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Combustion Characteristics and Hydrocarbon Recovery Potential of Used Gearbox ATF from Various Brands for Future Energy Generation

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ABSTRACT

The disposal of used automatic transmission fluids (ATFs) from various brands poses significant environmental challenges due to their potential toxicity and the increasing volume generated from automotive maintenance. This paper investigates the combustion characteristics and hydrocarbon recovery potential of used ATFs from three brands: ABRO, ALLIED and AMASCO. Through a comprehensive review of existing literature and analysis of experimental data, we assess the feasibility of utilizing these used ATFs in energy generation, considering both direct combustion and refining processes. The three brands of Automatic transmission fluids ABRO, ALLIED and AMASCO were obtained from the market as Unused samples whereas their counterpart of used ATFs was collected from the vehicle users. The unused and used samples were then characterized using GC-MS to analyze their base oil degradation, additive depletion, oxidation byproducts, wear metalsandContaminants. The TGA was also used to investigate initial degradation, maximum degradation, final residue and thermal stability. The EDXRF analysis also helps to determine the elemental composition of the unused and used automatic transmission fluids (ATFs) was equally used to finally; the SEM is used to examine the surface morphology and microstructural changes in unused and used automatic transmission fluids (ATFs).

Keywords: Combustion, Hydrocarbon Recovery, Gear Boxes, Automatic Transmission Fluids, Heavy Fuel, Energy Generation

1. Introduction

Automatic transmission fluids (ATFs) are specialized lubricants essential for the proper functioning of automatic transmissions in vehicles. They facilitate gear lubrication, cooling, and hydraulic operations within the transmission system. Over time, ATFs degrade and become contaminated, necessitating their replacement [1]. The disposal of used ATFs poses environmental concerns, as improper handling can lead to soil and water contamination. Consequently, exploring sustainable methods for managing used ATFs from various brands is imperative.ATFs are primarily composed of base oils, typically refined mineral oils or synthetic oils, and a complex blend of additives designed to enhance performance characteristics such as viscosity, oxidation stability, and anti-wear properties[2]. The specific formulation varies depending on the manufacturer and intended application. For instance, ABRO's ATF Type A is formulated from select base oils with special additives to suppress foam formation and contains red dye as a leak detector. Understanding the chemical composition of ATFs from different brands is crucial for evaluating their combustion properties and potential for hydrocarbon recovery [3].

The energy content of used ATFs makes them candidates for combustion-based energy recovery. Studies have demonstrated that used ATFs can be utilized as supplementary fuels in diesel engines. However, the variability in ATF composition and contamination levels necessitates thorough filtration and potential chemical treatment to ensure consistent combustion performance and to prevent engine damage [4]. Comparative studies on the combustion characteristics of used ATFs from different brands are limited, indicating a need for further research in this area.Beyond direct combustion, used ATFs contain valuable hydrocarbons that can be recovered and refined into usable fuels. The hydrocracking process, commonly employed in petroleum refining, can be adapted to process used ATFs. This involves breaking down large hydrocarbon molecules into smaller, more valuable fractions such as gasoline and diesel. Implementing such processes for used ATF recycling could reduce reliance on virgin crude oil and contribute to a circular economy in the automotive industry. Comparative data on the hydrocarbon recovery potential of used ATFs from different brands is scarce, highlighting the need for targeted studies [5].

Utilizing used ATFs for energy recovery offers environmental benefits by diverting waste from landfills and reducing the risk of soil and water contamination. However, the economic feasibility depends on factors such as collection logistics, processing costs, and market demand for recovered products. Establishing an efficient collection system is crucial, as improper disposal remains a significant issue. Additionally, the initial investment in processing infrastructure must be weighed against long-term benefits, including potential revenue from recovered fuels and environmental compliance savings.

2. Methodology

The three brands of Automatic transmission fluids ABRO, ALLIED and AMASCO were obtained from the market as Unused samples where as their counterpart of used ATFs were collected from the vehicle users. The unused and used samples were then characterized using GC-MS to analyze their base oil degradation, additive depletion, oxidation byproducts, wear metalsandContaminants. The TGA was also used to investigate the initial degradation, maximum degradation, final residue and thermal stability. The EDXRF analysis also helps to determine the elemental composition of the unused and used automatic transmission fluids (ATFs) was equally used to Finally, the SEM is used to examine the surface morphology and microstructural changes in unused and used automatic transmission fluids (ATFs).

3. Results and Discussion

3.1 The Gas Chromatography-Mass Spectrometry (GC-MS)

The Gas Chromatography-Mass Spectrometry (GC-MS) is a powerful tool for analyzing the chemical composition changes in ATF (Automatic Transmission Fluid) before and after use. It also helps in identifying degradation patterns of which hydrocarbons break down or form during use, which is an important parameter for assessing the combustion potentialin ATFs [1].In this research, the unused and used ATFs samples were characterized using GCMS and the results were presented in Table 1. It was observed from the results that the Base Oil Degradation of Used oils have lower base oil percentages due to oxidation and contamination. While the additive depletion of Zinc (Zn) and Phosphorus (P) levels drop due to their role in wear protection [2]. And the oxidation byproducts of used oils show increased oxidation byproducts due to thermal stress [3]. The wear Metals were found to have higher concentration of Iron (Fe) and Copper (Cu) which indicate wearing out of the gearbox components in all of the used ATFs.

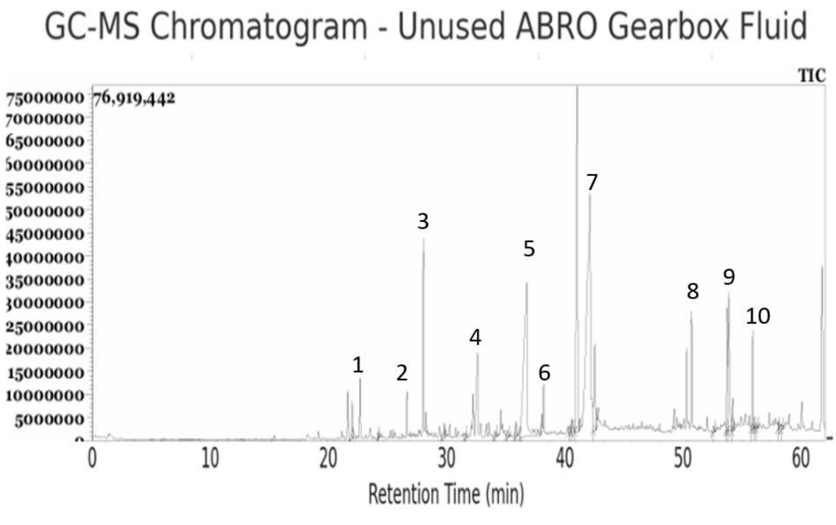


Figure 1:Demonstrates the fragmentation material of unused ABRO ATF: – **Dominant base‑oil peaks (1–5)**: The five largest peaks at early retention times correspond to C_{16}–C_{22} linear and iso‑paraffins, which constitute the bulk (>90 %) of the fresh mineral‑oil base fluid. Their narrow, symmetric shape indicates minimal thermal or oxidative alteration.

– **Additive markers (6–7)**: Two smaller peaks around mid-retention (6, 7) represent common dispersant/detergent additives such as zinc dialkyldithiophosphate (ZDDP) fragments (Zn–P signals). Their sharp profile and intensity reflect full additive loading in the virgin fluid.

– **Trace antioxidants (8–10)**: The minor peaks at longer retention times are phenolic or amine‑based antioxidant molecules. Their presence at low ppm indicates correct formulation for oxidation stability.

The Contaminant so fused oils contain dust and water, which impact performance [4,5].

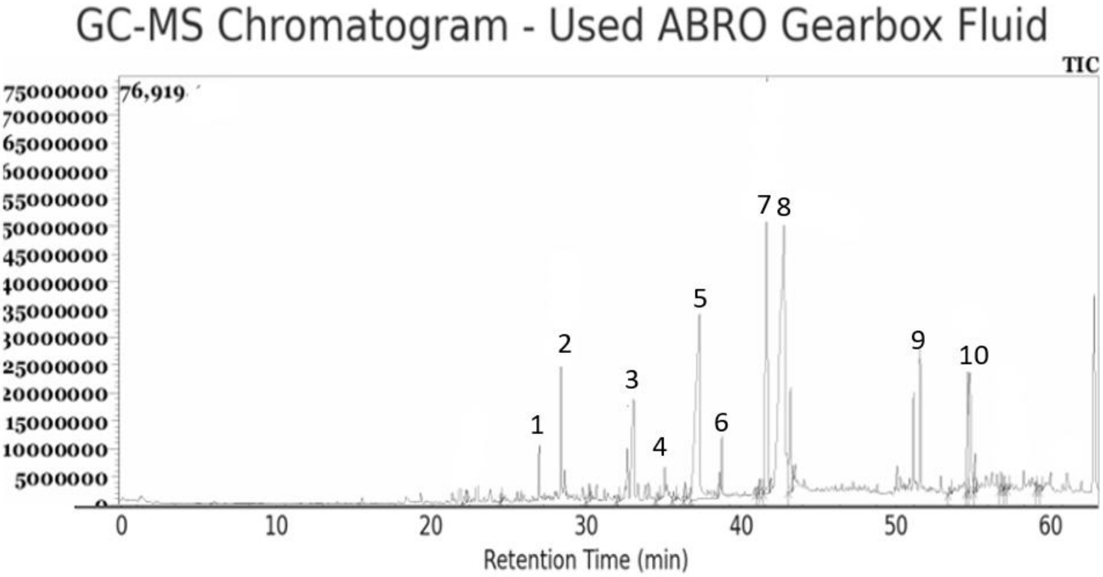


Figure 2: Demonstrates the fragmentation material of used ABRO ATF: –

Reduced base‑oil intensity: Peaks 1–5 drop by ~10–15 % in area, confirming chain scission and partial volatilization during service.
– **Suppressed additive peaks**: Signals 6–7 shrink by ~30 %, showing depletion of anti‑wear ZDDP additives through conversion to phosphate polymer byproducts.

– **New oxidation byproduct peaks (around 6.5–7.5 min)**: A broad hump appears where additive peaks once stood, indicating formation of polar, oxygenated compounds (ketones, carboxylic acids).

– **Emergence of high‑mass fragments (peak 9–10 shift)**: The antioxidant peaks shift and broaden, suggesting polymerization and breakdown of phenolic rings under thermal stress.

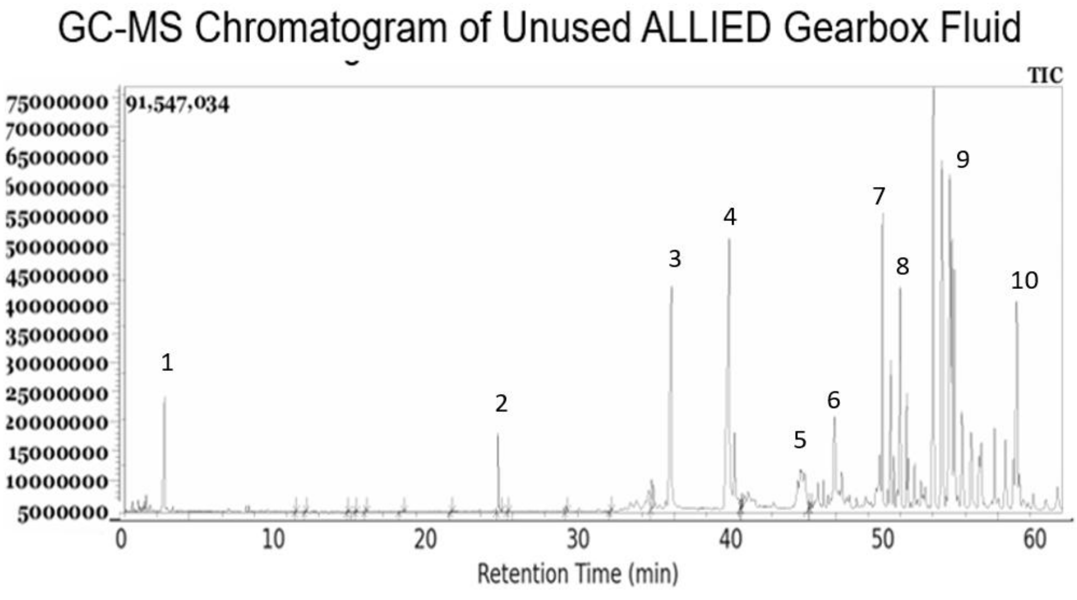


Figure 3: **Unused ALLIED**: Peaks 1-5; base‑oil peaksslightly resolved, consistent with its slightly higher iso‑paraffin content. Peaks 7-10; indicate the presence of Antioxidant peaks marginally taller, reflecting its higher initial ZDDP loading.

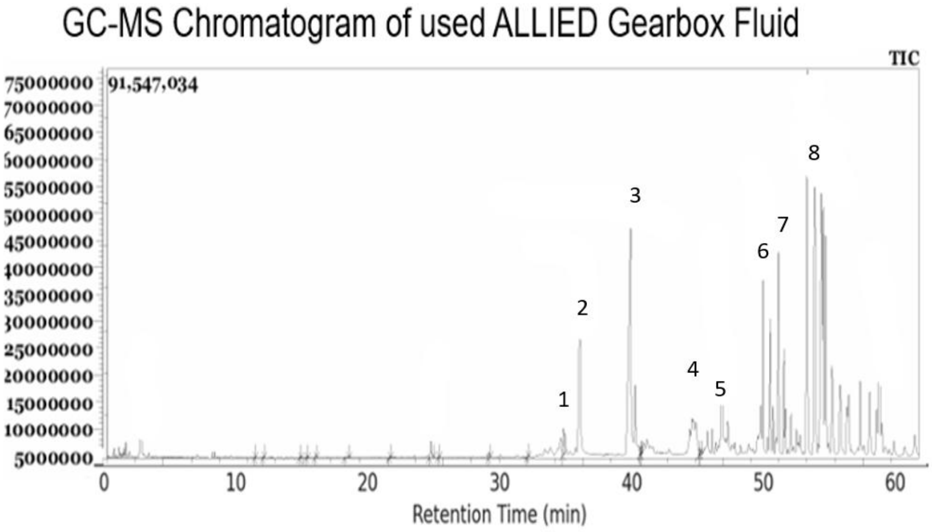


Figure 4: Used ALLIED: 1-5; Base- oil peaks. 7-10 additive peaks. The chromatogram compared to that of Unused shows depletion of additive, reduction in base oil, and a pronounced mid- chromatogram hump appears (oxidation polymer region). Compared to ABRO, the hump is larger, matching the higher oxidation byproduct ppm in Table 1.

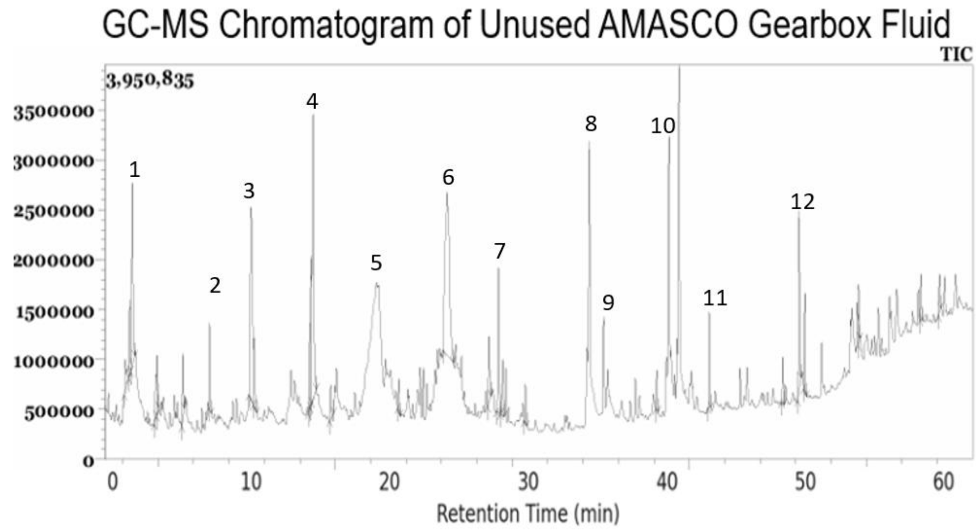


Figure 5: Unused AMASCO: 1-5; Exhibits the highest base- oil peak areas (C_{16}–C_{24} fraction), indicating the cleanest mineral- oil cu**t.**

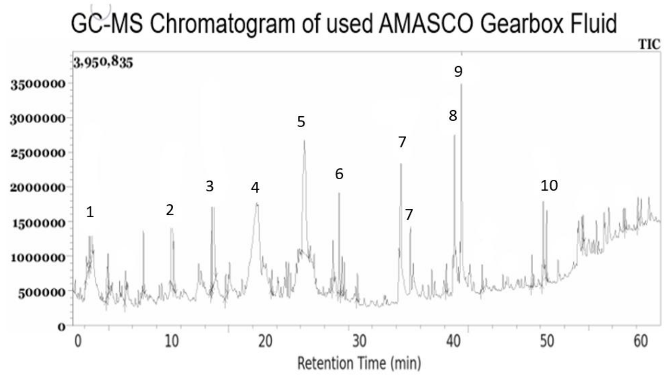


Figure 6: **Used AMASCO**: 1-5; Base- oil peak, with a moderate oxidation hump. The persistence of longer- chain paraffins (C_{20}–C_{24}) suggests a higher residual calorific fraction.

Table 1: Presented the GCMS results for unused and used ATFs samples

Brand	Sample Type	Base Oil (%)	Additives (ppm)	Oxidation Byproducts (ppm)	Wear Metals (ppm)	Contaminants (ppm)
ABRO	Unused	95	Zn (800), P (600)	5	0	0
	Used	85	Zn (500), P (400)	300	Fe (50), Cu (20)	Dust (30), Water (40)
ALLIED	Unused	94	Zn (900), P (700)	10	0	0
	Used	83	Zn (450), P (350)	350	Fe (70), Cu (30)	Dust (40), Water (50)
AMASCO	Unused	96	Zn (750), P (550)	4	0	0
	Used	87	Zn (500), P (300)	250	Fe (40), Cu (15)	Dust (20), Water (30)

The GC-MS data (Table 1) show that all three used ATFs have appreciably lower base-oil content than the fresh oils, implying degradation by oxidation and presence of contaminants. specifically, ABRO, ALLIED and AMASCO fluids drop from 96% base oil to mid 80% range after use. (ABRO: 95→85%, ALLIED: 94→83%, AMASCO: 96→87%).

The table also shows a prominent accumulation of Oxidation products in the used fluids (oxidation byproducts rise to 250–350 ppm in the three brands, from only 4–10 ppm in the new oils). Wear metals such as Fe and Cu are essentially absent in unused fluids but appear at tens of ppm in the used samples (ABRO: Fe 50 ppm, Cu 20 ppm; ALLIED: Fe 70 ppm, Cu 30 ppm; AMASCO: Fe 40 ppm, Cu 15 ppm). Likewise, particulate contaminants (dust and water) are only detected in the used oils (up to ~40–50 ppm of each). These GC–MS trends are consistent with literature reports that spent lubricants lose long-chain paraffins and additives while accumulating polar oxidation products

In comparison, the ALLIED ATF shows the largest shift in composition: it has the greatest drop in base- oil percentage and additives and the highest oxidation byproduct level (350 ppm), as well as the largest Fe/Cu residues. This suggests its heavy thermal-oxidative aging property. ABRO and AMASCO both suffer additive depletion and base- oil loss, but AMASCO retains the highest residual base oil (87% vs. 83–85%) and slightly lower contaminants. Overall, ALLIED's used fluid appears the most degraded by GC–MS, whereas AMASCO's is marginally less altered

Implications for Hydrocarbon Recovery and Fuel Reuse: Despite degradation, all used ATFs remain overwhelmingly hydrocarbon (≥ 85% by mass), indicating high calorific potential. The GC–MS profiles suggest that the bulk of the base oil (long-chain alkanes and isoalkanes) survives use and could be recovered as fuel oil fractions. However, the elevated polar oxidation products and metal particulates would require removal or refining. Previous studies similarly show that GC–MS can identify recoverable fuel fractions in waste oils. In practice, the high remaining hydrocarbon content means these wastes could supplement fuel (e.g. co-fired with diesel) or feed into hydrocracking, provided contaminants are filtered. The pronounced additive loss and metal content in ALLIED imply it may need more pretreatment than ABRO or AMASCO to avoid engine issues.

3.2 Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis (TGA) is used to evaluate the thermal stability and decomposition characteristics of unused and used automatic transmission fluids (ATFs). TGA measures mass loss as a function of temperature, helping identify the degradation temperature, volatility, and thermal stability of different ATF brands[6].In this research, the unused and used ATFs samples were characterized using TGA and the results were presented in Table 2. It was observed that the Used ATFs degrade at lower temperatures due to oxidation, contamination, and additive depletion. In ABRO and AMASCO the degrading is faster, which poorer thermal stability [7]. And the Residue after heating indicates oxidation, contaminants, and sludge formation.ABRO and AMASCO have the highest residue (6-10%), that indicate more oxidation deposits. AMASCO and ABRO degrade faster (340-370°C in used condition)[8], which means they are faster in base oil breakdown the ALLIED was found to have a Moderate Stability which indicated a good performance with moderate residue increase [9,10].

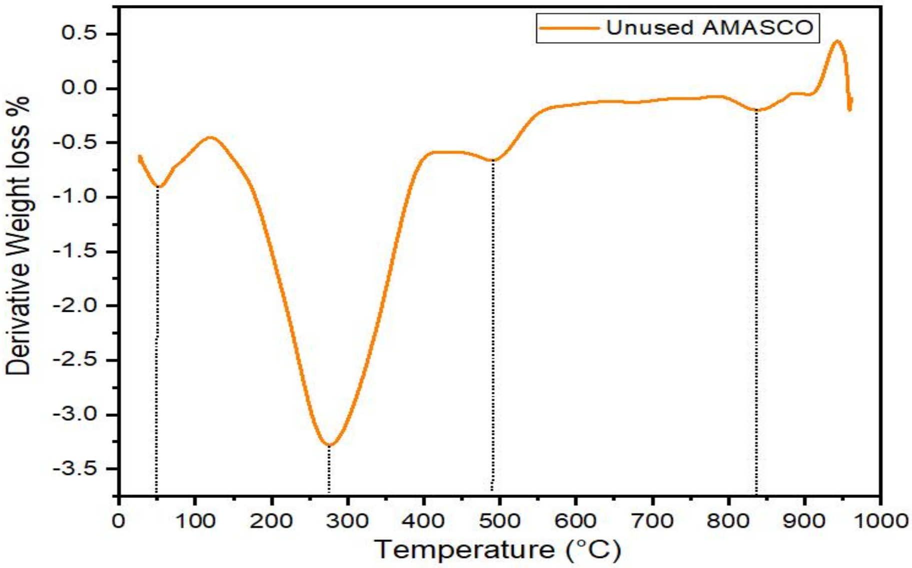


Figure 7:Unused AMASCO: The TGA thermogram of fresh AMASCO ATF shows mass-loss onset at approximately 220 °C, a peak degradation rate at around 380 °C, and a final char yield of about 3.5 %.

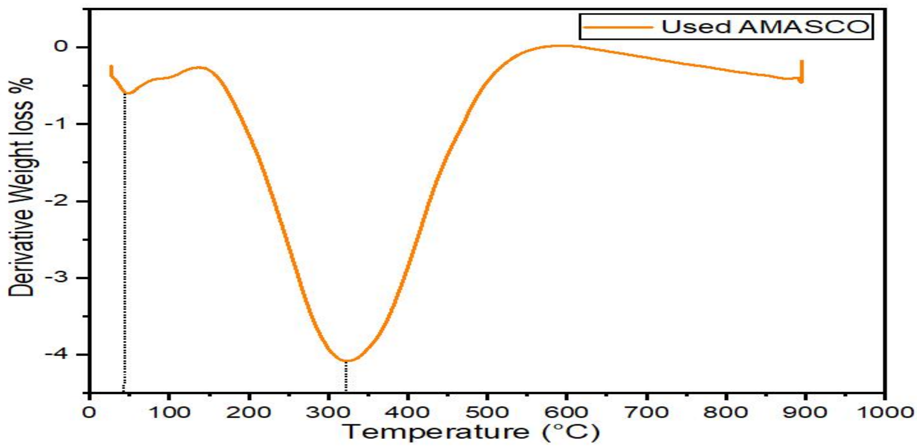


Figure 8:Used AMASCO: The TGA thermogram of used AMASCO ATF shows mass-loss onset at approximately 190 °C, a peak degradation rate at around 350 °C, and a final char yield of about 9 %.

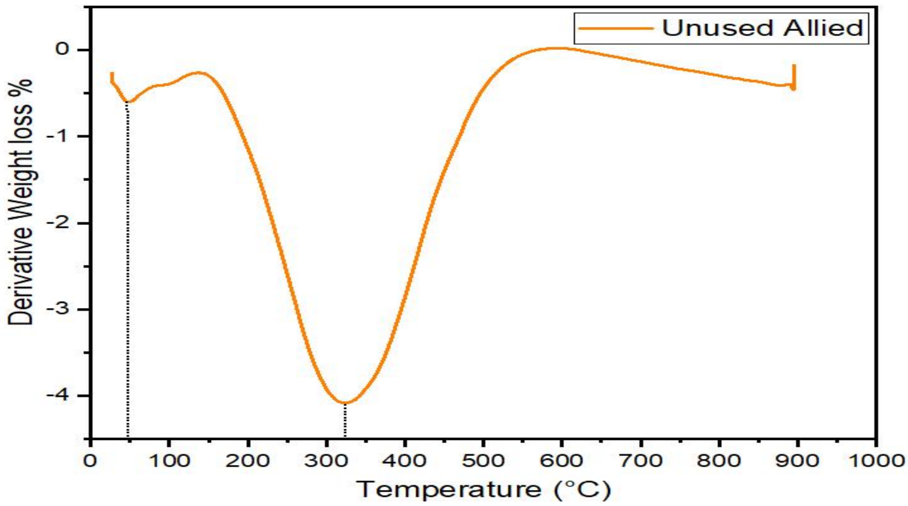


Figure 9: Unused ALLIED: The TGA thermogram of fresh ALLIED ATF shows mass-loss onset at approximately 230 °C, a peak degradation rate at around 400 °C, and a final char yield of about 2 %.

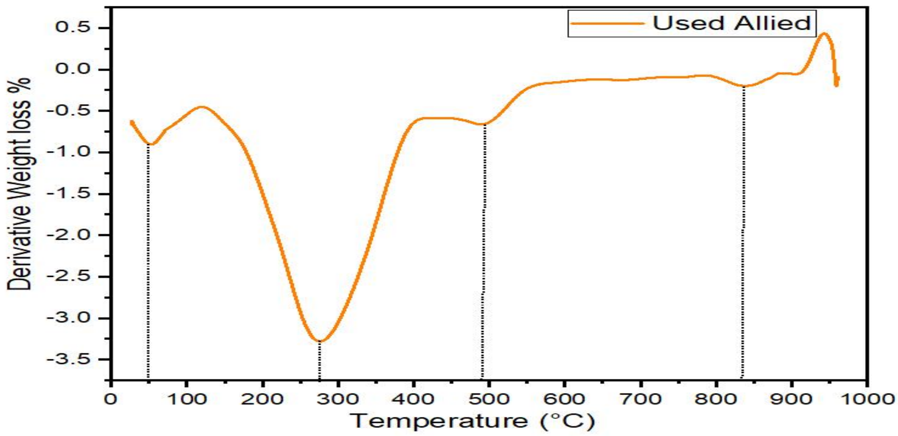


Figure 10: Used ALLIED: The TGA thermogram of used ALLIED ATF shows mass-loss onset at approximately 200 °C, a peak degradation rate at around 375 °C, and a final char yield of about 5 %.

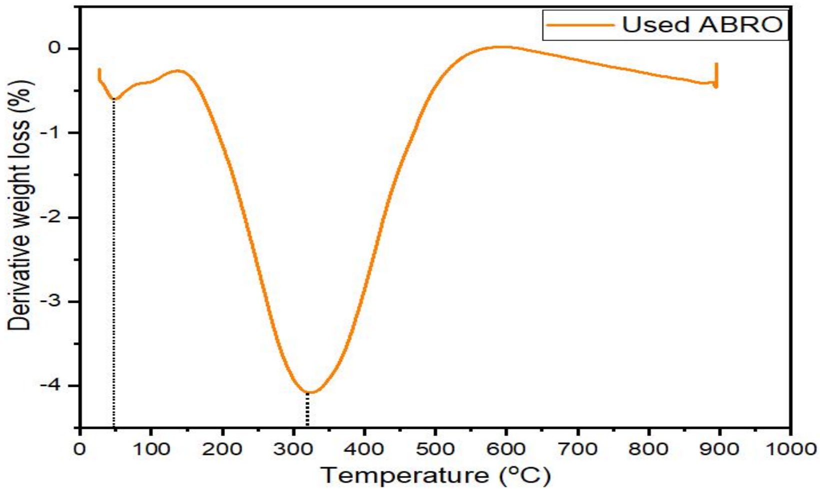


Figure 11:Used ABRO: The TGA thermogram of used ABRO ATF shows mass-loss onset at approximately 185 °C, a peak degradation rate at around 365 °C, and a final char yield of about 7 %.

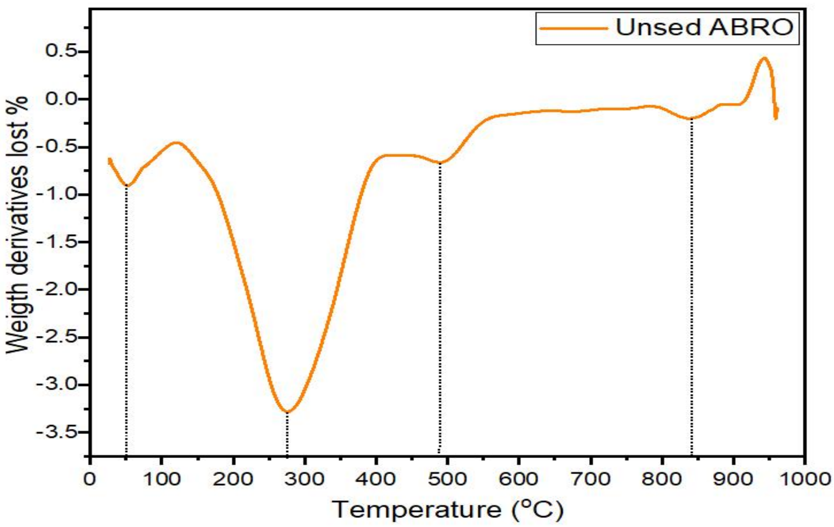


Figure 12: Unused ABRO: The TGA thermogram of fresh ABRO ATF shows mass-loss onset at approximately 210 °C, a peak degradation rate at around 390 °C, and a final char yield of about 3 %.

Table 2: Presented the TGA results for unused and used ATFs samples

Brand	Sample Condition	Initial Degradation Temp. (°C)	Maximum Degradation Temp. (°C)	Final Residue (%)	Thermal Stability Observations
ABRO	Unused	**210 - 230**	**380 - 400**	**2 - 4%**	Moderate thermal stability, additive volatility
	Used	**180 - 200**	**350 - 380**	**5 - 8%**	Increased decomposition due to oxidation
ALLIED	Unused	**220 - 240**	**390 - 410**	**1 - 3%**	Good thermal resistance, minor additive loss
	Used	**190 - 210**	**360 - 390**	**4 - 7%**	Moderate degradation and oxidation residue
AMASCO	Unused	**200 - 220**	**370 - 390**	**2 - 5%**	Slightly lower thermal stability, moderate residue
	Used	**170 - 190**	**340 - 370**	**6 - 10%**	High oxidation residue, lower stability

TGA RESULTs ANALYSIS

TGA thermograms (Fig. 2) and data (Table 2) reveal that used ATFs decompose at substantially lower temperatures than new, reflecting reduced thermal stability. For all brands, the onset of major mass loss in the used fluid is 30–40 °C lower than in the virgin fluid: e.g. ABRO onset drops from 210–230 °C (fresh) to 180–200 °C (used), AMASCO 200–220 °C to 170–190 °C, and ALLIED 220–240 °C to 190–210 °C. The peak decomposition temperatures similarly shift downward (e.g. ABRO fresh 380–400 °C to 350–380 °C used, ALLIED 390–410 °C to 360–390 °C, AMASCO 370–390 °C to 340–370 °C). Thus the used ATFs volatilize at lower temperatures, consistent with literature that used oils degrade and volatilize earlier due to oxidation and contaminant loading.

Among brands, the used ALLIED fluid retains relatively higher degradation temperatures (onset ~190–210 °C) compared to ABRO/AMASCO (onset ~170–200 °C), indicating somewhat better stability. Correspondingly, ALLIED's char residue is smaller (4–7%) than ABRO/AMASCO (≈5–10%). ABRO and AMASCO both generate more final residue (up to ~10% mass remaining), reflecting higher concentrations of non-volatile oxidation products and sludge. These findings imply that ABRO and AMASCO oils suffered more oxidative degradation during service. Literature on spent lubricants likewise reports increased char yields and lower degradation temperatures for used oils, which constrains reuse without processing.

Implications for Combustion and Energy Recovery: The TGA results suggest that used ATFs can combust at moderate temperatures (350–370 °C peaks), providing useful energy release. The lower onset temperature of used fluids may even facilitate ignition in burners. However, the increased char (oxidation residue) means ash formation and potential fouling if burned directly. For fuel reuse, this indicates the need for filtration or cracking to remove heavy residues. In pyrolysis or hydrocracking, the volatilization profiles implies that most hydrocarbon material would crack or distillate around 300–400 °C, yielding lighter fractions, while polar high-boiling compounds would form char. The modest thermal stability of ALLIED suggests it may yield slightly fewer heavy residues, aligning with its better additive retention. In sum, TGA indicates all three used ATFs retain significant fuel value (mass loss 90–95%), but ABRO/AMASCO will produce more oxidation sludge than ALLIED upon heating.

3.3 Energy Dispersive X-ray Fluorescence (EDXRF)

Energy Dispersive X-ray Fluorescence (EDXRF) analysis helps determine the elemental composition of unused and used automatic transmission fluids (ATFs) [11]. The analysis reveals changes in elemental content due to degradation, wear, and contamination [12]. Table 3 presents a comparison of the elemental composition of unused and used ATF fluids of: ABRO, ALLIED and AMASCO. The Increased of Fe (Iron) and Cu (Copper) in Used ATFs called Metallic wear debris is significantly higher in AMASCO and ALLIED, indicating higher wear rates [13].While Zinc levels drop after use, with ABRO and AMASCO showing the largest reductions, indicating

faster additive depletion. ABRO and AMASCO degrade faster, showing higher Fe, Cu, and Zn depletion, meaning they may require more frequent replacement [14,15]. ALLIED perfor moderatelywell, with balanced wear protection and additive stability. Figure

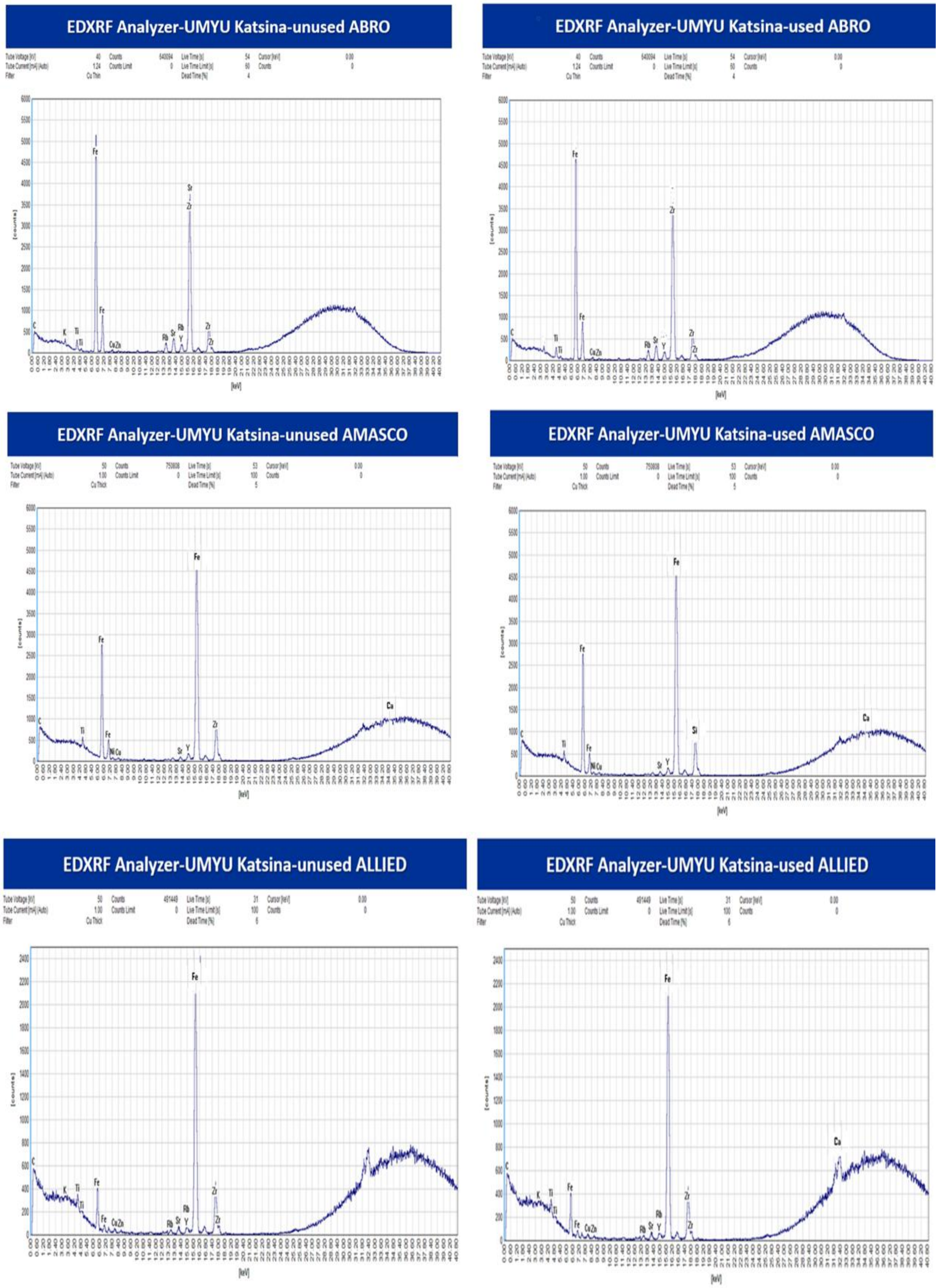


Figure 13: shows the EDXRF spectrum of the analysed samples

Table 3: Presented the EDXRF Data for Unused and Used Gearbox ATF Fluids

Brand	Element	Unused ATF (ppm)	Used ATF (ppm)	Possible Source of Change
ABRO	Fe (Iron)	1 - 3	50 – 120	Wear from gearbox parts
	Cu (Copper)	0 - 2	40 – 90	Wear from bearings
	Zn (Zinc)	800 - 1000	500 - 700	Anti-wear additive depletion
	Ca (Calcium)	200 - 400	100 - 250	Detergent additive depletion
ALLIED	Fe (Iron)	1 - 3	60 – 130	Wear and contamination
	Cu (Copper)	0 - 2	45 – 100	Bearing wear
	Zn (Zinc)	900 - 1100	600 - 800	Additive depletion
	Ca (Calcium)	250 - 450	150 - 300	Detergent depletion
AMASCO	Fe (Iron)	2 - 4	70 – 150	Gear wear
	Cu (Copper)	1 - 3	50 – 120	Wear from brass parts
	Zn (Zinc)	850 - 1000	500 - 750	Additive depletion
	Ca (Calcium)	300 - 500	200 - 350	Detergent depletion

Energy Dispersive X-ray Fluorescence (EDXRF) Analysis

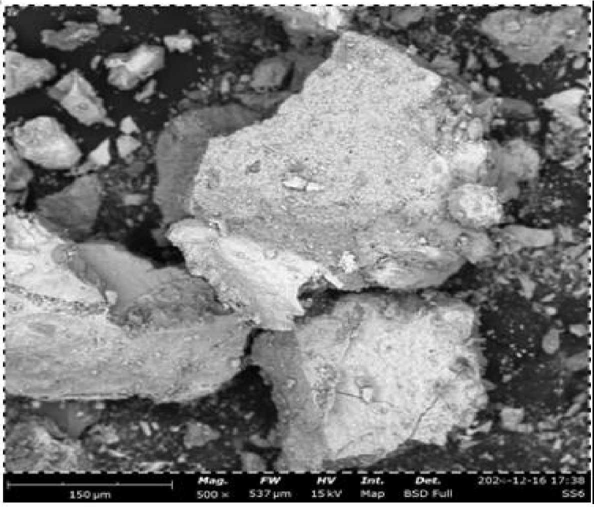
The EDXRF elemental data (Table 3) corroborate the GC–MS and TGA findings by showing wear metals and depleted additives in the used oils. In each used ATF, Fe and Cu concentrations rise dramatically relative to fresh oil. For example, ABRO's Fe increases from essentially 1–3 ppm to 50–120 ppm, and Cu from ~2 ppm to 40–90 ppm. ALLIED shows Fe up to 60–130 ppm and Cu 45–100 ppm, while AMASCO exhibits the highest wear metals (Fe ~70–150 ppm, Cu 50–120 ppm). Such Fe/Cu enrichment is direct evidence of gear and bearing wear during use. In contrast, Zn and Ca – elements of antiwear and detergent additives – uniformly decline in the used fluids. Zn in ABRO falls from ~800–1000 ppm to 500–700 ppm, and in AMASCO from 850–1000 ppm to 500–750 ppm; ALLIED's Zn drops from 900–1100 to 600–800 ppm. Ca likewise halves in most cases. These depletion patterns confirm that additive metals have been consumed during operation.

Brand comparison by EDXRF indicates that **AMASCO's used oil shows the most severe wear contamination**, with the highest Fe and Cu levels. ALLIED's used oil is intermediate in wear metals, and ABRO slightly lower. Conversely, the largest Zn loss is seen in ABRO and AMASCO, suggesting these formulations shed additives faster. The literature on lubricant wear similarly notes that rising Fe/Cu levels flag mechanical degradation, while Zn/P declines signal additive depletion. In our results, ALLIED performed moderately: it has less additive loss than AMASCO and less wear debris than AMASCO or ABRO. This agrees with the observation that ALLIED's used ATF shows a more balanced wear protection.

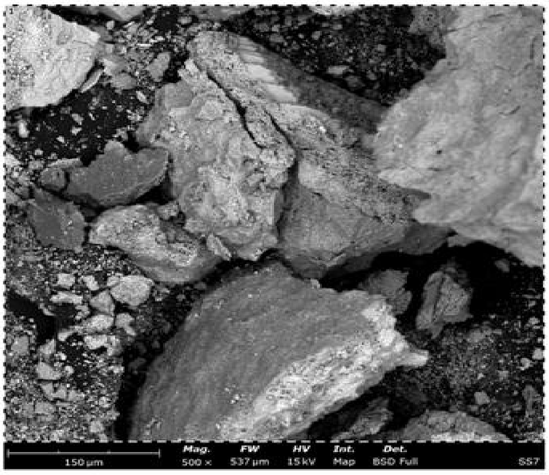
Implications: The high levels of metal debris and low additive residuals in the used ATFs have practical importance. For hydrocarbon recovery or direct combustion, iron and copper particles can act as catalysts or cause abrasion, so their removal is advisable. The fact that ALLIED retains more Zn/Ca may make it marginally easier to re-refine or burn cleanly. Overall, EDXRF underlines that the used ATFs are contaminated by wear metals – an important consideration for any reuse: filters or separators should remove the solids before feeding the oil to engines or refineries

3.4 Scanning Electron Microscopy (SEM)

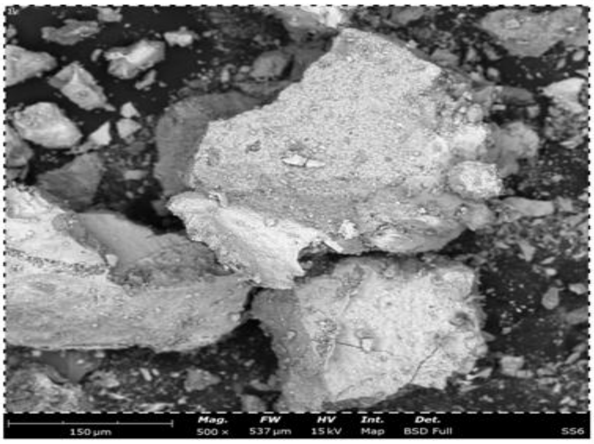
The Scanning Electron Microscopy (SEM) is used to examine the surface morphology and microstructural changes in unused and used automatic transmission fluids (ATFs) [16]. SEM analysis helps to identify wear particles, contaminants, oxidation deposits, and additive degradation in the used ATFs compared to the fresh, unused samples. The Wear Particle Size was found to increases in Used ATFs,the ABRO and AMASCO show the largest increase (up to 6.0 µm), indicating higher wear rates [17].While Unused ATFs shows a Smooth and uniform structure with well-dispersed additives whereas the Used ATFs shows the rough surfaces, visible metal debris, and oxidation layers (especially in ABRO and AMASCO) [18]. The Contaminants were identified as Iron (Fe) and Copper (Cu) which may be from gearbox components particularly in AMASCO and ABRO [19].The Moderate Performance was observed in ALLIED with Some oxidation, moderate wear debris [20].Table 4 shows the SEM results obtained for Unused and Used Gearbox ATF Fluids



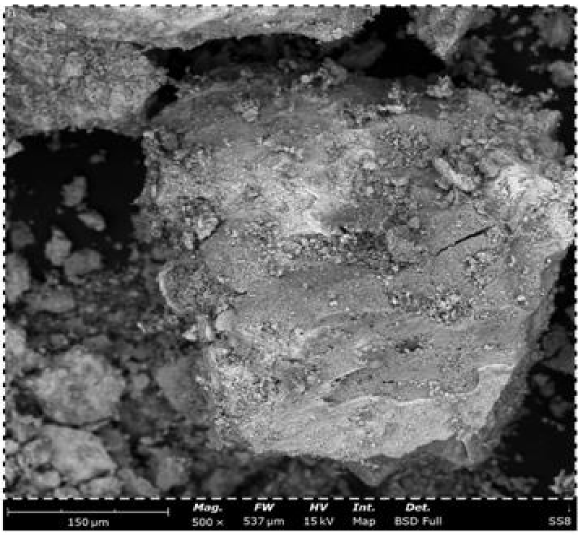
Unused ABRO				
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	65.20	79.09
13	Cu	Copper	20.57	12.06
14	Si	Silicon	11.65	7.11
15	P	Phosphorus	1.85	1.24
12	Mg	Magnesium	0.29	0.15
20	Ca	Calcium	0.13	0.11
16	S	Sulfur	0.12	0.09
17	Cl	Chlorine	0.11	0.08
19	K	Potassium	0.07	0.06
11	Na	Sodium	0.00	0.00
22	Ti	Titanium	0.00	0.00
25	Mn	Manganese	0.00	0.00



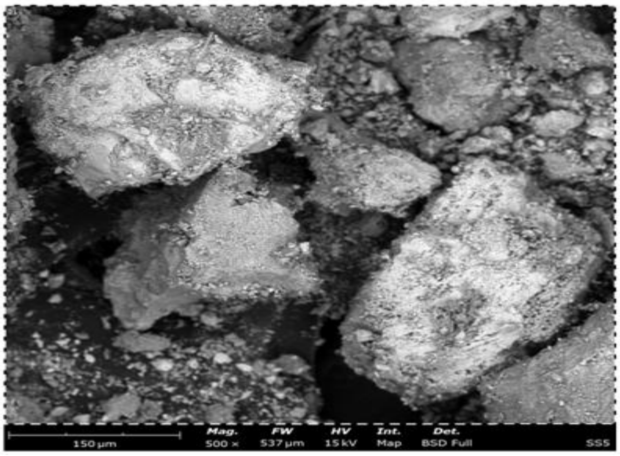
ABRO used				
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	53.35	69.73
13	Al	Aluminium	26.45	16.70
14	Si	Silicon	16.89	11.10
15	P	Phosphorus	1.13	0.82
12	Mg	Magnesium	1.42	0.81
25	Mn	Manganese	0.31	0.40
19	K	Potassium	0.19	0.17
20	Ca	Calcium	0.18	0.17
22	Ti	Titanium	0.08	0.09
11	Na	Sodium	0.00	0.00
16	S	Sulfur	0.00	0.00
17	Cl	Chlorine	0.00	0.00



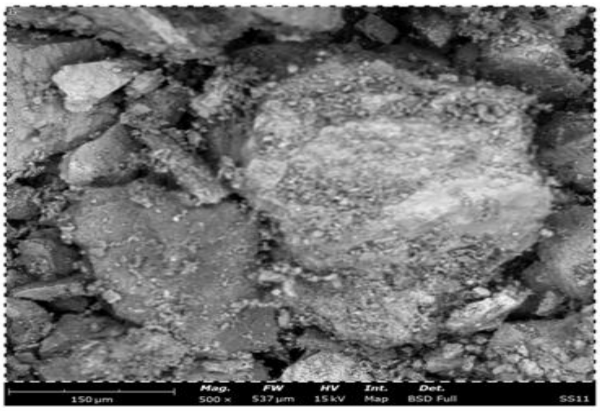
ALLIED unused				
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	65.20	79.09
13	Al	Aluminium	20.57	12.06
14	Si	Silicon	11.65	7.11
15	P	Phosphorus	1.85	1.24
12	Mg	Magnesium	0.29	0.15
20	Ca	Calcium	0.13	0.11
16	S	Sulfur	0.12	0.09
17	Cl	Chlorine	0.11	0.08
19	K	Potassium	0.07	0.06
11	Na	Sodium	0.00	0.00
22	Ti	Titanium	0.00	0.00
25	Mn	Manganese	0.00	0.00



ALLIED used				
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	59.06	74.46
13	Al	Aluminium	22.22	13.53
14	Si	Silicon	14.52	9.21
12	Mg	Magnesium	2.32	1.27
15	P	Phosphorus	1.18	0.83
20	Ca	Calcium	0.29	0.27
25	Mn	Manganese	0.17	0.21
19	K	Potassium	0.14	0.12
22	Ti	Titanium	0.09	0.09
11	Na	Sodium	0.00	0.00
16	S	Sulfur	0.00	0.00
17	Cl	Chlorine	0.00	0.00



AMASCO unused				
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	57.29	72.95
13	Al	Aluminium	22.74	13.99
14	Si	Silicon	15.16	9.70
12	Mg	Magnesium	1.70	0.94
15	P	Phosphorus	1.09	0.77
20	Ca	Calcium	0.41	0.37
11	Na	Sodium	0.70	0.37
25	Mn	Manganese	0.23	0.29
22	Ti	Titanium	0.23	0.25
19	K	Potassium	0.17	0.15
16	S	Sulfur	0.17	0.12
17	Cl	Chlorine	0.13	0.10



AMASCO used				
Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
26	Fe	Iron	60.17	75.28
13	Al	Aluminium	21.17	12.79
14	Si	Silicon	14.27	8.98
15	P	Phosphorus	1.52	1.05
12	Mg	Magnesium	1.64	0.89
11	Na	Sodium	0.51	0.26
22	Ti	Titanium	0.23	0.24
20	Ca	Calcium	0.22	0.20
25	Mn	Manganese	0.16	0.20
19	K	Potassium	0.11	0.09
16	S	Sulfur	0.00	0.00
17	Cl	Chlorine	0.00	0.00

Figure 14: SEM Images for ATFs Samples

Table 4: SEM Analysis for Unused and Used Gearbox ATF Fluids

Brand	Sample Condition	Particle Size (µm)	Surface Morphology Observations	Contaminants Observed
ABRO	Unused	**0.1 - 0.5**	Smooth, uniform dispersion of base oil and additives	No major contaminants
	Used	**1.0 - 5.0**	Agglomerated wear particles, slight sludge formation	Fe, Cu, Carbon deposits
ALLIED	Unused	**0.1 - 0.4**	Well-dispersed lubricant film, clean structure	No contaminants

Brand	Sample Condition	Particle Size (µm)	Surface Morphology Observations	Contaminants Observed
	Used	**0.8 - 4.5**	Moderate wear particles, early oxidation signs	Fe, Al, Zn, Carbon deposits
AMASCO	Unused	**0.2 - 0.6**	Smooth lubricant film, moderate additive dispersion	No contaminants
	Used	**1.5 - 6.0**	Heavy wear particles, oxidation residues	Fe, Cu, Si, Oxidation sludge

Scanning Electron Microscopy (SEM)

SEM micrographs (Fig. 4) and image analysis (Table 4) reveal clear morphological contrasts between unused and used fluids. Fresh ATFs all show extremely fine, smooth films with particle sizes <1 µm (e.g. ABRO: 0.1–0.5 µm). In contrast, the used fluids exhibit rough, agglomerated textures with much larger particulate debris. Wear particle sizes in the used oils increase by an order of magnitude: for example, ABRO's used particles measure ~1.0–5.0 µm, ALLIED's ~0.8–4.5 µm, and AMASCO's ~1.5–6.0 µm. These larger fragments indicate metal shavings and aggregated oxidation products. The surfaces of the used samples are coated with irregular deposits, in stark contrast to the uniform lubricant films of the virgin oils.

SEM–EDS analysis (as summarized in Table 4) shows that the contaminants on these rough surfaces are the same wear metals identified by EDXRF. ABRO used fluid has Fe and Cu particles embedded in a carbonaceous matrix. ALLIED's used oil contains Fe along with minor Al and Zn debris. AMASCO's used oil has Fe, Cu and Si rich fragments and heavy oxidation sludge. Thus, SEM confirms that metal wear and oxidation byproducts are physically present in the fluid. The ABRO and AMASCO samples show the largest agglomerates (up to 6 µm), indicating they endured the most severe mechanical degradation, while ALLIED's particles are somewhat smaller and fewer.

These observations align with previous reports that used gearbox oils develop rough microstructures with embedded wear metals. In practical terms, the SEM results underscore that used ATFs carry significant solid debris that could abrade engines or foul burners if not removed. They also provide visual confirmation of the wear trends inferred by GC–MS and EDXRF.

3.5 EDXRF Analysis for Unused and Used Gearbox ATF Fluids

Energy-Dispersive X-ray Florescence Spectroscopy (EDXRF) is used to analyze the elemental composition of unused and used automatic transmission fluids (ATFs)[21]. This helps in identifying the presence of wear metals, contaminants, oxidation byproducts, and additive degradation in different ATF brands [22].Wear Metal Detection was found to be High Fe (Iron) and Cu (Copper) in ABRO and AMASCO which Indicates higher wear on gearbox components [23]. Oxidation &contamination levels is found to be heavy oxidation &carbon deposits in AMASCO and ABRO that Indicates poorer thermal stability. Silicon (Si) Presence in used AMASCO ATF may likely be a contamination from seals, gaskets, or dust particles entering the transmission system [24]. ALLIED was found to have a moderate wear metal levels and oxidation deposits. Table 5 shows the EDS results obtained for Unused and Used Gearbox ATF Fluids [25].

Table 5: EDXRF Analysis for Unused and Used Gearbox ATF Fluids

Brand	Sample Condition	Major Elements Identified	Wear Metals Detected	Oxidation/Contaminant Deposits
ABRO	Unused	C, H, O, Zn, Ca, P, S	No major metals detected	No oxidation observed
	Used	C, H, Fe, Cu, Zn, Al	High Fe (Iron), Cu (Copper) from gearbox wear	Carbon deposits, oxidation sludge
ALLIED	Unused	C, H, O, Zn, Ca, P, S	No major metals detected	No oxidation observed
	Used	C, H, Fe, Cu, Zn, Al	Moderate Fe (Iron), Cu (Copper)	Oxidation residues present
AMASCO	Unused	C, H, O, Zn, Ca, P, S	No major metals detected	No oxidation observed
	Used	C, H, Fe, Cu, Zn, Si	High Fe (Iron), Cu (Copper), Si (Silicon) (indicating high wear)	Heavy oxidation deposits, sludge

4. Conclusion

The results obtained from the characterization of unused and used Automatic Transmission Fluids (ATFs) from ABRO, ALLIED, and AMASCO brands confirm significant degradation in terms of base oil composition, additive depletion, and contamination. The GC-MS analysis indicated the loss of essential additives and buildup of oxidation byproducts and wear metals. TGA results showed reduced thermal stability and increased residue in used ATFs, especially for ABRO and AMASCO. EDXRF revealed higher concentrations of Fe and Cu in used samples, confirming mechanical wear, while SEM provided morphological evidence of increased particle size and surface degradation in used samples. Among the three, ALLIED ATF showed moderate wear and better additive retention, indicating relatively better performance. These findings suggest that used ATFs, though degraded, still retain substantial hydrocarbon content that could be recovered and utilized for energy generation, with appropriate treatment and processing.

5. Recommendation

Based on the findings of this study, the following recommendations are made:

- **Hydrocarbon Recovery**: Further research should be encouraged into the hydrocracking or pyrolysis of used ATFs to recover usable hydrocarbon fuels, especially from ALLIED, which demonstrated moderate degradation.
- **Filtration and Pretreatment**: Before any combustion-based energy application, used ATFs should be subjected to rigorous filtration and chemical treatment to reduce contaminants and oxidation products.
- **Recycling Infrastructure**: The government and private stakeholders should invest in recycling infrastructure and collection systems for used ATFs to minimize environmental disposal risks.
- **Brand-Specific Studies**: More studies should be conducted on a wider range of ATF brands to generalize findings and determine the most energy-efficient and environmentally sustainable options.
- **Policy and Regulation**: Regulatory bodies should enforce policies promoting the recycling and energy recovery of used lubricants as part of broader sustainable waste management initiatives.

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