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Evaluating the Thermal and Mechanical Effects of Flame Retardant Additives during Reprocessing of Acrylonitrile Butadiene Styrene (ABS) and Fused Filament Production

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ABSTRACT

While flame-retardant additives are critical for improving fire safety, they often compromise the recyclability of thermoplastics. This study investigates how flame-retardants affect the recycling of acrylonitrile butadiene styrene (ABS) and its subsequent production into 3D printing filament. 2019 model ABS both with the flame-retardant additive (ABS-FR) and without (ABS) were taken from an old printer, crushed into uniform flakes, and subjected to chemical, thermal, and mechanical characterization. Although the FTIR profile of the sample were preserved, the incorporation of flame retardants markedly altered its thermal behavior. Compared to unmodified ABS (degradation onset: 350 °C; *T*g: 107 °C), ABS-FR demonstrated a lower thermal stability, with an earlier degradation onset at 325 °C, alongside a modestly reduced glass transition temperature of 103°C. Material processing was significantly affected, as evidenced by the lower melt flow rate of ABS-FR (30 ± 0.1 g/10 min) compared to ABS (41 ± 0.3 g/10 min). The extruded ABS-FR filament exhibits a considerably lower diameter (1.52 ± 0.03 mm) compared to ABS (1.80 ± 0.03 mm), thereby restricting its suitability for 3D printing applications. As anticipated, the compression-molded ABS-FR plates exhibited superior flame resistance. Crucially, the incorporation of flame retardants significantly modified the mechanical behavior of the material: ABS-FR demonstrated a higher tensile modulus (2574 ± 84.12 MPa) and lower tensile strength (31 ± 0.70 MPa), reflecting enhanced stiffness and lower load-bearing capacity. These findings underscore the critical trade-offs that flame retardants impose on recycled ABS, affecting fire safety, end-of-life processing, application viability, and mechanical performance.

Key Words: *Acrylonitrile-Butadiene-Styrene, Recycling, Additives, Filament, Flame Retardant*

1. Introduction

Increasing levels of solid waste are now a significant environmental challenge across the globe [1, 2, 3]. The deposited garbage consists of various waste types, with a notable portion coming from electrical and electronic equipment made of thermoplastic polymers [3, 4]. Refusing, reducing, reusing, and recycling are strategies designed to lessen the landfill impact of thermoplastic WEEE (waste electrical and electronic equipment). Among these strategies, recycling is the most favored method [1, 4]. Recycling and utilizing WEEE acrylonitrile butadiene styrene (ABS) waste offers a dual benefit: it mitigates environmental pollution from landfills while promoting the recovery of industrial materials [1, 3, 4].

The influence of flame retardant additives on the mechanical recycling of solid thermoplastic waste was reviewed. Initially, the study examined how mechanical melt reprocessing affects the flame retardant properties of various thermoplastic polymers recycled from waste electrical and electronic equipment (WEEE). Following this, strategies were explored to upgrade common polymer waste streams by incorporating virgin flame retardants into recycled plastics, with the goal of increasing the value of the resulting compound. The authors conclude that the impact of mechanically reprocessing flame-retardant plastics is highly influenced by the particular combination of the polymer and the flame retardant used. Additionally, while the decomposition of the flame retardant may not necessarily introduce other issues, it undeniably leads to a reduction in flame-retardant effectiveness [5]. The effectiveness of four non-halogenated flame retardants: aluminum trihydroxide (ATH), magnesium hydroxide (MDH), sepiolite (SEP), and a blend of metallic oxides and hydroxides (PAVAL) was investigated in conjunction with recycled acrylonitrile-butadiene-styrene (rABS) to develop a more environmentally friendly flame-retardant composite alternative. The UL-94 and cone calorimetric tests were conducted to assess the mechanical and thermo-mechanical properties of the resulting composites, along with their flame-retardant mechanisms. The particles, as anticipated, increased the stiffness of the rABS; however, this improvement came at the cost of its toughness and impact performance. To balance fire behavior with mechanical properties, composites with varying amounts of SEP and MDH were evaluated. The results indicated that the composite formulation rABS/MDH/SEP (70/15/15 wt.%) displayed a 75% longer time to ignition (TTI) and a residual mass after ignition that exceeded 60% of the original mass. Compared to unadditivized rABS, the material reduces the heat release rate

(HRR) by 62.9%, total smoke production (TSP) by 19.04%, and total heat release rate (THRR) by 13.77%, while preserving the original material's mechanical properties. These promising results indicate a potentially greener route for the production of flame-retardant composites [6]. The effects of diethylphosphinate, ammonium polyphosphate, and phosphorus-based flame retardant additives (PFR) on the mechanical performance and fire behavior of microcellular acrylonitrile-butadiene-styrene (ABS) were examined. A co-rotating twin-screw extruder was used to produce the microcellular ABS following the addition of a 25% concentration of PFR, diethylphosphinate, and ammonium polyphosphate. The MuCell® injection-molding method was used to process microcellular parts with nominal weight reductions of 10%, 15%, and 20%. The results show that adding PFR particles increased the storage modulus while decreasing the impact energy, as evaluated by dynamic-mechanical-thermal analysis and falling weight impact tests, respectively. In UL-94 vertical burning tests, all ABS/PFR foams showed self-extinguishing behavior regardless of weight drop. Heat release rate and combustion duration steadily decreased with increasing weight reduction in cone calorimeter tests, and a similar intumescent effect was noted [7]. Study of the development of polymer composites for rapid prototyping, using an acrylonitrile-butadiene-styrene (ABS) terpolymer matrix with PX200 as a flame retardant. Samples were produced via extrusion. Authors looked at how PX200 (5, 10, 15, and 20% by weight) affected the structural, flammability, and rheological properties of ABS-based composites. The UL94 rating and the limiting oxygen index (LOI) were used to assess flammability, while micro-cone calorimetry (MCC) was used to assess flame retardant performance. More emphasis was given to the effectiveness of the phosphorus flame retardant PX200 in the generated composites, as well as the quantitative and qualitative spread of fire. The study looked at the flame retardency index, fire growth rate index, fire potential index, and maximum rate of heat emission. Ultimately, it was revealed that the aryl bisphosphate utilized in this study showed gas phase action. Both the quantitative evaluation utilizing micro-cone calorimeter data and the lack of residues following combustion and thermolysis at 700 °C verified this. As a result, the limiting oxygen index (LOI) increased slightly to 20% for the composite containing 20% flame retardant, but the flammability rating stayed the same (HB40) [8]. Research on the development of a novel flame-retardant filament composed of ammonium polyphosphate (APP) and acrylonitrile-butadiene-styrene (ABS) was conducted using COMSOL finite element analysis-based software. Experimental results confirm that fused filament fabrication (FFF) is a viable direct manufacturing method for ABS

composites, as the printed specimens retained their key material properties without significant degradation [9]. The study focused on developing high-performance blends of PC/ABS made from highly contaminated, flame-retardant recycled polycarbonate (r-PC) and recycled acrylonitrile butadiene styrene (r-ABS) sourced from WEEE polymer waste. This research utilized three distinct WEEE fraction samples, which contained elevated levels of bromine, chloride, and phosphorus. By using the dissolution precipitation CreaSolv® method, the fractions were decontaminated from halogenated pollutants and purified from polymers other than PC. Additives and virgin ABS were used to improve mechanical properties. In the first two situations, the WEEE fractions underwent optical pre-sorting for polycarbonate (PC) prior to the processes of purification and decontamination. Analyses using gas chromatography (GC-ECD) and X-ray fluorescence (XRF) were conducted to confirm the effective removal of contaminants from recycled polycarbonate (r-PC). Three compatibilizers and several ABS grades were initially screened using laboratory-scale micro-compounding. Promising candidates were then up scaled for testing on a bench-scale twin-screw extruder. The resulting morphologies and fracture surfaces were examined via SEM to establish structure property relationships. Dynamic mechanical analysis (DMA), rheological dynamic analysis (RDA), and gel permeation chromatography (GPC) were employed to determine the chain-branching characteristics and molecular weight distribution of r-PC, while the melt rheology and solid-state mechanical behavior of the compatibilized r-PC/ABS blend were also thoroughly evaluated. Adding virgin ABS and an effective compatibilizer to a 60/40 recycled PC/ABS blend brings its performance nearly to virgin-grade levels. With this approach, r-PC content can easily exceed 55%. Furthermore, when a substantial proportion of CreaSolv®-based recycled ABS is used alongside only a minor fraction of virgin ABS, the overall recycled content can reach over 75% [10]. Despite the widespread use of ABS in additive manufacturing, little attention has been paid to how flame-retardant additives influence its mechanical recyclability and subsequent filament extrusion. This study investigates the influence of flame-retardant additives on the mechanical recycling process and subsequent 3D-printing filament production of acrylonitrile butadiene styrene (ABS). The study followed a sequential procedure that included material selection and cleaning, size reduction to produce flakes, sample production, characterization, comparative analysis, and a final interpretation of the result.

2. Materials and Methods

2.1 Material Collection and Preparation

Recovered acrylonitrile-butadiene-styrene (ABS) samples, comprising flame-retardant (ABS-FR) and without flame retardant (ABS), were initially collected from WEEE (from a discarded computer). Sample selection was done based on the prevalence of waste products in the local environment. Following appropriate sample collection, cleaning and grinding operations were performed sequentially to eliminate surface impurities and get the required dimensions for further examination.

2.2 Methods

2.2.1 Sample Preparation

Recycled ABS samples, one containing a flame-retardant additive (ABS-FR) and one without (ABS), were prepared and subsequently analyzed for their chemical, thermal, and mechanical properties via FTIR, EDX, TGA, DSC, melt flow, extrusion, fire resistance, tensile strength, and modulus testing.

2.2.2 Sample Designation

Ten samples were taken from each item, and recycled ABS-FR is designated by ABS_f, while ABS without flame retardant is designated by ABS_p, as illustrated in Tables 1 & 2, respectively.

Table 1.

Table 1. ABS-FR samples and their corresponding designations

Sample	sample1	Sample2	sample3	sample4	Sample6	Sample6	Sample7	Sample8	Sample9	Sample10
Designation	ABS_{f1}	ABS_{f2}	ABS_{f3}	ABS_{f4}	ABS_{f5}	ABS_{f6}	ABS_{f7}	ABS_{f8}	ABS_{f9}	ABS_{f10}

Table 2. ABS samples and their corresponding designations

Sample	sample1	Sample2	sample3	sample4	Sample6	Sample6	Sample7	Sample8	Sample9	Sample10
Designation	ABS_{p1}	ABS_{p2}	ABS_{p3}	ABS_{p4}	ABS_{p5}	ABS_{p6}	ABS_{p7}	ABS_{p8}	ABS_{p9}	ABS_{p10}

2.2.3 Sample characterization

The properties of both the PS-FR and PS samples were characterized according to ISO standards. Sample parameters and the corresponding characterization methods are summarized in Table 3.

Table 3. Characterization Methods and Standards for ABS-FR and ABS Samples

Characterization	Methods	Standards
FTIR Analysis	Fourier-transform infrared spectroscopy was performed using a PerkinElmer Spectrum instrument, utilizing a diamond attenuated total reflectance (ATR) accessory to probe molecular vibrations. The spectra were acquired across the 4000–600 cm^{-1} wavenumber range at a spectral resolution of 4 cm^{-1}, with data points collected at 1 cm^{-1} intervals and averaged to improve the signal-to-noise ratio.	ISO 10640:2011 standard was utilized
EDX Analysis	The SEM Joel IT300 machine was used for energy dispersive X-ray analysis (EDX) to determine the chemical composition of ABS-FR and ABS samples. The test's goal was to identify elements in the samples that were harmful to the environment.	ISO 16620-4:2024(en) standard was utilized
Thermo- gravimetric (TGA) Analysis	A Q5000 IR thermogravimetric analyzer was utilized to analyze the thermal degradation of ABS-FR and ABS samples. A 10 mg sample from each item was taken, and the tests were carried out at a rate of 10°C/min. The temperature runs from room temperature and increases to 700°C, with an airflow of 15 ml/min. The temperature of degradation began at the junction of two tangent lines, and the maximum temperature corresponded to the first derivative of weight loss.	ISO 11358-1:2014 standard was utilized
Differential Scanning Calorimetry (DSC) Analysis	A Mettler DSC 30 calorimeter (Swiss Mettler-Toledo) with a 10 mg sample and a nitrogen flow rate of 100 mL/min was used to conduct the DSC (Differential Scanning Calorimetry) test. First, samples of ABS-FR and ABS were heated at a rate of 10 degrees Celsius per minute from 0 to 200 degrees. The samples were then reheated from 0°C to 200°C at the same rate after being cooled from 200°C to 0°C at a rate of 10°C per minute. Finally, the inflection point of the thermometers was	ISO 11357-1:2023(en) standard was utilized

	utilized to determine the samples' glass transition temperature (Tg).	
Melt flow Analysis	ABS-FR and ABS powder granules were fed into a 4003DE capillary rheometer (Morgantown, PA, USA) equipped with a 162 mm × 9.55 mm barrel and an 8.0 mm × 2.096 mm die. Controlling temperature, load, and collection rate yielded a final diameter of 1.75 ± 0.10 mm, the recommended diameter for 3D printing.	ISO 1133-1:2022 standard was utilized
Extrusion Analysis	ABS-FR and ABS filament were extruded for 3D printing using a Thermo-Hake PTW16 intermeshing, co-rotating twin-screw extruder. This extruder has a 16 mm screw diameter, a 3 mm die, a length-to-diameter ratio of 25, and five individually controlled heating zones.	ISO 16790-1:2021 standard was utilized
Cone Calorimeter Analysis	The fire performance of both ABS-FR and ABS was evaluated using a cone calorimeter, with assessments based on oxygen consumption measurements during combustion. Throughout the experiment, the sample surface was subjected to varying heat fluxes. However, the introduction of excessive airflow caused the sample to ignite and burn. Ultimately, the samples were evaluated for mass loss, smoke production, heat release rate (HRR), total heat release rate (THRR), and time to ignition (TTI).	ISO 5660-1:2015 standard was utilized
Tensile Test Analysis:	Recycled dumbbell-shaped specimens of both ABS-FR and ABS underwent uniaxial tensile loading using an Instron 5969 electromechanical tester equipped with a 50 kN load cell. Samples were tested for tensile strength at break (σb), elongation at break (εb), and Young's modulus (E) at a crosshead speed of 0.25 mm/min. The average value of five replicates was taken.	ISO 527-1:2019 standard was utilized

3. Result and Discussion

3.1 FTIR Analysis

Flake samples (20 mg) of both ABS-FR and ABS were taken and subsequently analyzed via Fourier-transform infrared (FTIR) spectroscopy for sample confirmation. The resulting spectra are presented in Figure 1.

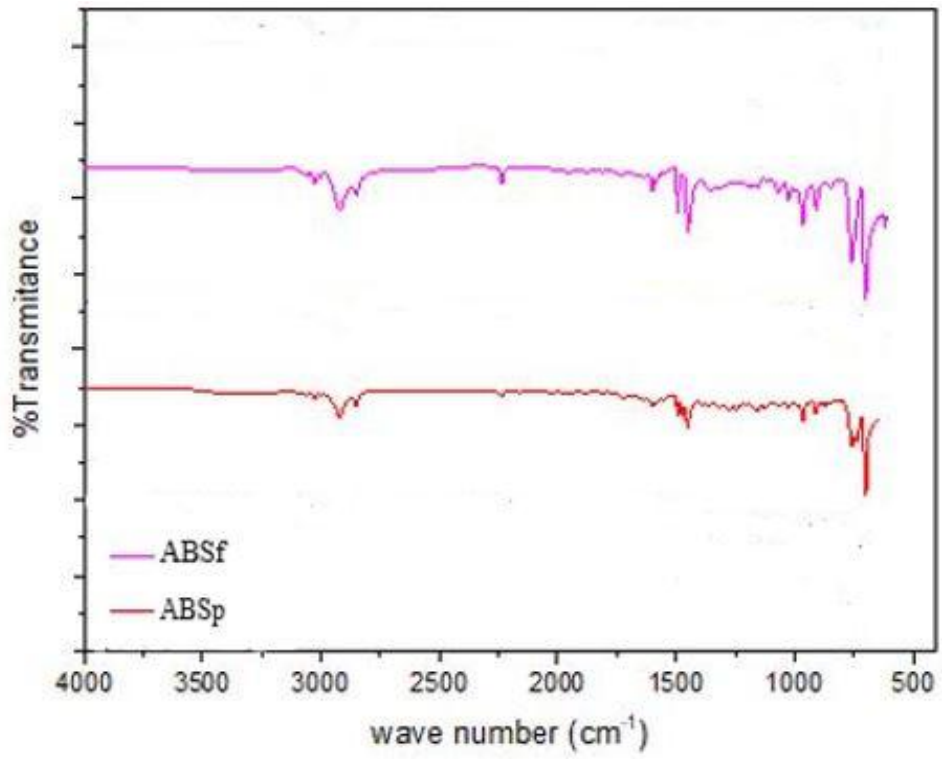


Figure 1. Results of the FTIR analysis of both the ABS-FR and ABS samples

FTIR analysis confirmed that the sample is acrylonitrile-butadiene-styrene (ABS), as indicated by its characteristic vibrational peaks: 3061–3062 cm^{-1}, C-H stretch aromatic; 2924–2850 cm^{-1}, C-H stretch aliphatic; 2238–2237 cm^{-1}, C≡N stretch; 1602 cm^{-1}, C=C stretch aromatic; 1494–1452 cm^{-1}, CH_3 and CH_2 bend vibrations; and 966–910 cm^{-1}, OOP, or out-of-phase, C-H bending vibrations. The last observed band emerged as a shoulder at 1028 cm^{-1}, accompanied by signals at 758 and 698 cm^{-1}, consistent with a monosubstituted aromatic benzene ring. While the 800–600 cm^{-1} spectral range is generally associated with C–Cl stretching vibrations, the bands at 758 and 698 cm^{-1} are more likely attributable to chloride-containing species derived from the flame-retardant additive.

3.2 EDX (Energy Dispersive X-ray) Analysis

To define the chemical composition, 20 mg samples of both ABS-FR and ABS were analyzed via SEM (Joel IT300). The results are presented as energy (keV) versus intensity (cps/eV) in Figure 2.

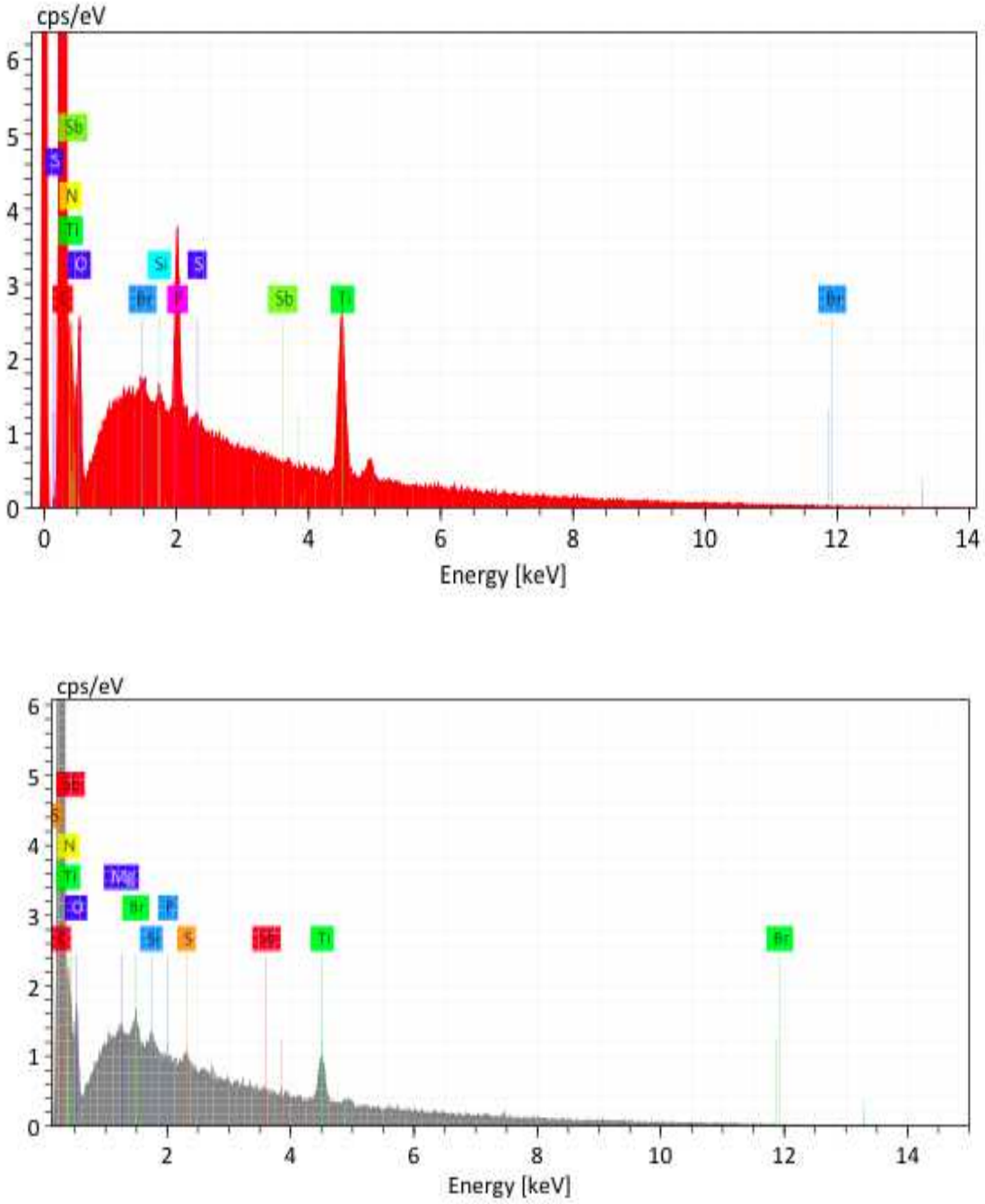


Figure 2. Elemental analysis diagrams for the ABS-FR and ABS samples, respectively

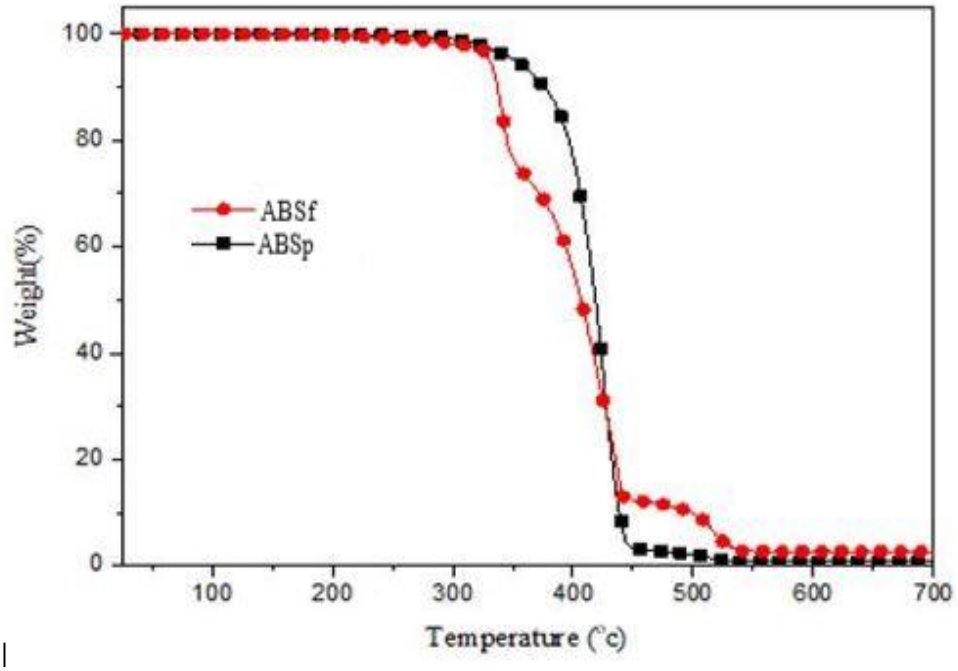
Table 4. Elemental analysis results for the ABS-FR and ABS samples

Element (%)	C	N	O	Ti	Br	Si	S	Mg	p
ABS-FR	90.26	6.41	2.54	0.51	0.02	0.02	0.02	0.22	0.23
ABS	91.79	6.36	1.61	0.17	0.01	0.02	0.02	0.01	0

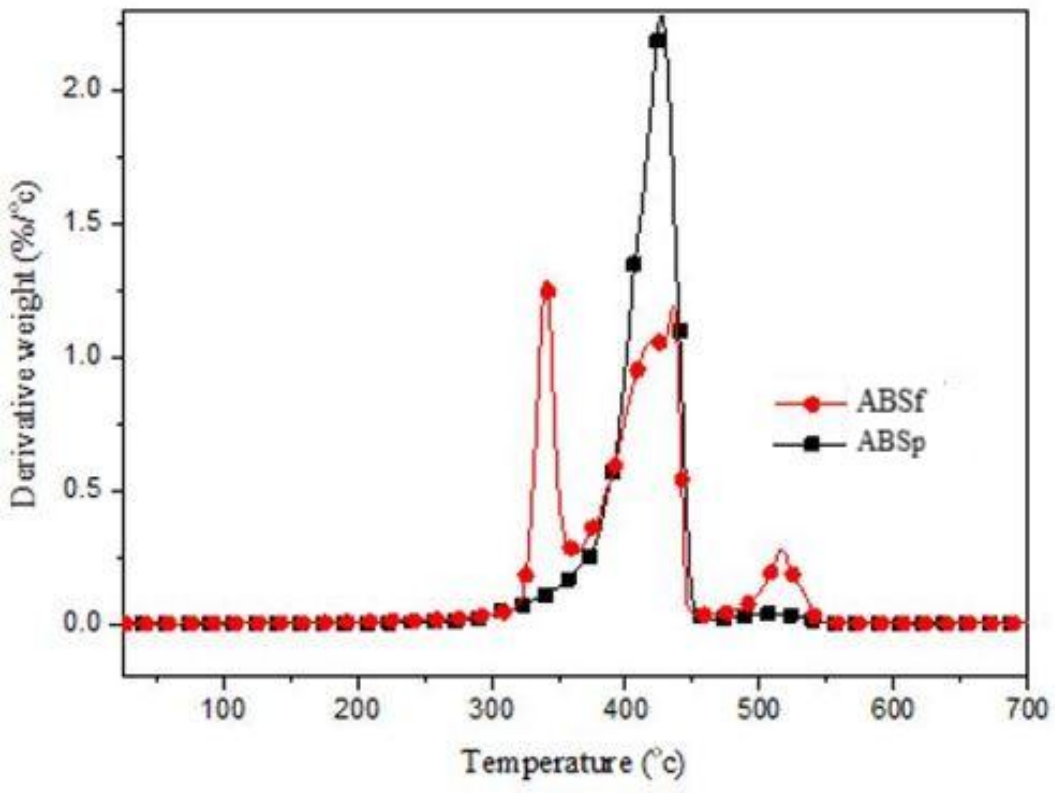
Both samples contained trace amounts of the hazardous elements bromine (Br) and titanium (Ti), as determined by compositional analysis. Pursuant to European Commission Regulation 1357/2014 [11], the permissible upper concentration limit for the hazardous elements bromine (Br) and titanium (Ti) in WEEE waste is 5,000 mg/kg (0.5% w/w). According to the European Committee for Standardization (CENELEC), the concentration of environmentally hazardous elements in plastics derived from WEEE must not exceed 2000 mg/kg (0.2%) [12]. However, the concentration of bromine and titanium affects the reprocessing of ABS, as both elements exceed the permissible threshold limits [13, 14, 15, 16, 17].

3.3 TGA analysis

Thermal degradation investigation was carried out using 10 mg samples of both ABS-FR and ABS. The samples were heated from room temperature to 700 °C at a constant rate of 10 °C/min while maintaining a 15 mL/min airflow. Figure 3 illustrates the resulting thermograms.



a) Sample Thermogravimetric analysis result



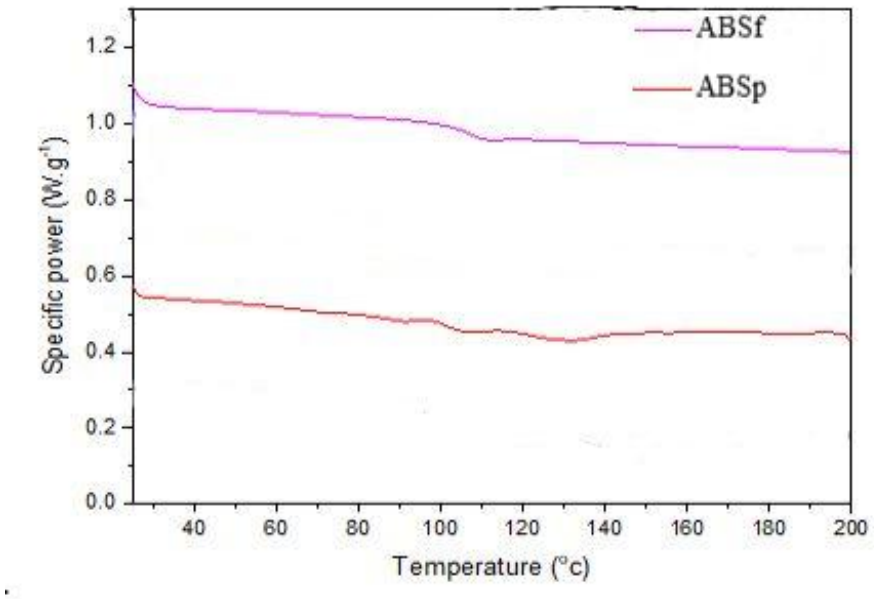
b) Sample Differential Thermogravimetric analysis result

Figure 3. Thermogravimetric analysis (TGA) thermograms of recycled acrylonitrile butadiene styrene (ABS) samples

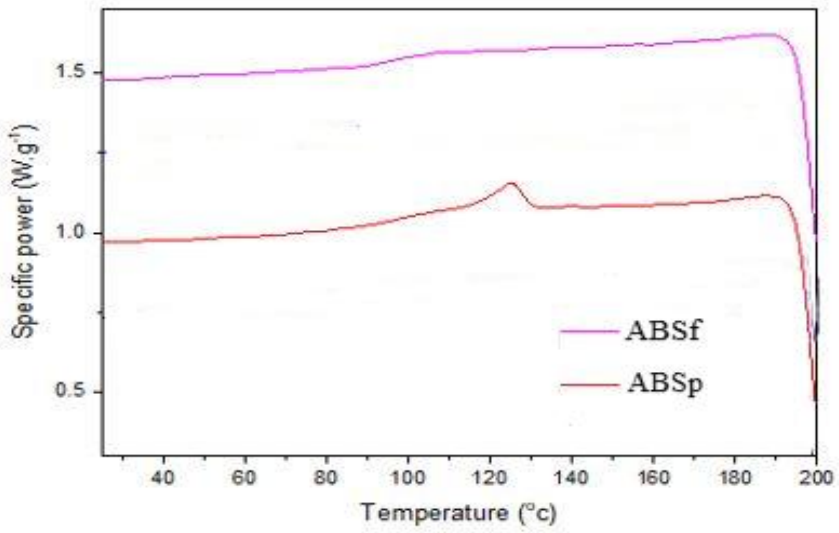
Thermal degradation of recycled ABS starts at 350°C, reaches 95% mass loss at 450°C, and achieves complete decomposition at 550°C. On the other hand, the thermogravimetric analysis of the ABS-FR samples revealed a two-stage degradation process. The initial weight loss, occurring between 325°C and 360°C, corresponds to the thermal decomposition of the acrylonitrile-butadiene-styrene (ABS) matrix [18, 19, 20]. The second stage of pyrolysis, which occurs between 360 and 448°C, is primarily attributed to the flame-retardant additive [21, 22]. Entering the second pyrolysis stage, the sample undergoes accelerated thermal decomposition, with a cumulative weight loss of 95% recorded at 600°C. Once 600°C is reached, no further degradation takes place until the temperature reaches its final setting of 700°C. Flame retardant additives play a critical role in the thermal degradation of acrylonitrile-butadiene-styrene (ABS) [21, 22, 23, 24]. FR plastics have lower onset temperatures for decomposition and weight loss during initial processing compared to non-FR or virgin plastics [24, 25] .

3.4 DSC Analysis

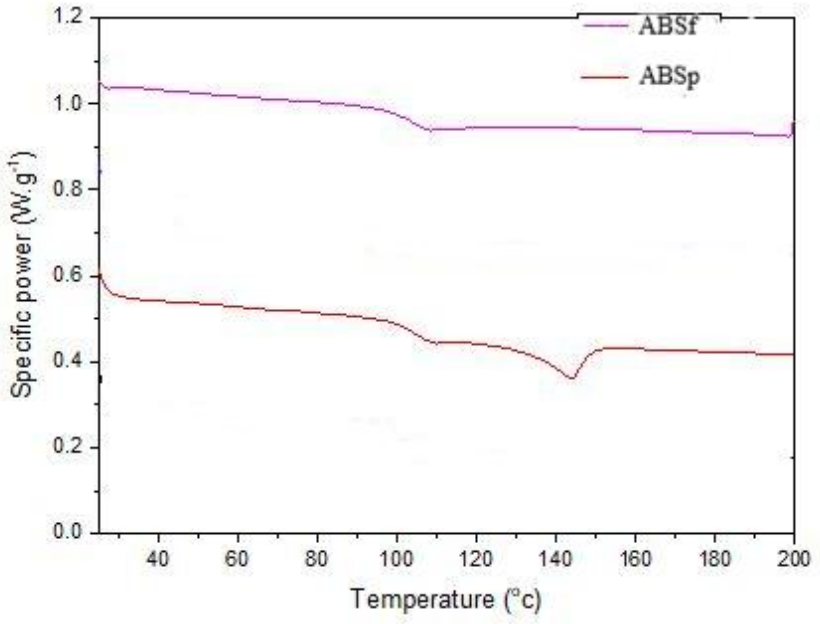
The glass transition temperatures (*Tg*) of ABS-FR and ABS (~10 mg) were determined via DSC under N_2 flow (100 mL/min). The samples were subjected to controlled heating-cooling cycles, and the resulting thermograms are presented in Figure 4.



First heating thermogram



Cooling thermogram



Second heating thermogram

Figure 4. Differential Scanning Calorimetry (DSC) thermograms of recycled acrylonitrile-butadiene-styrene (ABS) samples

Table 5. Thermal transition profiles of ABSf and ABSp

Sample	Tg (°C)
ABSf	103
ABSp	107

The first heating scan was discarded to eliminate thermal-stress effects, and the second scan was analyzed. As shown in Figure 4, the recycled ABS sample exhibited a glass transition temperature (Tg) of 107°C, while the ABS-FR sample showed a slightly lower Tg of 103°C. The 4°C depression in the thermal transition temperature indicates that the flame retardants function as plasticizers within the ABS matrix, thereby lowering the glass transition temperature [25, 26, 27, 28].

3.5 Melt Flow Analysis

The rheological properties of both the ABS-FR and ABS samples were determined in accordance with ISO 1133-1:2022. Testing was conducted at 220°C under a 10 kg load, with the results summarized in Table 6.

Table 6. Melt Flow Analysis Results for ABS-FR and ABS Samples

Sample	Melt flow rate (g/10min), 220 ℃, 10kg
ABSf	30 ± 0.1
ABSp	41 ± 0.3

As shown in Table 6, the melt flow rate (MFR) of ABS-FR is substantially lower than that of ABS. Consequently, this reduced MFR negatively impacts the throughput and efficiency of recycled ABS. Dispersed flame retardants create a physical barrier in molten ABS, raising internal friction and melt viscosity, which restricts flow [29, 30, 31].

3.6 Extrusion Analysis

Both samples were extruded using a Thermo-Hake PTW16 co-rotating twin-screw extruder (screw diameter: 16 mm; die diameter: 3 mm; L/D: 25) equipped with five temperature zones. The resulting filaments are shown in Figure 5.



a. *ABSp extruded filament*

b) *ABSf extruded filament*

Figure 5. Extruded filaments of ABS and flame-retardant ABS (ABS-FR)

Table 7. Processing parameters (temperature, linear density, and productivity) and the resulting filament diameter for both ABS and ABS-FR samples

	Temperature setting zones (°C)					Linear density	Productivity	Average diameter
Sample	T1	T2	T3	T4	T5	(g/m)	(g/min)	(mm)
ABSp	130	190	195	200	210	0.40	11.4	1.80 ± 0.03
ABSf	130	190	195	200	210	0.27	9.1	1.52 ± 0.03

Compared with ABS, ABS-FR exhibits a significantly lower linear density and productivity, as shown in Table 7. The higher density and plasticizing nature of flame retardant additives results in increased filament mass and decreased processing productivity. Consequently, a reduced filament diameter is necessary to attain the desired linear density [26, 27]. The average diameter of the ABS-FR filament (ABS-FR) is significantly below the standard 3D printing specification of 1.75 ± 0.1 mm. The ABS filament sample demonstrated a remarkable diameter for 3D printing. Its practical applicability was verified by printing a dumbbell-shaped specimen on the SHAREBOT next-generation 3D printer, as depicted in Figure 6.



a) *Sharbot 3D next generation machine printing ABSp filament*

b) *Produced* Dumbbell shape *ABSp speciemen*

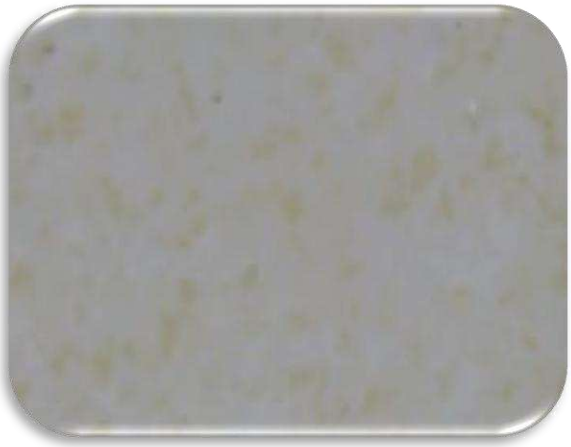
Figure 6. Recycled ABS Dumbbell Specimen Production

3.7 Cone Calorimetry Analysis

Plates of both ABS and ABS-FR were produced using a Carver Laboratory press machine (Fig. 7). Their flammability was subsequently evaluated using a cone calorimeter, with the results summarized in Tables 8 and 9.



1. *ABSp compression molded plate*



2. *ABSf compression molded plate*



3. *ABSp flamability test result*



4. *ABSf flamability test result*

Figure 7. Flammability Analysis of ABS and Flame-Retardant ABS (ABS-FR) Samples

Table 8. Flame Retardant Confirmation Analysis for ABS Samples

Sample	**FTIR**	**Fluorescence X**	**Cone**
ABSp	ABS	SiO_2, TiO_2 and sulfur	No confirmation of FR
ABSf	ABS-FR	Presence of phosphorus & TiO_2 FR	Confirmation of FR

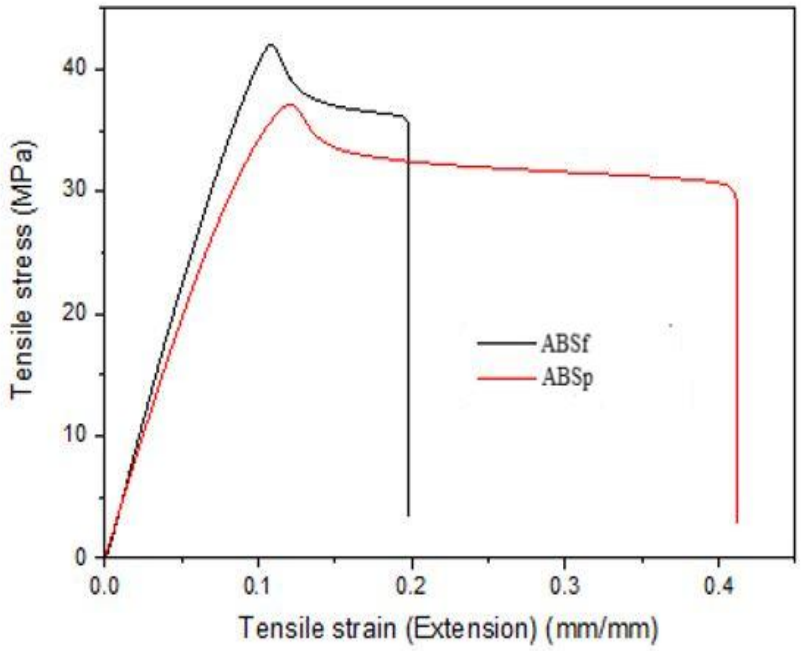
Table 9. Evaluation of Ignition and Combustion Parameters for ABS Test Samples

Samples	TTI(s)	PHRR (kw/m^2)	THR at the end of the test (MJ/m^2)	Final Mass (%)
ABSp	46	825	162	0
ABSf	51	427	132	2.6

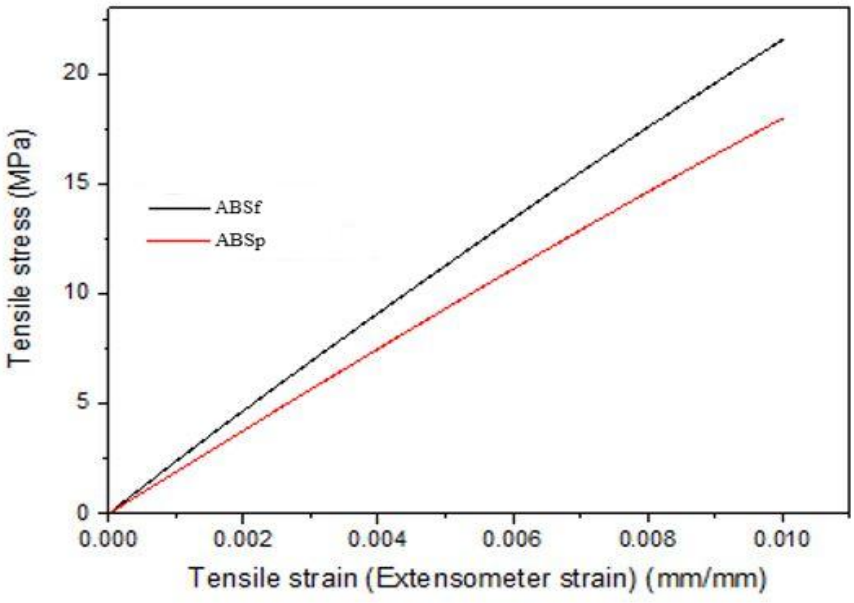
As it was presented in Table 9, ABS-FR shows a significantly higher time to ignition (TTI) in comparison with ABS. The flame retardant additives act as a heat sink (undergoing an endothermic process). This delays the samples from reaching pyrolysis temperature, which consequently increases the time to ignition (TTI) [32, 33]. However, ABS exhibits significantly higher peak heat release rate (PHRR) and total heat release (THR) values than ABS-FR. Flame retardants are non-combustible substances that take up space within materials, leading to a decrease in the proportion of combustible hydrocarbon fuel per unit weight. This dilution effect ultimately reduces both the total heat release rate and the peak heat release rate [33, 34, 35].

3.8 Tensile Testing Analysis

For tensile testing, dumbbell-shaped specimens were prepared via injection molding. The tensile strength, strain, and modulus were evaluated for both ABS and ABS-FR, and the results are presented in Figure 8.



a). Tensile Strength Test Result



b). Tensile Modulus Test Result

Figure 8. Tensile strength (a) and modulus (b) of ABS and ABS-FR

Table 10. Comparison of Tensile Modulus, Ultimate Tensile Strength, and Elongation at Break for ABS-FR versus ABS

Sample	E(Mpa)	σb (Mpa)	εb (mm)
ABSf	2574 ± 84.12	31 ± 0.70	0.2 ± 0.03
ABSp	1950 ± 50.03	37 ± 0.81	0.4 ± 0.14

As seen in Table 10, ABS having a flame-retardant additive has a greater Young's modulus than ABS without it. Flame retardants dispersed in a polymer matrix physically restrict the movement of polymer chains, increasing stiffness while decreasing toughness and impact resistance [36]. In contrast, recycled ABS containing flame-retardant additives exhibits reduced tensile strength and lower strain at failure. Flame retardant additives disrupt the entanglement and bonding between the long polymer chains of ABS, reducing the material's ability to withstand tensile forces [37, 38, 39].

4. Conclusion

Flame-retardant additives, while essential for enhancing fire safety, significantly affect the recyclability of acrylonitrile-butadiene-styrene (ABS). The earlier onset of degradation at 325°C and the lower glass transition temperature (103°C) of flame-retardant ABS (ABS-FR) affects the thermal stability of products manufactured from recycled material. The melt flow rate (MFR) of ABS-FR (30 ± 0.1 g/10 min) is notably lower than that of ABS (41 ± 0.3 g/10 min), which consequently diminishes processing throughput. Compared to recycled ABS (0.40 g/m, 14.4 g/min, 1.80 ± 0.03 mm), ABS-FR showed significantly lower linear density (0.27 g/m), productivity (9.1 g/min), and diameter (1.52 ± 0.03 mm), resulting in both reduced output and lower dimensional consistency. In line with expectations, ABS-FR exhibited a notable increase in flame resistance. Flame-retardant additives substantially alter the key mechanical properties of ABS. ABS-FR exhibits a higher tensile modulus (2574 ± 84.12 MPa) but shows marked reductions in both tensile strength and strain to failure (31 ± 0.70% and 0.2 ± 0.03, respectively). Consequently, this formulation is unsuitable for high-load-bearing applications.

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