

Article

Microwave Depolymerization of Various Plastic Wastes—Quarter-Scale Testing

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Abstract

Microwave-assisted depolymerization (MD) of heterogeneous postconsumer plastics was carried out in a quarter-scale reactor to evaluate product composition and the influence of feedstock type on oil quantity and quality. Various waste streams, including: PS, PP, ABS materials, keyboard housings, textile plastics, PCBs, and mixed electronic components, were processed in 3–6 kg batches using magnetron powers up to 2×1.55 kW. All experiments yielded a condensed liquid fraction, with color intensity correlating with aromatic content. FTIR spectroscopy showed that all oils consisted of hydrocarbon matrices dominated by aliphatic C–H stretching bands ($2956\text{--}2850\text{ cm}^{-1}$). Aromatic contributions varied significantly: PS produced oils rich in aromatic OOP C–H bands ($900\text{--}650\text{ cm}^{-1}$), PP yielded predominantly aliphatic oils with minor aromatic features, and ABS or electronics materials produced mixed aliphatic–aromatic profiles. Textile oils additionally exhibited carbonyl and O–H bands, indicating oxygenated decomposition products. Fractional distillation separated the oils into low-boiling aliphatic ($<250\text{ }^{\circ}\text{C}$) and heavier aromatic ($250\text{--}350\text{ }^{\circ}\text{C}$) fractions. These results suggest that MD reliably converts diverse plastic wastes into hydrocarbon oils whose spectroscopic characteristics reflect both feedstock composition and thermal pathways intrinsic to microwave heating.

Keywords: microwave depolymerization; quarter scale experiments; oil fractions; IR analysis

1. Introduction

1.1. Global Dynamics of Plastic Waste, Limitations of Existing Recycling Strategies

Since the mid-20th century, global plastic (P) production has expanded at an unprecedented rate, fundamentally reshaping material flows and waste streams; production increased from approximately 2 M Mg in 1950 to more than 390 M Mg in 2021, and the total mass produced is estimated to exceed 8.3 B Mg [1]. According to the comprehensive mass/balance model [1], nearly 79% of P have accumulated in landfills or the natural environment, while only 9% have entered formal recycling systems.

The short lifespan of consumer P equipment, often less than six months for packaging materials, combined with the rapid growth of single-use applications, has exacerbated the accumulation of persistent waste [2,3]. Forecasts suggest that by 2050, global annual P waste generation could reach 800 M Mg, with mismanagement rates increasing in regions lacking



Academic Editor: Sabino De Gisi

Received: 15 January 2026

Revised: 26 February 2026

Accepted: 3 March 2026

Published: 19 March 2026

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advanced recycling infrastructure [4]. Traditional recycling technique approaches have failed to keep pace with production; while mechanical recycling is widely implemented, it suffers from well-documented drawbacks, including progressive polymer degradation, contamination sensitivity, limited compatibility between polymer classes, and the down-cycling of materials into lower-value applications [3,5]. Furthermore, multilayer films, fiber-reinforced polymer, and heavily pigmented P remain practically unrecyclable via mechanical routes [6].

Chemical recycling, particularly thermal pyrolysis, has emerged as a more flexible strategy capable of processing heterogeneous and contaminated feedstocks [5,7]. However, many conventional pyrolysis studies report operating temperatures in the range of 450–550 °C with residence times from tens of minutes up to over an hour [5,6,8]. Moreover, the broad hydrocarbon distributions characteristic of pyrolysis oils can limit their direct use in refineries without upgrading processes [9]. These limitations have shifted attention toward alternative heating approaches, among which MD offers a fundamentally different mode of energy delivery.

1.2. Physicochemical Principles of Microwave Heating of Polymers

Microwave heating arises from the interaction between electromagnetic radiation (at 2.45 GHz) and matter through dipolar rotation and ionic conduction [7,10]. The resulting internal energy deposition contrasts sharply with conventional heating, where thermal energy must be transferred from externally heated reactor walls inward via conduction and convection. In practical operation, this difference translates into faster heating and a noticeably more dynamic thermal response than that observed in conventional wall-heated reactors, particularly during rapid changes in applied power.

Nevertheless, polymers (PM) such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET) have low dielectric loss factors, making them poor absorbers of microwave energy [8,11]. This is due to the material's inherent ability to dissipate electromagnetic energy into heat when subjected to an alternating electric field; a higher loss factor directly corresponds to superior microwave absorption, allowing materials to heat faster by dissipating more energy via polarization and conduction. As a result, microwave pyrolysis of P relies on the addition of microwave susceptors: materials capable of rapidly converting microwave energy into heat. Graphite, carbon black, biochar, and activated carbon are commonly used due to their high dielectric loss and electronic conduction pathways [12,13].

Graphite particles exposed to microwave irradiation can achieve T exceeding 1000–1200 °C within 10–20 s, significantly beyond what can be reached in conventional heating systems over comparable timescales [12,14]. These localized high T zones act as catalytic surfaces where PM chains undergo thermal cracking, producing radical intermediates that propagate depolymerization reactions [13]. Reported energy efficiencies for MD can reach 70–85% under optimized laboratory conditions, whereas conventional pyrolysis often exhibits efficiencies below 50% due to external heat losses [11].

Another distinguishing feature of microwave heating is its ability to preferentially couple with materials of differing dielectric properties, leading to selective heating effects. For instance, carbon-filled fractions of mixed P waste reach higher T than PM-only regions, enabling controlled initiation of depolymerization while leaving the surrounding material cooler [10,15,16].

1.3. MD Pathways for Major PM Classes

1.3.1. PE and PP

Polyolefins (by the way, representing nearly 60% of global P production [1,17]) degrade primarily through random scission and β -scission mechanisms under microwave conditions. In [18], it was reported that LDPE (low-density polyethylene) subjected to microwave irradiation in the presence of carbonaceous susceptors at 450–520 °C yields 65–75 wt% liquid hydrocarbons within 2–3 min. Product distribution was dominated by linear alkanes and alkenes in the C10–C15 range, reflecting minimal secondary aromatization.

Microwave pyrolysis of PP at 430–500 °C produces 55–70 wt% liquids within 3–7 min, with the product rich in branched hydrocarbons due to PP tertiary carbon sites [19]. In comparison, conventional pyrolysis studies typically report oil yields of 45–60 wt% for PE and PP, often requiring 20–40 min to reach comparable T [5].

Elsewhere [17], it is demonstrated that rapid, non-equilibrium heating of polyolefins can reduce apparent activation energies relative to conventional slow-heating experiments, supporting the potential advantages of microwave-based energy coupling. Liquid yields exceeding 80 wt% have been reported under optimized microwave conditions for certain PP feedstocks, particularly in reactors employing high surface area carbon susceptors [19,20].

1.3.2. PS

Among commodity PM, PS exhibits the highest monomer recovery potential due to its depolymerization mechanism. Styrene yields 75–85 wt% during microwave pyrolysis at 350–420 °C, significantly outperforming conventional pyrolysis, which typically delivers 50–60 wt% monomer at 450–500 °C [21]. Minimal char formation (<2 wt%) and narrow molecular weight distributions are observed under microwave irradiation [9]. Studies have also shown that microwave processing reduces secondary crosslinking reactions, preserving monomer integrity [9,21,22].

1.3.3. PET and Polyesters

Microwave-assisted glycolysis of PET has gained considerable attention due to the high-value monomers it produces. PET depolymerizes to BHET (bis(2-hydroxyethyl) terephthalate) in 5–15 min at 180–220 °C, whereas conventional glycolysis requires 60–180 min at similar T [23]. PET depolymerizes above 80% conversion rate during microwave methanolysis at 160–200 °C within 20–30 min, compared with 2–3 h under oil bath heating [24]. The acceleration is attributed to selective heating of catalysts and reactants, leading to enhanced reaction rates.

Recent studies have also explored microwave-assisted catalytic pyrolysis of PET, showing increased yields of terephthalic acid and reduced formation of oxygenated aromatics relative to traditional pyrolysis [25].

1.3.4. PVC and Halogenated PM

PVC (polyvinyl chloride) presents significant hazards during thermal conversion due to HCl evolution. Microwave pyrolysis with carbon susceptors moderates HCl release and suppresses formation of chlorinated aromatic compounds [26]. In other work [27], improved behavior when PVC was co-processed with polyolefins under microwave irradiation was observed, reducing local overheating and increasing hydrocarbon yields.

1.4. Challenges Arising from Heterogeneity in P Waste

Municipal solid waste (MSW) plastics comprise mixed PM, multilayer laminates, fillers, pigments, flame retardants, stabilizers, and moisture. Heating nonuniformity in mixed P under microwave irradiation can exceed 200 °C, with PE-rich fractions remaining

below 150 °C while carbon-containing regions surpass 400–600 °C [28]. These disparities lead to incomplete conversion and unpredictable product compositions.

Reported oil yields in microwave-assisted pyrolysis systems typically range between approximately 50 and 80 wt%, depending on polymer type, reactor configuration, and the presence of microwave susceptors [16,17,19].

This patent [29] mitigated these challenges by introducing 10–20 wt% carbon susceptors, demonstrating complete conversion within 5–10 min and oil yields of 60–70 wt%. In [30], 200–500 g of mixed waste batches was processed at 450–550 °C, observing distinct relationships between feed composition and product distribution: PP-rich feeds favored branched C5–C12 hydrocarbons, whereas PE-dominant feeds yielded linear C10–C20 alkanes.

Studies using pilot- or semi-pilot microwave reactors (0.5–5 kg capacity) [31] further indicate that moisture content and particle size distribution critically influence heating patterns, underscoring the need for systematic scale-up methodologies.

1.5. Scale-Up Constraints and Microwave Reactor Engineering

Scaling up microwave reactors is associated with several inherent physical constraints. Electromagnetic simulations [32] show significant standing wave formation in cavities exceeding 20 cm in characteristic dimension. The penetration depth at 2.45 GHz in carbon PM mixtures remains limited to 1–3 cm [33,34], restricting effective bed thickness unless agitation or mixing mechanisms are introduced.

Reliable operation is typically sustained only up to batch sizes of 150–200 g, while attempts beyond 300–500 g require specialized multimode cavities, rotating beds, or hybrid heating systems [33]. Improved uniformity can be achieved in agitated microwave beds [35], whereas multimode cavity excitation improved heating homogeneity by 30–45% relative to single-mode systems [36]. Mass/transfer limitations in molten PM beds are highlighted in [37], showing that reduced bubble escape leads to local accumulation of gaseous intermediates and increased secondary cracking.

Pilot-scale studies employing 1–5 kW microwave power sources [34,38] report mixed results, with heating non-uniformity, susceptor degradation, and reactor-wall arcing identified as recurring challenges. Nevertheless, these studies emphasize the potential of MD as a scalable platform if properly engineered.

In the broader context of strategies, classification of thermochemical processes such as MD as “chemical recycling” requires transparent and robust assessment frameworks. As highlighted by Giordano et al. [39], emerging circular economy technologies must be evaluated not only in terms of technical feasibility, but also through consistent mass/energy balances, product quality metrics, and environmental performance indicators. Without such structured assessment, contribution of advanced recycling routes to circular material flows may be overestimated. In this context, intermediate-scale experimental validation plays a crucial role in bridging laboratory demonstrations and industrial deployment.

1.6. Motivation and Objectives of the Present Work

Considering the extensive limitations of mechanical recycling [2,3], the slow and energetically inefficient nature of conventional pyrolysis [5–8], and the promising yet under-scaled advancement of MD [11,16,33], there exists a clear need for intermediate-scale experimental validation. The present work, “Microwave depolymerization of various plastic wastes: quarter-scale testing”, addresses this gap by evaluating MD of P wastes in typically a few kilograms, representative of the transitional region between laboratory and pilot scales (quarter of the design capacity of the pilot reactor, i.e., loads of 3–6 kg, above typical experiments from the literature).

The study examines thermal behavior, energy efficiency, phase distributions, and the influence of feed composition and material morphology. Through this approach, this work aims to generate insights directly applicable to pilot-scale systems and inform the engineering requirements for industrial implementation of MD technologies.

2. Materials and Methods

2.1. Reactor Description

Schematic diagrams of the depolymerization installation used, including the following systems: purge, reactor and batch material loading, temperature measurement, heating, electrical connections (Figure 1a), liquid product cooling and gaseous product outlet (Figure 1b), are presented. The microwave reactor employed in this study was an in-house constructed unit fabricated primarily from weldable structural steel, with several detachable joints incorporated to facilitate maintenance and sampling. The reactor consists of a cylindrical chamber with an effective internal volume of 35.3 L (dimensions: $L = 50$ cm, $D = 30$ cm), thermally insulated on the outside with glass wool to minimize heat losses. The batch material is placed directly inside this cylindrical chamber, which serves as the reaction zone.

A stainless steel tube penetrates the upper section of the reactor and houses a thermocouple (K-type, DT-3610B, CEM, Shenzhen, China), which provides sequential measurements of the gas phase temperature inside the reactor during MD. A second steel tube supplies N_2 (technical grade; Eltech and BLK Technical Gases (distributor), Warsaw, Poland) to establish an inert atmosphere. During standard tests, N_2 was introduced at a flow rate of $5\text{--}20\text{ L}\cdot\text{min}^{-1}$ (for 15–30 min), ensuring displacement of air.

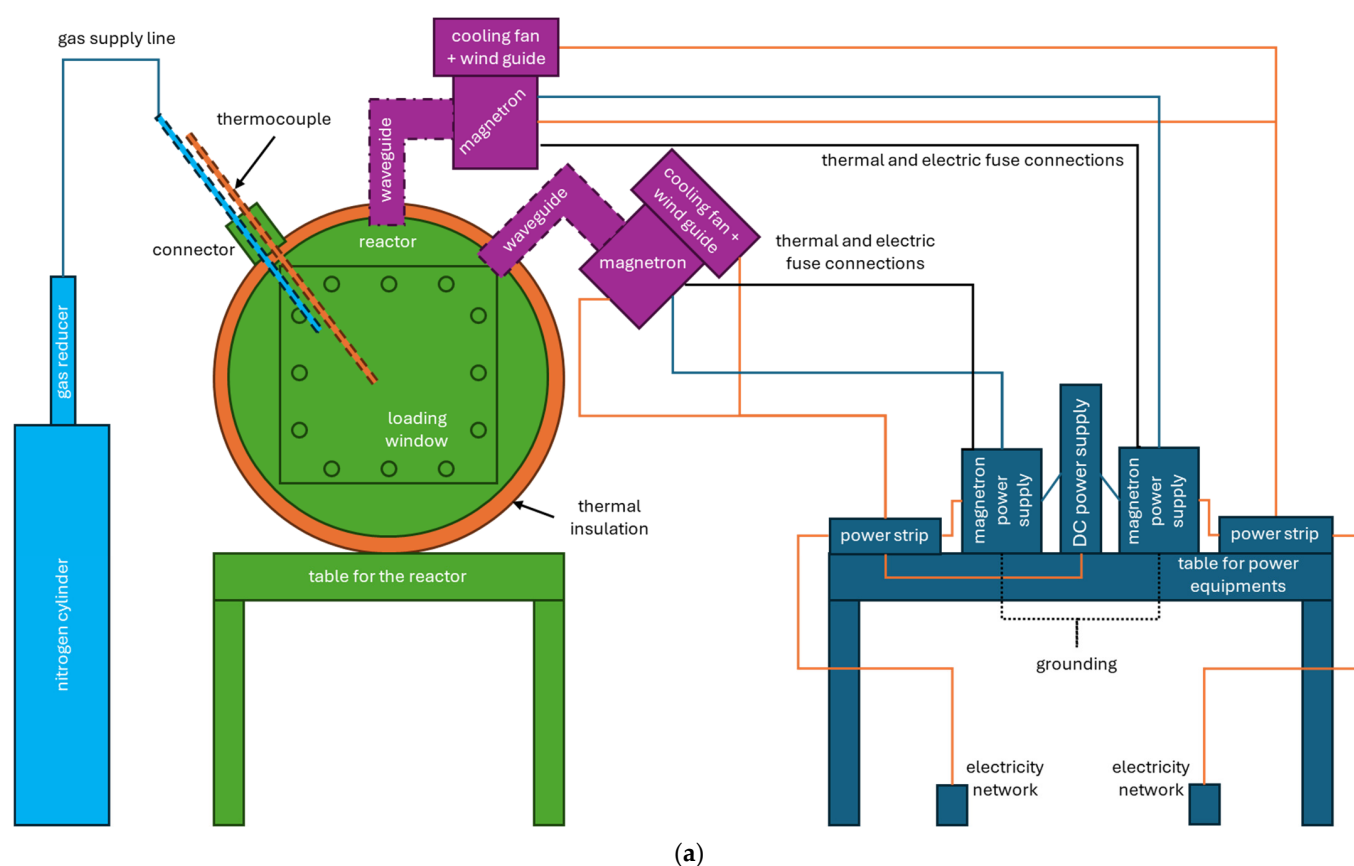


Figure 1. Cont.

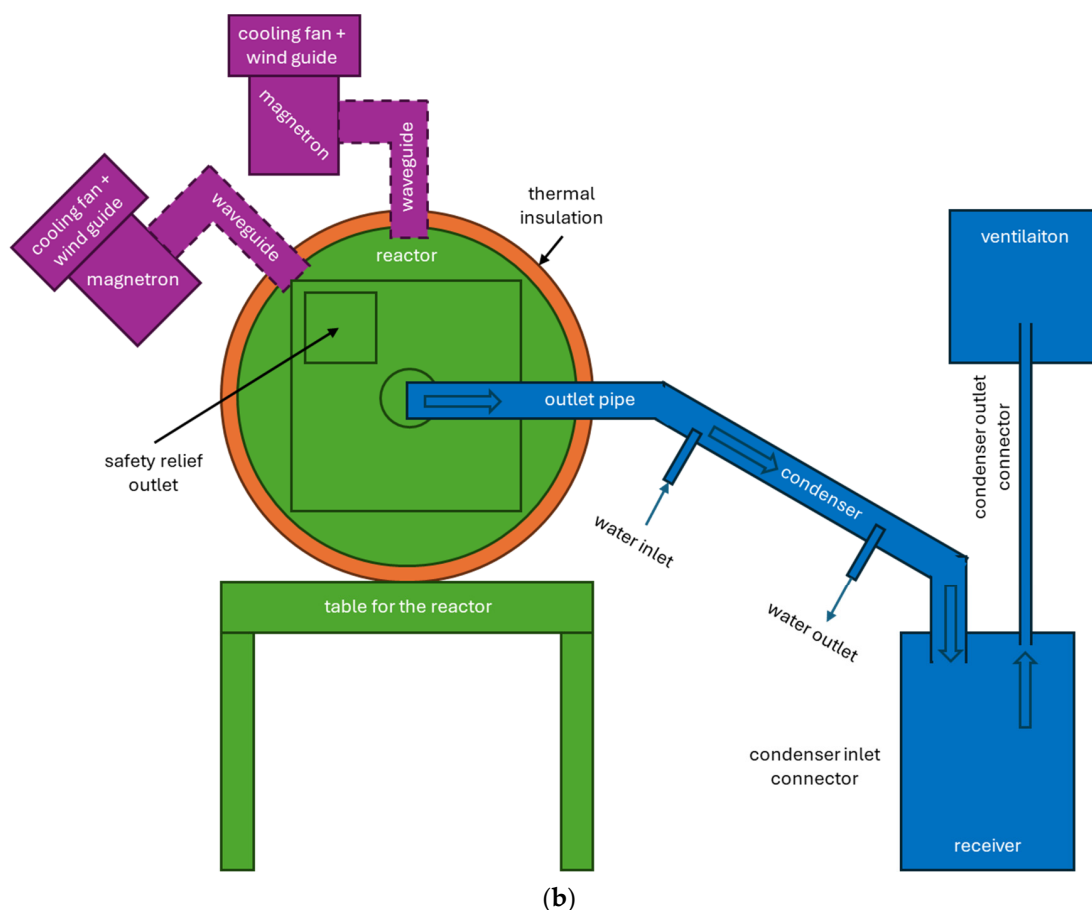


Figure 1. Depolymerization installation scheme: (a)—front view with systems: purge, reactor and batch material loading, temperature measurement, heating, electrical connections; (b)—rear view with systems: safety relief outlet, liquid-product cooling, gaseous-product outlet.

The reactor is additionally equipped with a safety relief outlet. This outlet is constructed as a flanged assembly fixed to the reactor body, sealed with a graphite gasket (Sigraflex Uniprom, SGL Carbon, Wiesbaden, Germany) and covered with a thin copper foil acting as a rupture membrane. Two rectangular waveguides (according to WR-340 specification), each terminating in a bolted flange, are welded directly onto the reactor wall. These waveguides transmit microwave radiation generated by one or two magnetrons (2M210-M1, 2455 Hz, Panasonic, Kadoma, Japan), which are rigidly mounted to the corresponding flanges. Material loading is carried out through a sealed access port; the loading window is fitted with a custom cut graphite gasket (same as mentioned earlier) and secured with multiple bolts to guarantee airtight closure during operation.

Volatile products generated during MD exit the reactor through a horizontally oriented outlet tube (inner diameter = 2 cm) welded to the chamber. This tube is connected via a clamped flexible hose to a glass condenser cooled with continuous water flow. The condensed liquid products are collected in a glass receiver (glass jar) located downstream of the condenser. This receiver accumulates the main oil fraction as well as condensed gaseous components. Electrical measurements, including voltage, current, and magnetron power consumption, were monitored using the following devices: magnetron power supplies (E-WB1500FD, Xi'an ECPS Electronics Technology Co., Ltd., Xi'an, China), DC power supply (PXN-1503D, Zhaoxin, Shenzhen, China), and a process calibrator/meter (Escort 2000, Escort Company, Taipei, China).

2.2. Experimental Procedure

After determining the optimal voltage value on the magnetron(s) at which the depolymerization T is obtained, hereinafter referred to as the process T (the T that is obtained at optimal voltage), the actual depolymerization tests were carried out at this voltage. The test procedure: batch material loading, N₂ purge, heating, product condensation, begins by placing the batch material into the reactor chamber through the loading window, which is then sealed and mechanically tightened. If necessary, if the condenser was clogged with sticky oil fractions after the previous test, the condenser was chemically cleaned with a suitable solvent. N₂ is introduced to purge the system, after which cooling water is circulated through the condenser. The magnetron(s) is/are then activated, and T, electrical parameters, and operating conditions are continuously recorded. Microwave irradiation causes rapid heating of the batch material, initiating MD. The volatile pyrolysis products are transported from the reactor to the condenser, where they are cooled and collected as the main oil fraction.

The process termination criterion was defined as the cessation of condensation of the liquid product. Upon completion of each test, the total volume of the collected oil fraction is measured to an accuracy of ± 10 mL, and a representative sample is withdrawn for analysis. The bulk liquid product is subsequently subjected to fractional distillation conducted in two T ranges: to 250 °C and 250–350 °C. Distillation is performed using a standard simple distillation apparatus consisting of a two-neck, round-bottom flask (4 L) equipped with a thermometer port and a vapor outlet. Cooling water serves as the condensing medium. The oil is heated using an electric heating mantle (98-II-C, 4000 mL, Chemland, Stargard, Poland). For safety, the entire distillation setup is operated inside a ventilated fume hood. Following each distillation step, samples of the distilled oils are collected for subsequent characterization. Non-condensed gaseous fractions are not recovered directly; instead, their volume is estimated from the difference between the initial volume of the collected oil fraction and the total volume of distillates.

2.3. Analytical Methods

All samples, namely the main oil fraction and the two distillation fractions (≤ 250 °C and 250–350 °C), were analyzed using infrared (IR) spectroscopy: the spectra were recorded on Perkin Elmer Frontier spectrometer (PerkinElmer, Waltham, MA, USA) (in the region of 4000–650 cm^{−1} with a resolution of 1 cm^{−1}; number of scans—32; correction—atmospheric (H₂O/CO₂); configuration: MIR TGS detector (PerkinElmer, Waltham, MA, USA), MIR source (PerkinElmer, Waltham, MA, USA), KBr beam splitter; measurement accessories: UATR attachment (PerkinElmer, Waltham, MA, USA) (diamond/ZnSe, 3-bounce). The obtained spectra were used to assess the chemical composition of the depolymerized products and to identify characteristic functional groups present in each fraction. In addition to qualitative band assignment, semi-quantitative comparison of selected spectral regions was performed as described below.

Measurements were performed using the Attenuated Total Internal Reflection (ATR) (PerkinElmer, Waltham, MA, USA) technique, which is standard in the analysis of oil products, eliminating the need for cuvettes and ensuring repeatable measurements for thin films:

- Optical System Preparation: Before sample application, the crystal surface was cleaned using a soft, lint-free tissue and a solvent appropriate for the matrix (isopropanol), drying the surface until streaks were completely removed.
- Background Correction: The background spectrum was recorded against air (clean crystal). This procedure was repeated after each measurement series and in the event of changes in ambient conditions (fluctuations in water vapor or CO₂ concentration).

- **Sample Application:** A small amount of oil (a few μL) was applied to the active area of the ATR crystal, ensuring thorough surface coverage and elimination of air bubbles.
- **Measurement Procedure:** Measurements were performed while maintaining constant parameters (number of scans, resolution, range). For quantitative analysis, a standardized baseline correction procedure was used, along with ATR correction when necessary. **Post-measurement procedure:** The crystal was cleaned immediately after sample removal to prevent the formation of a permanent residual film.

For comparative interpretation across feedstocks, band areas were evaluated after baseline correction (rubber-band/polynomial, identical settings for all spectra). Integrated absorbance was calculated over fixed wavenumber windows: aliphatic C-H stretching ($3000\text{--}2800\text{ cm}^{-1}$), aromatic ring region ($1605\text{--}1495\text{ cm}^{-1}$), carbonyl region ($1850\text{--}1650\text{ cm}^{-1}$), and hydroxyl region ($3600\text{--}3200\text{ cm}^{-1}$). The following spectral indices were used to describe relative contributions: Aromaticity Index $\text{ArI} = \int(1605\text{--}1495) / \int(3000\text{--}2800)$, Carbonyl Index $\text{CI} = \int(1850\text{--}1650) / \int(3000\text{--}2800)$, and Hydroxyl Index $\text{OHI} = \int(3600\text{--}3200) / \int(3000\text{--}2800)$. These calculated indices provide semi-quantitative comparative trends only; due to overlap and matrix effects (especially in ATR), they are not used for absolute compositional determination.

2.4. Batch Materials

The following materials were used as input materials (batch) for testing:

- PS—plastics from refrigerator and freezer drawers, household appliances, etc.;
- PP—office waste bins, lawn mower bins, compact disk cases (but not “jewel cases”);
- keyboards—scrapped keyboards with cut wires;
- PCB—class I and II printed circuit boards;
- AiO—rear parts of the AiO computer case (monitor backs), TFT monitors;
- textile—soiled work clothes (T-shirts, sweatshirts, jackets) and rags;
- ABS—cut television monitor housings;
- ABS “mix”—a mixture of various plastics, without prior segregation, mainly: ABS PC, polycarbonates from electronics, washing machine, printer and photocopier components, etc.;
- ABS drum, PP T2O—parts of washing machine drums made of plastic.

All materials were weighed on a scale Cely Dibal PS50-M (Dibal, Derio, Spain).

3. Results and Discussion

3.1. MD Tests

The effect of magnetron voltage on the thermal behavior of the reactor was examined for different feedstocks, as summarized in Table 1. For each experimental batch, the table lists:

- the operating voltage of the magnetron(s);
- the measured current and estimated microwave power;
- the maximum T recorded inside the reactor (via the thermocouple positioned in the gas phase).

The data encompass multiple feedstock types and heating conditions, allowing direct comparison between tests.

Across all test batches, raising the magnetron voltage resulted in higher internal T, but the relationship is not linear. Thus, small increases in voltage produce disproportionately large increases in T once microwave absorption becomes efficient.

PS demonstrates the most efficient microwave coupling, reaching $200\text{ }^{\circ}\text{C}$ at approximately 4.1 V and <1.1 kW magnetron power, whereas PP requires at least 3.3–3.5 V and

significantly higher cumulative energy input to achieve similar T. ABS and electronics-derived feedstocks occupy an intermediate position, while textile exhibits the slowest heating response.

Table 1. Dependence of T inside the reactor chamber on the voltage and power of the magnetron(s)—various tests.

Batch	T/Voltage/Power								
	V	1.5–2.3	2.9	3.3	3.9	4.1			
PS	°C	20–30	30–45	50–55	65–85	>200			
	V	1.5	1.9	2.3	2.9	3.3			
PP	°C	20	45	70	80	100			
	V	1.1	1.5–1.9	2.3	2.9	3.3	3.9	4.1	4.5
keyboards	°C	20	25	30–35	40	45–50	100–110	120–200	>200
	V	1.5	2.3	2.9	3.3	3.9	4.1		
PCB	°C	25	50	85	120	145	>200		
	V	1.5	1.9	2.3	2.9	3.3	3.9	4.1	
AiO	°C	40	60	75	110	120	130	>205	
	V	1.5	1.9	2.3	2.9	3.3	3.9	4.1	
textile	W	610	800	920	1110	1250	1410	1550	
	°C	20	25	30	40	60	95	>190	
									4.1
ABS drum, PP T2O	V	1.5	1.9	2.3	2.9	3.3	3.9	one magnetron	two magnetrons (2 × 4.1 V)
	°C	95–100	140–145	155	160	170–190	180–235	245	435
ABS drum, PP T2O, material ground in a shredder	V	1.1	1.5	1.9	2.3	2.9	3.3	3.9	4.1
	°C	20	25–40	50–75	75–95	105–120	120–140	140–170	>170
ABS “mix”	V	1.5	1.9	2.3	2.9	3.3	3.9	4.1	
	°C	45	60	75	95	120	140–155	>200	

A comparison of the voltage/temperature relationships for different feedstocks reveals clear differences in microwave coupling efficiency. PS: internal reactor T above 200 °C already at approximately 4.1 V and <1.1 kW magnetron power, confirming its rapid transition to a microwave-absorbing, partially carbonized state. By contrast, PP requires 3.3–3.5 V and substantially higher cumulative energy input to achieve similar T, reflecting its weaker dielectric response. ABS and electronics derive show intermediate behavior, whereas textile heats more slowly due to its heterogeneous PM composition. Taken together, the results show that differences in PM chemistry affect how efficiently microwave energy is transformed into heat in the tested system.

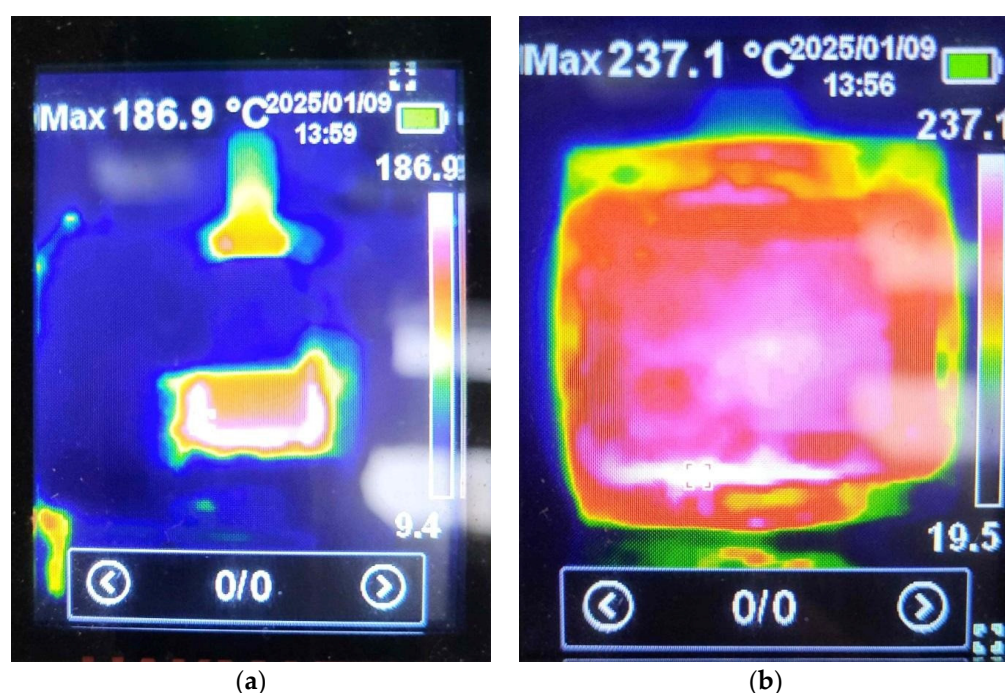
Table 2 is an example of the relationship between cumulative energy consumption of the magnetron and the T measured inside the reactor during the PS depolymerization test. As the experiment progressed, the energy delivered to the microwave system increased steadily, while the measured internal T exhibited a characteristic nonlinear rise. Initial heating required a relatively large amount of energy to achieve a modest T increase, reflecting the low microwave absorption efficiency of solid PS before the onset of thermal softening. Once the material began to melt and early stage depolymerization products formed, the heating rate increased noticeably. This behavior is consistent with the development of a carbonized surface layer and molten PM that enhance microwave coupling.

At higher cumulative energy inputs, T approached its maximum plateau, indicating that heat losses and endothermic depolymerization reactions balanced the microwave power absorbed by the feedstock.

Table 2. Dependence of the T inside the reactor chamber on the registered energy consumption on the magnetron—test with PS batch.

T, °C	30	120	200	210
energy consumption, kWh	0.15	0.8	3.7	4.1

A thermal imaging camera was used to observe the external T distribution of the reactor during microwave operation (Figure 2); it revealed a heterogeneous T field across the outer steel surface, reflecting the internal distribution of microwave energy within the reactor cavity. The hottest region was consistently located around the welded waveguide section where microwave radiation entered the chamber. This area exhibited a distinct thermal maximum, forming a clearly visible high-T cluster on the thermogram. Slightly elevated T was also noted along the upper portion of the cylindrical wall, corresponding to the zone in which the carbonaceous susceptor and PM mixture accumulated during processing.

**Figure 2.** Images from thermal imaging cameras: (a) max. 187 °C; (b) max. 237 °C—test with ABS drum batch, PP T2O.

The remaining areas of the reactor surface displayed moderate and relatively uniform T, indicating effective thermal insulation by the surrounding glass wool layer. Importantly, no abnormal hotspots or local overheating zones were observed near the flange seals or at the loading window, confirming that thermal stress was concentrated primarily in the intended energy input regions. The gradient shown in the thermographic image aligns with expectations for microwave-driven processes in which internal heating is dominated by the dielectric and conductive properties of the feedstock rather than by conduction through the reactor wall.

Overall, the thermal image provides visual confirmation of the characteristic heating behavior of microwave reactors, localized energy deposition at the susceptor interface and rapid heat buildup in regions directly exposed to high field intensity. These observations are consistent with the kinetic behavior inferred from oil formation profiles and support the interpretation that polymer decomposition is strongly influenced by localized interactions between microwave fields and carbonaceous susceptors.

Table 1, together with thermal imaging observations, suggests that:

- localized heating near the waveguide entry points results in rapid T rise;
- the thermocouple, which measures gas-phase T, underestimates the true local maxima in the solid phase;
- T gradients play an important role in the initiation of depolymerization reactions.

Hence, the measured T should be interpreted as approximate indicators of reaction conditions, reflecting the bulk thermal state rather than localized hot spots.

MD tests proceeded consistently across all examined feedstocks, producing a condensed oil fraction in every experiment and a non-condensed gaseous fraction whose volume decreased with increasing aromaticity of the starting PM (Figures 3–8). Materials rich in styrene or acrylonitrile softened rapidly and initiated volatilisation at lower apparent bulk T, whereas PP- and ABS-containing P required longer irradiation to reach equivalent conversion. This behavior is consistent with their different thermal pathways: styrenic PM undergo depolymerization via unzipping reactions, while polyolefins crack through random scission.

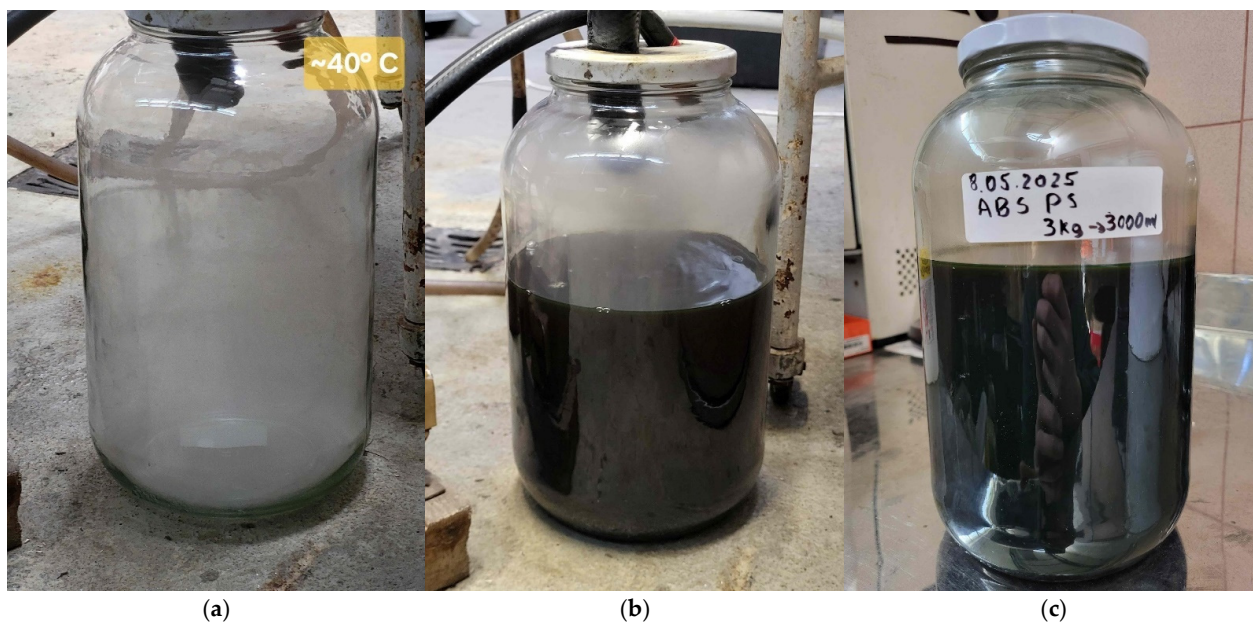


Figure 3. Condensation of the gaseous fraction (a), main fraction with (b) and without condensate (c) in the receiver—PS batch.

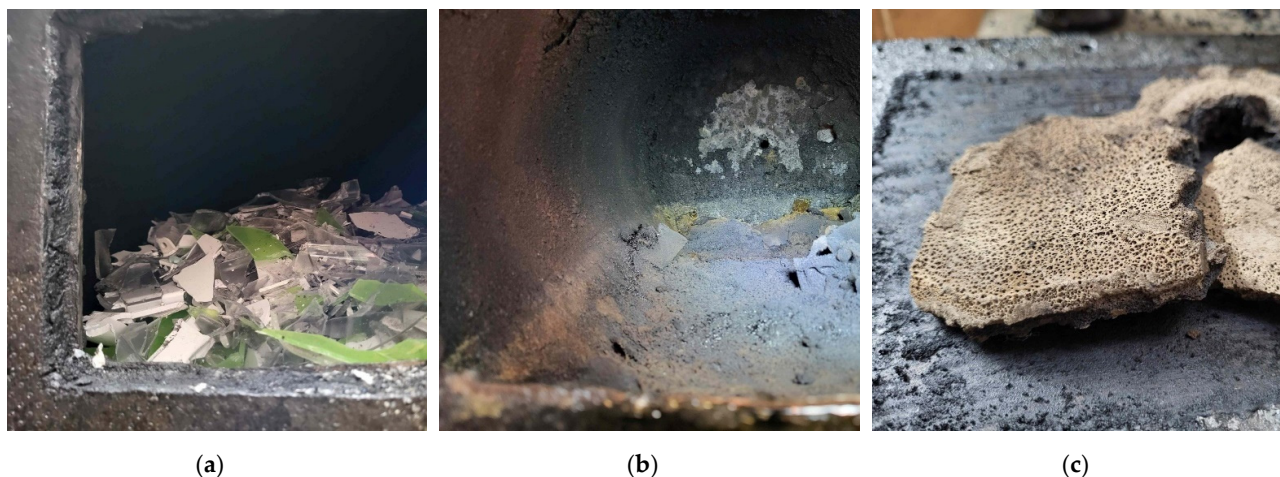


Figure 4. Batch before (a) and after (b,c) the process—PS batch.

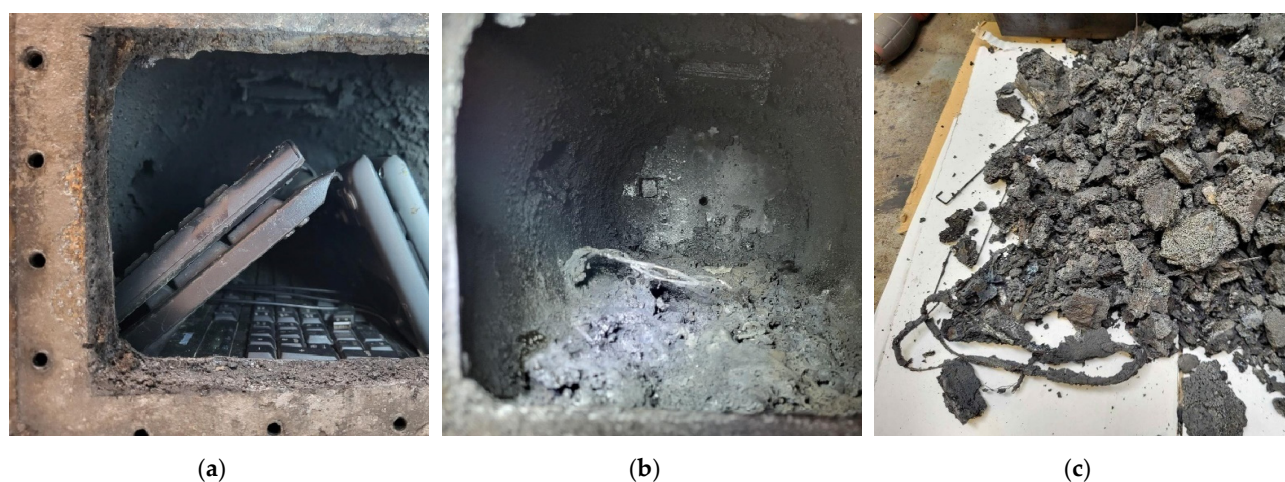


Figure 5. Batch before (a) and after (b,c) the process—keyboards batch.

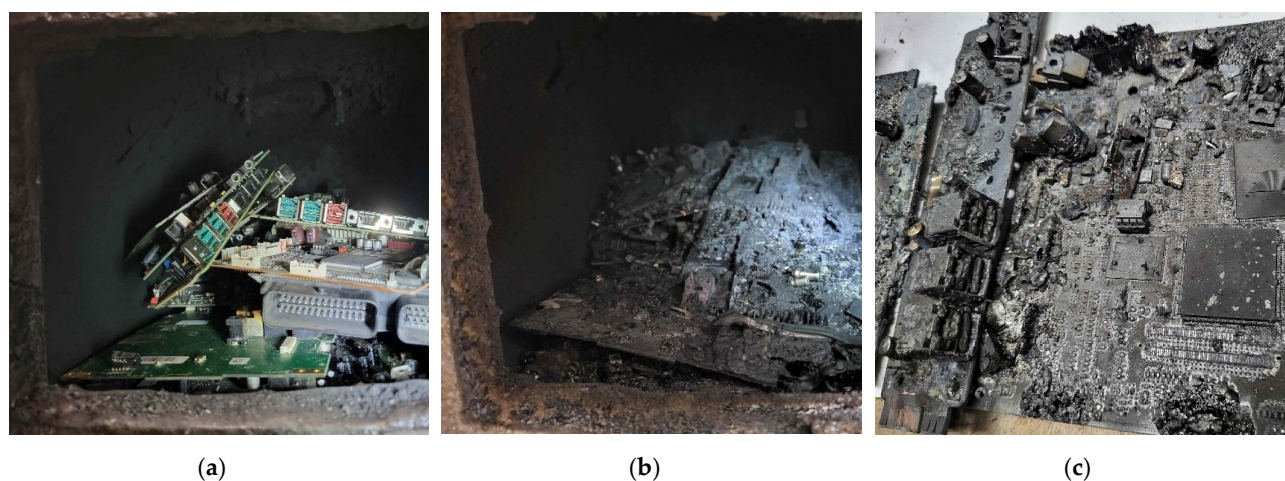


Figure 6. Batch before (a) and after (b,c) the process—PCB batch.

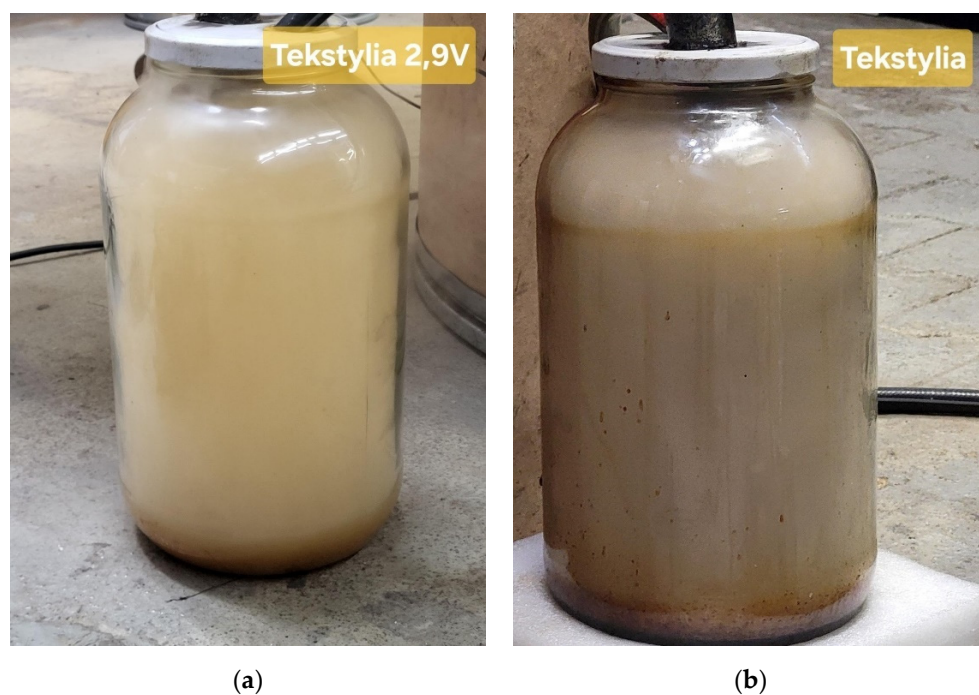


Figure 7. Condensation of the gaseous fraction (a), main fraction with condensate (b)—textile batch.

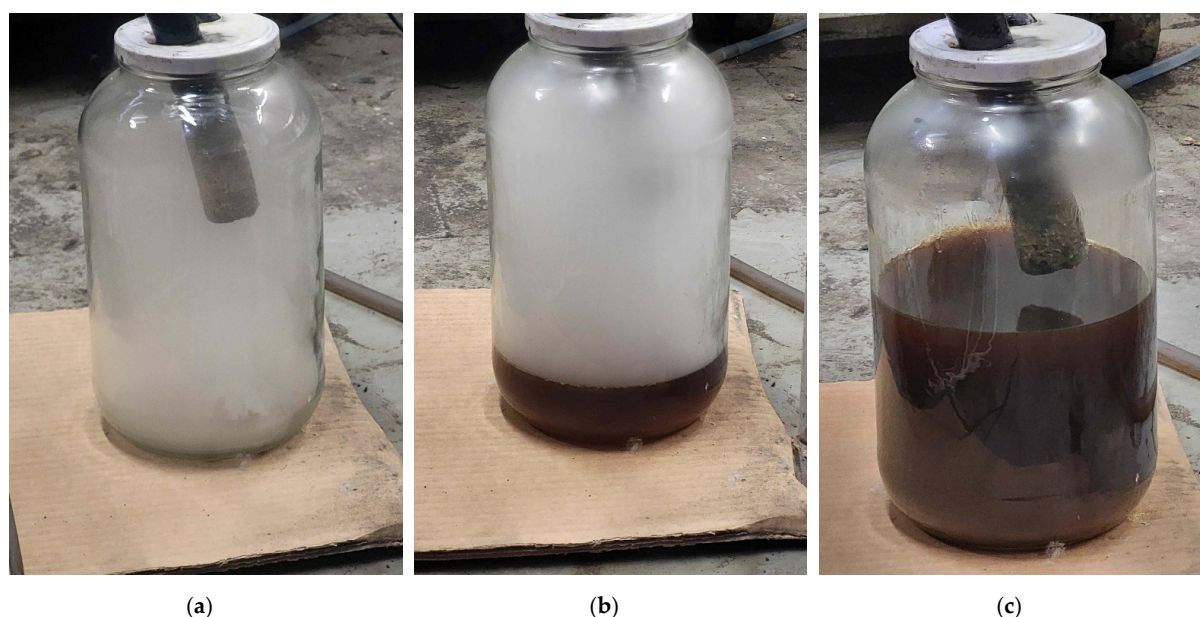


Figure 8. Condensation of the gaseous fraction (a), main fraction with (b) and without condensate (c) in the receiver—ABS drum batch, PP T2O, material ground in a shredder.

The condensed oils displayed noticeable color differences that correlated with chemical composition (Figures 3, 7 and 8). Oils obtained from polypropylene were the lightest, typically yellow to light orange and became darker only after distillation. ABS oils were orange/brown, whereas PS- and electronics-oils were distinctly dark brown, probably reflecting their higher aromatic content. Textile oils showed the greatest variability, ranging from yellow/brown to reddish, and in some cases exhibited slight turbidity, consistent with the presence of oxygenated species.

In all experiments, a solid residue was recovered from the reactor after cooling (Figures 4–6). Although the mass of the residue varied depending on the feedstock, its macroscopic appearance followed clear and reproducible patterns. Residues obtained from polyolefin-rich materials such as PP were typically minimal in quantity and appeared as fine, brittle black particles or thin carbonized films adhering to the reactor walls. Their morphology suggests advanced volatilisation of the PM and a high degree of thermal degradation, consistent with the low aromatic content of the PP oils.

In contrast, materials containing styrene, acrylonitrile, or ABS produced more substantial solid residues. These were generally dark brown to black and exhibited a porous, brittle structure. Such morphology is characteristic of partially carbonized PM matrices in which phenyl-containing segments undergo cross-linking and char formation during high T exposure. ABS-rich feedstocks produced residues with a more heterogeneous texture, often containing glossy fragments indicative of resolidified styrene-acrylonitrile domains mixed with more carbonized butadiene components. These observations align with the stronger aromatic signatures detected in corresponding liquid fractions.

Residues obtained from electronic P (keyboards, AiO) and PCB were more complex. Besides carbonaceous material, they often contained solid inclusions such as fillers, pigments, and inorganic fragments inherent to electronic waste streams. The residues were typically more rigid and irregularly shaped, occasionally showing metallic or mineral sheen. Their presence confirms that MD effectively volatilizes the organic fraction of such materials while leaving behind non-volatile components.

Textile feedstocks yielded residues that differed from both PM and electronic P. These residues were more fibrous, lighter in texture, and sometimes grayish rather than purely black. This appearance is consistent with the partial degradation of PE- or polyamide-based fabrics,

in which depolymerization leads to both volatile oxygenated compounds, as seen in the FTIR spectra, and solid oligomeric fragments that resist full volatilisation under microwave heating.

Overall, the macroscopic form of the residues correlates strongly with PM chemistry. Polyolefins leave minimal residue, styrenic and ABS generate more structured carbonaceous solids, and heterogeneous electronic wastes yield mixed organic and inorganic residues. These trends support the spectroscopic interpretations of the oils and further illustrate how feedstock composition dictates not only the chemical nature of the volatile products but also the physical characteristics of non-condensable by-products.

Table 3 presents a comparative overview of main oil fractions for several feedstocks, focusing on the intensities and relative dominance of aliphatic, aromatic, and oxygenated bands. The table captures subtle differences between materials processed under the same microwave conditions, including the presence of unsaturated =C-H bands, characteristic aromatic fingerprints, and carbonyl contributions. Based on raw data, the yield of the main fraction (liquid fraction), η [mL/kg], was calculated from the respective feedstocks, according to formula:

$$\eta_{mf,X} = \frac{V_{mf,X}}{m_X} \left[\frac{\text{mL}}{\text{kg}} \right] \quad (1)$$

where $V_{mf,X}$ is the volume of the main fraction from feedstock X and m_X is the mass of feedstock X.

The calculated spectral indices (ArI, CI and OHI), derived from the predefined integration windows described in Section 2.3, followed the same qualitative trends as the band-by-band interpretation presented above. PS- and PCB-derived oils exhibited the highest relative aromatic contribution (ArI), whereas PP oils showed the lowest aromaticity and the strongest aliphatic character. Textile-derived oils displayed the highest carbonyl and hydroxyl contributions (CI and OHI), consistent with their pronounced C=O and O-H bands. It should be emphasized that these indices are intended only as semi-quantitative descriptors supporting comparative interpretation; they are not used for absolute compositional determination due to band overlap and ATR-related matrix effects. Regarding the ABS drum batch, PP T2O, material ground in a shredder (Figure 9, Table 4):

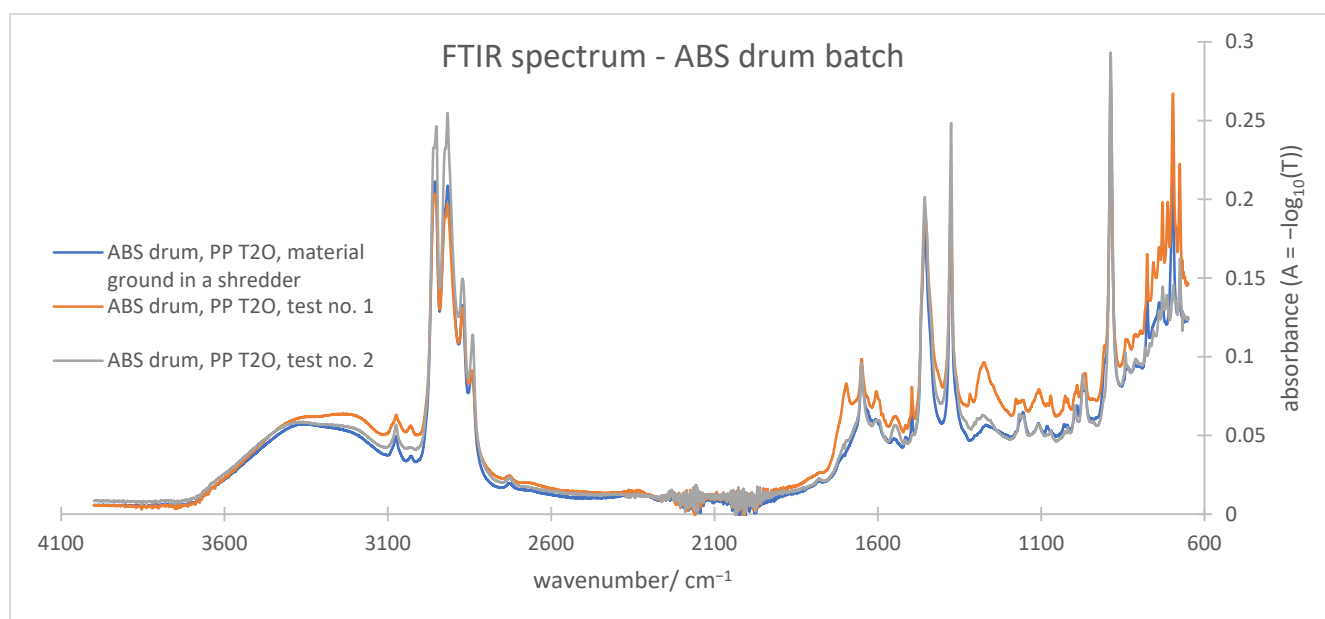


Figure 9. FTIR spectrum for main fraction—ABS drum batch, PP T2O. Source: authors' own measurements.

Table 3. Measured parameters, observations and comments—all MD tests.

Batch Material	No. of Tests	Total Load Quantity	Total Amount of Main Fraction	Process Conditions			Yield of Main Fraction, $\eta_{mf,X}$	Observations and Comments		
		kg, ± 0.001	mL, ± 10 mL	Max. T	Total Du-ration	Duration Reach the Max. T	mL/kg			
				$^{\circ}\text{C}$, ± 1 deg	min					
PS	9	27.000 (3.000 $\times$ 9)	25,250	200	185	ND	935	- after 15 min, gas appeared in condenser - after 25 min, main fraction occurred in condenser		
PP	2	6.000 (3.000 $\times$ 2)	4450	205	190	115	742	- after 15 min, gas appeared in condenser - after 20 min, main fraction occurred in condenser - main fraction is inhomogeneous (different fractions, suspension)		
AiO	1	3.000	2700	210	140	110	900	- after 10 min, gas appeared in condenser - after 25 min, main fraction occurred in condenser - main fraction is partially clear, with suspension		
ABS drum, PP T2O	2	6.000	3420	240	260	170 (70: 150 $^{\circ}\text{C}$)	570	- after 10 min (40 $^{\circ}\text{C}$), gas appeared in condenser - after 195 min, no more gases appear in condenser - after 320 min, no more main fraction occurred in condenser	There was a noticeable amount of carbon residue left in the reactor (greasy, loose and dusty).	two magnetrons, with starting power 675 W for each, gradually (in seven moves) increased in power to 1550 W
ABS drum, PP T2O, material ground in a shredder	1	3.000	2410	215	320	150 (10: 40 $^{\circ}\text{C}$)	803			
ABS “mix”	1	3.000	3450	235	180	ND	1150			
PCB	1	3.000	negligible	200	140	90	-	- after 10 min, gas appeared in condenser - after 30 min, main fraction occurred - after 65 min, no more gases appear in condenser - after 130 min, no more main fraction occurred in condenser	Residual PCB did not completely disintegrate after the process, but it is brittle.	
keyboards	1	4.600 in five charges	4050	185	180	140	880	- after 10 min, gas appeared in condenser - homogenous main fraction, no suspension	Residues are brittle and dust-free.	
textiles no. 1	1	1.000	300	185	300	ND	300	- intense gases in the initial phase of the process, gradual decrease in gas intensity after approx. 2 hr of the process, - unpleasant odor	After opening the loading window and mixing the residue—spontaneous ignition of the solid residue.	
textiles no. 2	1	2.000	negligible	195	210	ND	-	- after 10 min, there was “a blench” from the reactor - after 30 min, gas appeared in condenser - sudden increase in gas intensity in condenser at 50 $^{\circ}\text{C}$	- after the process was completed, it was necessary to clean the reactor outlet and the gas discharge hose because they were clogged - there was a lot of solidified, sticky material in the condenser	

The spectrum is dominated by aliphatic C-H bands (2955–2842 cm^{-1} and 1456/1377 cm^{-1}), consistent with a material with a high proportion of hydrocarbon chains (typical of hydrocarbon oil matrices) [40]. There is no clearly visible strong C=O ester band around ~ 1743 cm^{-1} . In this region, only a weak, broad maximum is visible around ~ 1735 – 1700 cm^{-1} , which is more consistent with [41]:

- a low content of carbonyl groups (e.g., oxidation products);
- contribution of additives (e.g., dispersants) in the formulated oils.

The ~ 3075 , ~ 1649 bands and the strong bands at $900\text{--}690\text{ cm}^{-1}$ indicate an unsaturated and/or aromatic component; positions at $900\text{--}690\text{ cm}^{-1}$ are classically attributed to OOP (out-of-plane) C-H deformations in aromatics, and the pattern around ~ 750 and $\sim 700\text{ cm}^{-1}$ is sometimes associated with a monosubstituted ring [42]. The broad band at $\sim 3358\text{ cm}^{-1}$ suggests trace O-H groups (moisture, alcohols, hydroperoxides/oxidation products). In pure hydrocarbon oils, the O-H signal is usually weak; its presence should be considered an indicator of contamination or oxidation or contact with polar material [41].

Table 4. FTIR spectrum interpretation—ABS drum batch, PP T2O, material ground in a shredder (based on [40–45]).

Position (cm^{-1})	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
~ 3358	medium, wide	O-H stretching (water/alcohols/hydroperoxides)	A wide band suggests a polar component or trace moisture/oxidation products; may be weak in pure hydrocarbon oils.
2955, 2916, 2871, 2842	from medium to very strong	C-H stretching: CH_3/CH_2 (aliphatic chains)	aliphatic fraction (long chains) typical of many mineral oils
~ 1649	medium	C=C stretching (alkenes/aromatics) or H-O-H bend (when water)	In the oil matrix, more often associated with unsaturation/aromaticity than with water (if no other strong water bands are present).
1456, 1377	strong	CH_2 scissoring (~ 1465), CH_3 bending (~ 1375)	very typical for aliphatic mixtures
~ 972	medium	=C-H OOP vibrations (alkenes)/oxidation components reported in references	The literature on engine oils indicates the usefulness of around 970 cm^{-1} in the context of changes during oxidation (depending on the system).
887, 775, 728, 697, 676	from medium to very strong	aromatic C-H OOP ($900\text{--}690\text{ cm}^{-1}$); for monosubstitution typically strong bands ~ 750 and ~ 700	The band pattern in the $900\text{--}690\text{ cm}^{-1}$ region is diagnostic for aromatics and substitution type; visible strong components at ~ 697 and ~ 775 (and others) support aromatic contribution.

Regarding ABS drum batch, PP T2O, test no. 1 (Figure 9, Table 5):

The spectrum is dominated by aliphatic C-H bands ($2956/2924/2871/2842$ and $1455/1377\text{ cm}^{-1}$), consistent with a sample with a high proportion of hydrocarbon chains (typical of many oils) [40]. The presence of bands ~ 3074 , $\sim 1605/1495$, and a strong system $900\text{--}690\text{ cm}^{-1}$ indicates an aromatic and/or unsaturated contribution [42]. Compared to the ABS drum batch, PP T2O sample, ABS drum, PP T2O shows a more pronounced band near $\sim 1700\text{ cm}^{-1}$ and a broader O-H shifted to lower wavenumbers ($\sim 3237\text{ cm}^{-1}$). This can be cautiously considered as an indication of a higher proportion of polar components/oxidation products.

Table 5. FTIR spectrum interpretation—ABS drum batch, PP T2O, test no. 1 (based on [40,42]).

Position (cm^{-1})	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
~ 3237 (wide)	medium	O-H stretching (water/water/alcohols/hydroperoxides)	Broad and shifted towards lower wavenumbers O-H is sometimes associated with a stronger hydrogen bond (e.g., oxidation products).
~ 3074	medium	=C-H stretching (alkenes/aromatics)	confirms an unsaturated (or aromatic) bond
2956	very strong	$\nu(\text{C-H})\text{ CH}_3$ (asym.)	dominance of the aliphatic fraction
2924 and ~ 2917	strong	$\nu(\text{C-H})\text{ CH}_2$ (asym., maximum $\sim 2922\text{--}2925$)	typical of long hydrocarbon chains
2871	strong	$\nu(\text{C-H})\text{ CH}_3$ (sym.)	typical for aliphatic mixtures
2842	medium	$\nu(\text{C-H})\text{ CH}_2$ (sym., ~ 2850)	confirmation of long chains
~ 1697	medium	weak C=O (oxidation) or contribution of ring bands/conjugated systems	In operating oils, the carbonyl region is diagnostic; absorption is visible near 1700 cm^{-1} , which may indicate possible oxidation products.

Table 5. Cont.

Position (cm ⁻¹)	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
~1649	medium	C=C stretching (alkenes/aromatics)	unsaturated (or aromatic) bond
~1605 and ~1495	medium	aromatic ring vibrations (C=C)/deformations	aromatic bonding
1455	strong	$\delta(\text{CH}_2)$ scissoring (~1465)	classic aliphatic band
1377	strong	$\delta(\text{CH}_3)$ bending (~1375)	
1276	medium	fingerprint area: C-C/C-O, possible addition of additives	Formulated oils may contain additives or aging products.
1177, 1107, 1071, 1026	weak/medium	fingerprint (C-C/C-O; complex vibrations)	
990–965	medium	vibrations related to unsaturation (=C-H)/“oil” components	According to the literature, changes in this area may accompany aging (contextual interpretation).
887.5	very strong	C-H OOP (alkenes/aromatics)	The strong band in the 900–690 cm ⁻¹ region is typical for aromatics; details of the pattern confirm the presence of a ring.
775.8; 728.8; 712.8; 696.8; 676	strong/very strong	C-H OOP (aromatics) and rocking CH ₂ (~722–730)	The pattern of 900–690 cm ⁻¹ is diagnostic for aromatics; at the same time ~722–730 cm ⁻¹ is characteristic for long chains (CH ₂ rocking).

Regarding ABS drum batch, PP T2O, test no. 2 (Figure 9, Table 6):

Table 6. FTIR spectrum interpretation—ABS drum batch, PP T2O, test no. 2 (based on [40–42,45]).

Position (cm ⁻¹)	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
2953; 2917	very strong	$\nu(\text{C-H})$ CH ₃ /CH ₂ (asym.)	strong aliphatic component (typical of a carbon-hydrogen matrix)
2871	strong	$\nu(\text{C-H})$ CH ₃ /CH ₂ (sym.)	confirms the presence of -CH ₂ -/-CH ₃ fragments.
2843	medium	$\nu(\text{C-H})$ (sym., mainly CH ₂)	band consistent with the presence of aliphatic chains.
1650	medium	C=C (alkenes/conjugated systems; general)	unsaturation/conjugated band; no specific compound identified
1601	medium	aromatic ring vibrations (ring modes)	supports the aromatic contribution in the spectrum.
1456; 1444	strong	$\delta(\text{CH}_2)/\delta(\text{CH}_3)$ (C-H deformations)	characteristic hydrocarbon bands; possible overlap
1424	medium	C-H deformations (general; mixtures)	auxiliary band, nonspecific
1376	very strong	$\delta(\text{CH}_3)$ bending (~1375)	clear contribution of methyl groups
1295; 1267; 1230	medium/weak	fingerprint area (complex vibrations; general assignments)	stripes in the fingerprint area; general interpretation
1171; 1168	weak/medium		
998	medium		
972	medium		
902	medium	C-H OOP (aromatics/alkenes; general)	supports unsaturated/aromatic input.
888	very strong		very clear band in the OOP area
842; 836; 817; 812	medium	aromatic C-H OOP (substitution dependent)	a set of bands supporting an aromatic interpretation
782; 766; 756; 739	medium	aromatic C-H OOP	in the aroma diagnostic area
728; 715	strong	CH ₂ rocking (~720–730) and/or layering with aromatic OOP	typical range for longer -CH ₂ - sequences; overlapping bands possible
695; 693	strong	aromatic C-H OOP	strong aromatic contribution in the 900–650 cm ⁻¹ region
675; 674	strong		additional intense bands in the aromatic area
667	medium		accompanying band in the diagnostic area

The spectrum of the ABS drum, PP T2O, test no. 2 indicates a strong aliphatic component (very strong $\nu(\text{C-H})$ in the range $\sim 2953\text{--}2917\text{ cm}^{-1}$ and strong deformations ~ 1456 and very strong $\sim 1376\text{ cm}^{-1}$) [40]. At the same time, features of unsaturation and/or aromatic contribution are present: a band at $\sim 3067\text{ cm}^{-1}$, ring modes (~ 1601 , ~ 1516 , $\sim 1493\text{ cm}^{-1}$) and a distinct C-H OOP region ($900\text{--}650\text{ cm}^{-1}$) with a very strong maximum at $\sim 888\text{ cm}^{-1}$ and strong bands around $\sim 695\text{--}667\text{ cm}^{-1}$ [42]. In the carbonyl region ($\sim 1733\text{--}1678\text{ cm}^{-1}$), there is absorption of weak intensity; without a reference sample of the same formulation, no conclusions about oxidation processes can be drawn based on C=O alone.

Regarding ABS “mix” batch (Figure 10, Table 7):

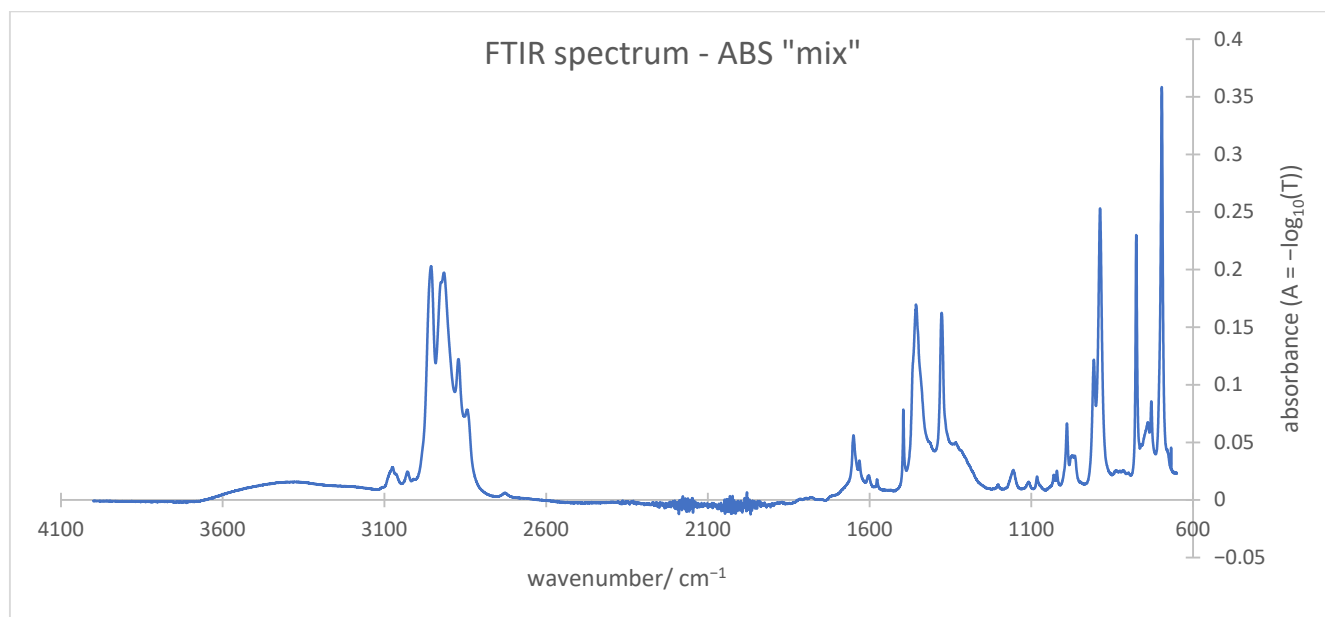


Figure 10. FTIR spectrum for main fraction—ABS “mix” batch. Source: authors’ own measurements.

Table 7. FTIR spectrum interpretation—ABS “mix” batch (based on [41–45]).

Position (cm^{-1})	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
2956, 2916, ~ 2871 , ~ 2844	very strong/strong	C-H stretching CH_3/CH_2	aliphatic fraction (hydrocarbon chains), typical of oils
$\sim 1649\text{--}1650$	medium	C=C stretching (alkenes/aromatics)	In hydrocarbon oils, they are often associated with an unsaturated/aromatic bond (no strong C=O).
~ 1495	medium	aromatic ring vibrations/C-H deformations	confirms the presence of an aromatic ingredient
1456, 1377	strong	$\delta(\text{CH}_2)$ scissoring; $\delta(\text{CH}_3)$ bending	typical “oil” (aliphatic) bands
~ 990 and $\sim 973\text{--}965$	medium/weak	vibrations related to non-saturation ($=\text{C-H}$) / “fingerprint”	auxiliary region; interpretation dependent on matrix and additives
~ 906 and 887	strong/very strong	aromatic C-H OOP ($900\text{--}650$)	very clear aromatic signal in the diagnostic region $900\text{--}650\text{ cm}^{-1}$
775 and ~ 697 (and $\sim 729/740$)	very strong/medium	aromatic C-H OOP; $\sim 722\text{--}730$ also CH_2 rocking	The arrangement of $\sim 690\text{--}710$ and $\sim 730\text{--}770\text{ cm}^{-1}$ is often observed for an aromatic ring (often also in the context of monosubstitution), and $\sim 722\text{--}730\text{ cm}^{-1}$ is typical for long CH_2 chains (rocking).

In ABS “mix,” the dominant C=O ester band at $\sim 1743\text{ cm}^{-1}$, which is characteristic of many esters (it is usually strong in such oils), is not observed [40]. The spectrum is, however, strongly “hydrocarbonic”: aliphatic C-H has a distinct aromatic contribution ($900\text{--}650\text{ cm}^{-1}$). Such features are consistent with a hydrocarbon matrix (e.g., mineral oil/formulation with an aromatic component), but the exact class should not be determined

based on FTIR alone without a reference sample. The sample is dominated by aliphatic bands (2956/2916/2871/2844 and 1456/1377 cm^{-1}), typical of hydrocarbon/oil mixtures. Very strong bands in the region $\sim 900\text{--}650\text{ cm}^{-1}$ (especially ~ 887 , ~ 775 and $\sim 697\text{ cm}^{-1}$) indicate a significant contribution of aromatic structures (OOP C-H vibrations) [45]. The lack of a strong C=O band $\sim 1743\text{ cm}^{-1}$ suggests that this is a service oil, the carbonyl “oxidation” signal is not dominant (requires comparison with a standard).

ABS materials produced oils with a mixed aliphatic–aromatic character. In both ABS drum PP T2O and ABS mix batches, strong aliphatic stretching bands were accompanied by an extensive system of aromatic OOP bands between 900 and 690 cm^{-1} , including characteristic maxima around 775 cm^{-1} and 697 cm^{-1} . Compared with other feedstocks, ABS oils often contained a broader O-H envelope (3200–3400 cm^{-1}) and low-intensity carbonyl bands near 1700 cm^{-1} , which may indicate minor oxidation or the presence of polar additives found in ABS formulations. The mixed aromatic/aliphatic character is consistent with the expected behavior of styrenic blends such as ABS or related materials containing both aromatic and aliphatic domains. Nevertheless, FTIR does not uniquely resolve the specific blend composition or the relative contribution of individual copolymer segments.

Regarding PCB batch (Figure 11, Table 8):

The spectrum indicates a hydrocarbon matrix with C-H bands (ca. 2960–2870 cm^{-1}), but at the same time, very strong aromatic bands (ca. 1595/1500 and a distinct 812/752/691 cm^{-1} pattern) suggest a significant contribution of an aromatic component in the sample [42]. The presence of absorption near $\sim 1702\text{ cm}^{-1}$ (carbonyl region) may indicate compounds with a C=O group, which is often associated with oxidation products in operating oils [41]. The broad $\sim 3327\text{ cm}^{-1}$ (O-H) band strengthens the hypothesis of the presence of polar components (moisture/oxidation products), but does not in itself determine the cause.

Table 8. FTIR spectrum interpretation—PCB batch (based on [41–45]).

Position (cm^{-1})	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
~ 3327	medium, wide	O-H stretching (water/water/ alcohols/hydroperoxides)	Presence of polar components or oxidation products; broad band, consistent with hydrogen bonding.
~ 2961 ; ~ 2957	medium	$\nu(\text{C-H})\text{ CH}_3/\text{CH}_2$ (asym.)	Aliphatic bands typical of a hydrocarbon matrix; here less dominant than aromatic ones $900\text{--}650\text{ cm}^{-1}$.
~ 2871	medium	$\nu(\text{C-H})\text{ CH}_3$ (sym.)	Typical aliphatic band; supports the aliphatic fraction.
~ 1702	medium	C=O (carbonyl region: ketones/ acids/ aldehydes/ esters)	in operating oils, the $1800\text{--}1650\text{ cm}^{-1}$ region is sometimes diagnostic for oxidation; the presence of the band may indicate carbonyl compounds.
~ 1595	strong	C=C aromatic ring	aromatic ring
~ 1500	strong	C=C/ aromatic ring vibrations	Confirms the presence of an aromatic ingredient.
~ 1473	medium	$\delta(\text{CH}_2)/\delta(\text{CH}_3)$ (C-H deformations) + possible aromatic overlap	Region susceptible to superposition; general interpretation (aliphatic deformations).
~ 1365	medium	$\delta(\text{CH}_3)$ bending (~ 1375)	typical for the aliphatic fraction
~ 1168	weak/medium	fingerprint: C-C/C-O (additives/aging products may also contribute)	The attribution remains cautious; possible contribution of additives or degradation products.
~ 1071	weak/medium	fingerprint: C-C/C-O	
~ 885	medium/strong	C-H OOP (aromats/ alkenes)	confirmation of the presence of aromas
~ 812	strong	aromatic C-H OOP (substitution type)	The $900\text{--}690\text{ cm}^{-1}$ region is diagnostic of aromas; a strong band supports the aromatic contribution.
~ 752	strong	aromatic C-H OOP	The band pattern at $900\text{--}690\text{ cm}^{-1}$ suggests a significant contribution of aromatic structures.
~ 722	weak/medium	CH_2 rocking (long sequences $-\text{CH}_2-$)	Possible contribution of long chains; in this sample the $900\text{--}650\text{ cm}^{-1}$ region is dominated by aromatics, so assignment requires caution.
~ 691	strong	aromatic C-H OOP	strong aromatic bond in the diagnostic area

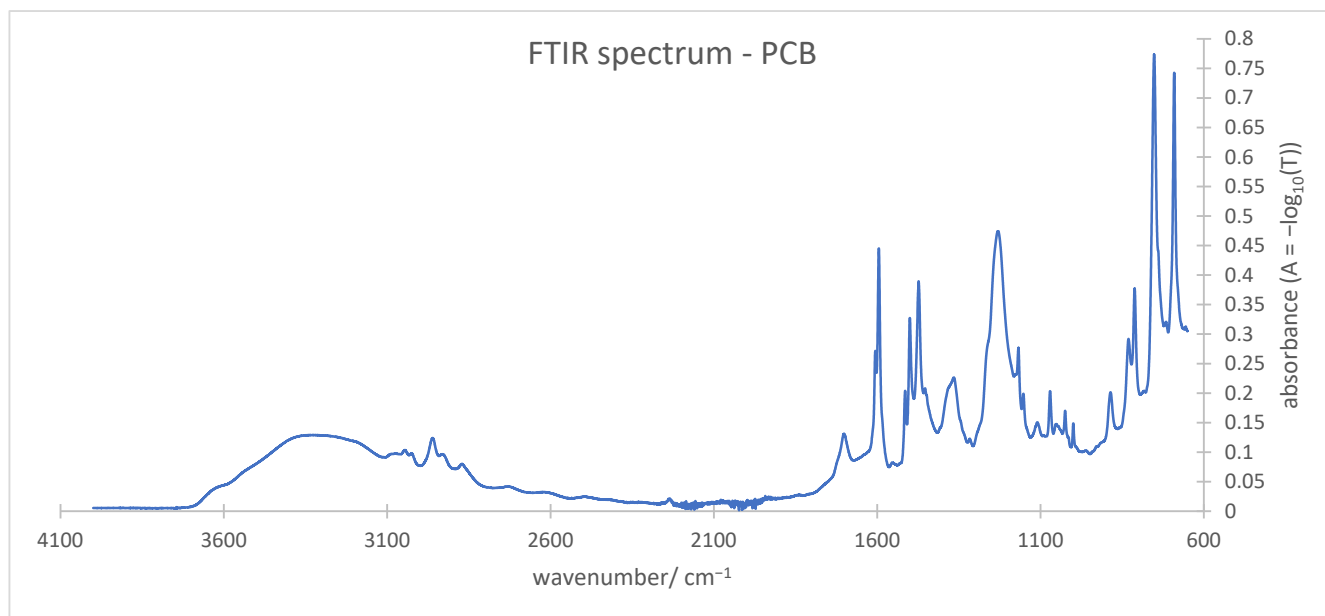


Figure 11. FTIR spectrum for main fraction—PCB batch. Source: authors' own measurements.

PCB oil displayed a prominent aromatic/unsaturated contribution, consistent with an aromatic-rich oil fraction typical of resin-containing feedstocks. Given the complex composition of PCB materials, contributions from resinous and flame-retarded components are plausible; however, FTIR does not enable unambiguous identification of specific resin systems or brominated species. Elemental/halogen analysis and GC-MS would be required for confirmation. The FTIR spectrum showed strong aromatic C-H OOP bands (900–650 cm^{-1}), supported by aliphatic stretching modes. The absence of strong carbonyl bands suggests limited oxidation despite the heterogeneous and flame-retarded nature of PCBs.

Regarding keyboards batch (Figure 12, Table 9):

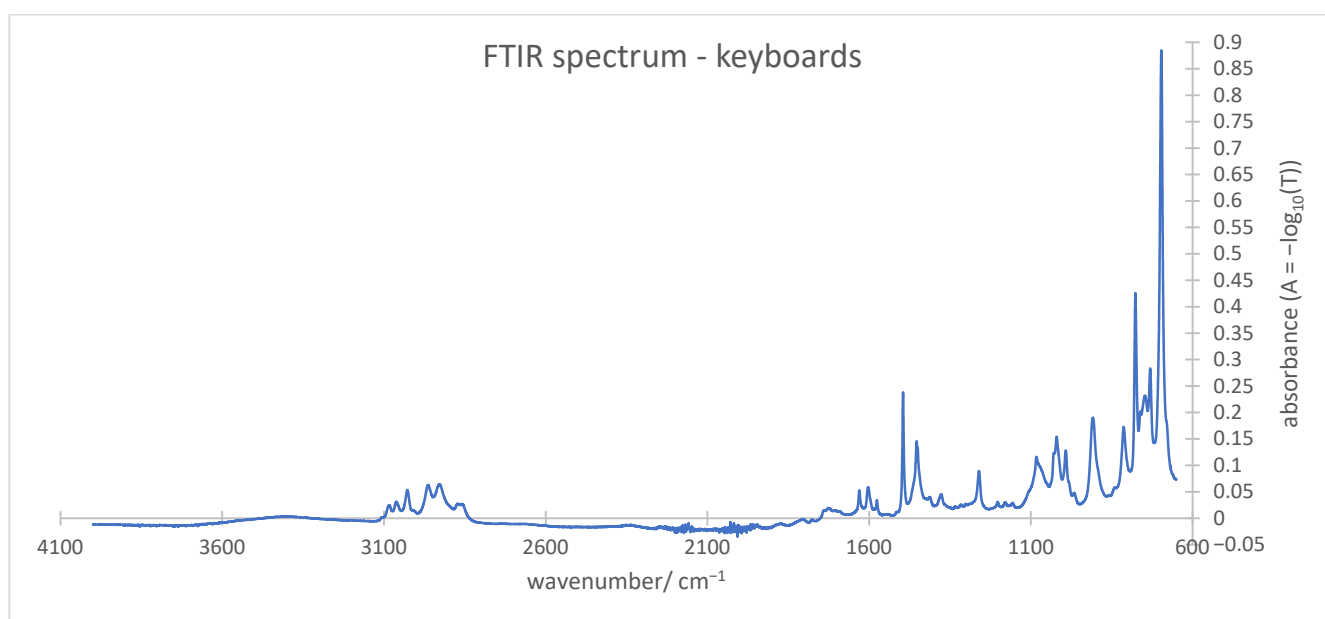


Figure 12. FTIR spectrum for main fraction—keyboard batch. Source: authors' own measurements.

The spectrum clearly indicates a significant contribution of the aromatic component: strong ring bands (ca. 1495 cm^{-1}) and a very strong system in the 900–650 cm^{-1}

region (especially $\sim 696\text{--}697\text{ cm}^{-1}$) [45]. An aliphatic bond (C-H at $2960\text{--}2850\text{ cm}^{-1}$ and $1456/1377\text{ cm}^{-1}$) is present, but not dominant as in typical “paraffin” oils [40]. The carbonyl region ($\sim 1740\text{--}1700\text{ cm}^{-1}$) is very weak, and the O-H band at $3600\text{--}3200\text{ cm}^{-1}$ is not prominent among the main spectral features; this does not support the thesis of strong oxidation or the presence of a large amount of esters; however, the evaluation of the oxidation trend requires comparison to the spectrum of a fresh reference sample of the same formulation [41].

Table 9. FTIR spectrum interpretation—keyboards batch (based on [41,45]).

Position (cm^{-1})	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
~ 1495	strong	C=C aromatic ring/aromatic vibrations	indicates a pronounced aromatic bond
~ 1456	medium	$\delta(\text{CH}_2)$ scissoring (approx. 1465) + possible aromatic overlay	typical of hydrocarbons; in oils often one of the main deformation bands
~ 1020	medium	fingerprint (C-C/C-O; complex vibrations)	“crowded” scope; only general assignment
~ 908 and ~ 813	medium	aromatic C-H OOP ($900\text{--}690$)	supports aromatic interpretation (diagnostic region for aromas)
~ 776 , ~ 746 , ~ 731	strong	aromatic C-H OOP	The band arrangement is typical for aromatics; it depends on the type of substitution (should not be assigned to a specific compound).
~ 722	medium	CH_2 rocking (long $-\text{CH}_2-$ sequences) and/or overlapping in the aromatic region	The $900\text{--}650\text{ cm}^{-1}$ region is very aromatically intense, so the contribution of “pure” CH_2 rocking should be treated with caution.
$\sim 696\text{--}697$	very strong	aromatic C-H OOP ($900\text{--}690$)	dominant spectral band; strong signal from aromatic bond
~ 676	medium	aromatic C-H OOP	additional aromatic component in the diagnostic area

Regarding AiO batch (Figure 13, Table 10):

The spectrum clearly indicates a significant contribution of the aromatic component: strong ring bands (e.g., 1596 , 1495 cm^{-1}) and a very strong system at $900\text{--}650\text{ cm}^{-1}$ (especially 697 and 691 cm^{-1}). An aliphatic bond (C-H at $2962/2929\text{ cm}^{-1}$ and deformations around $1452/1363\text{ cm}^{-1}$) is present, but does not dominate as clearly as in typical paraffin samples [45]. The carbonyl region ($\sim 1700\text{--}1650\text{ cm}^{-1}$) is very weak, and the O-H band (3385 cm^{-1}) is weak; this does not suggest strong oxidation in the sense of a clear increase in C=O [41].

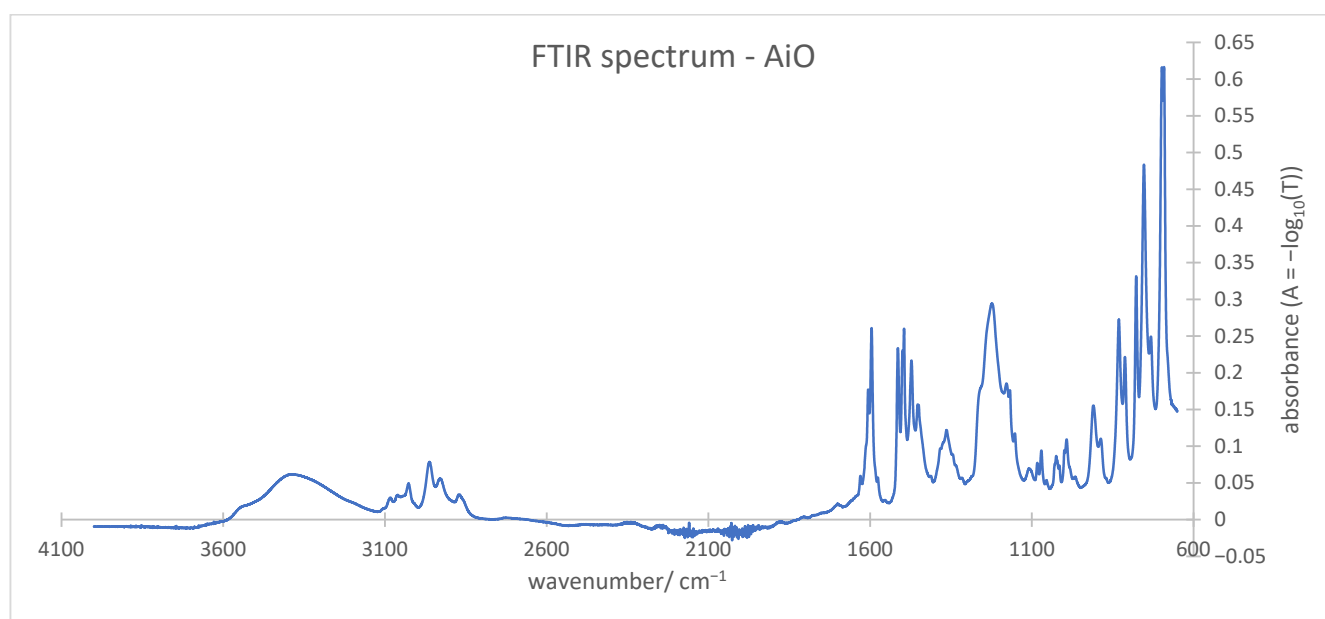


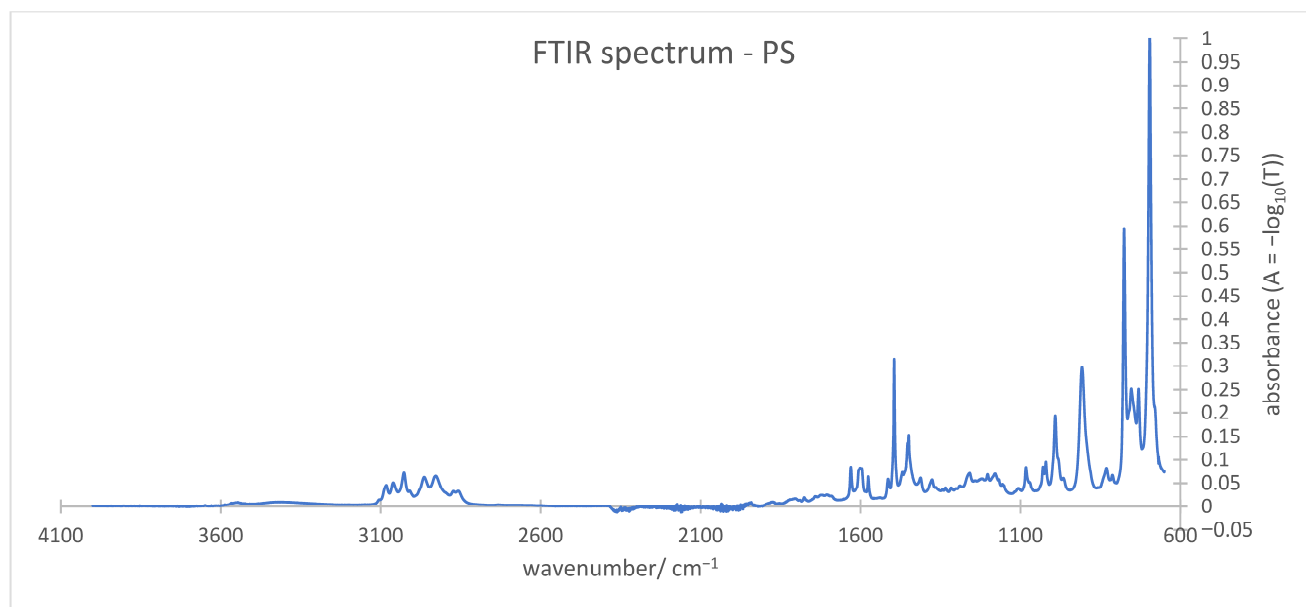
Figure 13. FTIR spectrum for main fraction—AiO batch. Source: authors’ own measurements.

Table 10. FTIR spectrum interpretation—AiO batch (based on [41,45]).

Position (cm ⁻¹)	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
1596	strong	C=C aromatic ring (ring stretching)	clear aromatic signal
1514, 1495	medium/strong	aromatic ring vibrations	confirms the presence of aromatic structures (a set of aromatic bands is often observed in this area)
1452	medium	$\delta(\text{CH}_2)/\delta(\text{CH}_3)$ + possible aromatic overlap	typical hydrocarbon deformation band; region prone to overlay
1363	medium	$\delta(\text{CH}_3)$ bending (around ~1375)	confirms the presence of methyl groups
1223	strong	fingerprint (C-C/C-O; complex vibrations)	“crowded” scope; possible contribution of base/additives/aging products
1178, 1071, 998	medium/weak	fingerprint (C-C/C-O)	
909, 887	medium	aromatic C-H OOP (900–690)	enhances the identification of the presence of aromas
831, 812	strong/medium	aromatic C-H OOP (substitution type)	diagnostic part for aromatics (substitution-dependent pattern; do not assign to a specific compound)
777, 753, 732	strong/very strong	aromatic C-H OOP	very clear aromatic “signature” in the 900–650 cm ⁻¹ region
697, 691	very strong		dominant spectral bands; typical of aromatic structures
676	medium		additional aromatic bond in the diagnostic area

Oils from keyboard housings and AiO showed strong aromatic contributions similar to PS oils but combined with a more evident aliphatic baseline. Spectra displayed ring-stretching bands at 1596–1495 cm⁻¹, overlaid onto typical C-H aliphatic patterns. The region 900–650 cm⁻¹ was strongly aromatic, with several intense peaks around 697 cm⁻¹, 731 cm⁻¹, and 776 cm⁻¹. The combination of aromatic and aliphatic signatures aligns with the known PM composition of such components, which include styrene-based PM, polycarbonate blends, and ABS formulations.

Regarding the PS batch (Figure 14, Table 11):

**Figure 14.** FTIR spectrum for main fraction—PS batch. Source: authors’ own measurements.

The spectrum of the PS batch sample is dominated by aromatic signals, especially in the region 900–650 cm⁻¹ (the strongest band is around 696 cm⁻¹, strong around 776 cm⁻¹). Such bands are typical of OOP C-H vibrations in aromatic structures. An aliphatic bond

(C-H bands at $2960\text{--}2850\text{ cm}^{-1}$ and deformations around $1450/1376\text{ cm}^{-1}$) is present, but in this sample it has a smaller spectral contribution than the aromatic part [45]. The carbonyl region ($\sim 1705\text{ cm}^{-1}$) is very weak, and the O-H band ($\sim 3403\text{ cm}^{-1}$) is trace; on this basis, there is no evidence to support the conclusion that it is “strongly oxidized” [41].

Table 11. FTIR spectrum interpretation—PS batch (based on [40–42,45]).

Position (cm^{-1})	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
~ 1495	medium	aromatic ring vibrations	one of the typical aromatic bands
~ 908	medium	aromatic C-H OOP ($900\text{--}690$)	stronger aromatic signal in the diagnostic area
~ 776	strong	aromatic C-H OOP	one of the main aromatic bands in the region $900\text{--}690\text{ cm}^{-1}$
~ 754 ; ~ 731 ; ~ 728	medium	aromatic C-H OOP and possible overlap with CH_2 rocking $\sim 722\text{--}730$	The region may contain both an aromatic contribution and a contribution of long $-\text{CH}_2-$ sequences (contextual interpretation).
~ 696	very strong	aromatic C-H OOP ($900\text{--}690$)	dominant spectrum band; very clear aromatic “signature”
~ 682	medium	aromatic C-H OOP	an additional component in the diagnostic area of aromas

The polystyrene batch exhibited the clearest aromatic signature. The main oil fraction was dominated by a strong and highly structured system of OOP aromatic C-H vibrations in the $900\text{--}650\text{ cm}^{-1}$ region, with the most intense band at $\sim 696\text{ cm}^{-1}$. Aromatic ring-stretching bands near 1495 cm^{-1} further supported this interpretation. These features are consistent with the well-known aromatic character of PS-derived oils and with the formation of styrenic/aromatic species typically reported in PS depolymerization. However, FTIR alone does not allow direct identification of styrene or specific oligomers, confirmation would require GC-MS analysis. The relatively small contribution of aliphatic C-H stretching in this sample suggests that secondary cracking into lighter aliphatic hydrocarbons was limited, which is consistent with the high aromatic content expected from styrene-rich oils.

Regarding the PP batch (Figure 15, Table 12):

Table 12. FTIR spectrum interpretation—PP batch (based on [40,42,45]).

Position (cm^{-1})	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
2956	very strong	$\nu(\text{C-H})\text{ CH}_3/\text{CH}_2$ (asym.)	strong aliphatic component typical of a hydrocarbon/oil matrix
2925	very strong	$\nu(\text{C-H})\text{ CH}_2$ (asym., $\sim 2922\text{--}2925$)	confirms the presence of numerous $-\text{CH}_2-$ groups (aliphatic chains)
2872	strong	$\nu(\text{C-H})\text{ CH}_3$ (sym.)	typical aliphatic band in oils
2855	medium	$\nu(\text{C-H})\text{ CH}_2$ (sym., ~ 2850)	supports the presence of long methylene sequences
1456	strong	$\delta(\text{CH}_2)$ scissoring (~ 1465)	one of the key deformation bands of the aliphatic fraction
1377	strong	$\delta(\text{CH}_3)$ bending (~ 1375)	confirms the presence of methyl groups in the oil matrix
1109; 1077; 1021; 991	very weak/weak	fingerprint (C-C/C-O)	“crowded” scope; without formulation information, only general assignment
908	medium	aromatic/alkenyl C-H OOP	The $900\text{--}690\text{ cm}^{-1}$ region is diagnostic for aromas (OOP).
888	very strong	C-H OOP (aromatics/alkenes)	strong contribution of aromatic structures/unsaturated systems in the diagnostic area
776; 746; 740	medium	aromatic C-H OOP	a set of OOP strands typical of aromatic structures
728	strong	CH_2 rocking ($\sim 720\text{--}730$) and/or layering with OOP aromatics	In oils, the $\sim 722\text{--}730\text{ cm}^{-1}$ band is sometimes attributed to “ CH_2 rocking” of long chains; here overlap with aromatic bands of the same area is possible.
698	very strong	aromatic C-H OOP	one of the dominant signals of the aromatic region $900\text{--}690\text{ cm}^{-1}$
676	medium		additional aromatic component in the diagnostic area

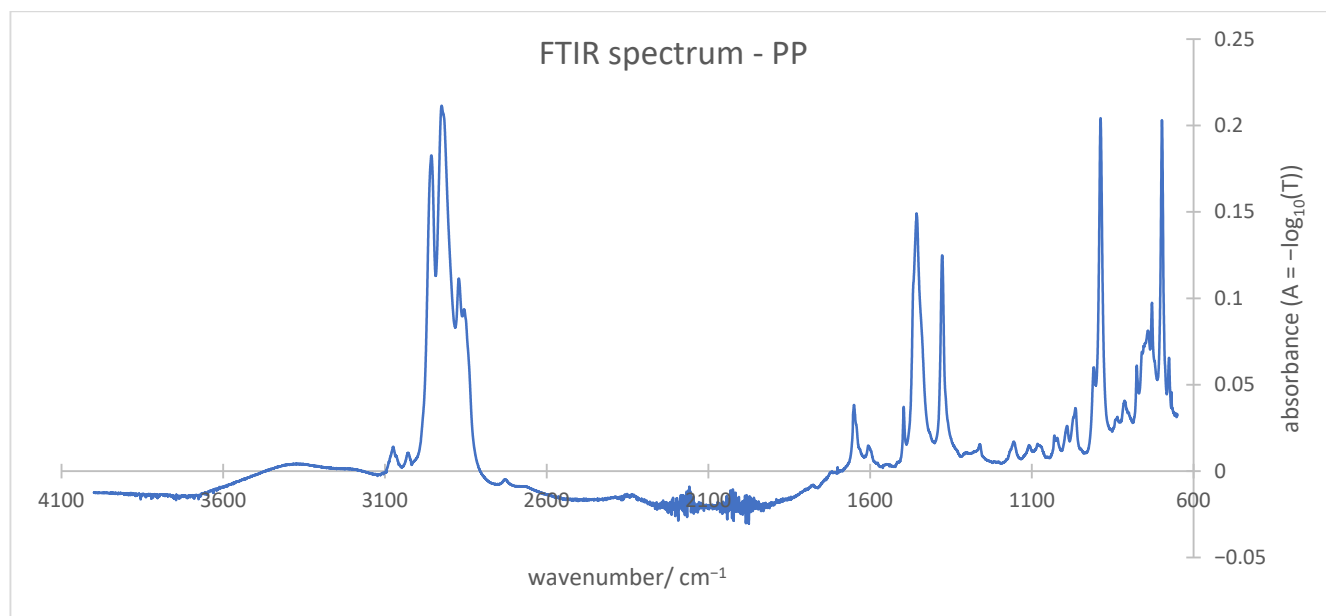


Figure 15. FTIR spectrum for main fraction—PP batch. Source: authors' own measurements.

The spectrum of the sample obtained from PP indicates a hydrocarbon matrix with a significant aliphatic fraction (very strong C-H stretching: 2956 and 2925 cm⁻¹, and deformations at 1456 and 1377 cm⁻¹) [45]. At the same time, very strong OOP bands occur in the 900–650 cm⁻¹ region (including 888 and 698 cm⁻¹), which supports the conclusion of a noticeable contribution of aromatic/unsaturated structures [42]. The carbonyl region (~1800–1650 cm⁻¹) does not show a strong maximum around ~1700 cm⁻¹; consequently, there is no basis for speaking of a “significant increase in C=O” (oxidation) based on FTIR alone.

The PP batch produced an oil dominated by aliphatic chains, as expected from the structure of PP. Strong asymmetric and symmetric C-H stretching bands at 2956, 2925, 2872, and 2855 cm⁻¹ were observed. Nevertheless, the PP oil also exhibited pronounced aromatic/unsaturated signatures, most notably intense bands at ~888 cm⁻¹ and ~698 cm⁻¹, consistent with the presence of unsaturated and/or aromatic structures in the product mixture. Such signals suggest the presence of unsaturated and/or aromatic structures in addition to the dominant aliphatic matrix expected from PP. The origin of these aromatic features (e.g., secondary aromatization versus contributions from additives or secondary reactions) cannot be resolved by FTIR alone and would require complementary molecular analysis.

Regarding textile batch, test no. 1 (Figure 16, Table 13):

Although the total volume of the main fraction was negligible, it was still sufficient to record FTIR spectra for qualitative assessment. Textile test no. 1 sample shows a clear presence of C=O carbonyl groups (strong bands around ~1703–1695 cm⁻¹, with an additional band around ~1733 cm⁻¹). In performance oils, the carbonyl region is often used as an indicator of oxidation, but similar bands can also result from formulation components (e.g., ester bases) [41]. Aliphatic C-H bands are visible (2960–2850 cm⁻¹, 1450–1380 cm⁻¹), consistent with the hydrocarbon matrix/-CH₂- chains [40]. The region 900–650 cm⁻¹ is very intense (e.g., ~758, ~732, ~699, ~684, ~678 cm⁻¹), which confirms the presence of aromatic and/or unsaturated structures (OOP C-H vibrations) [42]. The fingerprint range (ca. 1300–900 cm⁻¹) is distinct (e.g., ~1267, ~1230, ~1177, ~1105, ~1071, ~1020 cm⁻¹) [44].

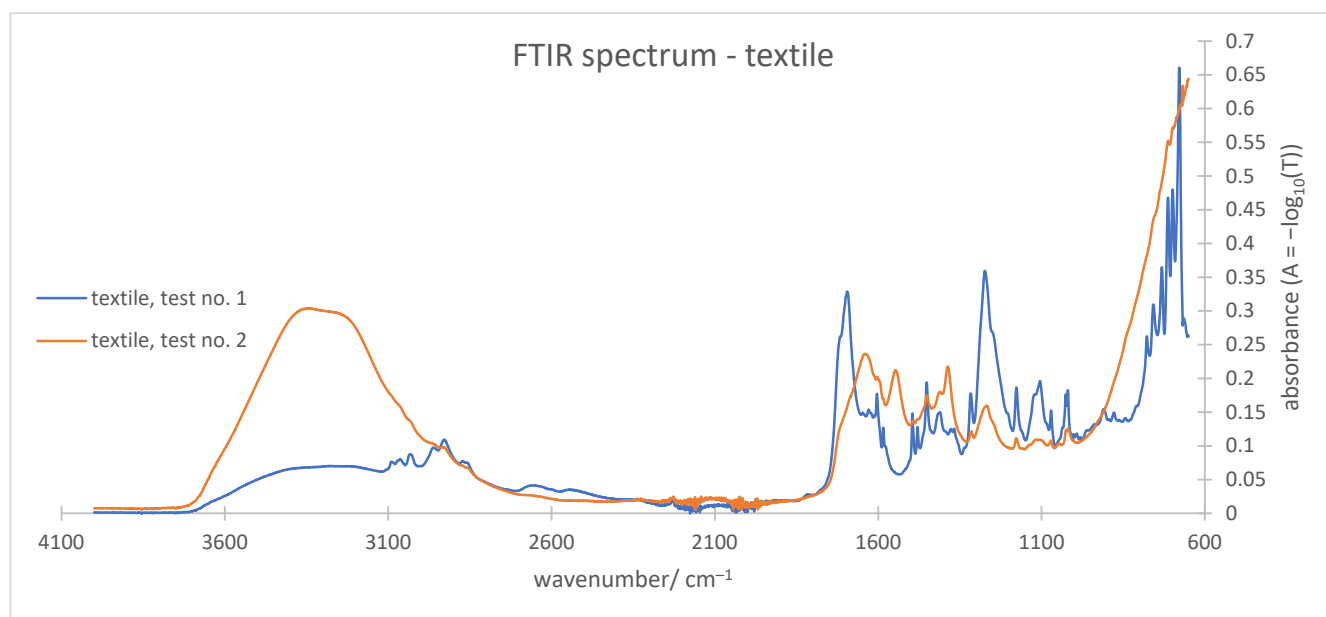


Figure 16. FTIR spectrum for main fraction—textile batch. Source: authors’ own measurements.

Table 13. FTIR spectrum interpretation—textile batch, test no. 1 (based on [40,42,45]).

Position (cm ⁻¹)	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
~1733	medium	C=O (typically esters; generally “carbonyl region”)	The C=O signal indicates a significant contribution of carbonyl compounds (e.g., ester components or oxidation products).
~1703; ~1695	strong	C=O (carbonyl region 1800–1650 cm ⁻¹)	Very pronounced absorption around ~1700 cm ⁻¹ ; in operating oils, the C=O region is sometimes used diagnostically for oxidation, but it may also originate from formulation components (e.g., ester bases).
~1647	medium	C=C (alkenes/conjugated systems; aromatic contribution possible)	The band may accompany unsaturated components; it can be interpreted together with the region 900–650 cm ⁻¹ .
~1604; ~1495	medium	vibrations of the aromatic ring (ring stretching)	supports the presence of an aromatic component
~1458/~1452	weak/medium	δ(CH ₂)/δ(CH ₃) (C-H deformations)	Typical hydrocarbon bands; may overlap with other vibrations in mixtures.
~1267	strong	fingerprint (often C-O/C-C; in esters also ν(C-O) contribution)	A “crowded” range; with a strong C=O, may be consistent with the presence of ester functions, but may not identify unambiguously.
~1230; ~1177; ~1105; ~1071; ~1020; ~992	medium/weak	fingerprint (C-O/C-C; complex vibrations)	In formulated oils, fingerprint signals may originate from the base (e.g., ester), additives, or aging products.
~909; ~880; ~824; ~805	medium	C-H OOP (aromatics/alkenes)—region 900–690 cm ⁻¹	Diagnostic region for aromatic structures; band arrangement supports aromatic/unsaturated contribution.
~778; ~758; ~739; ~732	medium/strong	aromatic C-H OOP	set of OOP bands typical for aromatics
~715	strong	CH ₂ rocking (~720–730) and/or layering with aromatic OOP	In oils, the ~722–730 cm ⁻¹ band is sometimes associated with long -CH ₂ - sequences, but in mixtures it may overlap with aromatic OOP.
~699; ~684; ~678	very strong/strong	aromatic C-H OOP	a very intense “signature” of the aromatic region; in this sample it is one of the dominant features of the spectrum.

Regarding textile batch, test no. 2 (Figure 16, Table 14):

The spectrum of the textile sample, test no. 2, is characterized by the simultaneous presence of:

- prominent O-H bands (ca. 3393–3307 cm⁻¹);

- a C=O carbonyl region (ca. 1703–1693 cm^{−1}, additionally ~1733 cm^{−1}).

This pattern may be consistent with the presence of oxygenated components or oxidation products, but a definitive analysis requires comparison to a fresh reference sample of the same formulation [41]. The 900–650 cm^{−1} region is very intense (many strong O-H bands), indicating a significant contribution from aromatic/unsaturated structures [42]. The aliphatic component (C-H at 2960–2850 cm^{−1} and C-H deformations) is present, but compared to the dominant aromatic and carbonyl region, it is not dominant [40].

Table 14. FTIR spectrum interpretation—textile batch, test no. 2 (based on [40,42,45]).

Position (cm ^{−1})	Intensity (Descriptive)	Assignment (Most Typical)	Interpretive Commentary
~3393; ~3307	strong, wide	O-H stretching (water/water/alcohols/hydroperoxides)	A clear share of polar components; in operating oils it may accompany oxidation products (interpretation with caution without a reference sample).
~3067	medium	=C-H stretching (alkenes/aromatics)	indicates unsaturation or aromatic contribution
~1703; ~1693	medium	C=O (carbonyl region 1800–1650 cm ^{−1})	Pronounced carbonyl absorption; in oil diagnostics, the C=O region is sometimes associated with oxidation, but similar bands may also originate from formulation components (e.g., ester bases).
~1643	medium	C=C (alkenes/conjugated systems; aromatic contribution possible)	The band is distinct and should be interpreted together with the strong 900–650 cm ^{−1} region.
~1603; ~1492	medium	vibrations of the aromatic ring (ring stretching)	supports the presence of aromatic ingredients
~1451	medium	δ(CH ₂)/δ(CH ₃) (C-H deformations)	typical hydrocarbon band; in mixtures possible overlap with other vibrations
~1384	medium	δ(CH ₃) bending (~1375).	confirms the presence of methyl groups
~1267	medium	fingerprint (often C-O/C-C; in esters also ν(C-O) contribution)	A “crowded” range; with CO present, it may be consistent with oxygen functional involvement, but the assignment remains generic.
~902; ~880	medium	C-H OOP (aromatics/alkenes)—region 900–690 cm ^{−1}	Diagnostic region for aromatics; presence of bands supports “aromatic/unsaturated contribution”.
~824; ~805	medium/strong	aromatic C-H OOP	Part of the OOP pattern dependent on substitution type; without the library, do not identify a specific compound.
~770; ~751; ~739; ~725; ~715	strong/very strong		very distinct aromatic “signature” at 900–650 cm ^{−1}
~715 (±)	very strong	possible stacking: CH ₂ rocking (~730–720) and OOP aromatic	In oils, the ~722–730 cm ^{−1} band is sometimes associated with long -CH ₂ - sequences (rocking), but in this sample the region is strongly “aromatic”, so the assignment is only cautious.
~693; ~677; ~671	very strong	aromatic C-H OOP	dominant spectral bands in the diagnostic area of aromas

Textile batches (test no. 1 and test no. 2) were chemically distinct from remaining oils. In addition to aliphatic C-H bands, these samples exhibited strong, broad O-H absorptions (3300–3390 cm^{−1}) and pronounced carbonyl stretching around 1703–1693 cm^{−1}. The coexistence of O-H and C=O bands indicates the presence of oxygenated compounds. This pattern may be consistent with polyester-derived components and/or oxidation processes; however, without reference materials and molecular-level analysis, the exact origin of these oxygenated species cannot be definitively assigned. Despite oxygenated features, these oils also showed intense aromatic OOP bands in the diagnostic 900–650 cm^{−1} region, indicating the formation of aromatic intermediates during depolymerization.

Textile oils were unique in simultaneously exhibiting aliphatic C-H bands, strong aromatic contributions, and pronounced carbonyl absorption near 1700 cm^{−1}. This combination indicates that polyester components and other oxygenated PM underwent partial decomposition to yield oxygen-containing hydrocarbons, differentiating them from the largely oxygen-free oils of polyolefin origin.

A clear relationship was observed between PM origin and FTIR spectral characteristics. PS-rich inputs produced oils with dominant aromatic signals, particularly in the 900–650 cm^{-1} diagnostic region, where OOP C-H vibrations confirmed the presence of mono- and disubstituted aromatic structures. PP oils showed the strongest aliphatic contribution, as reflected by intense 2956–2850 cm^{-1} stretching bands and deformation modes near 1450/1375 cm^{-1} . ABS materials produced mixed spectra combining both aliphatic and aromatic features, consistent with their styrene-acrylonitrile-butadiene composition.

Diagnostic FTIR bands were interpreted at the level of polymer families rather than individual compounds. Strong aliphatic C-H stretching and deformation bands (3000–2800 and $\sim$ 1460/1375 cm^{-1}) are characteristic of polyolefin-derived hydrocarbon matrices, whereas ring-mode bands ($\sim$ 1600–1500 cm^{-1}) combined with structured C-H out-of-plane vibrations (900–690 cm^{-1}) are typical of styrenic/aromatic polymers. However, these regions are prone to overlap in complex oil matrices, and therefore assignments remain qualitative.

Overall, FTIR analysis in this study serves not only for functional-group identification, but also for comparative assessment of aromatic vs. aliphatic dominance, relative oxidation trends, and feedstock-dependent chemical fingerprints under identical microwave conditions. While molecular-level speciation requires GC-MS or elemental analysis, FTIR provides robust, reproducible evidence of structural trends across different waste streams.

Across all investigated feedstocks, the main liquid fractions displayed spectral signatures characteristic of hydrocarbon oils. In every batch, FTIR spectra revealed a strong set of aliphatic C-H stretching bands between 2956 and 2850 cm^{-1} , combined with deformation modes near 1450 cm^{-1} and 1375 cm^{-1} , indicating the presence of long, saturated hydrocarbon chains typical of depolymerized polyolefins. Overall, FTIR results indicate that, despite the heterogeneity of the feedstocks, microwave heating predominantly generates oils with C-H matrices. However, the nature of the aromatic contributions differs substantially between materials.

Table 3 reinforces the trends observed earlier:

- ABS oils contain a balanced mixture of aliphatic and aromatic bands. Their spectra typically show bands at $\sim$ 3070 cm^{-1} and $\sim$ 1600/1495 cm^{-1} , indicating aromatic segments from styrene-acrylonitrile, combined with aliphatic chains from butadiene or other additives.
- Keyboard and AiO batches show even stronger aromatic signatures, often with very intense signals around 697 cm^{-1} and related OOP deformations. This reflects the presence of high aromatic P (e.g., HIPS-like materials or ABS blends with enhanced styrene content).
- PCB oils show mixed character but with a notably strong aromatic contribution. Occasional C=O bands ($\sim$ 1700 cm^{-1} ; present but not dominant) indicate partial oxidation or decomposition of resinous components present in PCB laminates.

Based on the relative intensity of aromatic ring bands (1605–1495 cm^{-1}) and the structured OOP region (900–690 cm^{-1}), supported by the calculated aromaticity index (ArI), aromatic contribution increases qualitatively along the sequence: PP < ABS < keyboards $\approx$ AiO < PCB. This trend reflects differences in the original polymer chemistry; however, it should be interpreted as a semi-quantitative comparison derived from FTIR band ratios rather than as an absolute compositional ranking. This trend reflects the underlying PM chemistry and demonstrates that MD preserves key features of PM backbones, especially for styrenic and aromatic P. The presence of oxygenated species in selected feedstocks highlights the influence of non-PM additives (resins, pigments, fillers) on decomposition pathways.

Beyond functional-group identification, FTIR enables semi-quantitative comparison of aromaticity, relative oxidation level (via carbonyl index), and the balance between saturated and unsaturated structures. Changes in relative intensity of predefined spectral windows provide insight into depolymerization pathways and differences between feedstocks, even when exact molecular species cannot be resolved. Thus, FTIR serves as a robust tool for comparative assessment of oil classes generated under identical processing conditions.

To avoid over-interpreting FTIR as a compound-specific tool, the comparative assessment below in Table 15 is presented as a relative (trend-based) ranking rather than absolute index values. The ranking is derived from relative prominence of predefined spectral windows: aliphatic C-H stretching ($3000\text{--}2800\text{ cm}^{-1}$), aromatic ring region ($1605\text{--}1495\text{ cm}^{-1}$) together with the diagnostic aromatic OOP region ($900\text{--}690\text{ cm}^{-1}$), carbonyl region ($1850\text{--}1650\text{ cm}^{-1}$), and hydroxyl region ($3600\text{--}3200\text{ cm}^{-1}$). Due to band overlap and matrix/ATR effects, this approach is used only to support qualitative trends; compound-level confirmation requires complementary GC-MS and/or elemental analysis.

Table 15. Relative FTIR-based ranking of main oil fractions (trend-only, no absolute index values).

Feedstock/ Fraction	Aliphatic Character (C-H $3000\text{--}2800$; $1450/1375$)	Aromatic/Styrenic Character ($1605\text{--}1495$; OOP $900\text{--}690$)	Oxygenated Character (C=O $1850\text{--}1650$; O-H $3600\text{--}3200$)	Key Interpretation Notes
PP	high	low/moderate	low	Dominant polyolefin-like hydrocarbon matrix; aromatic OOP features present but secondary/overlapping.
ABS oils (drum/mix)	moderate/high	moderate/high	low/moderate	mixed aliphatic–aromatic signature typical of styrenic blends; possible contribution of additives/aging products
keyboards	moderate	high	low	strong aromatic OOP system; aliphatic C-H present but less dominant
AiO	moderate	high	low	pronounced aromatic fingerprint; weak C=O/O-H contribution
PCB	low/moderate	high	low/moderate	Strong aromatic signature; carbonyl/O-H bands suggest polar components; resin/flame-retarded feedstock requires GC-MS/elemental confirmation.
PS	low/moderate	very high	low	Most structured aromatic OOP region; FTIR consistent with aromatic-rich products but not compound-specific.
textile (no. 1 & 2)	low/moderate	high	high	Clear C=O and O-H together with aromatic OOP; consistent with oxygenated constituents but not uniquely assignable by FTIR.

The trend-based ranking corroborates the qualitative band assignments discussed in Section 3.1: polyolefin-derived oils show the strongest aliphatic C-H contribution, styrenic/aromatic feedstocks show dominant aromatic OOP patterns, and textile-derived oils exhibit the most pronounced oxygenated features. Because several regions may overlap (e.g., $\sim 1650\text{--}1640\text{ cm}^{-1}$ and $900\text{--}730\text{ cm}^{-1}$), this table is intended as a comparative descriptor rather than an absolute compositional measure.

3.2. Main Fractions Distillation Tests

Fractional distillation provided additional insight into the molecular composition of depolymerized oils by separating low-boiling aliphatic compounds from heavier aromatic and oxygenated species.

Table 16 summarizes the outcomes of fractional distillation performed on the main oil fractions. For each feedstock batch, it reports the volume of the low-boiling distillate (<250 °C), higher-boiling distillate (250–350 °C), the estimated gas fraction, and the relative contribution of each distillate to the original oil. It also records qualitative observations such as behavior during heating. The <250 °C fraction accounted for 39–67% of total oil depending on feedstock, while the 250–350 °C fraction represented 8–23%. This distribution suggests potential differentiation between fuel-range hydrocarbons and heavier aromatic-rich streams.

Table 16. Measured parameters, observations, comments and statistics—all main fractions distillation tests.

Batch Material from Which the Main Fraction Was Obtained	Test No.	Load Quantity	Distillate						Gas Fractions (Estimated) ¹		Amount of Distillates Per Unit of Main Fraction			Observations and Comments
			Obtained at 250 °C		Obtained at 250–350 °C		Total		Quantity	Volume Percent	Distillate Obtained at 250 °C	Distillate Obtained at 250–350 °C	Total	
			Quantity	Volume Percent	Quantity	Volume Percent	Quantity	Volume Percent						
			mL, ±10 mL	mL, ±10 mL	v/v, %	mL, ±10 mL	v/v, %	mL, ±10 mL						
PS	1	6000	3500	58.3	470	7.8	3970	66.1	2030	33.9	580, 58%	80, 8%	660, 66%	- noticeable foaming during distillation in the T range of 135–155 °C - condensation for inside the receiver appears at approx. 180 °C
	2	6550	3800	58.0	890	13.5	4690	71.5	1860	28.5	580, 58%	140, 14%	720, 72%	
	3	5200	2900	55.7	1020	19.6	3920	75.3	1280	24.7	560, 56%	200, 20%	760, 76%	
	4	4500	3000	66.6	650	14.4	3650	81.0	850	19.0	670, 67%	140, 14%	810, 81%	
	5	3000	1900	63.3	380	12.6	2280	75.9	720	24.0	630, 63%	130, 13%	760, 76%	
	average and standard deviation	5050 σ = 1390	3020 σ = 730	60.4 σ = 4.4	680 σ = 270	13.6 σ = 4.2	3700 σ = 880	74.0 σ = 5.5	1350 σ = 586	26.0 σ = 5.5	600, 60% σ = 40	140, 14% σ = 40	740, 74% σ = 60	
ABS drum	1	1790	900	50.3	300	16.7	1200	67.0	590	33.0	500, 50%	170, 17%	670, 67%	
	2	1750	350	20.0	310	17.7	660	37.7	1090	62.3	200, 20%	180, 18%	380, 38%	
	3	1710	900	52.6	400	23.4	1300	76.0	410	24.0	530, 53%	230, 23%	760, 76%	
	4	1070	600	56.0	210	19.6	810	75.6	260	24.4	560, 56%	200, 20%	760, 76%	
	5	1120	390	34.8	200	17.8	590	53.0	530	47.0	350, 36%	180, 18%	530, 53%	
	average and standard deviation	1490 σ = 360	630 σ = 270	42.7 σ = 15.1	280 σ = 80	19.0 σ = 2.7	910 σ = 320	61.8 σ = 16.5	580 σ = 310	38.2 σ = 16.5	430, 43% σ = 150	190, 19% σ = 30	620, 62% σ = 160	
PP	1	2400	1150	48.0	430	18.0	1580	66.0	820	34.0	480, 48%	180, 18%	660, 66%	-
	2	2050	800	39.0	500	24.3	1300	63.4	750	36.6	390, 39%	240, 24%	630, 63%	
	average	2230	980	43.5	470	21.2	1450	64.7	790	35.3	430, 43%	210, 21%	640, 64%	
keyboards	1	4050	2600	64.2	350	8.6	2950	72.8	1100	27.2	640, 64%	90, 9%	730, 73%	-
AiO	1	2950	1600	54.2	500	16.9	2100	71.1	850	28.9	540, 54%	170, 17%	710, 71%	-

¹ as the amount of liquid that has volatilized.

Increased residue formation limited to aromatic-rich oils, particularly those from ABS and PCB-containing feedstocks, produced slightly more residue in the boiling flask, consistent with their higher oligomer content. However, boiling-range classification alone does not provide molecular-level identification and should not be interpreted as equivalent to chromatographic characterization.

Regarding PS distillates (Figure 17):

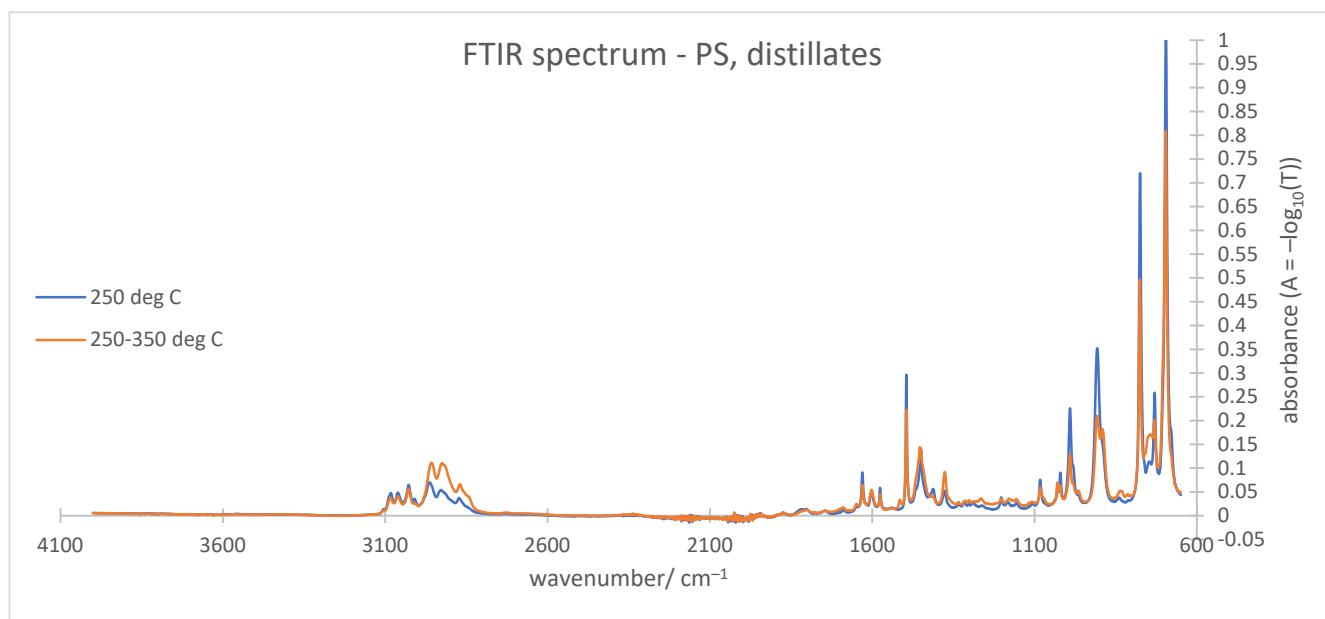


Figure 17. FTIR spectrum for distillates—PS batch. Source: authors' own measurements.

PS distillates are characterized by a pronounced aromatic signature, with dominant OOP C–H vibrations in the $900\text{--}650\text{ cm}^{-1}$ region, consistent with the persistence of styrenic oligomers (particularly $\sim 695\text{ cm}^{-1}$, strong $\sim 692\text{ cm}^{-1}$, and prominent $\sim 775\text{ cm}^{-1}$) [42]. An aliphatic component is present (C–H stretching $2963\text{--}2857\text{ cm}^{-1}$, deformations ~ 1450 and $\sim 1377\text{ cm}^{-1}$), but it is not dominant relative to the aromatic region [40]. The carbonyl region (~ 1746 and $\sim 1689\text{ cm}^{-1}$) is trace. Based on the FTIR spectrum, the extent of oxidative transformations cannot be reliably assessed.

Regarding PP distillates (Figure 18):

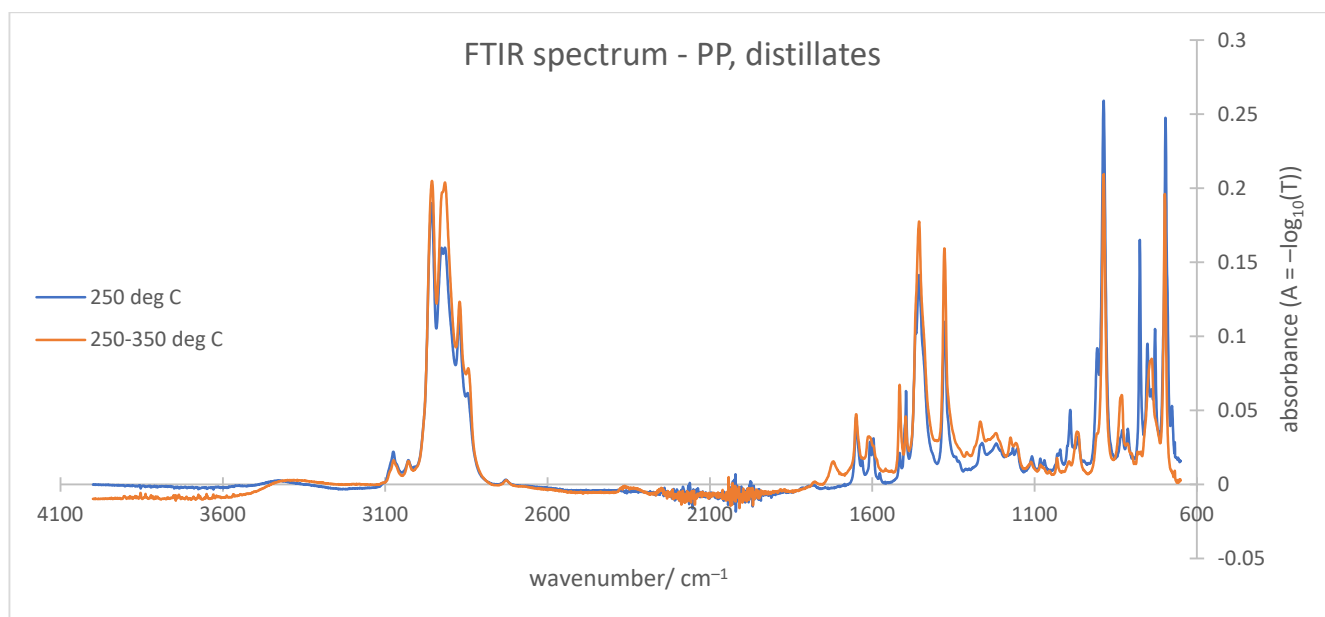


Figure 18. FTIR spectrum for distillates—PP batch. Source: authors' own measurements.

PP distillates spectra indicate a significant contribution of the aliphatic fraction (strong $\nu(\text{C-H})$ bands in the range of $\sim 2960\text{--}2850\text{ cm}^{-1}$ and 2916 cm^{-1} , and deformations $\sim 1456/1444$ and $\sim 1377\text{ cm}^{-1}$) [42]. At the same time, an aromatic/unsaturated contribution is present, as confirmed by ring-mode bands ($\sim 1600\text{--}1500\text{ cm}^{-1}$) and a distinct C-H OOP region ($900\text{--}650\text{ cm}^{-1}$) with a very strong band at ca. 887 cm^{-1} and a very strong band at ca. $699\text{--}698\text{ cm}^{-1}$ [41]. No clearly dominant carbonyl C=O band was observed in the typical range of $\sim 1723\text{--}1650\text{ cm}^{-1}$; therefore, no conclusion about oxidation is made based on this spectrum.

Regarding ABS drum distillates (Figure 19):

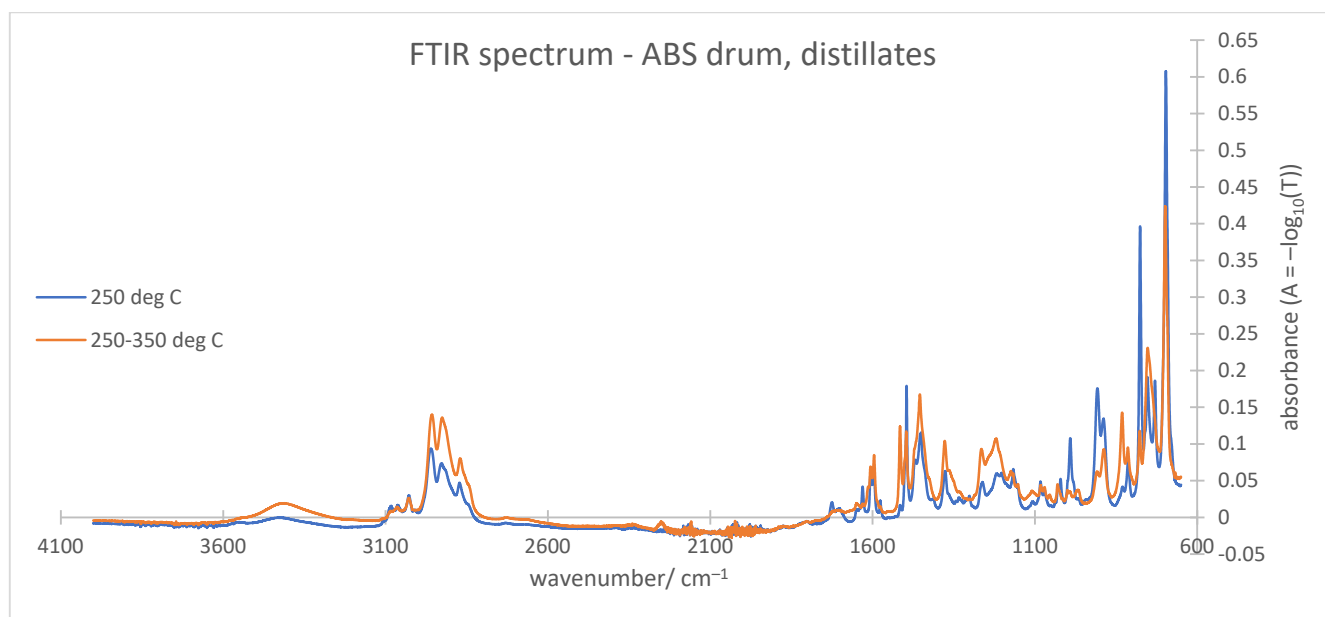


Figure 19. FTIR spectrum for distillates—ABS drum batch. Source: authors' own measurements.

ABS drum distillates spectra are dominated by aromatic signals, particularly in the region $900\text{--}650\text{ cm}^{-1}$ (the strongest bands around $697\text{--}700\text{ cm}^{-1}$, strong around $776, 753$ and 691 cm^{-1}), and ring bands around ~ 1595 and $\sim 1496\text{ cm}^{-1}$, typical of C-H OOP vibrations in aromatic structures [42]. An aliphatic component (C-H at $2957\text{--}2857\text{ cm}^{-1}$ and deformations $1450\text{--}1376\text{ cm}^{-1}$) is present but not dominant, consistent with a hydrocarbon matrix typical of oils [40]. The carbonyl region (ca. $1725\text{--}1700\text{ cm}^{-1}$) is very weak, so based on the spectrum alone there is no evidence to detect a significant “increase in C=O” (oxidation) [41].

Regarding keyboard distillates (Figure 20):

The spectra of keyboard distillates are dominated by aromatic signals, especially in the range $900\text{--}650\text{ cm}^{-1}$: a very strong band at $\sim 696\text{ cm}^{-1}$ and strong bands at ~ 700 and $\sim 776\text{ cm}^{-1}$ (C-H OOP vibrations), as well as a ring band at about 1495 cm^{-1} [42]. An aliphatic component (C-H stretching $2960\text{--}2850\text{ cm}^{-1}$ and deformations $\sim 1450/1375\text{ cm}^{-1}$) is present, but relatively weak compared to the aromatic “signature” [40]. The carbonyl region ($\sim 1733\text{--}1705\text{ cm}^{-1}$) is weak [41].

Regarding AiO distillates (Figure 21):

The spectra of AiO distillates are dominated by aromatic signals in the region $900\text{--}650\text{ cm}^{-1}$, particularly a very strong band around 696 cm^{-1} and strong bands around $700, 776$, and 691 cm^{-1} , consistent with assignment to aromatic C-H OOP vibrations [42]. An aliphatic component (C-H stretching $2962\text{--}2857\text{ cm}^{-1}$, deformations $\sim 1458\text{--}1377\text{ cm}^{-1}$) is present, but in these samples it does not dominate aromatic signals [40]. The carbonyl

region ($\sim 1742\text{--}1687\text{ cm}^{-1}$) is trace. It is difficult to draw conclusions about oxidation based on a single spectrum [41].

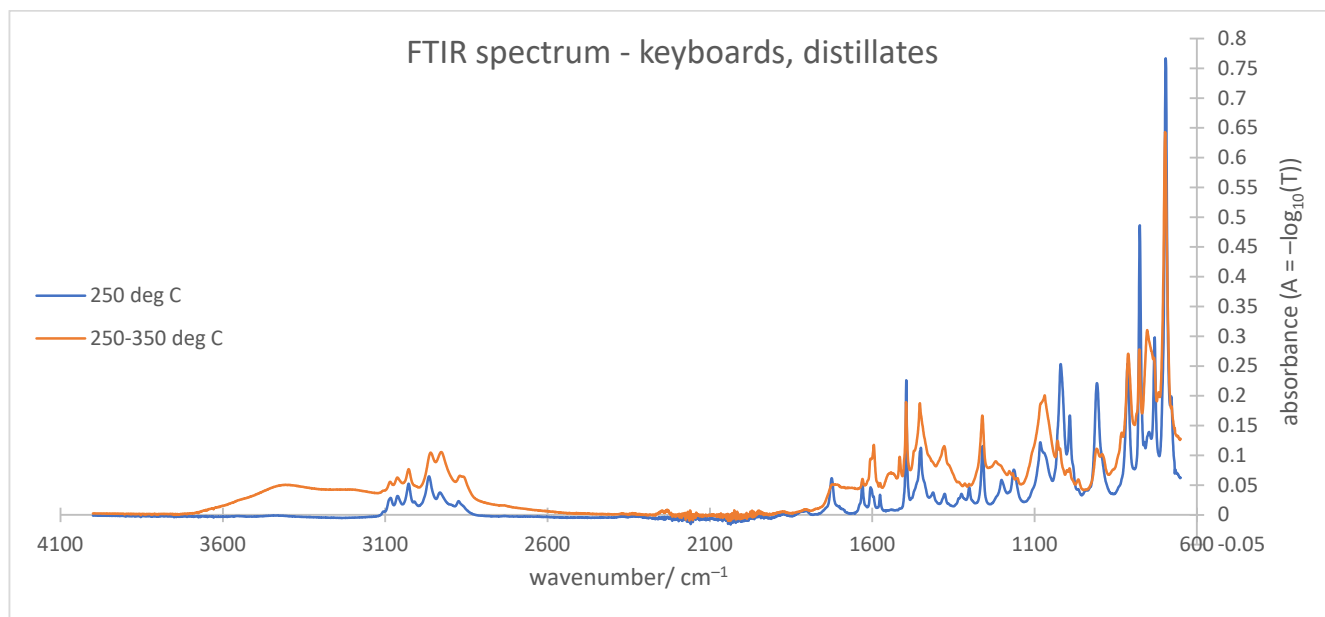


Figure 20. FTIR spectrum for distillates—keyboards batch. Source: authors' own measurements.

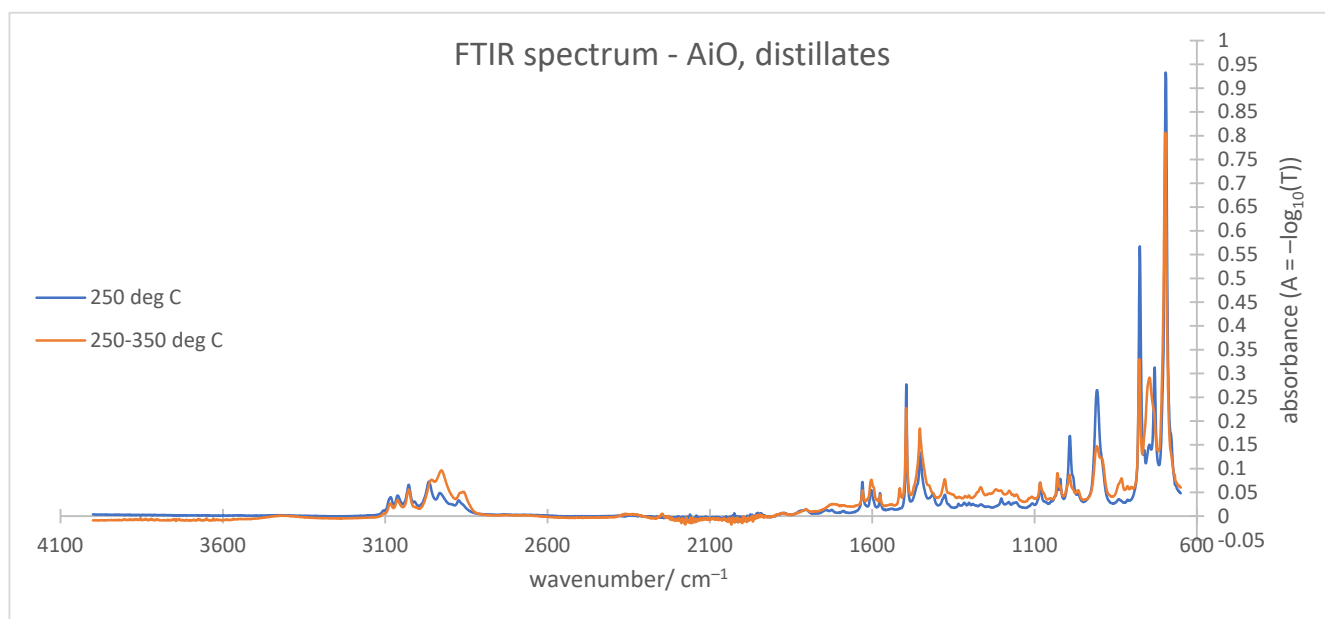


Figure 21. FTIR spectrum for distillates—AiO batch. Source: authors' own measurements.

Distillation behavior correlates strongly with the chemical profile of each feedstock: PP produces 60–70% of low-boiling, aliphatic fractions, whereas styrenic and P yield predominantly 250–350 °C fractions, consistent with higher aromatic content and lower volatility.

Regardless of feedstock type, the <250 °C distillates consistently exhibited a shift toward aliphatic hydrocarbons compared with the corresponding parent oils. The intensity of C-H stretching bands at $2956\text{--}2850\text{ cm}^{-1}$ typically increased relative to aromatic ring vibrations, indicating enrichment in saturated hydrocarbons. Aromatic OOP bands were still present but generally of reduced intensity, consistent with the removal of heavy aromatic oligomers into the higher boiling fraction.

The 250–350 °C fractions consistently exhibited stronger aromatic signatures. In the PS distillates, the aromatic system (900–690 cm^{-1}) remained dominant, confirming that styrene dimers, trimers, and heavier aromatic structures boiled in this range. In ABS distillates, aromatic bands intensified relative to aliphatic components, reflecting the higher boiling points of aromatic oligomers and possible heteroatom-containing fragments originating from additives. Textile-heavy fractions retained strong C=O and O-H signatures, indicating persistence of oxygenated compounds in this boiling range.

Taken together, these observations show that fractional distillation effectively separates oils into two compositionally distinct fractions: a lighter, predominantly aliphatic fraction and a heavier, more aromatic and oxygenated fraction.

Several key patterns emerge:

- PP oils produce the highest proportion of low-boiling (<250 °C) distillates, consistent with their aliphatic character and the presence of lighter linear and branched hydrocarbons.
- PS oils show a more balanced distribution but with a distinct shift towards 250–350 °C fractions, reflecting heavier aromatic hydrocarbons and styrene oligomers.
- ABS, keyboards and AiO oils generate significant amounts of high-boiling fractions, often accompanied by dark residues, indicating the presence of aromatic oligomers or decomposition products from P.

3.3. Comparative Interpretation Across Feedstocks

The comparative evaluation of all investigated feedstocks reveals systematic relationships between polymer structure, thermal response under MD, product distribution, and spectroscopic characteristics of the resulting oil products.

From a quantitative perspective, clear differences were observed in total yield and residue formation depending on polymer type. PS gives one of the highest yields; in contrast, PP generated slightly lower yields. Mixed-electronic P (ABS, keyboards, AiO, PCB) exhibited intermediate behavior, reflecting their heterogeneous composition and/or the presence of additives or fillers. Textile feedstock showed increased formation of oxygenated fractions, consistent with partial contribution of polyester-type components and secondary reactions.

FTIR analysis confirms that product composition closely follows the structural features of the original polymer matrix. PS oil exhibited intense aromatic OOP C–H bending bands (900–650 cm^{-1}), indicating preservation of styrenic structural motifs and formation of aromatic-rich fractions. In contrast, PP oils were dominated by strong aliphatic C–H stretching bands (2956–2850 cm^{-1}) with comparatively weaker aromatic signals, consistent with chain scission of saturated polyolefin backbones. ABS and mixed WEEE P displayed combined aliphatic–aromatic profiles, reflecting simultaneous degradation of styrenic and aliphatic domains. Textile oils showed additional carbonyl contributions, suggesting partial oxidation or decomposition of oxygen-containing polymer structures.

Diagnostic FTIR features were interpreted in terms of polymer families rather than specific compounds. Intense aliphatic bands at 2956–2850 cm^{-1} with deformation modes near 1460/1375 cm^{-1} are typical of hydrocarbon matrices and are consistent with polyolefin-derived oils; however, PE/PP cannot be unambiguously discriminated by FTIR alone. Aromatic contributions were inferred from ring-mode bands near 1600–1500 cm^{-1} together with the structured C–H OOP region (900–690 cm^{-1}), which is characteristic of styrenic/aromatic polymer backbones (e.g., PS/SAN/ABS/HIPS), yet similar patterns may also arise from aromatic additives or secondary aromatization. Oxygenated features (C=O at ~1850–1650 cm^{-1} and O–H at 3600–3200 cm^{-1}) may indicate oxidation products, ester-containing constituents, or polar additives; without reference oils and molecular-level

analysis, assignments remain qualitative. Several bands (e.g., $\sim 1650\text{--}1640\text{ cm}^{-1}$) may contain overlapping contributions from C=C stretching and H-O-H bending; therefore, interpretation was made contextually and in combination with adjacent diagnostic regions.

Overall, FTIR analysis demonstrates that microwave treatment of heterogeneous polymeric feedstocks produces oils dominated by hydrocarbon functional groups, with varying relative contributions of aliphatic, aromatic, and oxygenated structures depending on the original material. The technique clearly differentiates polyolefin-like, styrenic/aromatic-rich, and oxygen-containing oil profiles at the functional-group level. However, due to spectral overlap and the complexity of formulated polymer systems, FTIR is not sufficient for compound-level identification. Complementary GC-MS and elemental analyses are required to fully validate the proposed compositional trends.

A clear relationship was observed between feedstock origin and FTIR spectral characteristics. Polyolefin-derived oils (e.g., PP) showed dominant aliphatic C-H stretching ($2956\text{--}2850\text{ cm}^{-1}$) and deformation bands ($\sim 1450/1375\text{ cm}^{-1}$), typical of saturated hydrocarbon matrices [40]. In contrast, PS-rich inputs produced oils with dominant aromatic features, particularly in the diagnostic $900\text{--}690\text{ cm}^{-1}$ region, where structured C-H out-of-plane vibrations confirmed the presence of aromatic ring systems [42]. ABS and related materials generated mixed spectra combining both aliphatic and aromatic signatures, consistent with styrenic blends containing both saturated and aromatic domains.

Across all investigated feedstocks, the main liquid fractions displayed functional-group signatures characteristic of hydrocarbon oils, with varying relative contributions of aliphatic, aromatic, and oxygenated structures. The calculated semi-quantitative indices (ArI, CI, OHI) indicate that aromatic contribution increases qualitatively along the sequence: PP < ABS < keyboards $\approx$ AiO < PCB. This trend reflects differences in the original polymer chemistry and formulation. The calculated ArI values increased progressively from polyolefin-derived oils to styrenic and PCB-derived fractions, consistent with the relative intensity of aromatic ring and OOP bands. CI and OHI values remained low for polyolefin samples and were elevated only in textile-derived oils, reflecting the presence of oxygen-containing species. Numerical index values are consistent with qualitative spectral interpretation.

It should be emphasized that FTIR provides functional-group level information and that several spectral regions (notably $1600\text{--}1500\text{ cm}^{-1}$ and $900\text{--}690\text{ cm}^{-1}$) may be affected by band overlap in complex oil matrices. Therefore, the above ranking represents a semi-quantitative comparison based on predefined integration windows rather than an absolute compositional determination.

While FTIR clearly differentiates between predominantly aliphatic, aromatic-rich, and oxygenated oil profiles, compound-level identification and verification of specific molecular products require complementary techniques such as GC-MS and elemental analysis.

Because FTIR provides functional-group level information, compound-level identification of volatile and liquid products requires complementary techniques such as GC-MS of the gas/liquid fractions and elemental analysis (including halogens where relevant). The present conclusions therefore refer to functional-group trends rather than definitive molecular speciation.

Distillation behavior further differentiates the feedstocks: the $<250\text{ }^{\circ}\text{C}$ fraction accounted for a substantial portion of total oil in polyolefin and PS samples, indicating the formation of relatively low-molecular-weight hydrocarbons; the $250\text{--}350\text{ }^{\circ}\text{C}$ fraction was more pronounced in aromatic-rich systems and in mixed-electronic P, suggesting the presence of heavier oligomeric or condensed aromatic structures.

The results demonstrate that MD preserves key structural signatures of the original polymers while modifying product distribution through feedstock-dependent thermal and

chemical pathways. The consistency between FTIR fingerprints and distillation profiles supports the internal coherence of the dataset and confirms that polymer chemistry remains the primary determinant of product characteristics under applied microwave conditions.

4. Conclusions

Based on the experiments performed, quarter-scale MD was able to convert heterogeneous postconsumer P into liquid hydrocarbon products, although some variability between runs was observed. All tested materials, ranging from commodity P such as PP, PS, ABS, keyboards, PCBs, and textiles, yielded liquid fractions dominated by aliphatic and aromatic hydrocarbons in proportions characteristic of their PM origin. FTIR analysis consistently showed that polyolefin oils were predominantly aliphatic, styrenic materials produced strongly aromatic oils with clear ring substitution patterns, and ABS or electronics-derived feedstocks resulted in mixed aliphatic–aromatic compositions. Textile oils exhibited additional carbonyl and O–H bands, suggesting pathways involving oxygenated intermediates.

Microwave heating enabled rapid depolymerization, producing oils with broadly similar spectral fingerprints across repeated tests, confirming the stability of the process. Fractional distillation further revealed that low-boiling fractions (<250 °C) were dominated by aliphatic hydrocarbons, whereas higher-boiling fractions (250–350 °C) contained more aromatic or oxygenated components, highlighting the molecular diversity of the derived oils.

Metallic components probably pass mainly to the solid residue, while halogen ones to the liquid phase, but verification of this thesis would require further analysis in future studies.

While the process proved technically viable across a broad range of waste streams, its performance remains dependent on reactor configuration and feed heterogeneity, which should be addressed in future scale-up studies. The consistency of the spectral trends across diverse P provides a foundation for future process optimization, particularly for scaling up to pilot and industrial reactors where feed heterogeneity and heating uniformity remain critical engineering challenges.

Future work should complement FTIR-based characterization with chromatographic and elemental analyses, and incorporate more precise gas quantification and energy balances to fully assess the techno-economic potential and environmental performance of the process.

Author Contributions: Conceptualization, J.K.; methodology, J.K. and W.K.; software, A.P., B.S., J.K. and W.K.; validation, A.P.; formal analysis, A.P. and B.S.; investigation, A.P. and W.K.; resources, W.K.; data curation, A.P., W.K. and B.S.; writing—original draft preparation, A.P.; writing—review and editing, J.K. and M.K.; visualization, A.P.; supervision, J.K. and M.K.; project administration, M.K.; funding acquisition, M.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to thank the entire Eco Harpoon community who directly and indirectly contributed to the research and its publication.

Conflicts of Interest: Author Andrzej Piotrowicz, Janusz Kolczyński, Mirosław Kostrzewa, Wojciech Kaczmarek were employed by the company Eco Harpoon Recycling Sp. z o.o. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

P	plastic(s)
MD	microwave assisted depolymerization
PM	polymer(s)
PE	polyethylene
PS	polystyrene
PP	polypropylene
PET	polyethylene terephthalate
LDPE	low-density polyethylene
BHET	bis(2-hydroxyethyl) terephthalate
PVC	polyvinyl chloride
MSW	municipal solid waste
PCB	printed circuit board
AiO	“all-in-one”, a specific computer in which all the components necessary for operation are located in the monitor housing
TFT	type of display found in monitors and laptops screens
ABS	acrylonitrile butadiene styrene
IR	infrared spectroscopy
OOP	out-of-plane
σ	standard deviation

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