



Iranian Research Organization
for Science and Technology
(IROST)



Sustainable reclamation of transformer oils via tailored mesoporous γ -alumina: Oil regeneration and durability performance of adsorbents

Kousar Dinarvandi^a, Abdolreza Samimi^{a*}, Davod Mohebbi-Kalhari^a, Mojghan Zakeri^a, Reyhaneh Zakeralhosseini^b

^aDepartment of Chemical Engineering, Faculty of Engineering, University of Sistan and Baluchestan, Zahedan, Iran.

^bDepartment of Materials and Metallurgical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran.

ARTICLE INFO

Document Type:
Research Paper

Article history:
Received 20 February 2026
Received in revised form
13 August 2026
Accepted 18 July 2026

Keywords:
Transformer oil regeneration
 γ -Alumina adsorbents
Acid leaching
Surface morphology
Attrition resistance

ABSTRACT

The large volumes of waste oils produced by electric power generation systems have heightened concerns about their disposal. As an alternative, the regeneration and reclamation of these oils are environmentally preferred. This study investigates the regeneration of contaminated transformer oil using mesoporous γ -alumina adsorbents synthesized from cost-effective boehmite. Two synthesis routes, thermal-chemical (TC) and chemical-thermal (CT), were evaluated using Taguchi's L16 orthogonal array to optimize the preparation conditions. The performance of the synthesized adsorbents in oil regeneration was then assessed through a one-step batch adsorption process and multiple saturation cycles. Textural characterization by BET analysis identified the optimal TC-derived γ -alumina with a specific surface area of $226.76 \text{ m}^2 \text{ g}^{-1}$, a pore volume of $0.25 \text{ cm}^3 \text{ g}^{-1}$, and an average pore diameter of 5.95 nm . The optimized adsorbent demonstrated superior physicochemical performance in treated oil, significantly improving the total acid number (TAN), dielectric dissipation factor (DDF), and electrical resistivity. In addition, it exhibited low mechanical erosion (3.35% within a particle size range of $0.710\text{--}0.850 \text{ mm}$), outperforming comparable commercial products ($\sim 7.04\%$ erosion). FTIR and GC-MS analyses confirmed the effective removal of key contaminants, including 1,2-benzenedicarboxylic acid derivatives (diisooctyl ester and mono-(2-ethylhexyl) ester). Based on the latest literature, the comparison of thermal-chemical and chemical-thermal synthesis routes, along with their effects on pore-size distribution and the attrition strength of $\gamma\text{-Al}_2\text{O}_3$ adsorbents, represents a novel aspect of this study and warrants further investigation to maximize adsorption performance.

*Corresponding author Tel.: +98 9128299127

E-mail: a.samimi@eng.usb.ac.ir, samimi683@yahoo.co.uk

DOI: 10.22104/aet.2026.8150.2291

COPYRIGHTS: ©2026 Advances in Environmental Technology (AET). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution 4.0 International (CC BY 4.0) (<https://creativecommons.org/licenses/by/4.0/>)

1. Introduction

With economic and urban development, power infrastructure, including high-voltage transformers, largely depends on the quality of its insulating oil [1]. Rapid growth in energy demand further underscores the importance of insulation performance in oil-immersed electrical equipment; therefore, effective management and operational strategies are essential [2]. High dielectric strength and efficient heat dissipation are key requirements for insulating oils to ensure optimal transformer performance [3]. However, during operation, thermal stress and oxidation can trigger chemical reactions that generate harmful byproducts in the oil, potentially leading to irreversible damage in severe cases [4–6]. In addition, with prolonged service, degradation products from the transformer's oil-paper insulation system may dissolve into the oil, making routine testing and analysis critical for condition monitoring [7].

To ensure reliability, transformer oils should undergo standardized characterization at regular intervals to assess electrical and physicochemical properties. Adherence to these standards provides valuable insight into insulation performance and is mandatory in some countries. Internationally recognized standards, such as IEC 61125 and IEC 60247, define key characteristics for evaluating insulating-oil quality [8]. Moreover, large volumes of used transformer oil, owing to poor biodegradability and biotoxicity, should not be released into the environment, as they can contaminate soil and water, harm living organisms, and threaten socioeconomic stability and public safety. Therefore, recycling and regenerating used oil for reuse is essential [9–11].

Transformer performance and lifespan can be improved by reclaiming contaminated oil using adsorption processes, which can effectively reduce undesirable contaminants [4,5]. Numerous adsorbents have been explored for transformer-oil regeneration, including activated bauxite [12], zeolite [13], kaolin clay [14], calcium carbonate phosphate microparticles (CACP), chitosan biopolymers [15], and activated carbon [16]. Nevertheless, these materials face notable technical limitations. For example, bauxite-based processes can generate substantial waste, while

CACP microparticles often involve high production costs [15], limiting their practicality for oil purification [17]. In addition, activated carbon, zeolite, and kaolin clay particles may reduce purification efficiency under certain conditions [18].

Among alumina-based minerals, boehmite (γ - AlOOH) has a layered crystal structure that makes it valuable across many applications. It serves as a precursor for aluminum oxides and is used in the synthesis of membranes, adsorbents, catalysts, and catalyst supports [19,20]. Alumina-based adsorbents have been widely applied for pollutant removal, with performance attributed to their distinctive chemical properties and surface physicochemical characteristics [21,22]. Recent studies further indicate that adsorption performance is strongly governed by structural and physicochemical features. Spiridon et al. [23] reported that highly porous materials dominated by micropores exhibited less efficient adsorption of oil pollutants, highlighting the importance of optimizing pore-size distribution. Jankovic et al. [24] demonstrated that a mesoporous adsorbent structure improved sulfur-compound removal from transformer oil, with performance influenced by specific surface area and porosity. Kai Fei et al. [25] similarly emphasized the pivotal role of γ - Al_2O_3 pore structure, showing that variations in surface area and pore volume substantially affect pollutant-removal efficiency. Bekele et al. [26] examined γ - Al_2O_3 morphology before and after adsorption and found evidence of pore filling by adsorbed species, underscoring the need to optimize pore volume and surface area to sustain performance. Currently, transformer-oil regeneration is performed using boehmite-based adsorbents, which exhibit strong contaminant adsorption capacity and improve the physicochemical properties of the oil [21].

Despite these advances, a systematic comparison between thermal-chemical and chemical-thermal synthesis routes for optimizing the pore volume and surface area of γ - Al_2O_3 is currently missing. Furthermore, there is a lack of data regarding the synthesis of cost-effective boehmite under controlled conditions and its subsequent influence on the pore-size distribution, acid-site distribution, and attrition strength of the resulting adsorbents. A deeper investigation into the relationship

between these structural properties, saturation behavior, and oil-regeneration efficiency is essential to maximize adsorption performance. This study evaluated the distinct effects of two synthesis sequences, heat treatment followed by acid leaching (TC) and the reverse order (CT), on the chemical composition, structural characteristics, and surface morphology of porous particulates produced from boehmite ore. Process parameters were optimized using Taguchi's L16 orthogonal array, with leaching factors tuned to improve performance. We further assessed how these material properties influence the physicochemical and electrical performance of transformer oil. Using internationally standardized oil tests, we determined the total oil volume processed by the adsorbent and evaluated adsorbent saturation behavior. This work provides actionable insights for optimizing synthesis protocols to enhance adsorbent performance in oil treatment, particularly with respect to adsorbent-to-oil ratio (solid/liquid, S:L), pollutant removal efficiency, and adsorbent attrition resistance. In addition, variations in hydrocarbon pollutant composition were investigated using Fourier transform infrared (FTIR) spectroscopy and gas chromatography-mass spectrometry (GC-MS).

2. Materials and methods

2.1. Materials

Boehmite ore (Al_2O_3 : 45.005 Wt%) was sourced from an Iranian mine in the Zagros Mountains. For synthesis, 37% hydrochloric acid (HCl) purchased from Sigma-Aldrich was used for acid-leaching, and an advanced laboratory furnace was used for heat treatment. Used power-transformer oil was supplied by the Regional Electric Company (initial sulfur content ($140.77 \text{ mg}\cdot\text{g}^{-1}$), Asaluyeh, and was evaluated in the adsorption and purification experiments described in subsequent sections. For comparison, a commercial adsorbent was procured from Porocel (Canada).

2.2. Adsorbent synthesis

The adsorbents were synthesized using a top-down approach to obtain a suitable pore-size distribution. Activation of raw boehmite to $\gamma\text{-Al}_2\text{O}_3$ for use as an adsorbent was performed using two synthesis sequences: a thermal-chemical route

(TC), in which heat treatment preceded acid leaching, and a chemical-thermal route (CT), in which acid leaching preceded heat treatment. Boehmite ore was ground, washed, dried, and then sieved (sub-sieve) to obtain particle-size fractions of 0.710–0.850 mm and 1.00–1.18 mm to match commercial adsorbent size ranges. Heat treatment was carried out at 400–600 °C for 6 h with a heating rate of 2 °C/min [21]. For acid leaching, the selected particle-size fractions were dispersed in an HCl solution at 80 ± 5 °C to remove undesirable constituents, then dried at 90 °C for 24 h. Leaching conditions for producing activated alumina were optimized according to the parameters listed in Table 1. Finally, materials produced via both TC and CT routes were repeatedly washed with water until the rinse water reached the target pH.

Table 1. Acid leaching factors and levels.

Variables	Levels	
Synthesis method	TC	CT
Mesh size (mm)	0.710-0.850	1.0-1.180
S:L (g/cc)	1:5	1:10
Acid concentration (M)	6	7
Time (h)	1	2
pH of rinsing water	4	7

2.3. Experimental design of adsorbents

The primary objective of this study was to investigate the structural properties of the adsorbents, particularly porosity development and specific surface area, to achieve regenerated oil with the desired physicochemical, attrition resistance, and electrical performance under standard test conditions. To balance experimental workload with optimization reliability, Taguchi design of experiments (DOE) using Minitab was applied for experimental planning and parameter optimization [27]. The Taguchi approach aims to minimize the influence of noise factors (N) on performance while maximizing the effects of controllable (signal) factors (S). A higher signal-to-noise (S/N) ratio indicates that the controllable parameters more effectively dominate variability from uncontrollable sources [28]. Accordingly, process parameters were systematically varied to quantify their effects on the resulting material properties [29]. In the Taguchi experimental design, analysis of variance (ANOVA) was utilized to verify the adequacy of the parameters affecting adsorbent specific surface area.

2.4. Leaching process

Each chemical species has a characteristic standard electrochemical potential (E°) that governs its tendency to undergo oxidation or reduction. Electrochemically generated free radicals are highly reactive intermediates whose composition and charge state can be defined based on the electrochemical conditions under which they are produced [30]. These radicals, either organic or inorganic, often drive subsequent chemical transformations. In aqueous-phase systems, the electrode potentials associated with radical species can serve as useful indicators of reactivity and may correlate more directly with reaction kinetics than the potentials of corresponding non-radical species [31]. The dissolution reactions of boehmite ore constituents (e.g., titanium oxide, alumina, and silica) in hydrochloric acid during the leaching step are illustrated in Figure 1.

2.5. Characterization of adsorbents

The specific surface area and pore-size characteristics of the adsorbents were determined by the Brunauer–Emmett–Teller (BET) method using a GasSorb-II instrument (Japan, Belsorp, Mini2), based on N_2 adsorption–desorption

isotherms at 196 °C measured with a static volumetric adsorption apparatus. Elemental and chemical compositions were analyzed using a wavelength-dispersive X-ray fluorescence (WDXRF) spectrometer (PW1410, Philips, Netherlands). Adsorbent morphology was examined by scanning electron microscopy (SEM; KYKY, China-EM3900M), and crystalline phases were identified by X-ray diffraction (XRD). XRD patterns were collected on a Bruker D8 Advance diffractometer using $Cu\ K\alpha$ radiation over a 2θ range of 10° – 80° . Fourier transform infrared (FTIR) spectroscopy (TENSOR II, Bruker, Germany) was used to identify functional groups, with spectra recorded from 4000 to $400\ cm^{-1}$. Gas chromatography–mass spectrometry (GC–MS) (GC 6890/MSD 5973, Agilent Technologies, USA) equipped with an HP-5 capillary column was used to identify and quantify low-concentration constituents in complex mixtures; helium served as the carrier gas, hexane as the solvent, and the total run time was 30 min. Oil acidity (total acid number, TAN) was measured using a potentiometric titrator (TITROLINE® 7000, SI ANALYTICS, Germany) and reported as mg KOH/g. Interfacial tension (IFT) between oil and water was measured using a tensiometer (K9-MK1, KRÜSS, Germany) in accordance with IEC 62961 and ASTM D971.

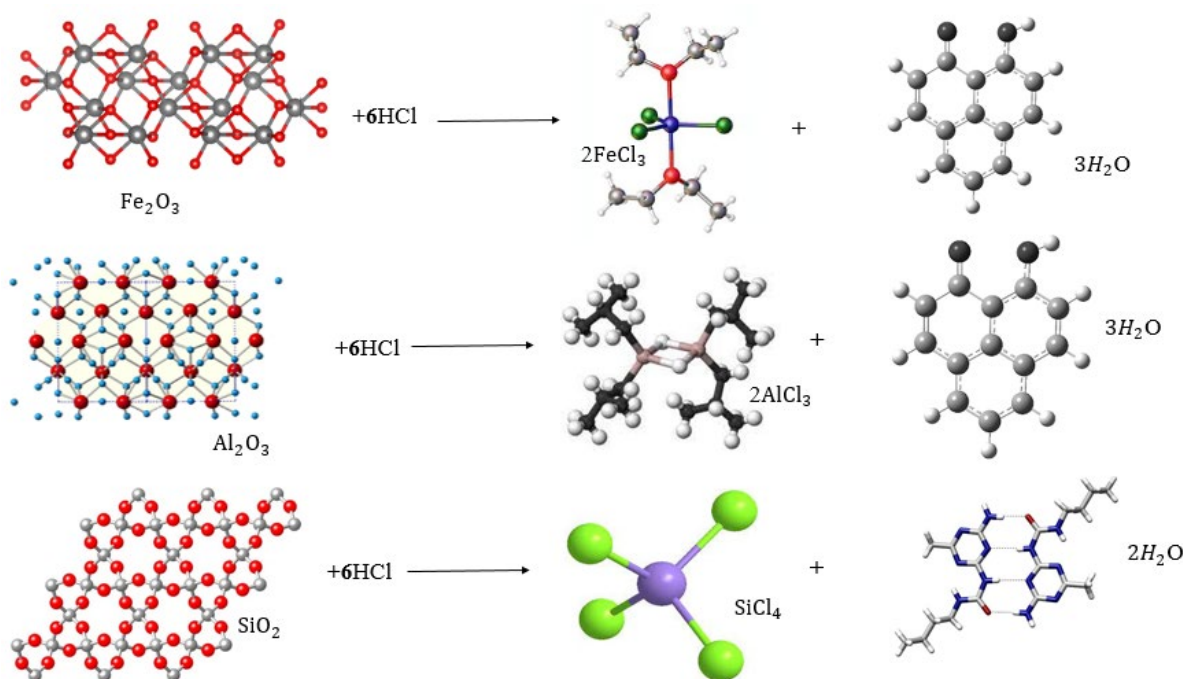


Fig. 1. Dissolution reactions of boehmite ore constituents during chemical treatment with HCl.

To assess insulating-oil quality, dielectric dissipation factor (DDF) and resistivity were measured using an HZJD-2Z instrument (China) following IEC 60247. All measurements were performed at ambient temperature and at 90 °C.

2.6. Attrition resistance of adsorbent

The attrition resistance of the adsorbents was evaluated after synthesis and oil regeneration by measuring the mass percentage of fine debris (smaller than 50-mesh sieve size). In both steps, the final adsorbent mass was separated from fine debris during the final washing stage.

3. Results and discussion

3.1. Characterization of the adsorbents

Pore size distribution (PSD) is a key structural parameter that strongly influences adsorption capacity. To maximize performance, PSD should be tuned to balance pore volume, accessibility, and selectivity according to the target adsorbate and application [32]. Accordingly, N_2 adsorption/desorption isotherms were collected to evaluate the effects of synthesis sequence (TC vs. CT), particle size (mesh fraction), leaching time, HCl concentration, solid-to-liquid (S:L) ratio, and rinse-water pH on the adsorbent structure. Pore-volume distributions, as a function of pore radius, were calculated using the Barrett-Joyner-Halenda (BJH) model. The experimental design and results are summarized in Table 2 and Figure 2. Table 2 lists the Taguchi L16 orthogonal array and the selected 6 replicate runs (i.e., average and standard deviations for samples 3, 6, 2, 9, 15, and 12). The parameter ranges are used to optimize the synthesis conditions, together with the measured responses (BET specific surface area, cumulative pore volume, and average pore diameter). Regarding the Barrett-Joyner-Halenda (BJH) analysis, the pore-size distribution and pore volume calculations (shown in Figures 2A and 2B) were derived from the desorption branch of the isotherm. In the figures, the area under each curve represents cumulative pore volume versus pore radius for all samples and for selected runs, respectively. Figure 2C shows the N_2 adsorption/desorption isotherms of the selected samples. BET and isotherm data for the commercial adsorbent are reported elsewhere [21].

As shown in Figure 2A and Table 2, the TC route consistently outperformed the CT route, particularly with respect to porosity development, micro-mesopore modification, and overall structural refinement. The highest BET surface areas were obtained for TC-treated samples (run 12: 245.93 m^2/g ; run 15: 226.76 m^2/g ; run 9: 176.16 m^2/g). In contrast, CT samples exhibited substantially lower surface areas (run 2: 99.64 m^2/g ; run 6: 77.85 m^2/g ; run 3: 39.38 m^2/g).

A similar pattern was observed for cumulative pore volume. Among TC samples, run 12 showed the largest pore volume (0.3456 cm^3/g), followed by run 15 (0.25 cm^3/g) and run 9 (0.20 cm^3/g). CT samples showed lower pore volumes, clustering at ~0.15–0.18 cm^3/g . In terms of average pore diameter, CT samples tended to have larger pores (run 3: 21.47 nm; run 6: 12.41 nm; run 2: 10.08 nm), whereas TC samples exhibited smaller average pore diameters (run 15: 5.95 nm; run 9: 6.27 nm; run 12: 7.08 nm), indicating a shift toward more finely distributed mesoporosity. Collectively, these results suggest that CT processing produces fewer but wider pores, while TC processing yields a denser network of smaller mesopores, consistent with the markedly higher surface areas and pore capacities. Consequently, TC-derived materials offer greater available surface and pore volume, supporting improved adsorption-separation performance. The isotherms in Figure 2C further support these observations. In particular, TC samples (runs 12 and 15) exhibited Type IV isotherms with H1-type hysteresis loops, which are characteristic of mesoporous solids with relatively uniform pore-size distributions. The pronounced hysteresis in the desorption branches reflects capillary condensation within mesopores and is consistent with higher adsorbed volumes at elevated relative pressures ($p/p_0 > 0.8$). Overall, TC samples from runs 12 and 15, corresponding to the 1.00–1.18 mm and 0.710–0.850 mm size fractions, respectively, emerged as the most promising candidates, combining the highest surface area and pore volume with moderately small pore diameters. These attributes are favorable for applications requiring rapid adsorption kinetics and high surface exposure. Conversely, CT samples (runs 2, 3, and 6) showed very low surface areas, suggesting poor pore density and/or partial pore collapse, which would limit adsorption performance despite their larger

average pore sizes. Among the investigated parameters, the pH of the rinse water after leaching is an important control variable, reflecting the extent of residual-acid removal and impurity elimination [33].

In addition, both leaching temperature and duration strongly influence extraction efficiency: higher temperatures increase the energy available to disrupt bonds between gangue species and the acid medium, improving impurity removal while requiring careful control to avoid excessive dissolution of the target phase [34]. Taken together, these findings indicate that synthesis sequence governs the extent and selectivity of metal leaching, thereby shaping pore volume and PSD. The TC route

likely promotes oxidation of metallic impurities during heat treatment, facilitating their subsequent removal during acid leaching and reducing impurity retention in the final adsorbent [21,35].

More broadly, leaching selectively dissolves metal oxides, and pre-heating can alter the boehmite microstructure in ways that increase accessible surface area and porosity, yielding a more favorable adsorbent architecture.

Based on pore-volume profiles (highest, average, and lowest pore volumes across pore radii), representative adsorbents from both TC and CT routes were selected for used-oil regeneration experiments, and the performance of selected samples was evaluated for repeatability.

Table 2. Taguchi L16 orthogonal array of experimental parameters, obtained responses for all 16 runs (a) and selected 6 replicates, with their average values and standard deviation (b).

Run (a)	Parameters						Responses		
	Synthesis	Mesh size (mm)	S:L (g/cc)	Conc. (M)	Time (h)	pH	Cumulative surface of pores $a_{s, \text{long}}$ (m^2/g^{-1})	BJH total pores volume ($\text{cm}^3/\text{g}^{-1}$)	Average pore diameters (nm)
1	CT	0.710-0.850	1:10	6	1	4	66.27	0.16	10.47
2	CT	1.00- 1.18	1:10	6	1	7	99.64	0.18	10.07
3	CT	0.710-0.850	1:05	7	2	4	39.38	0.18	21.47
4	CT	1.00- 1.18	1:05	7	2	7	87.14	0.15	10.29
5	CT	0.710-0.850	1:10	7	1	7	92.37	0.18	12.49
6	CT	1.00- 1.18	1:10	7	1	4	74.44	0.18	12.35
7	CT	0.710-0.850	1:05	6	2	7	77.29	0.18	11.82
8	CT	1.00- 1.18	1:05	6	2	4	77.85	0.18	12.35
9	TC	0.710-0.850	1:05	6	1	4	176.16	0.20	6.27
10	TC	1.00- 1.18	1:05	6	1	7	241.76	0.30	6.45
11	TC	0.710-0.850	1:10	7	2	4	206.19	0.30	7.43
12	TC	1.00- 1.18	1:10	7	2	7	245.93	0.34	7.08
13	TC	0.710-0.850	1:10	6	2	7	238.92	0.33	7.05
14	TC	1.00- 1.18	1:10	6	2	4	201.86	0.33	8.12
15	TC	0.710-0.850	1:05	7	1	7	226.76	0.25	5.95
16	TC	1.00- 1.18	1:05	7	1	4	205.91	0.26	6.43

Table 2. Continued.

Run (b)	Average specific surface area (m^2/g^{-1})	$a_{s, \text{log}}$	Average cumulative pore volume ($\text{cm}^3/\text{g}^{-1}$)	V_{BJH}	Average pore diameter (nm)
2	82.96 ± 23.6		0.175 ± 0.02		10.27 ± 0.28
3	32.84 ± 9.25		0.135 ± 0.06		18.29 ± 4.48
6	63.52 ± 15.44		0.155 ± 0.04		11.33 ± 1.44
9	165.74 ± 14.74		0.245 ± 0.06		6.11 ± 0.23
15	215.38 ± 24.38		0.255 ± 0.01		7.28 ± 1.89
12	245.47 ± 19.14		0.295 ± 0.06		6.72 ± 0.47

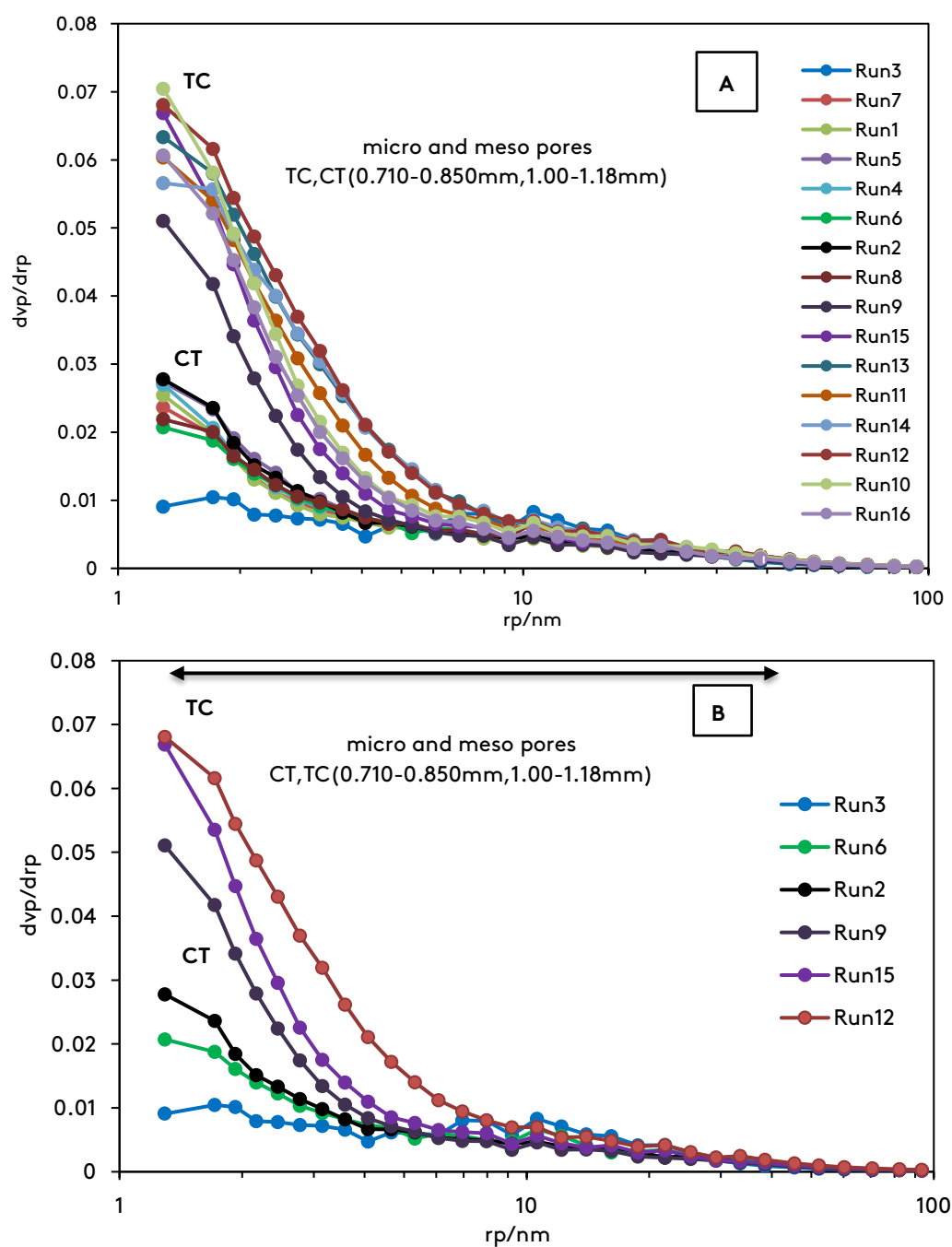


Fig. 2. BJH analysis for synthesized TC and CT samples (A), selection of the highest, average and lowest synthesized samples (B), and N_2 -adsorption-desorption isotherms (C).

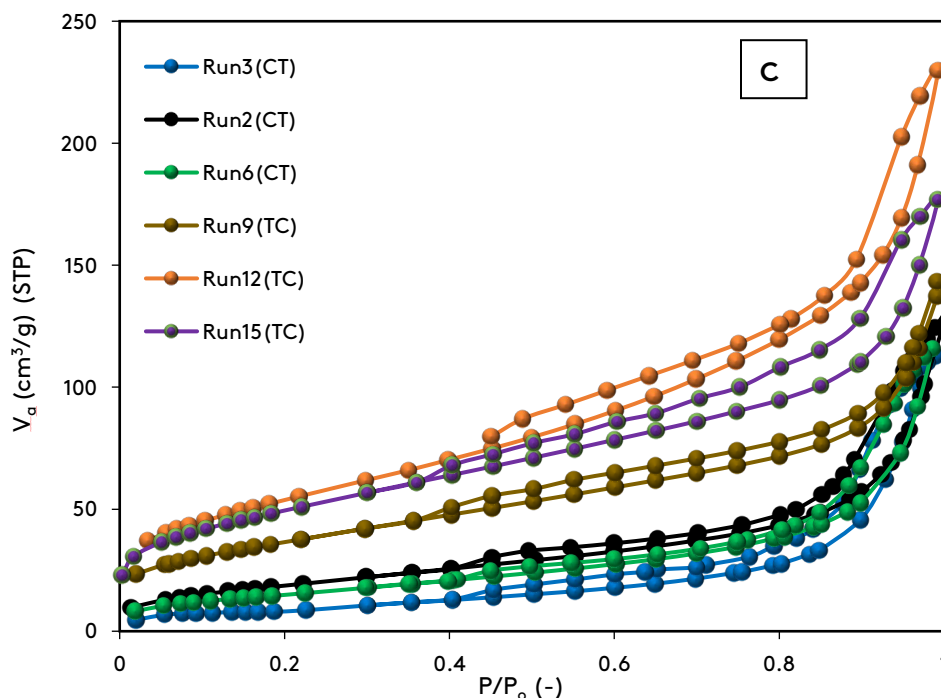


Fig. 2. (Continued) BJH analysis for synthesized TC and CT samples (A), selection of the highest, average and lowest synthesized samples (B), and N_2 -adsorption-desorption isotherms (C).

Figures 3A and 3B present the mean signal-to-noise (S/N) ratios and interaction plots for six key variables influencing adsorbent performance: synthesis sequence, mesh size, solid-to-liquid ratio (S:L), HCl concentration, leaching time, and rinse-water pH.

Based on Table 2 and Figures 2 and 3, the largest S/N ratios and the steepest main-effect trends were observed for the TC synthesis route and rinse-water pH, indicating that these factors most strongly drive the response and represent the most favorable settings for maximizing adsorption efficiency. The pronounced slopes in these plots identify the parameters with the greatest influence and therefore the highest leverage for process optimization.

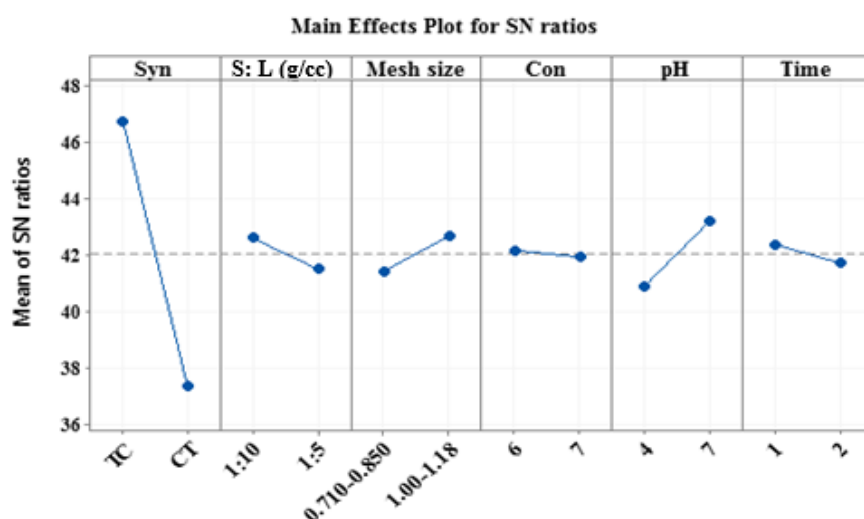
In contrast, near-parallel lines in the interaction plots indicate minimal interaction between the corresponding factors (e.g., mesh size, acid concentration, or leaching time), suggesting limited synergistic effects within the tested ranges and, consequently, lower optimization potential for those factor combinations [36]. The full interaction matrix is shown in Figure 3B. Notably, the lines for the synthesis route (TC/CT) and rinse-water pH are non-parallel, indicating a meaningful interaction between these factors. By comparison, acid

concentration and leaching time exhibit largely parallel trends, consistent with negligible interaction effects on adsorbent synthesis under the studied conditions. Other factor pairs show modest deviations from parallelism, suggesting weaker but potentially relevant interactions.

Table 3 summarizes the analysis of variance for the BET specific area response of the Taguchi analysis and clarifies which synthesis variables most strongly drive the response. The primary response variable used in the ANOVA was the BET specific surface area, as it was considered the main indicator for evaluating the textural performance of the synthesized adsorbent. Pore volume and pore diameter were used as complementary parameters in the interpretation of the optimization results and are not shown.

The results explain nearly all of the observed variability ($R^2 = 98.88\%$), with a similarly high adjusted R^2 (98.13%) and strong predictive ability ($R^2(\text{pred}) = 96.45\%$). The residual standard deviation ($S = 10.4188$) indicates that the unexplained variability is modest relative to the overall response magnitude. The synthesis route (TC vs. CT) is the dominant driver of performance ($F = 743.19$, $p < 0.001$), contributing ~93.85% of the total adjusted sum of squares.

A



B

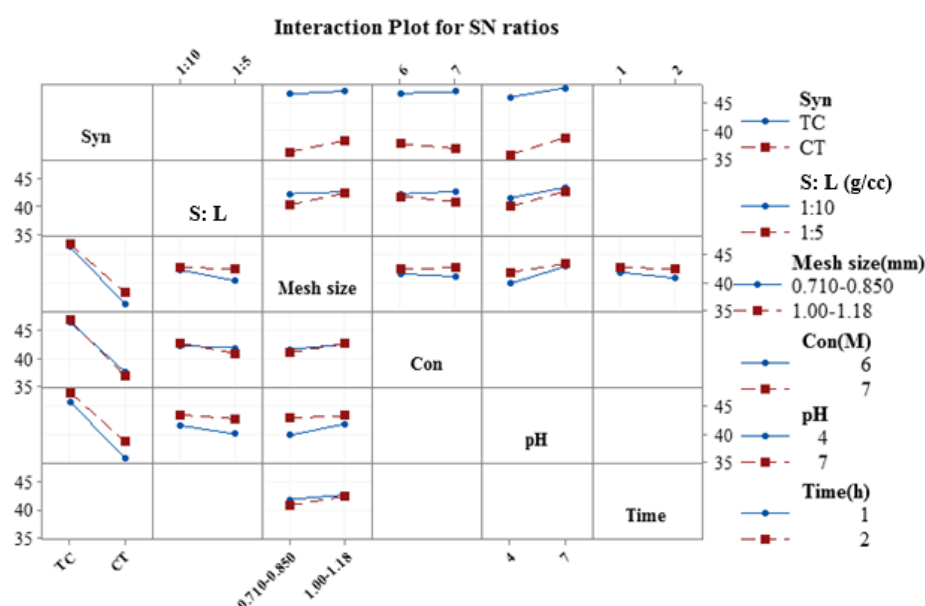


Fig. 3. Mean signal-to-noise (S/N) ratios for synthesis parameters and interaction plots from Taguchi analysis.

Table 3. Analysis of variance for response of BET specific surface area.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Synthesis	1	80674.5	80674.5	743.19	0.000
Mesh size	1	678.2	678.2	6.25	0.034
S/L	1	542.5	542.5	5.00	0.052
Concentration	1	9.3	9.3	0.09	0.777
Time	1	4.6	4.6	0.04	0.842
pH	1	4054.8	4054.8	37.35	0.000
Model Summary		S	R-sq	R-sq(adj)	R-sq(pred)
		10.4188	98.88%	98.13%	96.45%

This indicates that the processing sequence overwhelmingly determines the resulting adsorbent structure/performance, consistent with earlier observations that TC produced markedly higher surface area and pore volume than CT.

Practically, this means optimization efforts should prioritize the synthesis sequence before fine-tuning secondary parameters. Rinse-water pH is the second most influential factor ($F = 37.35$, $p < 0.001$), accounting for ~4.72% of the variance.

Although its contribution is much smaller than the synthesis route, it is clearly significant and provides meaningful leverage for improving the product. This aligns with the interpretation that rinse pH reflects the extent of residual acid/impurity removal after leaching; insufficient neutralization can leave residual chloride/acidic species or impurities that affect surface chemistry and pore accessibility, whereas appropriate washing helps stabilize the desired porous structure. Mesh size shows a statistically significant effect at the 0.05 level ($F = 6.25$, $p = 0.034$), but its practical contribution is comparatively small ($\sim 0.79\%$). This pattern, a statistically significant yet modest contribution, suggests particle-size fraction influences outcomes (e.g., via leaching kinetics, diffusion path length, or heat-treatment uniformity), but it does not dominate the response. Mesh size is therefore better viewed as a “fine-tuning” parameter once the synthesis route and rinse control are fixed. The S:L ratio is borderline ($F = 5.00$, $p = 0.052$; contribution $\sim 0.63\%$). From a process standpoint, S:L likely governs acid availability and mass transfer during leaching; even if not strictly significant here, it may still matter for scale-up, cost, and reproducibility. Acid concentration ($F = 0.09$, $p = 0.777$) and leaching time ($F = 0.04$, $p = 0.842$) are clearly non-significant in the explored ranges and contribute negligibly ($< 0.02\%$ combined). Practically, this is useful: concentration and time can potentially be selected based on operational constraints (cost, safety, throughput) without materially sacrificing the response, so long as settings remain within the validated range.

The strong significance of the synthesis route and rinse pH also agrees with the interaction-plot interpretation (non-parallel trends), suggesting that the effectiveness of rinsing may depend on whether TC or CT was used. If the goal is further refinement, a follow-up design that explicitly includes selected interaction terms (or response-surface optimization around TC + rinse pH) would be the most efficient next step.

Collectively, the ANOVA supports a clear hierarchy of control. First, the synthesis sequence should be selected as the primary lever (with TC preferred). Next, rinse-water pH should be carefully controlled. Mesh size (and potentially the S:L ratio)

can then be adjusted to improve process practicality. In contrast, acid concentration and leaching time showed minimal statistical influence within the investigated ranges and may therefore be chosen primarily based on efficiency, safety, and economic considerations.

The XRD patterns in Figure 4 demonstrate the evolution of the crystalline structure during the transformation of boehmite into alumina under different synthesis conditions. The XRD spectrum of raw boehmite (Ref. Code: 01-083-2384) exhibits sharp and intense crystalline diffraction peaks at 2θ of $14.8^\circ \pm 1$, $28.4^\circ \pm 1$, $38.5^\circ \pm 1$, and $55.6^\circ \pm 1$, consistent with its crystalline nature and in good agreement with the literature [37,38].

Significant fluctuations in the spectra and intensity of signals observed during the thermal treatment/acid leaching (TC) and acid leaching/thermal treatment (CT) processes indicate the transformation of boehmite ($\text{AlO}(\text{OH})$) to the $\gamma\text{-Al}_2\text{O}_3$ phase (JCPDS Card No. 10-0425 for γ -alumina) with a tetragonal structure. The samples exhibiting broader diffraction peaks possess lower crystallinity and smaller crystallite sizes.

Furthermore, the XRD results suggest that the acid concentration applied during the synthesis does not induce any significant structural degradation of the resulting gamma-alumina. Samples in both synthesis methods have appeared with broad peaks at 2θ values of about $24.5^\circ \pm 1$, $38.2^\circ \pm 1$, $45.6^\circ \pm 1$, $48.9^\circ \pm 1$, and $66.9^\circ \pm 1$.

The chemical composition of raw boehmite, activated alumina, and commercial samples, as determined by XRF analysis, is presented in Table 4. The XRF results show that raw boehmite consists predominantly of Al_2O_3 , SiO_2 , along with trace elements of Fe and Ti.

As shown in Table 4, the loss on ignition (L.O.I) value, indicating sample weight loss after heating, decreases significantly in the activated samples compared to raw boehmite. This reduction in L.O.I corresponds to an increase in Al_2O_3 content and an efficient removal of gangue metals from the structure. Following purification, the TC activated sample exhibits a notable reduction in Fe, Si, and other impurities, attributable to the synthesis process. Comparing TC and CT, it is evident that the order of heat treatment and chemical leaching

significantly influences impurity removal efficiency. These findings align well with BET analysis, suggesting that the CT process does not

facilitate effective leaching of impurities, nor does it significantly alter porosity or pore volume.

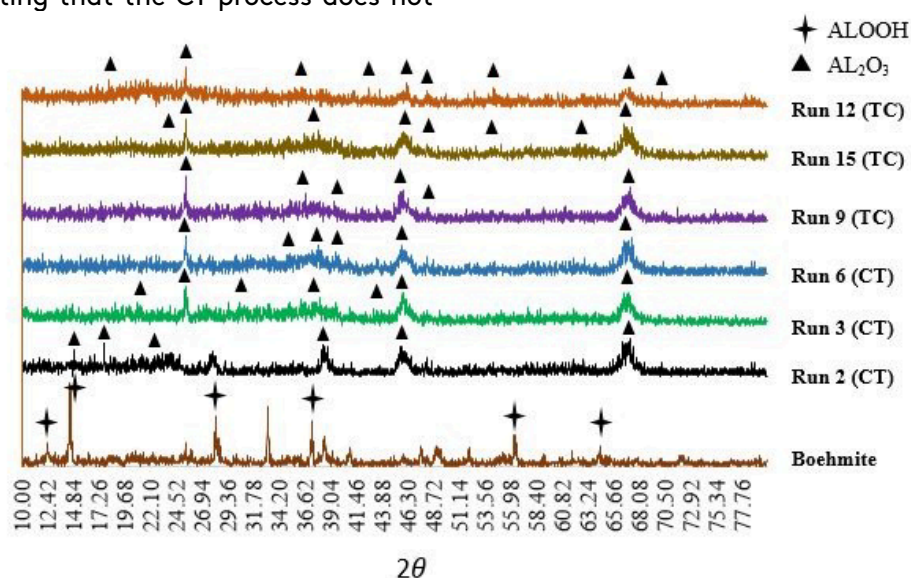


Fig. 4. XRD patterns of raw boehmite and synthesized adsorbents of TC and CT.

3.2. Stepwise regeneration of transformer oil

These adsorbents were selected based on their pore volume change as a function of pore radius to assess their influence on the oil's physical and electrical properties, including total acid number (TAN), resistivity, and dielectric dissipation factor (DDF).

To evaluate the adsorbent longevity, 40 g of the adsorbent sample was placed in contact with 200 g of used transformer oil (weight ratio of 1:5, adsorbent to oil) in a glass beaker under 75 °C for 1 h, with a stirring speed of 300 rpm. The adsorption process was conducted in six consecutive steps, introducing 200 grams of the original used oil to the adsorbent sample at each step.

After each test, the settled adsorbent particles in the oil glass beaker were separated and then

subjected to the next step. Table 5 presents the used transformer oil specifications based on ASTM/IEC standards.

The physical and electrical characteristics of the used oil, as well as the regenerated oil treated with TC, CT, and commercial samples, were evaluated using standard characterization methods (Table 5). The results show that regenerated oil treated with the CT adsorbent (runs 3, 6, and 2) exceeded permissible limits for TAN, DDF, and resistivity. In contrast, TC adsorbents (runs 12, 15, and 9) and the commercial sample performed better in TAN, DDF, and resistivity analyses.

Notably, samples of runs 12, 15, and the commercial adsorbent surpassed the standard electrical limits for transformer oil from the fourth step onward.

Table 4. Chemical composition of raw boehmite, synthesized samples, and commercial samples.

Adsorbents/ oxide	Al ₂ O ₃	SiO ₂	TiO ₂	Fe ₂ O ₃	CaO	MgO	MnO	Na ₂ O	K ₂ O	L.O.I
Raw boehmite	45.005	24.29	7.97	13.10	0.502	0.247	0.016	0.045	0.091	13.46
Run 9	77.327	10.89	3.18	2.41	0.010	0.161	0.024	N	0.02	5.17
Run 12	78.543	10.93	3.16	2.02	0.060	0.154	0.01	N	0.005	4.41
Run 15	78.051	11.49	3.83	2.04	0.027	0.063	0.013	N	0.017	4.09
Run 3	71.637	14.35	3.35	3.68	0.087	0.204	0.019	0.022	0.055	6.97
Run 2	72.642	31.13	3.44	3.197	0.045	0.257	0.015	0.037	0.05	7.99
Run 6	73.316	13.82	3.61	2.92	0.045	0.291	0.02	0.045	0.049	6.29
Commercial	80.41	3.70	0.17	2.22	0.090	0.190	-	0.11	0.060	12.65

L.O.I. loss on ignition value.

Table 5. Physico-chemical properties of used oil regeneration with selected adsorbents in six steps.

Properties	Standard	Limits	Used Oil	step	CT		TC				Commercial
					Run2	Run6	Run3	Run12	Run15	Run9	
TAN (mg KOH/g)	IEC 62021	Max. 0.01	0.056	1	0.04	0.04	0.04	0.005	0.006	0.008	0.006
				2	0.05	0.04	0.05	0.008	0.005	0.01	0.008
				3	0.05	0.04	0.07	0.009	0.007	0.02	0.01
				4	0.06	0.04	0.08	0.01	0.01	0.03	0.01
				5	0.06	0.06	0.08	0.04	0.04	0.05	0.03
				6	0.06	0.06	0.08	0.06	0.04	0.06	0.05
DDF (90°C)	IEC 60247	Max. 0.005	0.0451	1	0.01	0.008	0.007	0.000	0.000	0.001	0.000
				2	0.01	0.011	0.009	0.001	0.001	0.001	0.001
				3	0.02	0.016	0.016	0.004	0.002	0.004	0.002
				4	0.02	0.013	0.014	0.004	0.002	0.005	0.003
				5	0.02	0.018	0.013	0.005	0.003	0.005	0.005
				6	0.02	0.017	0.012	0.005	0.004	0.012	0.006
Resistivity (90°C) (GΩm)	IEC 60247	-	4.8	1	36.2	47.6	59.5	335	548	217	246
				2	23.2	29.7	37.2	289	354	202	233
				3	13.4	20.1	32.9	105	206	96.1	211
				4	16.2	33.1	26.6	66.9	187	93.9	146
				5	16.3	23.5	27.1	60.6	145	90.8	98
				6	19.6	22.6	26.4	51.4	105	88.4	85

Transformer oil specifications[21].

However, in the third synthesis step, the TAN of regenerated oil from run 9 slightly exceeded the standard limit (max. 0.01 mg KOH/g).

The DDF and resistivity are highly sensitive to polar contaminants formed during oil oxidation and aging, and can severely compromise transformer performance [12,21]. As indicated in Table 5, reclaimed oil treated with TC adsorbents (runs 12 and 15) and the commercial adsorbent exhibited superior DDF reduction compared to CT adsorbents, with resistivity measurements further supporting these results. This is a critical finding, as low DDF and elevated resistivity can directly threaten the reliability of transformer insulation [39,40].

The synthesis process plays a significant role in improving morphological properties. In Figure 5, SEM analysis illustrates the differences in surface morphology among all samples. As mentioned earlier, the developed TC treatment yields more appropriate adsorbents compared to the CT treatment. Samples subjected to acid treatment exhibit a hybrid structure, composed of irregular debris and amorphous granules [33].

As seen in Figure 5A, the raw boehmite SEM image shows particles of varying sizes. After the TC process (Figures 5B, C), the images indicate the formation of a dense surface, which would be as a

result of improved heat treatment and chemical metals extraction compared to the initial raw particles. In Figure 5D, the commercial sample displays larger clusters with a more porous structure. Considering the surface morphology of TC adsorbents, along with BET results, confirms the aggregation of dense mesopore γ -Al₂O₃ particles compared to raw boehmite and commercial particles with diverse cluster shapes and sizes.

3.3. Single step adsorption of samples in regeneration of transformer oil

Based on the results of previous analyses of the oil's physical and electrical properties, adsorbents from runs 12 and 15, along with the commercial adsorbent, were selected for further oil purification due to their superior performance in terms of TAN, DDF, and resistance. Since these adsorbents approached saturation in the fourth step under standard conditions, a single-step experiment was conducted to further evaluate them. Specifically, 800 g of oil was mixed with 40 g of adsorbent in a glass beaker at 300 rpm for 4 h. This test aimed to assess the treated oil's physical and electrical properties, and the adsorbents' attrition resistance.

Table 6 summarizes the one-step regeneration average results that was repeated two times.

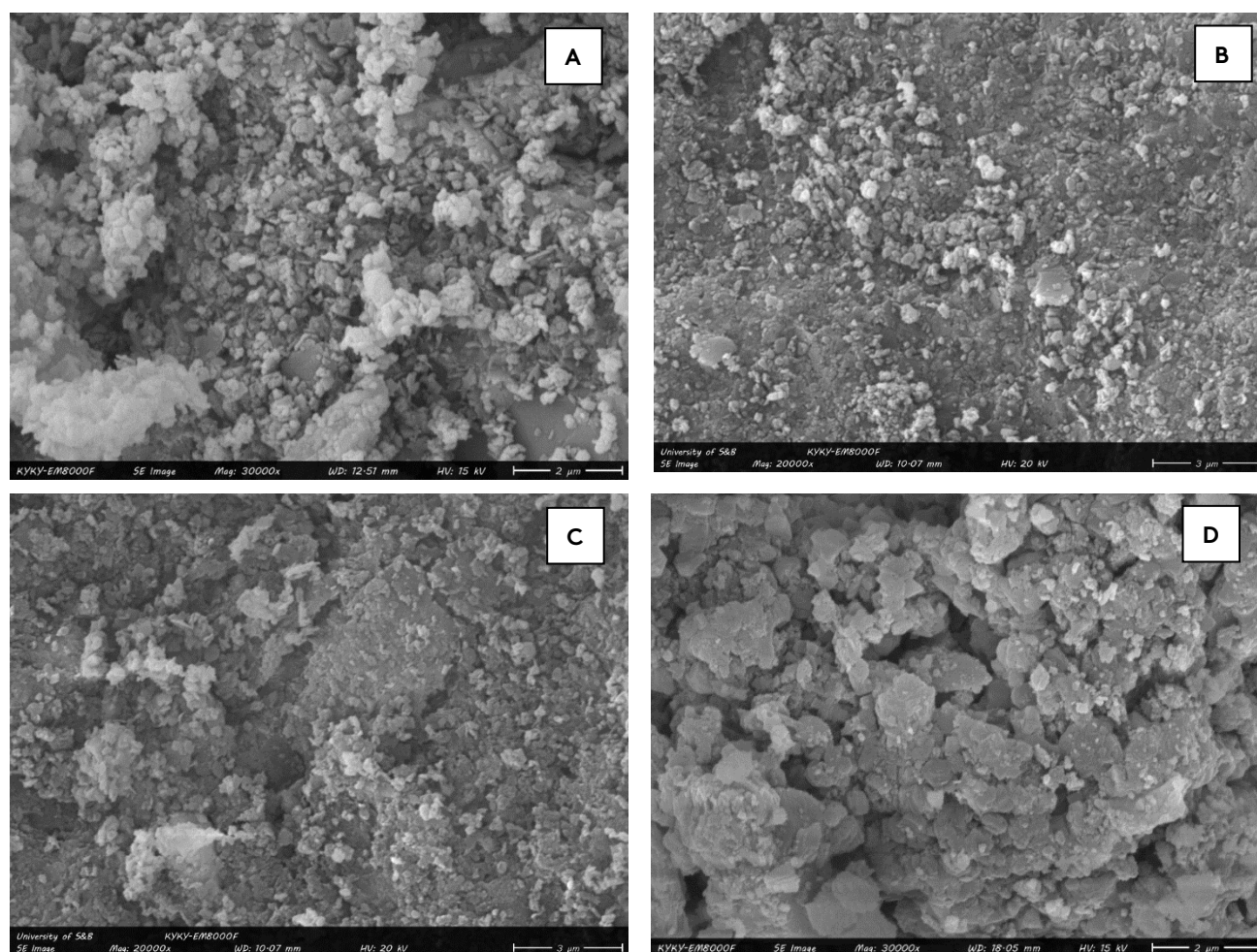


Fig. 5. SEM micrographs of raw boehmite (A), run 12 (B) and run15 (C) samples, and commercial one (D).

Table 6. Properties of one-step oil regeneration using adsorbents.

Properties	TC sample		Commercial sample
	Run12	Run15	
TAN (mg KOH/g)	0.008±0.0005	0.007±0.000	0.009
DDF (90°C)	0.005±0.000	0.004±0.000	0.003
Resistivity (90°C) (GΩm)	133.7±0.1	141.0±0.2	136.9
IFT (mN/m)	34.9	34.5	36.2

As seen, all three adsorbents met the criteria for regenerated oil (max. 0.01 mg KOH/g TAN, max. 0.005 DDF, max. Resistivity GΩm, and max. 43 mN/m IFT).

Figure 6 illustrates the average attrition values of the adsorbents after synthesis and oil regenerations. In terms of attrition after regeneration, the commercial sample exhibited ~7.04% attrition, while runs 12 and 15 showed 5.95% and 3.35%, respectively. Despite the low attrition rates of the adsorbents, larger adsorbents (e.g., run 12: 1.00-1.18 mm and commercial

sample) led to more attrition, making them more susceptible to mechanical breakdown. Run 12 had higher attrition than run 15, due to its larger mesh size and pore volume ($1.0\text{-}1.18\text{ mm}$, $245.93\text{ m}^2\text{g}^{-1}$, $0.34\text{ cm}^3\text{g}^{-1}$).

However, the attrition of run 12 adsorbent was still less than the commercial sample, despite of its larger mesh size. Furthermore, run 15 adsorbent exhibited less attrition compared to the commercial one despite having the same mesh size ($0.710\text{-}0.850\text{ mm}$). Thus, run 15 adsorbent was deemed acceptable in all measured aspects.

Although Run 12 showed the highest BET specific surface area, the selection of Run 15 as the optimum sample was based on a comprehensive evaluation rather than on surface area alone. In addition to BET surface area, other important performance indicators, such as pore-size distribution, pore volume, adsorption efficiency in transformer oil treatment, and mechanical erosion resistance, were considered.

Run 15 provided the most balanced overall performance among these parameters, which made it more suitable as the optimum adsorbent for practical application. Figure 7 shows the sample of the transformer oil before and after regeneration. The GC-MS spectra of both the used and regenerated transformer oil are shown in Figures 8 and 9.

Analysis of the GC chromatograms indicates that the transformer oil samples consist of hydrocarbons with the general formula C_nH_{2n+2} . As shown in Figure 8, the value of n ranges from 9.42 to 21.49 for the used transformer oil, whereas the regenerated oil exhibits a broader range of 9.01 to 28.82. Additionally, Fig. 8 reveals that both used and regenerated oils contain C_{16} , C_{24} , and C_{26} compounds.

The corresponding MS spectra (Figures 9A-B) confirmed the presence of pollutants such as 1,2-Benzenedicarboxylic acid, diisooctyl ester, and 1,2-benzenedicarboxylic acid mono (2-ethylhexyl) ester in the used oil. In contrast, no such contaminants were detected in the regenerated oil (Figure 9C). During the pyrolysis of the transformer

oil, the cleavage of C-H and C-C bonds generates -H ions and free radicals, which undergo complex chemical reactions to recombine and form new hydrocarbon products [41].

This analysis confirms that the regeneration process not only restores the hydrocarbon profile closer to that of fresh oil but also concurrently facilitates the removal of deleterious oxidation by-products.

Consequently, this enhances the chemical stability and purity of the oil, thereby restoring its functional properties and extending its suitability for reuse in transformer applications.

Figure 10 and Table 7 show the observed peaks and assigned bonds in recorded FTIR of used transformer oil and run 15 adsorbents before and after adsorption [42-45].

Table 7A displays the FTIR peaks observed in the used transformer oil, corresponding to standard paraffinic compounds. Based on the GC-MS analysis, the spectra may show isobutanol bands (broad O-H at $3300\text{--}3500\text{ cm}^{-1}$, sharp C-H at $2800\text{--}3000\text{ cm}^{-1}$), and possible phthalate contaminant bands ($C=O$ at 1720 cm^{-1}). Sharp bands typically indicate specific vibrational modes, such as C-H stretching ($\sim 3000\text{ cm}^{-1}$) or $C=O$ stretching ($\sim 1700\text{ cm}^{-1}$). These peaks appear at wavenumbers 724, 1376, 1456, and $2853\text{--}2951\text{ cm}^{-1}$. The peak at 724 cm^{-1} arises from C-H σ -bonds in CH_2 groups of long-chain aliphatic compounds [46]. Broad bands often associated with hydrogen-bonded groups due to intermolecular interactions, like O-H or N-H stretching ($\sim 3200\text{--}3600\text{ cm}^{-1}$).

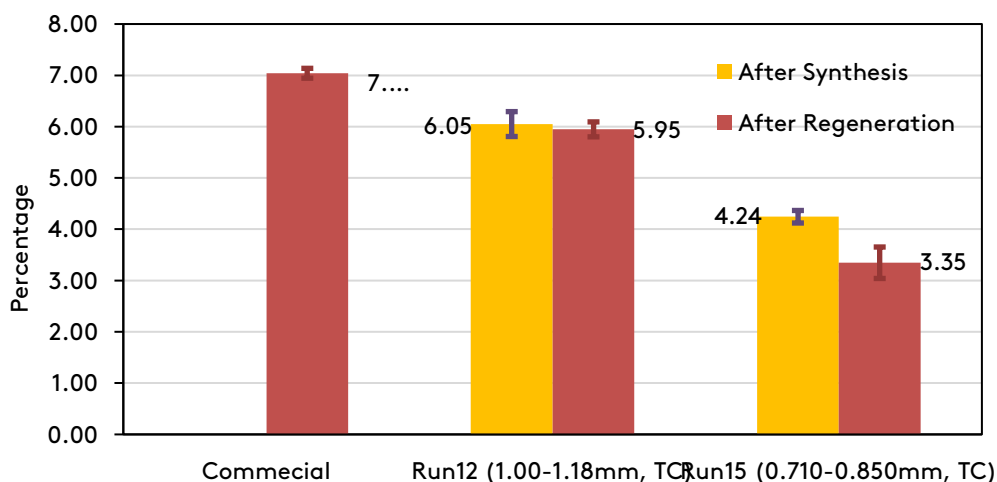


Fig. 6. The attrition behavior of the optimized adsorbents after leaching synthesis and oil regeneration.



Fig. 7. Transformer oil color before and after reclamation process.

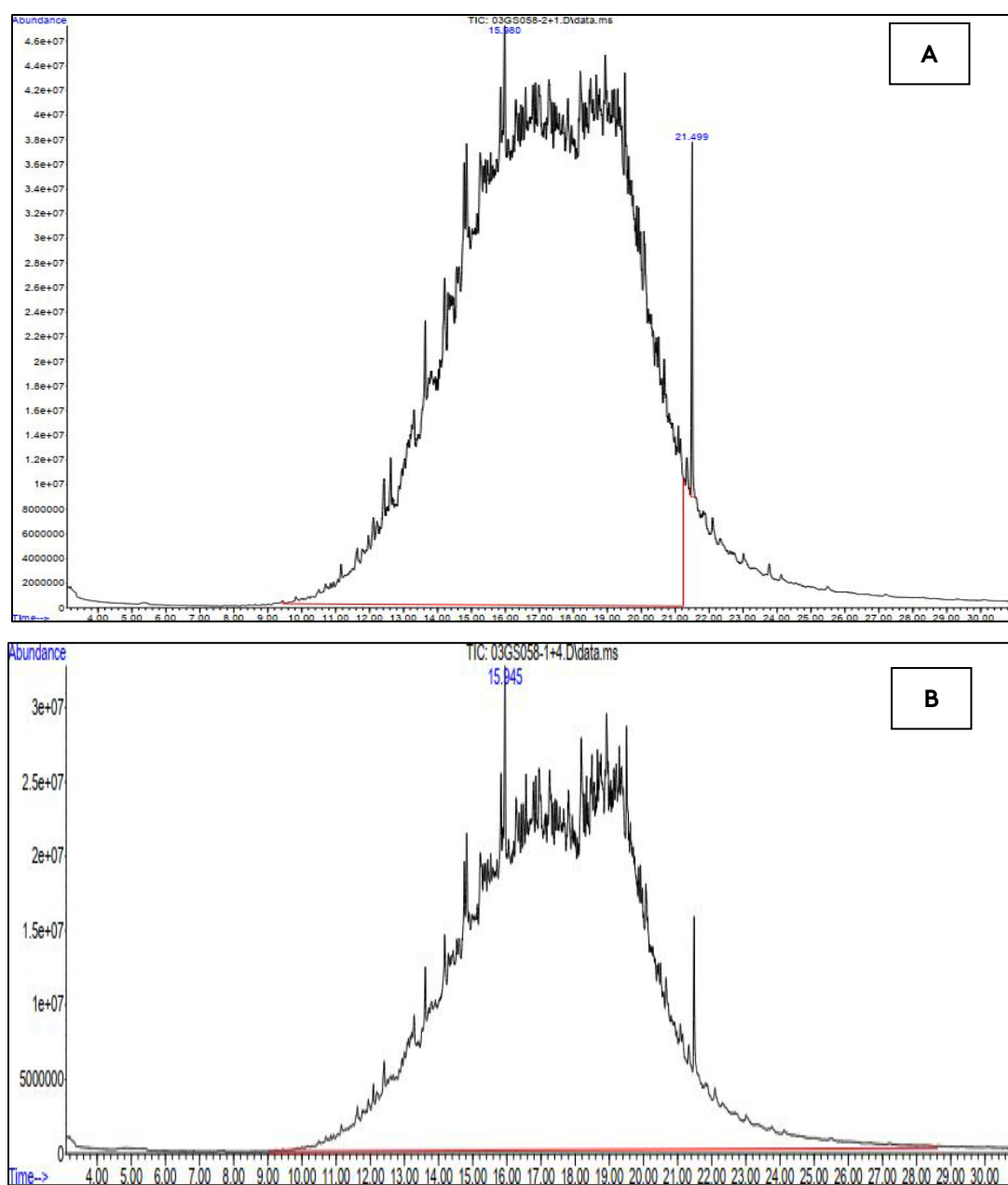
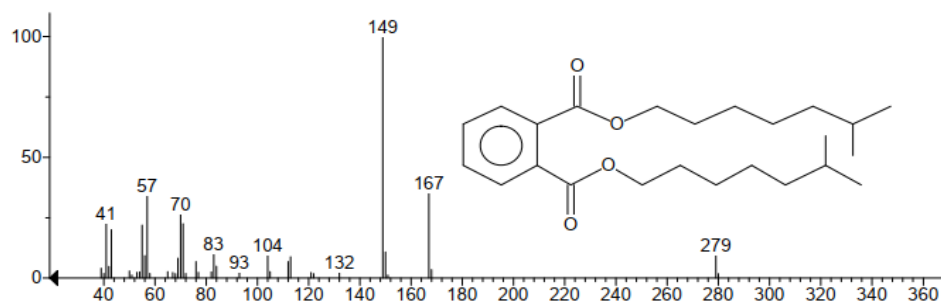


Fig. 8. Gas Chromatograph of (A) used oil and (B) regenerated transformer oil.

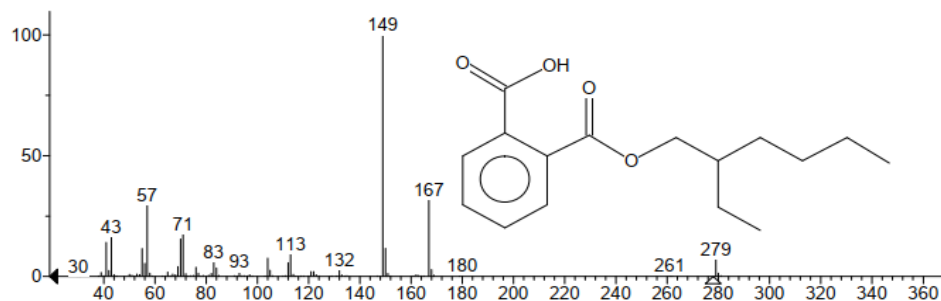
Hit 1 : 1,2-Benzenedicarboxylic acid, diisooctyl ester

C₂₄H₃₈O₄; MF: 853; RMF: 948; Prob 35.3%; CAS: 27554-26-3; Lib: replib; ID: 20061.



Hit 2 : 1,2-Benzenedicarboxylic acid, mono(2-ethylhexyl) ester

C₁₆H₂₂O₄; MF: 837; RMF: 868; Prob 20.3%; CAS: 4376-20-9; Lib: mainlib; ID: 110647.



Hit 2 : Ethyl iso-allocholate

C₂₆H₄₄O₅; MF: 780; RMF: 780; Prob 5.84%; Lib: mainlib; ID: 6556.

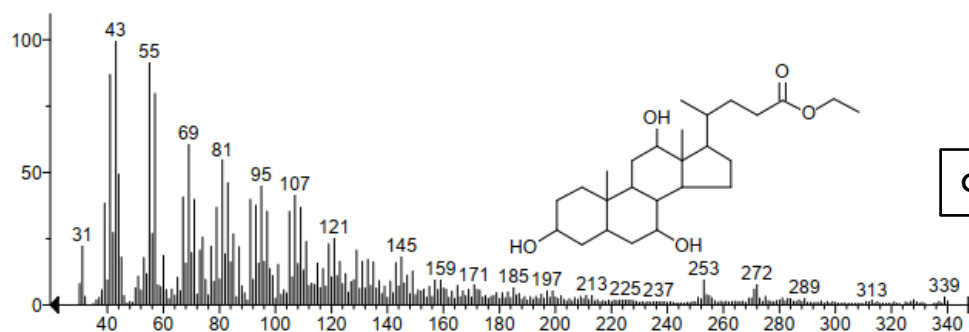


Fig. 9. The mass spectra of used transformer oil (A, B) including 1,2-benzenedicarboxylic acid, diisooctyl ester, 1,2-benzenedicarboxylic acid, mono(2-ethylhexyl) ester, and regenerated oil (C) including ethyl iso-allocholate.

Additional functional groups, including CH, CH₂, and CH₃, are identified at 1377 cm⁻¹, 1458 cm⁻¹, 2922 cm⁻¹, and 2853 cm⁻¹, corresponding to alkane C–H stretching vibrations (CH₃ and CH₂) [43,47]. The peaks at 2922 cm⁻¹ and 2855 cm⁻¹ also suggest the presence of carboxylate (C(=O) OH) groups [48].

The FTIR analysis confirms that transformer oils undergo oxidation and sulphuration over time. Oxidation leads to acid formation, while sulphuration promotes sludge accumulation; both processes can cause corrosion and operational degradation in transformers [44]. The higher

adsorption observed in the used oil reflects increased impurity levels due to aging.

Table 7B reveals that several peaks remain consistent before and after adsorption of the adsorbent. Common FTIR bands near 441, 542, 793, 920, 1054, and 2922 cm⁻¹ are observed in both samples, with their corresponding bond assignments detailed in Table 7(B). The peak at 1458 cm⁻¹ arises from the bending vibration of C–H σ-bonds in CH₂ groups, while the peak at 1377 cm⁻¹ is attributed to the bending vibration of C–H σ-bonds in CH₃ groups within aliphatic compounds [46].

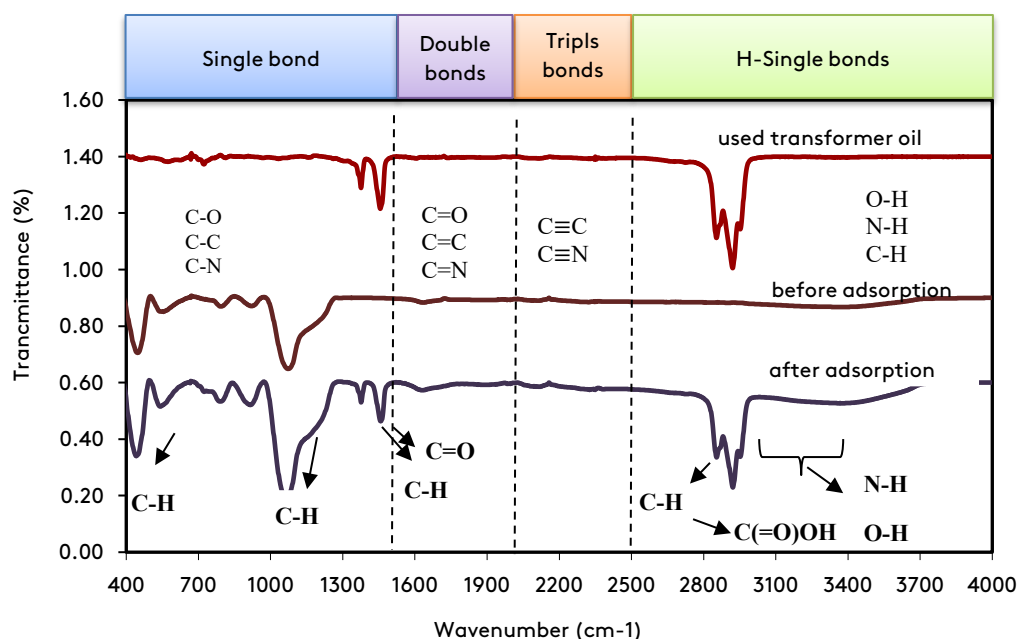


Fig. 10. FTIR spectrum of used transformer oil, before and after adsorptions.

Table 7. The FTIR peaks and the assigned bonds of used transformer oil (A), and samples before and after adsorption (B).

FTIR Peak position (cm ⁻¹)	Assigned Bonds	A
2955	=C-H stretching of the carbon-carbon double bonds	
2855	CH stretching, CH ₃ methylene group	
2922	C-H bend	
1456	C-H symmetric bend	
1376	CH ₃ bend	
724	C-H out of the plane stretching of the standard carbon-carbon bond	
FTIR Peak position (cm ⁻¹)	Assigned Bonds	B
3367	O-H functional group	
2922	C-H bond	
2855	CH stretching, CH ₃ methylene group	
1458	C-H symmetric bending (alkanes) methyl and methylene	
1377	C-H bending of the alkanes (iso-propyl split)	
1054	C-H asymmetric swing	
789-541	Aromatic compounds	
441	H-C-H symmetrical swing and O-H swing	

This FTIR reaction pathway aligns with GC-MS results, confirming that carboxylic acid content rises during adsorption. Porous γ -Al₂O₃ proves effective in removing acidity from waste transformer oil, with its performance dependent on specific surface area and pore volume [49].

4. Conclusion

We developed a cost-effective approach to regenerate used transformer oil by synthesizing

high-performance γ -alumina adsorbents from cost-effective boehmite using optimized thermal-chemical (TC) and chemical-thermal (CT) treatment sequences.

Taguchi-based optimization produced meaningful improvements in key structural attributes, specific surface area, pore volume, and particle-size distribution, leading to improved impurity removal while minimizing attrition. Among the synthesized materials, Run 15 (surface area: 226.76 m² g⁻¹; pore

volume: $0.25 \text{ cm}^3 \text{ g}^{-1}$; mesh size: 0.710–0.850 mm) provided the best balance of adsorption efficiency and mechanical durability. As a concluding remark, Run 15 achieved superior contaminant removal and substantially reduced attrition. Transformer oil regenerated using the TC-derived adsorbent (Run 15) also showed marked improvements in key physicochemical indicators, including DDF (0.004), TAN (0.007), and resistivity (141).

FTIR and GC–MS analyses further corroborated the effective removal of polar and acidic species, including 1,2-benzenedicarboxylic acid derivatives. Notably, the optimized adsorbent maintained performance under harsh operating conditions, sustaining prolonged saturation times and high mechanical strength without meaningful degradation (e.g., fine-particle generation) or loss of regeneration efficiency. Overall, the results demonstrate the potential of the synthesized adsorbent for transformer oil regeneration while emphasizing that further pilot-scale evaluation, regeneration/reusability assessment, and long-term operational studies are still required before industrial implementation can be fully established.

Acknowledgement

Hereby, the authors would like to acknowledge the financial support of the project by Pouya Pajuhesh Arvid Pazh (PPAP) (Moham Shargh Group).

Author's contribution

Kousar Dinarvandi: Performing the research and writing the original draft as a PhD student; **Abdolreza Samimi:** Conceptualization, supervision, editing the article; **Davod Mohebbi-Kalhari:** Monitoring the design of experiments; **Mojhgan Zakeri:** Reviewing the article; and **Reyhaneh Zakeralhosseini:** Data curation. All authors have read and approved the final version of the manuscript.

Conflict of interest

No potential conflict of interest was reported by the authors.

Data availability

Not Applicable.

Funding

This research received funding from Pouya Pajuhesh Arvid Pazh (PPAP) (Moham Shargh Group).

References

- [1] Zheng, K., Li, W., Wang, W., Chen, H., Huang, C., Ren, Q., & Qin, C. (2019). Preparation and characterisation of carboxymethyl-chitosan/sodium phytate composite membranes for adsorption in transformer oil. *International Journal of Biological Macromolecules*, 132, 658–665.
<https://doi.org/10.1016/j.ijbiomac.2019.03.239>
- [2] Kim, T.-H., An, S. Y., & Gim, G. H. (2026). Electrical properties of liquid insulation oil under varying electrode shapes and temperatures. *Korean Journal of Materials Research*, 36(1).
<https://doi.org/10.3740/MRSK.2026.36.1.26>
- [3] Jia, Y., Luo, X., Ji, S., Zhao, D., Qiu, Z., & Li, S. (2025). Pressure and stress characteristics of transformer tank with power-frequency arc fault in oil. *Thin-Walled Structures*, 210, Article 112986.
<https://doi.org/10.1016/j.tws.2025.112986>
- [4] Guerbas, F., Adjaout, L., & Abada, A. (2023). Accelerated thermal aging effect on the new and reclamation transformer oil behavior. In *2023 IEEE Electrical Insulation Conference (EIC)* (pp. 1–4). IEEE.
<https://doi.org/10.1109/EIC55835.2023.10177372>
- [5] Wang, Y., Ma, G., Gao, D., Wang, Y., Xie, Y., Gao, X., Du, H., & Ji, J. (2024). Transformer oil-dissolved methane detection based on non-adiabatic tapered fiber using polyacrylate and cryptophane-A overlay deposition. *Sensors and Actuators B: Chemical*, 400, Article 134869.
<https://doi.org/10.1016/j.snb.2023.134869>
- [6] Yang, F., Zhou, L., Gui, Y., Tao, J., Zhang, J., Zhang, Q., & Xu, L. (2026). Adsorption performance of transition metal (Ag, Pb, and Ni)-modified ZrSe_2 monolayers toward dissolved gases (CO , CO_2 , CH_4 , and C_2H_4) in oil-immersed power transformers: A DFT study. *Surfaces and Interfaces*, Article 108471.
<https://doi.org/10.1016/j.surfin.2026.108471>

- [7] Chen, X., Chen, S., Yang, D., Luo, H., Yang, P., & Cui, W. (2021). Quantitative prediction of aging state of oil-paper insulation based on Raman spectroscopy. *AIP Advances*, 11. <https://doi.org/10.1063/5.0035682>
- [8] Atanasova-Höhlein, I. (2021). IEC 60296 (Ed. 5)–A standard for classification of mineral insulating oil on performance and not on the origin. *Transformers Magazine*, 8, 86–91. <https://hrcak.srce.hr/file/363648>
- [9] Zhu, H., Zong, C., Fang, L., Zhang, H., Sun, Y., Tian, Y., Zhang, S., & Wang, X. (2026). Intelligent machine learning-based spectroscopy for condition monitoring of energy infrastructure: A review focused on transformer oils and hydrogen systems. *Processes*, 14(2), Article 255. <https://doi.org/10.3390/pr14020255>
- [10] Mahankali, S., Velpula, R., & Rao, D. (2026). Experimental investigation of transformer fault diagnosis using integrated DGA and physical inspection. *Electric Power Systems Research*, 254, Article 112669. <https://doi.org/10.1016/j.epsr.2025.112669>
- [11] Gherdaoui, C. E., Fontaine, H., Delbarre, J.-P., Debiak, R., Sansano, R., Hutin, O., & Roussey, A. (2025). Enhancing fumes catalytic treatment in transformer oil regeneration: A study on catalyst performances and process conditions. *Journal of Environmental Chemical Engineering*, Article 117181. <https://doi.org/10.1016/j.jece.2025.117181>
- [12] Safiddine, L., Hadj-Ziane Zafour, A., Fofana, I., Skender, A., Guerbas, F., & Boucherit, A. (2017). Transformer oil reclamation by combining several strategies enhanced by the use of four adsorbents. *IET Generation, Transmission & Distribution*, 11(11), 2912–2920. <https://doi.org/10.1049/iet-gtd.2016.1995>
- [13] Fofana, I., Wasserberg, V., Borsi, H., & Gockenbach, E. (2004). Drying of transformer insulation using zeolite. *IEEE Electrical Insulation Magazine*, 20(1), 20–30. <https://doi.org/10.1109/MEI.2004.1266362>
- [14] Hafez, A., Gerges, N., El-nagar, K., Mohamed, S., & Hashem, A. (2015). Reclamation of old transformer oil using kaolin clay. *International Journal of Advanced Scientific and Technical Research*, 4, 752–769.
- [15] Laurentino, A., Parize, A., Laranjeira, M., Martins, A., Mayer, N., & De Favere, V. (2007). Regeneration of insulating mineral oil by carbonated amorphous calcium phosphate-chitosan adsorbent. *Process Safety and Environmental Protection*, 85(4), 327–331. <https://doi.org/10.1205/psep06057>
- [16] Al-Zuhair, S., Noura, H., & Fardoun, A. (2011). Using activated carbon from waste date-pits as an adsorbent for transformer oil regeneration. In *2011 World Congress on Sustainable Technologies (WCST)* (pp. 69–72). IEEE. <https://doi.org/10.1109/WCST19361.2011.6114241>
- [17] Vu, T. T., La, T. V., Vu, M. K., Huynh, D. C., & Tran, N. K. (2020). Highly efficient adsorbent for the transformer oil purification by ZnO/graphene composite. *Arabian Journal of Chemistry*, 13(11), 7798–7808. <https://doi.org/10.1016/j.arabjc.2020.09.011>
- [18] Vu, T. T., La, T. V., & Vu, T. G. (2022). The highly efficient purification capacity of rGO-zeolite composites for aged oil in transformer machines. *Arabian Journal of Chemistry*, 15(3), Article 103683. <https://doi.org/10.1016/j.arabjc.2021.103683>
- [19] He, F., Li, W., Pang, T., Zhou, L., Wang, C., Liu, H., Li, M., & He, X. (2022). Hydrothermal synthesis of boehmite nanorods from alumina sols. *Ceramics International*, 48(12), 18035–18047. <https://doi.org/10.1016/j.ceramint.2022.02.212>
- [20] Huang, H., Wang, L., Cai, Y., Zhou, C., Yuan, Y., Zhang, X., Wan, H., & Guan, G. (2015). Facile fabrication of urchin-like hollow boehmite and alumina microspheres with a hierarchical structure via Triton X-100 assisted hydrothermal synthesis. *CrystEngComm*, 17(6), 1318–1325. <https://doi.org/10.1039/c4ce02133a>
- [21] Dinarvandi, K., Samimi, A., Mohebbi-Kalhari, D., Zakeri, M., & Zakeralhoseini, R. (2024). Synthesis of mesoporous γ -alumina from a low-grade boehmite ore: Effect of thermal/chemical processing order on physico-chemical characteristics of adsorbent and regeneration of used transformer oils. *Chemical Engineering Research and Design*, 209, 72–80. <https://doi.org/10.1016/j.cherd.2024.07.059>

- [22] Li, M., Si, Z., Wu, X., Weng, D., & Kang, F. (2014). Facile synthesis of hierarchical porous γ - Al_2O_3 hollow microspheres for water treatment. *Journal of Colloid and Interface Science*, 417, 369–378.
<https://doi.org/10.1016/j.jcis.2013.11.071>
- [23] Spiridon, I., Apostol, I., Dinu, M. V., Anghel, N., & Doroftei, F. (2024). New porous adsorbents based on natural polymers for treatment of motor oil contaminated wastewaters. *Journal of Polymer Science*, 62(22), 5411–5423.
<https://doi.org/10.1002/pol.20240280>
- [24] Jankovic, J., Lukic, J., Planojevic, J., Kolarski, D., & Janackovic, D. (2022). Application of highly selective adsorbent in the removal of elemental sulfur and other corrosive sulfur compounds from mineral insulating oils. *IEEE Transactions on Dielectrics and Electrical Insulation*, 29(1), 54–61.
<https://doi.org/10.1109/TDEI.2022.3148479>
- [25] Fei, K., Dong, Z. Y., Shi, L., Meng, X., & Liu, N. (2024). K_2CO_3 -loaded γ - Al_2O_3 for acid removal in waste transformer oil. *Asia-Pacific Journal of Chemical Engineering*, 19(2), Article e3016.
<https://doi.org/10.1002/apj.3016>
- [26] Bekele, E. A., Korsu, H. A., & Desalegn, Y. M. (2024). Electrolytic synthesis of γ - Al_2O_3 nanoparticle from aluminum scrap for enhanced methylene blue adsorption: Experimental and RSM modeling. *Scientific Reports*, 14, Article 16957.
<https://doi.org/10.1038/s41598-024-67656-9>
- [27] Abdollahi, M., Atashi, H., & Tabrizi, F. F. (2017). Parametric investigation of γ -alumina granule preparation via the oil-drop route. *Advanced Powder Technology*, 28(5), 1356–1371.
<https://doi.org/10.1016/j.apt.2017.03.004>
- [28] Kermani, M., Samimi, A., Mohebbi-Kalhari, D., Beigmoradi, R., Shokrollahzadeh, S., Xia, A., Sun, C., Sun, F., Ashori, A., & Madadi, M. (2024). Pulsed electric field treatment for efficient oil extraction from *Nannochloropsis salina* microalgae: A green and sustainable approach. *Journal of Polymers and the Environment*, 32, 5888–5901.
<https://doi.org/10.1007/s10924-024-03347-w>
- [29] Walkowicz, J., Staśkiewicz, J., Szafirowicz, K., Jakrzewski, D., Grzesiak, G., & Stępnik, M. (2013). Optimization of the ASPN process to bright nitriding of woodworking tools using the Taguchi approach. *Journal of Materials Engineering and Performance*, 22, 410–420.
<https://doi.org/10.1007/s11665-012-0288-y>
- [30] Koppenol, W. H., Stanbury, D. M., & Bounds, P. L. (2010). Electrode potentials of partially reduced oxygen species, from dioxygen to water. *Free Radical Biology and Medicine*, 49(3), 317–322.
<https://doi.org/10.1016/j.freeradbiomed.2010.04.011>
- [31] Armstrong, D. A., Huie, R. E., Koppenol, W. H., Lymar, S. V., Merényi, G., Neta, P., Ruscic, B., Stanbury, D. M., Steenken, S., & Wardman, P. (2015). Standard electrode potentials involving radicals in aqueous solution: Inorganic radicals (IUPAC Technical Report). *Pure and Applied Chemistry*, 87(11–12), 1139–1150.
<https://doi.org/10.1515/pac-2014-0502>
- [32] Schull, C. (1948). The determination of pore size distribution from gas adsorption data. *Journal of the American Chemical Society*, 70(4), 1405–1410.
<https://doi.org/10.1021/ja01184a034>
- [33] Wen, J., Yuan, R., Jiang, T., Yu, T., & Zhang, Y. (2024). Solvothermal synthesis and adsorption performance of layered boehmite using aluminum chloride and high-alumina fly ash. *Chinese Journal of Chemical Engineering*, 70, 280–290.
<https://doi.org/10.1016/j.cjche.2024.03.008>
- [34] Edwards, M., Russell, R., Shimskey, R., & Peterson, R. (2010). Bench-scale testing of the continuous sludge leaching process. *Separation Science and Technology*, 45(12–13), 1807–1813.
<https://doi.org/10.1080/01496395.2010.493799>
- [35] Han, X., Wang, Y., Zhang, N., Meng, J., Li, Y., & Liang, J. (2021). Facile synthesis of mesoporous silica derived from iron ore tailings for efficient adsorption of methylene blue. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 617, Article 126391.
<https://doi.org/10.1016/j.colsurfa.2021.126391>
- [36] Hao, J., Wang, X., Wang, Y., Guo, F., & Wu, Y. (2022). Optimization, kinetic studies of tin leaching from waste printed circuit boards and selective tin recovery from its pregnant solution. *Metals*, 12(6), Article 954.
<https://doi.org/10.3390/met12060954>

- [37] Behmadi, R., Mokhtarian, M., Ghadrian, K., Davoodi, A., & Hosseinpour, S. (2022). Development of a low-cost activated mesoporous bauxite for the reclamation of used transformer oil. *Separation and Purification Technology*, 280, Article 119826. <https://doi.org/10.1016/j.seppur.2021.119826>
- [38] Soni, P., Sur, A., Gaba, V. K., & Sah, R. P. (2025). Review on improvement of adsorption refrigeration systems performance using composite adsorbent: Current state of art. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 47(1), 8031–8055. <https://doi.org/10.1080/15567036.2021.1927252>
- [39] Elele, U., Nekahi, A., Arshad, A., & Fofana, I. (2022). Towards online ageing detection in transformer oil: A review. *Sensors*, 22(20), Article 7923. <https://doi.org/10.3390/s22207923>
- [40] Soni, R., & Mehta, B. (2021). Review on asset management of power transformer by diagnosing incipient faults and faults identification using various testing methodologies. *Engineering Failure Analysis*, 128, Article 105634. <https://doi.org/10.1016/j.engfailanal.2021.105634>
- [41] Zhang, J., Guo, Y., Pau, D., Li, K., Xie, K., & Zou, Y. (2021). Pyrolysis kinetics and determination of organic components and N-alkanes yields of Karamay transformer oil using TG, FTIR and Py-GC/MS analyses. *Fuel*, 306, Article 121691. <https://doi.org/10.1016/j.fuel.2021.121691>
- [42] Wan, F., Du, L., Chen, W., Wang, P., Wang, J., & Shi, H. (2017). A novel method to directly analyze dissolved acetic acid in transformer oil without extraction using Raman spectroscopy. *Energies*, 10(7), Article 967. <https://doi.org/10.3390/en10070967>
- [43] Kalathiripi, H., & Karmakar, S. (2017). Analysis of transformer oil degradation due to thermal stress using optical spectroscopic techniques. *International Transactions on Electrical Energy Systems*, 27(9), Article e2346. <https://doi.org/10.1002/etep.2346>
- [44] Meena, R. R., Chaki, S., Khimani, A. J., & Deshpande, M. (2018). Transformer oil degradation study by chromatography, spectroscopy and dissolved gas analysis. *Petroleum & Coal*, 60.
- [45] Abi Munajad, C. S. (2018). Fourier transform infrared (FTIR) spectroscopy analysis of transformer paper in mineral oil-paper composite insulation under accelerated thermal aging. *Energies*, 11(2), Article 364. <https://doi.org/10.3390/en11020364>
- [46] Darwish, M. M., Hassan, M. H., Abdel-Gawad, N. M., Lehtonen, M., & Mansour, D. E. A. (2024). A new technique for fault diagnosis in transformer insulating oil based on infrared spectroscopy measurements. *High Voltage*, 9(2), 319–335. <https://doi.org/10.1049/hve2.12405>
- [47] Pillai, S. S., Aarathy, A., Gopinath, D., Aryanandiny, B., & Sankar, B. (2020). Effects of magnetite and titania nanoparticles on properties of transformer insulating oil. *Nano Express*, 1(2), Article 020040. <https://doi.org/10.1088/2632-959X/abb715>
- [48] Oparanti, S. O., Salaudeen, I. K., Adekunle, A. A., Oteikwu, V. E., Galadima, A. I., & Abdelmalik, A. A. (2023). Physicochemical and dielectric study on Nigerian Thevetia peruviana as a potential green alternative fluid for transformer cooling/insulation. *Waste and Biomass Valorization*, 14, 1693–1703. <https://doi.org/10.1007/s12649-022-01949-w>
- [49] Wang, Y., Dou, P., You, X., Liu, Q., Fei, Z., Chen, X., Zhang, Z., Tang, J., Cui, M., & Qiao, X. (2023). Naphthenic acids removal from model transformer oil by diethylamine modified resins. *Molecules*, 28(6), Article 2444. <https://doi.org/10.3390/molecules28062444>

How to cite this paper:



Dinarvandi, K., Samimi, A., Mohebbi-Kalhari, D., Zakeri, M. & Zakeralhoseini, R. (2026). Sustainable reclamation of transformer oils via tailored mesoporous γ -alumina: Oil regeneration and durability performance of adsorbents. *Advances in Environmental Technology*, 12(4), 491-511. DOI: 10.22104/aet.2026.8150.2291