the chemical activation of palm kernel shell carbon using Zinc Chloride (ZnCl2) at an impregnation ratio of 1:1 mass basis for 24 h, and carbonisation was done at 500 ˚C for 30 min, 60 min, and 90 min, respectively called as PKSAC30, PKSAC60 and PKSAC90. For adsorption testing, PKSAC90 gave the highest percentage removal of β-carotene of 69% (Hidayu et al., 2019)

The bleaching earths obtained by acid activation are more porous materials than the natural bentonite for use as adsorbents (Noyan et al., 2007). The acid activation boosts the behaviour of the clays by manipulating their physical and chemical properties, which is highly responsible for the removal of impurities (Yassin et al., 2022). The acid treatment of bentonite produces different physicochemical properties from the non-activated clays, e.g., surface area and cation exchange capacity (CEC), thus increasing the adsorption capacity. Acid activation of bentonite results in an increase in silica SiO2 content. This increase in SiO2 is accompanied by a decrease in Al2O3, Fe2O3, and MgO2. There is a decrease in the relative number of cations belonging to the octahedral sheet and an increase in the Si/Al + Fe+ Mg ratio (Taha et al., 2011; Berhe et al., 2023). It is assumed that the chemical changes that take place in the structure during activation due to acid treatment lead to vacancies in the crystal lattice. As a consequence, there will be an increase in the adsorptive power of the activated bentonite. To provide charge equilibrium, due to activation of bentonite, the protons of sulphuric acid replace the exchangeable cations such as Na+ and Ca2+, which are present between the layers. However, the protons of the activating agent H2SO4 cannot fill all the empty spaces left by ions such as Al3+ and Mg2+ that occupy the octahedron centre; hence, vacancies will occur. It is also possible that the protons of the hydroxyl groups may become more labile as a result of the structural deformation due to acid activation. The surface area of the activated bentonite increases by increasing the acid concentration (Taha et al., 2011). Berhe et al. (2023) observed greater SiO2 contents in the acid activated bentonite and smaller contents of Al2O3, Fe2O3, MgO and CaO than the native bentonite clay and further attributed the 2M HCl to have effected increase in SiO2 content, due to the octahedral cations have shifted into the solution while the silicon, owning to its insolubility.

Motlagh et al. (2011) observed the leaching of adsorbent with H2SO4 solutions of various concentrations (2–7N) at 80±2 oC for 2 h. Thus, concluded that acid activation of the bentonite sample with 7N sulphuric acid yielded an adsorbent material which was highly efficient in the bleaching of the oil, and this functioned better than the commercial clay product under the same conditions. Usman et al. (2012) prepared different concentrations of hydrochloric acid (0.0 M, 0.2 M, 0.5 M, 1.0 M, 2.0 M, and 3.0 M) to be activated with the clay sample, and the mixture was heated at 105 ◦C for 30 minutes. They confirmed that the clay has poor bleaching action, as shown by percent colour reduction. The colour reduction for natural clay was 9.1 %. This value only increased to 27.3 % after 3M HCl activation, a value still very low for effective bleaching (Usman et al., 2012). After observing the activation of clay treated by three different acid concentrations (15 %, 20 % and 25%) with HCl, HNO3, and H2SO4, Yassin et al. (2022) concluded that all the clay samples activated with H2SO4 demonstrated the highest bleaching efficiency (94.5% efficiency) compared to the clays activated with HCl and HNO3 under similar conditions.

**3.1 Bentonite Clay and Applications**

Bentonite is a natural mineral that has a crystal structure made of layered silicates (Chen et al., 2020). Bentonite constitutes a specific category of clay predominantly comprised of the mineral montmorillonite (MAT, 2023). This clay exhibits significant absorbent properties and is utilised across a multitude of industries, encompassing cosmetics, pharmaceuticals, and construction (MAT, 2023). A prevalent application of bentonite is as a drilling fluid within the oil and gas sector (MAT, 2023). When combined with water, bentonite generates a slurry that serves to lubricate and cool the drill bit while concurrently facilitating the removal of debris from the borehole (MAT, 2023). Bentonite is used as a binding agent in the production of iron ore pellets. It also contributes to the strength and durability of cement and concrete and is used in their manufacturing (MAT, 2023). Because bentonite can absorb oils and pollutants from the skin, it is commonly used in cosmetics formulations such as face masks and skincare products (MAT, 2023). Additionally, it finds application in toothpaste as a natural polishing agent (MAT, 2023). Bentonite's versatility extends to numerous other applications, including wastewater treatment, vegetable oil purification, and cat litter production (MAT, 2023). It stands as a multifaceted and valuable substance that possesses numerous essential industrial and commercial applications (MAT, 2023).

**3.3.1 Availability of Bentonite Clay in Nigeria**

Nigeria possesses substantial reserves of bentonite distributed across various states, with verified deposits recorded in areas such as Edo, Ondo, Plateau, Adamawa, Borno, Ogun, Kogi, and Ogun states (Chen et al., 2020). Scholarly research suggests that nearly 700 million tonnes of bentonite reserves are present, with certain locales, particularly the Niger Delta, potentially containing in excess of 4 billion tonnes (Igwilo et al., 2020). Nonetheless, these naturally occurring clays are primarily composed of calcium and frequently necessitate beneficiation (e.g., sodium activation) to augment their swelling capacity and adsorption efficacy, in accordance with API standards. Initiatives aimed at processing indigenous bentonite have been documented in northeastern Nigeria, particularly in Gombe State, where the application of chemical agents such as NaHCO₃ has enhanced the rheological properties for various industrial uses (Igwilo et al., 2020).

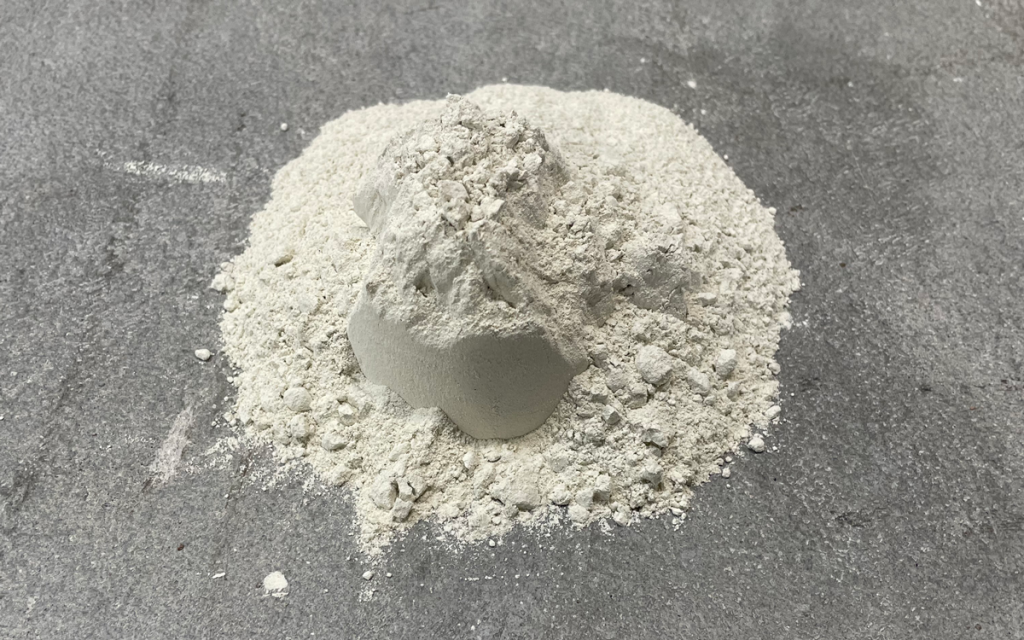


Figure 1: Bentonite (Source: MAT, (2023))

**3.1.2 Physical and chemical properties of bentonite**

Bentonite possesses numerous physical and chemical characteristics that contribute to its usefulness across different industries (Mat, 2023). These properties can be broadly classified into physical and chemical categories.

Physically, the natural colour of bentonite varies with its mineralogical makeup and contaminants (Mat, 2023). It is typically light grey or beige, but can be green, red, or brown due to the presence of iron oxides, organic materials, or other trace minerals (Murray, 2006). These colour variations are not merely aesthetic; they frequently represent variances in chemical makeup and adsorption capabilities (Mat, 2023). In terms of texture, bentonite is recognised for its smooth, powdery consistency and can be easily crumbled when dry (Mat, 2023). This small particle size leads to a large surface area and plasticity, making it perfect for creating slurries, as necessary in applications such as drilling, sealing, or suspensions (Toor et al., 2015). The density of bentonite also plays a crucial role in its performance. It has a bulk density of 2.0–2.7 g/cm³, which varies depending on moisture content, compaction, and mineral makeup (Chen et al., 2020). Because of its larger swelling capacity and lower specific gravity, sodium bentonite often has a lower bulk density than calcium bentonite (Mat, 2023). Another critical feature is its swelling capacity. This swelling is caused by interlayer water molecules infiltrating between the clay sheets, notably in sodium bentonite (Mat, 2023). This feature is necessary for its use in liner systems, oil purification, and drilling muds (Mat, 2023).

Chemically, bentonite's properties are equally significant. It primarily consists of montmorillonite, though it also includes additional minerals like feldspar, calcite, quartz, and pyrite, which can affect its reactivity and mechanical characteristics (Sajid, 2018; Mat, 2023). The prevalence of montmorillonite is responsible for bentonite significant plasticity, ion exchange potential, and chemical stability (Mat, 2023). A key chemical property is its cation exchange capacity (CEC). Bentonite, which is rich in montmorillonite, possesses a significant CEC, generally ranging from 70 to 150 meq/100g (Mat, 2023). This characteristic enables it to capture positively charged ions such as Ca²⁺, Mg²⁺, K⁺, and heavy metals (De Gisi et al., 2016; Mat, 2023). As a result, bentonite serves as a valuable resource in the areas of water purification, transformer oil recovery, and soil enhancement (Mat, 2023). Another important chemical feature is the pH. Bentonite displays a slightly alkaline pH, typically in the range of 8.0 to 10.5, when mixed with water (Taha et al., 2011; Mat, 2023). This alkaline property enables it to act as a buffering agent in environmental contexts and to neutralize acidic pollutants in oil (Mat, 2023). The chemical composition of bentonite can be summarised by the generalised formula for montmorillonite, its primary mineral: (Na,Ca)₀.₃₃(Al,Mg)₂Si₄O₁₀(OH)₂·nH₂O (Mat, 2023). The (Na,Ca)₀.₃₃ represents the exchangeable cations situated within the interlayer space. The (Al,Mg)₂ signifies the occupants of the octahedral layer. Si₄O₁₀(OH)₂ denotes the tetrahedral silica sheets along with hydroxyl groups (Mat, 2023). The term nH₂O refers to a variable quantity of water molecules that contribute to the material swelling and hydration. These layered silicate structures allow for the reversible absorption and release of water and cations, which is fundamental to bentonite role as a regenerative adsorbent in the reclamation of transformer oil (Berhe et al., 2023; Mat, 2023).

The structural properties of bentonite make it an effective adsorbent (Sajid, 2018; Toor et al., 2015). Bentonite adsorption property results from the existence of both positive and negative charges on its surfaces (Safiddine et al., 2017). This material primary attributes have low hydraulic conductivity, swelling capacity, and high cation exchange capacity (De Camillis et al., 2016; Sajid, 2018). Of all the smectites, calcium bentonite is the most common and may be found all over the world (Sajid, 2018). In comparison to calcium bentonite, sodium bentonite is more uncommon and swells more in water (Murray, 2006). However, to improve its adsorption efficiency, especially for specific contaminants, several modifications have been developed. Table 5 presents the properties of bentonite.

**Table 5:** Physico-Mechanical and Chemical Properties of Bentonite (Souhila et al., 2022; Almery and Ahmed, 2021)

|  |  |  |
| --- | --- | --- |
| References | Property | Value |
| Souhila et al. (2022) | Humidity (%) | <12 |
|  | Granulometry of fine elements (%) | 95 |
|  | Water content (%) | 9 |
|  | Swelling rate (mL/2 g) | 25–27 |
|  | Liquid limit (%) | 181 |
|  | Plastic limit (%) | 30 |
|  | Plasticity Index (%) | 151 |
|  | Impact Resistance (kg cm/cm³) | 40 |
|  | MgO₃ (%) | 1 |
|  | Na₂O (%) | 4 |
|  | CaO (%) | 2 |
|  | Fe₂O₃ (%) | 3 |
|  | Al₂O₃ (%) | 19 |
|  | SiO₂ (%) | 58 |
|  | Other minerals (%) | 13 |
| Almery and Ahmed (2021) | pH  SiO2 %  Fe2O3 %  Al2O3 %  TiO2 %  CaO %  Na2O %  MgO %  K2O %  L.O.I %  Surface Area (m2/g)  Pore Volume (Cc/g) | 5  65.22  2.42  16.76  0.55  0.56  0.15  2.7  0.36  10.72  206.62  0.171 |

**3.2 Palm Kernel Shell (PKS) and Applications**

Palm kernel shell (PKS), is an abundant lignocellulosic agro-waste produced by the palm oil industry. It has received a lot of interest as a sustainable and low-cost adsorbent (Udokpoh & Nnaji, 2023). The intrinsic chemical composition, high carbon content, and porous structure make it ideal for adsorbing a variety of pollutants in both aqueous and non-aqueous environments (Uchegbulam et al., 2022).

With an annual global production exceeding 20 million tons, the availability of PKS positions it as an ideal resource for effective waste management and resource recovery. When converted into activated carbon through processes such as pyrolysis, PKS exhibits a highly porous structure characterised by a large surface area, which significantly enhances its adsorption capabilities. This unique surface chemistry allows PKS-derived activated carbon to effectively capture and remove various contaminants, including oxidation by-products, organic acids, sludge, and other deteriorative compounds commonly found in aged transformer oil. As a result, the use of PKS not only helps reduce the environmental footprint associated with palm oil production but also offers a viable and efficient method for maintaining the quality and extending the lifespan of transformer oil in electrical infrastructure (Ghani et al., 2015). Palm kernel shell activated carbon (PKSAC) has been utilized in various industries, including water treatment, gas purification, air purification, and spill clean-up (Ghani et al., 2015). Activated carbon based on different materials has also been used as adsorbents for recycling used lubricant oils. The properties of Palm Kernel Shell (PKS) have been presented in Table 6.

**Table 6:** Properties of oil palm kernel shell (Baffour-Awuah et al., 2021; Boadu et al., 2018)

| References | Property | Values |
| --- | --- | --- |
| Faudi et al., (2012) | Micropore surface area (m²/g) | 0.20 |
| (Textural characteristics, proximate and ultimate analyses of PKS) | Apparent density (g/cm³) | 1.47 |
|  | Solid density (g/cm³) | 1.53 |
|  | BET Surface area (m²/g) | 1.60 |
|  | Porosity (%) | 3.90 |
|  | Lignin (%) | 53.40 |
|  | Cellulose (%) | 29.70 |
|  | Hemicellulose (%) | 47.70 |
|  | Ash (%) | 1.10 |
|  | Volatile (%) | 0.10 |
|  | Moisture (%) | 7.96 |
|  | Carbon (%) | 18.70 |
| Fono-Tamo et al., (2014) | Specific heat capacity (kJ/kg·K) | 1.983 ± 0.01 |
| (Physico-thermal properties of PKS) | Specific gravity | 1.26 ± 17.4 |
|  | Bulk density (kg/m³) | 0.68 ± 0.05 |
| Boadu et al., (2018) | Thermal conductivity (W/m·K)  BET surface area (m² g⁻¹)  Porosity (%)  Ash  Moisture (%) | 101.4 ± 0  717.142  65  14.2  20.4 |
| Okorolgwe et al., (2014) | Porosity (%) | 28.00 |
| (Bulk physical and chemical characteristics of PKS) | Ash content (%) | 8.68 |
|  | Molecule content (%) | 6.1 |
|  | Bulk density (kg/m³) | 740.00 |
|  | Lignin (%) | 53.85 |
|  | Cellulose (%) | 6.92 |
|  | Hemicellulose (%) | 26.116 |
| Ikumapay and Akinlabi, (2012) | Carbon (wt%) | 60.70 |
| (Elemental composition of PKS at 20 min, 100 cm) | Oxygen (wt%) | 38.00 |
|  | Silicon (wt%) | 1.00 |
|  | Aluminium (wt%) | 0.10 |
|  | Iron (wt%) | Not determined |
|  | Caesium (wt%) | 0.10 |
|  | Potassium (wt%) | 0.10 |
| Dagwa et al., (2012) | Carbon (wt%) | 63.02 |
| (Elemental composition of PKS at 15 min, 150 amplitude) | Oxygen (wt%) | 36.04 |
|  | Aluminium (wt%) | 0.43 |
|  | Silicon (wt%) | 0.17 |
|  | Phosphorous (wt%) | 0.17 |
|  | Potassium (wt%) | 0.17 |
|  | pH of PKS | 4.41 ± 0.08 |
| Yacob et al., (2013) | Carbon (wt%) | 46.18 |
| (Elemental composition of PKS) | Oxygen (wt%) | 45.08 |
|  | Aluminium (wt%) | 3.47 |
|  | Silicon (wt%) | 5.25 |
| Dagwa et al., (2012) | Avg true density (g/cm³) | 1.58 ± 0.07 |
| (Physical and chemical characteristics of PKS) | Powder porosity (%) | 6.76 ± 0.42 |
| Ninduangdee et al., (2015) | Moisture content (%) | 11.16 ± 0.16 |
| (Ultimate and proximate analysis, chemical structure, and lower heating value of PKS) | Moisture sorption (%) | 2.00 ± 0.54 |
|  | Angle of repose (°) | 34.09 ± 4.77 |
|  | Aug compressibility index | 18.58 ± 5.58 |
|  | Hydration capacity (%) | 150.08 ± 76.91 |
|  | Hausner ratio | 1.2328 |
| Samotu et al., (2015) | Carbon (%) | 48.06 |
| (Chemical composition of PKS ash particulates) | Hydrogen (%) | 6.38 |
|  | Nitrogen (%) | 1.27 |
|  | Oxygen (%) | 34.10 |
|  | Sulfur (%) | 0.09 |
|  | W (%) | 5.4 |
|  | VM (%) | 71.1 |
|  | FC (%) | 18.8 |
|  | A (%) | 4.7 |
|  | Lignin (%) | 46.3 |
|  | Cellulose (%) | 33.4 |
|  | Hemicellulose (%) | 14.4 |
|  | Lower heating value (heat capacity) | 16.3 |
|  | Al₂O₃ (%) | 7.6 |
|  | SiO₂ (%) | 25.1 |
|  | P₂O₅ (%) | 2.4 |
|  | SO₃ (%) | 1.4 |
|  | K₂O (%) | 15.0 |
|  | CaO (%) | 12.3 |
|  | TiO₂ (%) | 0.92 |
|  | CrO₃ (%) | 0.26 |
|  | MnO (%) | 0.74 |
|  | Fe₂O₃ (%) | 12.3 |
|  | NiO (%) | 0.2 |
|  | CuO (%) | 1.4 |
|  | Yb₂O₃ (%) | 0.9 |

This shows that PKS is primarily composed of carbon, oxygen, silicon, aluminum, iron, potassium, calcium, and copper (Baffour-Awuah et al., 2021). PKS/ash can be utilized in energy production, as a water purification agent like activated carbon, and as a reinforcing material in the development of metals, ceramics, and polymers, in addition to friction stir welding and processing (Baffour-Awuah et al., 2021). In all applications of PKS/ash, the distinctive behaviour of the product is influenced by the texture and specific particle size. Therefore, macro-particles perform less effectively, while micro-particles and nanoparticles show improved effectiveness and efficiency, in that order (M. Ikumapa & T. Akinlab, 2018). The angle of repose for PKS indicates that the material flows smoothly and easily when pulverized, and the average compressibility index and Hausner ratio further affirm the good flow of this material (Baffour-Awuah et al., 2021). This implies that with reduced particle size, there is an increase in true density, compressibility index, powder porosity, and hydration capacity (Baffour-Awuah et al., 2021). The shape of pulverized PKS appears to be spherical, as observed through SEM imaging. The variations in elemental composition, as shown in Table 6, could be due to differences in PKS varieties, types of soil, and their compositions, as well as geographical factors (Daud et al., 2016).

PKS ash contains a substantial amount of silicon, which results in its pronounced brittleness. The presence of a significant percentage of iron (Fe) and aluminum (Al) contributes to the material strength (Baffour-Awuah et al., 2021). These characteristics make it an excellent reinforcement material for composite development and manufacturing, especially in plastic composites (Samotu et al., 2015). As a lignocellular fiber, PKS exhibits unique combustion properties, demonstrating lower combustion and thermal reactivity compared to empty fruit bunch fiber (EFB) and oil palm mesocarp fiber (OPMF), both of which are viable sources for fuel and energy generation, as shown in Table 6 (Ninduangdee et al., 2015). Additionally, PKS serves as a good insulator, aligning well with its thermogravimetric properties (Fono-Tamo et al., 2014).

**3.3 Alternative Adsorbents for Transformer Oil Regeneration**

Other materials also have potential for recovering used transformer oil. These alternatives include specific industrial/chemical materials and activated carbons made from other agricultural wastes. The electrical and physicochemical characteristics of aged oils can be effectively restored by both types.

**3.3.1 ZnO/Graphene composite**

Graphene has outstanding physical, chemical, and electronic properties among the carbon nanomaterials. It is a two-dimensional material with a single layer of sp2 network of carbon atoms and is considered the thinnest and hardest material known to date (Upadhyay et al., 2013). Graphene inherently displays significant properties, including a large surface area (∼2630 m2 g−1). These unique properties make it a promising material for a variety of applications, including the removal of pollutants. The presence of active groups such as hydroxyl, carbonyl, and epoxy groups on the surface of graphene oxide enables it to interact with a wide variety of molecules and thus can undergo surface modification (Upadhyay et al., 2013). Recently, studies on the utilisation of self-assembled metal oxide nanomaterials on graphene and reduced graphene oxide for the removal of different pollutants have been reported. The incorporation of metal oxide nanoparticles on graphene limits their restacking and aggregation, thereby enhancing the surface area of the composite, offering mechanical strength to the composite, and further increasing the robustness of the adsorbent (Upadhyay et al., 2013). The adsorption efficiency of the graphene can be greatly enhanced by making a composite of it with other nanomaterials (Upadhyay et al., 2013). The ZnO/Graphene composite attracts significant attention among various reduced graphene oxide RGO/metal oxide composites. Apart from the application in the purification of aged transformer oil, the ZnO/Graphene composite is widely used for several applications such as photodetector, photocatalyst, or adsorbent for wastewater decontamination (Tan Vua et al., 2020). Recently, reduced graphene oxide (RGO) has become an excellent adsorbent material for wastewater treatment due to its high adsorption capacity (Tan Vua et al., 2020). The RGO has a large surface area, unreduced oxygen functional groups, and vacancy defects on the surface. Numerous methods, such as solvothermal, chemical vapor deposition, and hydrothermal, have been reported for the fabrication of ZnO/Graphene. Tan Vua et al. (2020) combined the reduction of GO with the synthesis of ZnO nanoparticles in one step using the sonification process to purify transformer oil. Zhao et al. (2013) explored the potential and validity of G−ZnO composites as effective adsorbents for the removal of contaminants, environmental remediation, and further provided insights into the adsorption behaviour of G−ZnO composites.

**3.3.2 Magnesium oxide (MgO)**

Magnesium oxide has been applied in catalytic and adsorption fields (Li, 2019). Magnesium oxide (MgO) is a viable adsorbent option for CO2 capture applications and fluoride removal (Perera et al., 2024; Wang et al., 2023). MgO has an advantage over other metal oxide adsorbents because it needs a lower regeneration temperature (Perera et al., 2024). Different researchers have explored the synthesis of MgO to improve its treatment effect, which includes the use of vanadium and carbon doping, SBA-15 and CMK-3, surfactant-assisted method following hydrothermal-treatment, polyvinyl alcohol, hybrid sol–gel combustion method, and ethylene glycol (Li, 2019). MgO has properties that make it suitable for efﬁciently absorbing pollutants and impurities. MgO exhibits excellent adsorption, porosity, and a large surface area, making it highly effective for regenerating used transformer oil. Its chemical stability guarantees the quality and effectiveness of reclaimed oil over time. Moreover, MgO is affordable, easily accessible, and environmentally safe. (Durairaj et al., 2024). Durairaj et al. (2024) used MgO in the reclamation of aged transformer oil. Their experiments were carried out on a laboratory scale using a specially designed plant, in which the oil was heated and then passed through a MgO absorbent cartridge to remove impurities. Saffidine at al. (2017) incorporated MgO amongst their used adsorbents to regenerate used transformer oil.

**3.3.3 Date Pit**

Date pits (DPs) are the byproducts of dates and account for approximately 10% of the total weight of dates. The physico-chemical structure of DPs, as well as being abundantly available at a low cost, is the main factor in choosing pits as an ideal adsorbent (Bouchelta et al., 2008). Utilizing this abundant waste not only provides a profitable avenue for date farmers but also addresses environmental concerns related to waste disposal and resource management (Babel and Kurniawan, 2003). The raw date pit and burnt date pit can be used as adsorbents with the burnt date pit having better surface area and pore structure (Bouchelta et al., 2008). In addition to being an economically viable source of AC, the conversion of date pits into activated carbon contributes to waste minimization efforts by repurposing what would otherwise be considered agricultural waste (Al-Zuhair et al., 2011). Previous research has demonstrated the successful preparation of DP-AC through methods such as physical activation and chemical activation, leading to adsorbents with promising characteristics. Al-Zuhair et al. (2011) utilized date pits for reclaiming spent transformer oil.

**3.3.4 Coconut Shell**

Coconut shell is a highly promising agro-waste material utilized as a base for producing activated carbon. This activated carbon acts as an effective adsorbent in the regeneration of transformer oil. Its high carbon content, low ash content, and excellent porosity render it particularly well-suited for removing degraded compounds, oxidized byproducts, and sludge-forming substances from used transformer oil. Raw coconut shells, a sustainable resource, undergo an initial process of charring at temperatures between 400 and 600 °C in an oxygen-limited environment. This process converts the shells into char, which serves as the foundational material for activated carbon. To further develop the char's porosity and surface area, it is subjected to activation using either steam or chemical agents, such as potassium hydroxide (KOH) or phosphoric acid (H₃PO₄). This activation occurs at high temperatures, often reaching up to 900 °C, significantly enhancing the material's ability to adsorb contaminants. Studies have demonstrated that modified coconut shell activated carbon exhibits significantly enhanced adsorption capabilities for polar degradation products, such as formaldehyde, as well as aromatic oxidized hydrocarbons. This improved performance highlights the potential for utilizing coconut shell activated carbon in various applications, particularly in the remediation of contaminated oils and other industrial processes (Yang et al., 2022). Coconut shell-based activated carbon is a highly effective adsorbent that can be regenerated and reused multiple times, making it a sustainable option for various applications. One prominent method for regeneration is thermal regeneration, which entails heating the activated carbon to approximately 300 °C in an inert atmosphere, such as nitrogen or argon. This process effectively removes adsorbed contaminants and restores the carbon's surface area and pore structure (Yang et al., 2022). Research has shown that even after undergoing 100 regeneration cycles, the activated carbon maintained over 90% of its original adsorption efficiency. This remarkable resilience not only highlights the longevity of coconut shell-based activated carbon but also underscores its economic viability as an alternative to other adsorbents, contributing to cost savings and resource conservation in industries that rely on adsorption processes, such as water treatment and air purification (Du & Zhou, 2018).

1. **Adsorption in Transformer Oil Regeneration**

Adsorption is a surface phenomenon in which solute molecules, known as adsorbates, attach to the surface of a solid material termed the adsorbent until equilibrium is achieved and no additional adsorption occurs (Musah et al., 2021). This method, which depends on the adsorbent's high surface area and porous nature, is very successful at eliminating impurities from solutions. Atomic, ionic, or molecular species are drawn to and held in place by residual surface forces, which cause adsorption. Either batch or column flow approaches can be used (Duraisamy et al., 2022). Adsorption is divided into two categories based on the type of forces at play: chemical adsorption (chemisorption) (Králik, 2014), which refers to the creation of stronger chemical bonds, either covalent or ionic, between the adsorbent and adsorbate (Wang et al., 2020a; Zhang et al., 2019), and physical adsorption (physisorption), which involves weak van der Waals forces (Aljamali et al., 2021). At higher temperatures, chemisorption usually results in the production of monomolecular layers, it is irreversible, and occasionally causes the adsorbed molecules to dissociate (Dąbrowski, 2001).

**4.1 Factors Influencing Adsorption.**

Several factors influence the adsorption process and determine its efficiency. A key factor is temperature; since adsorption is an exothermic process, lower temperatures promote the reaction's forward motion following Le Chatelier's principle, which improves adsorption (Conant et al., 2011; Saha & Chowdhury, 2011). The process is also impacted by pressure because, in general, higher pressure promotes adsorption until a saturation point is achieved. After this, adsorption is not improved by additional pressure increases (Meng et al., 2016). Up to the saturation limit, adsorption efficiency is improved by increasing the adsorbate concentration while maintaining a steady solution volume (Bhattacharya et al., 2006). Similarly, more adsorption is encouraged by a larger starting solute concentration in the solution. Another important consideration is the adsorbent surface area; since adsorption takes place on the surface, a larger surface area offers more active sites and increases adsorption rates (Rafatullah et al., 2010; Wang et al., 2020b).

Furthermore, by expanding the number of accessible adsorption sites, activation of the adsorbent greatly increases its efficacy. Heating or chemical treatment with acids like HCl or H₂SO₄ can accomplish this activation (Noyan et al., 2007). Clay samples activated with sulphuric acid (H₂SO₄) showed the maximum bleaching effectiveness, especially those treated with a 25% H₂SO₄ concentration, according to Yassin et al. (2022). The process is also affected by the adsorbate composition; more soluble adsorbates are often adsorbed more quickly. Finally, the rate and capacity of adsorption are determined by the physicochemical nature of the adsorbent, underscoring the significance of material properties in maximizing adsorption performance (de Carvalho Costa et al., 2024).

1. **Reclamation of Used Transformer Oil**

**5.1 Overview of used transformer oil reclamation**

While the principles of transformer oil degradation and the rationale for reclamation are well established, evaluating the true effectiveness of these processes requires rigorous empirical validation. The success of oil regeneration cannot be measured by visual inspection or single-parameter analysis alone; rather, it must be quantified across a range of critical physicochemical properties that directly impact transformer performance. These include breakdown voltage (BDV), moisture content (ppm), acid number (mg KOH/g), interfacial tension, dielectric dissipation factor (tan δ), and electrical resistivity. Each of these parameters serves as a proxy for the oil dielectric health, chemical stability, and suitability for continued use in high-voltage equipment (Safiddine et al., 2017; Tiwari et al., 2024)

Given the diversity of reclamation approaches ranging from thermal vacuum treatment to adsorption using various materials, it is essential to evaluate these methods using empirical data. Quantitative assessment of oil parameters such as breakdown voltage, moisture content, acid number, and dielectric dissipation factor before and after treatment provides a measurable basis for judging the efficacy of different reclamation strategies. The empirical results presented in Table 7 consolidate findings from recent experimental studies and field applications, highlighting the extent to which physical and chemical regeneration methods can restore the critical performance characteristics of used transformer oil to levels compliant with international standards (Rodiah et al., 2020; Yusupov et al., 2023; Oumert et al., 2017).

**Table 7:** Findings from recent experimental studies and field applications, highlighting the methods used to restore the critical performance characteristics of used transformer oil to levels

| S/N | Raw materials | Regeneration process | Adsorbent/sample preparation method | Results | References |
| --- | --- | --- | --- | --- | --- |
| 1 | Activated carbon (ACH), silica gel (SG), magnesium oxide (MO), and activated bentonite (AB) | Centrifugation, dehydration | Bentonite preparation: (H2SO4) at 75 % (w/w) and a weight ratio of 0.3 with respect to the weight of the oil. Centrifugation at 5000–9000 tr/min. Temperature 70-80 oC, Vacuum pressure 0.5mmHg, 1mmHg | Dielectric breakdown voltage=70 kV, kinematic viscosity=7.64 mm2/s, density=0.87 g/ml,  water content=12 ppm | (Safiddine et al., 2017) |
|  |  | Sorption and filtration | Adsorbents: 1 % ACH, 6 % SG, 1 % MO and 2 % AB | Acid number=0.018 mgKOH/g, dissipation factor=0.0012, permittivity=2.11 resistivity= 916.34 × 109  Ω.m,colour factor=1.6 |  |
| 2 | Fuller's earth and activated Bentonite | Adsorption, heating, agitation and filtration | Bentonite preparation: sulphuric acid (H2SO4). Agitation for 90mins; heated at 80 OC | Dissipation factor=0.00053 tgδ, acidity=0.02 mgKOH/g, water content=15 ppm, index colour=0.45 and resistivity=970 GΩm. | (Guerbas et al., 2017) |
| 3 | KSKsilica gel, permutite NaA, and natural zeolites | Dehydration | Silica gel preparation: Activated in a drying cabinet at a temperature of 160 oC for 6 h. | Oxidation number=0.1 mgKOH/g, Yield of volatile acids=0.004 mg KOH/g, Mass moisture content=0.001 %, Flash temperature=135 OC, Breakdown voltage=62 kV and dielectric losses=1.06 % | (Gainullina and Tutubalina, 2020) |
| 4 | Activated carbon (AC) | Heating, Adsorption, Agitation, filtration | 10 g AC in 500ml of used oil. 450 to 500 rpm (rotations per minute) for 30 minutes | Breakdown voltage=32 kV, flash point=166 OC, fire point=177 OC viscosity=17 cst | (Vanitha et al., 2016) |
| 5 | Fuller earth clay | Contact (use of digital hot plate magnetic stirrer), filtration | Experimental condition: two level, 3factors: weight of fuller earth (50 g, 100 g), stirring speed (500 rpm, 1000 rpm) and oil temperature (60 oC, 80 oC) | Breakdown voltage= 15 kV/mm, total acid number=0.0365 mg  KOH/g and dynamic viscosity=7.225 cP | (Ghani et al., 2020) |
| 6 | Activated Bentonite (AB) Activated Carbon (AC) purchased and Silica Fume (SF) | Heating, Adsorption, Agitation, filtration | Bentonite activated by 2N of H2SO4. Experimental conditon: 400ml aged oil, 70 oC,90 oC, 1:5 AB+SF, 1:7 SF+AC and 3:1, 5:1, 7:1 AB+SF; 30 mins, overnight | Acidity=0.072 mgKOH/g, dissipation factor=0.0039 and breakdown voltage=78 kV | (Taha et al., 2020) |
| 7 | Iraqi clay, Algerian clay, and zeolite | Settling, filtration, thermo vacuum evaporation, and clay treatment | Clay to oil ratio 2/100, and time 5 mins, temperature 80 oC. Thermo vacuum evaporation at 175 ˚C and 241 mm Hg | Water content=32 ppm, break down voltage=55 kV and the acidity=0.028 mgKOH/mg | (Mohammed and Kadhum, 2010) |
| 8 | Activated Bentonite | Heating, Adsorption, (Ultra bath Sonicator), filtration, addition of silica gel, Agitation, filtration | 5 g of activated bentonite for 500 ml of aged transformer oil; 100 oC; silica gel pellets in the ratio of 1 g to 100 ml of oil and stirring with a speed of 550rpm for 5 h | flash point=153 OC, fire point=160 OC, viscosity=30 cst and Breakdown Voltage (BDV)=28 kV | (Thanigaiselvan and Raja, 2016) |
| 9 | Bentonite clay | Heating, adsorption, Agitation (magnetic stirrer), filtration | Bentonite activation:7 N concentrated sulphuric acid (H2SO4); 500 ml aged transformer oil with 5 g activated bentonite;750 rotations per minute (RPM); 80 oC | breakdown voltage=25 kV, viscosity=37 cst, flash point=147 oC and fire point=153 oC | (Raymon and Karthik, 2014) |
|  |  |  | With addition of antioxidants; Propyl Gallate (PG), Alpha Tocopherol (α-T),Citric Acid (CA) | breakdown voltage=45 kV, viscosity=35 cst, flash point=152 oC and fire point=160 oC |  |
| 10 | Activated Carbon | Heating, adsorption, Agitation (magnetic stirrer), filtration | 10 g of Activated Carbon (AC) for 500ml of used transformer oil (UTO); 90oC; 800 to 1000 rpm | Breakdown strength=27 kV, viscosity=35C, flash point=162 oC and fire point=182 oC | (Rathna et al., 2017) |
|  |  |  | With antioxidants:500 ml UTO + 10g AC + 2g CA (Citric Acid) + 2g AA (Abscorbic Acid) | Breakdown strength=39 kV, viscosity=27.2 C, flash point=194 oC and fire point=208 oC |  |
| 11 | Fuller’s earth, bentonite and Palm Shell Activated Carbon | Adsorption, heating, Agitation (magnetic stirrer), filtration, degasification and drying | 500 ml of used transformer oil was mixed with 5 g of FE, bentonite and PSAC, respectively. 80 °C, stirring speed of 750 rpm for 1 h | dissolved decay products (DDP)=212.23, breakdown voltage=21 kV | (Ghani et al., 2015) |
| 12 | Kaolin clay | Heat and filtration, Adsorption, Fine filtration, Degasification and dehydration | One liter of used transformer oil, 20% kaolin dosage, 30 mins, 60 oC | Acidity=0.01 mgKOH/g, breakdown voltage=74 kV, viscosity=10.8 cst, colour=1 degree, water content=9 ppm, some undesirable gases were within standard limits | (Hafez et al., 2015) |
| 13 | Bentonite clay | Adsorption | Calcined at 600 OC and 700 OC for 2 h. The calcined samples were treated with 25 wt. % sulfuric acid and 4 M HCL | Dielectric strength=74 kV, viscosity=11 mm2/s and flash point=149 OC | (Nasrat and Hassan, 2012) |

**5.2 Major steps in reclaiming spent transformer oil**

The reclamation of spent transformer oil involves a methodical approach that aims to restore both the electrical and physicochemical characteristics of the oil, thus prolonging its useful life and minimizing environmental impact (Ghani et al., 2018). Laboratory-scale reclamation by contact is typically performed to assess the viability of the reclamation process for a specific oil and to estimate the properties that can be achieved if the reclamation takes place on-site (Ghani et al., 2018). Researchers have been observed to combine various processes in the laboratory setting to attain regeneration. The order and conditions for each process step may differ depending on the degradation level of the oil and the chosen adsorbents (Safiddine et al., 2017). The major steps involved are explained in detail below:

**Heating:** Heating is often the initial and foundational step in the transformer oil reclamation process (Sabau, 2001). The spent transformer oil is subjected to a specified temperature before adding the adsorbents (Vanitha et al., 2016; Taha et al., 2020; Thanigaiselvan and Raja, 2016; Raymon and Karthik, 2014; Rathna et al., 2017; Hafez et al., 2015). The spent oil is heated to remove moisture content (Raymon and Karthik, 2014) from the oil. In some cases, researchers were observed to add the adsorbents to the used oil before heating (Guerbas et al., 2017; Ghani et al., 2015). The typical temperature range falls between 60 °C and 100 °C since this interval is adequate for vaporizing water without compromising the oil (Vanitha et al., 2016; Taha et al., 2020; Rathna et al., 2017). In certain situations, adsorbents are introduced after the oil has reached the optimal temperature, promoting effective adsorption kinetics. Conversely, some techniques incorporate adsorbents into the oil before heating it. Guerbas et al. (2017) and Ghani et al. (2015) indicate that the simultaneous heating and mixing of the oil-adsorbent combination results in better impurity breakdown and more effective acid removal, implying that thermal energy boosts adsorption interactions and aids in the dissolution of degradation products (Guerbas et al., 2017). These variations in process order underscore the adaptability of the heating step based on the specific contaminants present and the characteristics of the adsorbents used.

**Agitation:** During heating, stirring is utilized to guarantee an even distribution of adsorbents throughout the oil, thereby optimizing the contact surface area for adsorption reactions. The combination of the used transformer oil and adsorbents is stirred with a magnetic stirrer (Ghani et al., 2020; Raymon and Karthik, 2014; Rathna et al., 2017; Ghani et al., 2015; Vanitha et al., 2016), (Taha et al., 2020) to achieve uniform dispersion of additives in the fluids while keeping the fluid temperature and stirring speed consistent during the blending process (Vanitha et al., 2016). In laboratory experiments, a constant stirring speed and controlled temperatures are upheld to replicate real-world scenarios (Ghani et al., 2020; Raymon and Karthik, 2014; Taha et al., 2020). Rathna et al. (2017), for example, stirred at 800 rpm for 30 minutes, and Thanigaiselvan and Raja, (2016) used an ultrasonic bath sonicator, which not only improves mixing but also creates cavitation, a phenomenon that breaks up sludge particles and makes it easier to remove impurities that are tightly bound. When working with excessively viscous or highly polluted oils, stirring is especially important.

**Filtration:** After sufficient mixing and contact time, the mixture of oil and adsorbent is subjected to filtration to eliminate sludge, which consists of adsorbed degradation products, exhausted adsorbents, and insoluble particulate matter. Filtration typically employs methods such as filter papers, vacuum-assisted filtration systems, or pressure filters. Ghani et al. (2020) highlighted that filtration not only eradicates physical impurities but also facilitates initial quality assessment of the recovered oil. Several researchers, including Vanitha et al. (2016), Taha et al. (2020), and Guerbas et al. (2017), conducted property evaluations (e.g., dielectric strength, moisture content, viscosity) after filtration to determine the effectiveness of the initial reclamation phases. This step serves as a checkpoint before advancing to more energy-demanding processes like centrifugation or vacuum dehydration.

**Centrifugation:** This process removes water and sludge from the spent transformer oil (Safiddine et al., 2017). Centrifugal force is used in a hydro-cyclone or centrifuge to separate out and quickly remove both water and solid contaminants from the oil (Gos et al., 2015; Safiddine et al., 2017). In Safiddine et al. (2017) study, the used oil was treated in the MAB separator (Marque Alfa Laval S.A. – OriginSpain) with a high-speed centrifugation technique (5000–9000 tr/min). This treatment was repeated in a closed circuit for four to five passes of the total oil volume, with the temperature of the oil in circulation <70°C and a vacuum of <1 mmHg (Safiddine et al., 2017). This system was passed around in a closed loop for 4 to 5 cycles, greatly lowering moisture content and particle contaminants. Operating under vacuum during centrifugation further prevents oxidation and maintains oil quality (Hnatov et al., 2021). Consequently, the oil after centrifugation exhibits a significant rise in dielectric breakdown voltage and a decrease in acid number, aligning it more closely with the standards of fresh oil.

**Dehydration and Degasification:** The last and arguably most important step is the dehydration and degasification of the oil, particularly for high-voltage uses. This is usually carried out with a vacuum dehydrator, and this eliminates dissolved water and trapped gases by utilizing low pressure (below atmospheric) along with moderate heat (Safiddine et al., 2017). This process is crucial for reinstating the oil electrical insulating properties and the chemical stability (Safiddine et al., 2017). A vacuum dehydrator was employed to extract water and lighter hydrocarbons (Safiddine et al., 2017). Thanigaiselvan and Raja (2016) added silica gel to achieve dehydration and this reduced water content that enhanced the effectiveness of the oil.

1. **Industrial and Environmental Applications**

**6.1** **Potential for Large-Scale Implementation**

The use of Palm kernel shell and bentonite in transformer oil reclamation procedures presents encouraging prospects for extensive industrial uses (Uchegbulam et al., 2022). Both materials are widely accessible, particularly in areas like Nigeria, where the manufacturing of palm oil produces large amounts of Palm kernel shell as agro-waste. When bentonite is modified by acid activation, its adsorption ability is increased, which makes it useful for eliminating impurities from spent transformer oil (Duraisamy et al., 2022; Loai et al., 2011). Palm kernel shell-derived activated carbon has also shown promise in the adsorption of contaminants (Uchegbulam et al., 2022). Adoption of these materials can be facilitated without requiring a significant capital expenditure by adapting their use to already-existing oil treatment infrastructures. The availability of raw materials and the ease of their activation processes are the foundations of this scalability potential. Traditional or low-tech kilns can be used to pyrolyse palm kernel shells, and locally accessible sulphuric or hydrochloric acid can be used to acid-activate bentonite. The technology can be implemented in both urban and rural industrial centres. Furthermore, many transformer service facilities already have the necessary equipment, which includes stirrers, heating units, and simple filtration systems, and it is typically inexpensive.

Additionally, the method works well with transportable and modular systems that may be set up at transformer stations, negating the need to transfer huge amounts of used oil to centralised treatment facilities. Operational and logistical expenses can be greatly decreased by this decentralisation. From a policy standpoint, waste valorisation incentives, subsidies, and environmental laws that support sustainable transformer oil management could all help to encourage the industrial adoption of such natural adsorbents.

**6.2 Cost and Sustainability Considerations**

Economically, using Palm kernel shell and bentonite offers a more affordable option to traditional oil treatment techniques. The low cost and local sourcing of the raw materials lowers the expenses associated with procurement and transportation. Furthermore, these adsorbents capacity for regeneration and reuse results in long-term financial savings (Vakili et al., 2024). Environmentally, this strategy aligns with sustainable practices by valorising agricultural waste and decreasing the environmental footprint associated with transformer oil reclamation.

In terms of material costs, palm kernel shells are often freely available as agricultural residue, and bentonite is abundant in many countries and relatively inexpensive compared to synthetic adsorbents or commercial clays. These characteristics reduce the initial capital investment needed to launch a reclamation operation. Also, because the materials are biodegradable and non-toxic, disposal costs are minimized, further improving the economic feasibility.

Furthermore, both adsorbents can be recycled repeatedly without undergoing appreciable performance degradation, which contributes to sustainability. Their adsorption capabilities can be restored by chemical or thermal regeneration techniques, increasing their usefulness and lowering the requirement for constant raw material input. In addition to reducing material usage, this reuse lessens the operating interruptions brought on by replacing the adsorbent. Adoption of these sustainable adsorbents boosts demand for clay activation and agro-waste processing services, which benefits local economies more broadly. As a result, jobs in system operation, processing, and material procurement are created. Businesses that use these environmentally friendly solutions can also gain from carbon credits, corporate sustainability incentives, and enhanced public perception. The usage of modified bentonite and palm kernel shell is an appealing and ethical industrial approach when combined with cost-effectiveness, sustainability, and local economic integration.

**6.3 Environmental Impact and Circular Economy Integration**

The circular economy is supported when bentonite and palm kernel shell are used in transformer oil reclamation. This method encourages resource efficiency and lessens landfill waste by turning agricultural waste into useful treatment materials. Its appropriateness for sustainable industrial applications is highlighted by the adsorbent non-toxic nature and the reclamation process ecological impact. This strategy has a variety of environmental implications. First, using agricultural waste, such as palm kernel shells, prevents biomass from being burned or dumped in landfills, which lowers greenhouse gas emissions and lessens air and soil pollution. The ecological expenses of long-distance material transportation and the extensive industrial processing needed for imported materials or synthetic resins can also be avoided by sourcing and processing modified bentonite locally. Conventional reclamation techniques produce toxic sludge that needs to be handled and disposed of carefully, endangering ecosystems and human health. However, the cyclical value of bentonite and PKS-based adsorbents is further enhanced by the fact that they can be securely disposed of after usage or even recycled.

1. **Conclusion**

Transformer oil composition and degradation products, adsorbent activation, and regeneration approaches have all been thoroughly assessed in this paper. The major causes of transformer oil deterioration are oxidation, moisture, and heat stress, which result in sludge development, acidity, and lower dielectric strength. Adsorption efficiency is greatly increased by bentonite modifications (such as acid activation), which also improve properties of transformer oil, such as dielectric strength, viscosity, acid number, moisture content, flash point, and fire point. Bentonite clay adsorbs contaminants in spent transformer oil. Palm kernel shell activated carbon adsorbs pollutants because of the lignocellulosic composition and porous structure. When compared to the disposal or replacement of used transformer oil, integrated reclamation methods (heating, agitation, centrifugation, and adsorption) and locally sourced adsorbents (bentonite clay, palm kernel shell) provide a sustainable approach for restoring oil qualities that are close to fresh oil. Investigating the long-term effects of reclaimed oil on transformer insulation systems to ensure effective performance and safety is recommended for future work.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

**Acknowledgement**

The authors acknowledge the late Prof. Benson O. Evbuomwan for his invaluable contributions to this research. His intellectual input and commitment played a crucial role in this work. We honour his memory and the lasting impact he had on this study.

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