STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Special Issue 3, 2026
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Development and Characterization of Rubber Composites using E-Waste Residue as Functional Filler

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Abstract

In the present study, residue generated during the recycling of end-of-life printed circuit boards (PCBs) was utilized as a functional filler in natural rubber to fabricate eco-friendly composites using mixing and molding techniques. Chemical analysis of the residue revealed the presence of several metals, including copper, iron, lead, tin, and zinc. The presence of these metals highlights the need for proper recycling and safe management of PCB residues, as their release into the environment can cause serious ecological contamination and potential health risks to living organisms. At the same time, the metal-rich nature of the residue indicates its potential for several functional material applications. Incorporating the residue into a rubber matrix for radiation shielding provides a sustainable and environmentally responsible approach for converting hazardous waste into useful value-added materials. The developed rubber composites were evaluated for mechanical, thermal, and radiation shielding properties. The e-waste residue content was varied from 0 to 600 phr to investigate its influence on composite performance. With increasing filler content up to 600 phr, hardness increased from 45 to 87 Shore A, and density increased from 0.89 to 2.42 g/cm³, indicating improved compactness. X-ray radiographs showed significant improvement in radiation shielding due to the high metal content present in the residue. SEM analysis confirmed uniform filler dispersion and dense microstructures, indicating potential applications in advanced radiation shielding products and protective materials.

Keywords: *E-waste, Residue, Functional Filler, Rubber composites, value-added materials.*

INTRODUCTION

Electronic waste comprises of discarded electrical and electronic equipment and their components that are no longer intended for use and have reached the end of their functional life. The widespread use of electronic devices has contributed to the rapid growth of electronic waste generation [1, 2]. Advances in technology and limited operational lifespans of electronic devices have accelerated this growth. The improper handling and disposal of e-waste has emerged as a serious environmental and public health concern due to its complex composition and hazardous nature [3]. E-waste contains a wide range of toxic substances, including heavy metals such as Pb, Cd, and Cr as well as flame retardants and polychlorinated biphenyls that leach into soil, water, and air [4, 5]. When these toxic constituents are released into the environment, they pose significant risks to ecosystems and human health, including neurological damage, respiratory disorders, and carcinogenic effects [6]. These concerns have stimulated growing research interest in the development of sustainable polymer composite materials that enable the utilization of waste-derived resources, promoting environmentally responsible waste management while supporting value-added material applications.

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Received Date: March 12, 2026
Accepted Date: March 31, 2026
Published Date: May 08, 2026

Citation: Rajesh Kumar, Basant Lal, Arti Maan, Mukul Das. Development and Characterization of Rubber Composites using E-Waste Residue as Functional Filler. Journal of Polymer & Composites. 2026; 14(Special Issue 3): S512–S523p.

Printed circuit boards (PCBs), which form the backbone of almost all electronic devices, are among the most valuable yet hazardous components of e-waste due to their high content of precious elements such as Cu, Au, Ag, Ni and Si [7,8]. In developing countries such as India, the informal sector plays a dominant role in e-waste collection and recycling activities [9]. One of the most commonly practiced techniques for metal recovery involves the open burning of PCBs to remove polymeric fractions and extract valuable metals. This process results in formation of large quantities of black residue and emission of hazardous fumes that cause severe environmental pollution and occupational health hazards [10-12]. Despite the economic value of metals present in e-waste, the lack of efficient, environmentally benign recycling technologies results in substantial material loss and secondary contamination. These limitations highlight the urgent need for innovative and sustainable approaches to e-waste management that not only enable resource recovery but also mitigate environmental pollution and human health hazards.This emphasize the need for alternative strategies that enable the utilization of such residues within material systems rather than treating them as waste.

The residue generated from PCB contains a substantial amount of carbon-rich material formed through the incomplete combustion of epoxy resins and other organic constituents [13, 14]. This residue not only contains carbonaceous residue matter but also some significant amounts of metallic constituents originating from the PCB structure [15-17]. Rather than being discarded, such residues present an opportunity for value-added utilization as functional fillers in composite materials.

Carbonaceous residue is primarily composed of elemental carbon and is widely used as a functional filler in polymer and rubber industries [18]. It is typically produced through the incomplete combustion or thermal decomposition of hydrocarbon sources. Rubber-based composites offer a versatile platform for incorporating waste-derived fillers due to their flexibility, processability, and ability to accommodate high filler loadings. Carbonaceous residue is widely recognized as an effective functional filler in rubber matrices, where it enhances mechanical strength, abrasion resistance, and durability through strong filler–matrix interactions [19, 20]. When carbonaceous residue rich PCB residue is incorporated into rubber, the carbonaceous phase contributes reinforcement, while the embedded metal content enhances the functional performance of the composite. This combination of rubber and carbon-rich residue along with the metallic components enables the development of multifunctional composites with potential shielding and protective applications [21, 22]. This approach reduces the environmental impact associated with PCB burning residues but also promotes sustainable material development through the conversion of hazardous waste into value-added composite products.

The present study focuses on the development of composite materials using e-waste residues, particularly from used printed circuit boards, combined with rubber as a binder. The carbon-rich residue from PCBs not only provides reinforcement but also retains metallic content that can contribute to functional properties of the composite, while rubber enhances various properties [23]. By utilizing these waste-derived materials, the study aims to create value-added composites that address environmental challenges associated with both e-waste and rubber disposal [24]. The main objective is to promote sustainable material development by converting hazardous waste into functional composites with potential applications, including X-ray shielding, thereby reducing the environmental footprint and supporting eco-friendly solutions in material engineering. This strategy contributes to sustainable material development by promoting the use of waste derived resources in rubber matrix and hence reducing environmental burdens associated with electronic waste disposal.

EXPERIMENTAL

Materials

E-waste residue was collected from local recycling sites. Following standard testing procedures, the residue was dried, cooled at ambient temperature, and then assessed. In the chemical analysis of the e-waste residue, increased concentrations of copper, tin, calcium, silicon, and aluminum were discovered, whereas lower concentrations of lead, cadmium, chromium, antimony, and nickel were detected.

Natural rubber in the form of pale crepe was obtained locally and used as the elastomeric matrix. Sulfur, employed as the vulcanizing agent, was purchased from Merck Millipore, Germany, and utilized without further purification. Magnesium oxide, serving as an activator, was procured from CDH (P) ltd., while Zinc stearate from Sigma-Aldrich, USA, was included to assist in the vulcanization process. Accelerators, N-Cyclohexyl-2-benzothiazolesulfenamide (CBS) and N-tert-Butyl-2-benzothiazolesulfenamide (TBBS), were also obtained from Merck Life Science Pvt Ltd., India and were used as such. All of these materials were utilized as such without any additional purification.

Methods

Characterization of E- Waste Residue

The e-waste residue was initially characterized to evaluate its physicochemical properties, including chemical composition, carbon black content, particle size distribution, CHNS elemental composition, thermal degradation behavior, and density. Prior to characterization, the residue was oven-dried to remove moisture. The dried material was then mechanically ground using a scrap grinder to reduce the particle size, followed by sieving to obtain a uniform particle fraction suitable for further analysis and composite preparation.

Chemical Characterization

Chemical characterization of the e-waste residue was performed in accordance with standard analytical guidelines using instrumental techniques. A known quantity of the residue was placed in a ceramic crucible and heated in a muffle furnace at 400℃ for 6 h to remove volatile and organic components. The resulting ash was fused with a carbonate flux consisting of potassium carbonate and sodium carbonate for the determination of metallic constituents such as Si, Cu, Fe, Pb, Al, Ba, B, Sn, Sb, Cr, W, and Zn.

The fused mass was dissolved in a 1:1 (v/v) HCl–water solution, evaporated to dryness, and dissolved again in the same acid mixture. The solution was boiled to precipitate silica (SiO_2), followed by filtration. The filtrate was analyzed using Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES) to quantify metal concentrations.

The residue retained on the filter paper was thoroughly washed with hot water until chloride-free, ignited at 600–1000℃, and weighed. Subsequently, a few drops of concentrated H_2SO_4 and 3–5 mL of hydrofluoric acid were added, and the sample was re-ignited at 900–1000℃. Silica content was calculated using the gravimetric method:

$$\%SiO_2 = \frac{(W2-W1)}{\text{Weight of Sample}} * 100$$

Tungsten content was determined separately by heating 1 g of the e-waste residue in a Teflon crucible at 600℃ for 6 h, followed by acid digestion using HF and HNO_3. The resulting solution was analyzed by ICP-OES.

Carbon Black Content: Carbon Black Content can be determined in accordance with IS: 2530 standard [25]. Preheat the combustion boat and allow it to cool in a desiccator. Accurately weigh approximately 1 g of the e-waste residue and place it in the combustion boat. Position the boat with the sample at the center of the combustion tube and insert a stopper with a nitrogen inlet at one end. Pass nitrogen through the tube at a flow rate of 1.7 ± 0.3 L/min. Heat the furnace to 500 ± 5℃ and maintain this temperature for 10 minutes. After heating, allow the furnace to cool for 5 minutes while maintaining the nitrogen flow. Finally, remove the combustion boat, cool it in a desiccator for 20–30 minutes, and record the final weight of the sample in grams.

Calculation

$$\% \text{ Carbon Black} = \frac{(W1-W2)}{W3} * 100$$

Where W_1 = weight in g of the boat before heating in air, W2 = weight in g of the boat after heating in air, and W_3 = weight in g of the material taken for the test.

Particle Size Analysis: Particle size distribution of the e-waste residue was determined using a Particle Size Analyzer (Microtrac S3500, Microtrac Inc., USA). Measurements were carried out over a size range of 0.2 μm to 2800 μm. The Turbotrac accessory was employed to enable dry-mode analysis of the e-waste residue.

CHNS Analysis: CHNS analysis was carried out to determine the elemental composition (C, N, and S) of the e-waste residue using a CHNS analyzer (ElementarVario EL, Langenselbold, Germany). Approximately 3–5 mg of the sample was weighed, mixed with vanadium pentoxide as an oxidizing agent, and sealed in a tin capsule. The capsule was combusted in an oxygen atmosphere at 850℃, followed by reduction at 1000℃, where the tin facilitated rapid and complete oxidation.

The combustion products (CO_2, SO_2, and NO_2) were transported by helium through oxidation (tungsten trioxide) and reduction (copper) catalysts maintained at 1000℃, converting nitrogen oxides to N_2. The resulting gases were then carried by helium for elemental quantification.

Thermogravimetric Analysis (TGA): Using the TGA technique, a substance's mass is measured in a controlled environment as a function of temperature and time. The TGA analysis of the residue from e-waste was performed using a TGA analyzer in an inert environment with a heating rate of 10 minutes up to 1000℃. At various temperatures, weight loss was noted.

Density: Density of the e-waste residue was measured using a pycnometer. The pycnometer volume was determined using water (density 0.9965 g/mL at 27℃). The sample density was then calculated as the ratio of sample mass to the measured pycnometer volume at the test temperature.

Preparation of E-Waste Rubber Composite

The e-waste residue was segregated in different particle sizes (25, 75, 100 and 150) using the corresponding sieves of different mesh size. The e-waste rubber composites were prepared using different compositions of natural rubber, e-waste residue (as such or in different particle size), magnesium oxide, zinc stearate, N-Cyclohexyl-2-benzothiazolesulfenamide (CBS), N-tert-Butyl-2-benzothiazolesulfenamide (TBBS), and sulfur using milling and molding operations. In milling operation, rubber was first masticated on a laboratory two-roll mill for 4-5 minutes. Subsequently, e-waste residue was added and the rubber and e-waste residue were compounded in the two roll mill for 10-12 minutes. Activators, accelerators and sulfur were added in the composition and milling was continued for next 15 min. The e-waste residue rubber composite was molded at 160℃ and 30 ton pressure by a compression molding machine in the form of sheet of 150 cm x 5 cm x 2 mm dimensions. Post curing of prepared e-waste residue-rubber sheet was done at 100℃ for 1hr.

Characterization of E-Waste Residue-Rubber Composite

Hardness: Hardness test of the e-waste rubber composite sheet was determined using a Shore A durometer in accordance with the test method ASTM D2240 [26]. All specimens were conditioned at 23 ± 2℃ prior to testing to ensure consistency in results.

Tensile Strength: Tensile strength of the e-waste rubber composite sheet was determined in accordance with the guidelines of the specification ASTM D 412 [27], using a Universal testing machine (H50KT, Tinius Olsen, UK) at a speed of 500 mm/min. Dumb-bell shaped samples were prepared having overall length 115 mm & width of narrow portion 4.2 ± 0.2 mm. They were conditioned at 23±2℃ for 3 hrs before testing.

Abrasion Resistance: To evaluate the abrasion resistance of the e-waste residue–rubber composite sheets, disk-shaped specimens with a diameter of 100 mm were prepared. The specimens were conditioned at a temperature of 23 ± 2℃ and a relative humidity of 50 ± 5% prior to testing. Abrasion testing was conducted under identical environmental conditions in accordance with the specified test procedure [28]. During the test, CS-10 Taber abrasive wheels were used with an applied load of 1000 g, and the specimens were subjected to 1000 abrasion cycles. The abrasion resistance of the composite sheets was determined by measuring the weight loss of the specimens after completion of the test.

Tear Strength: The tear strength of the e-waste rubber composite sheets was determined following ASTM D624 [29] (Type C) test standards using a Universal Testing Machine (Model H50KT, Tinius Olsen, UK). The tests were performed at a crosshead speed of 500 mm/min. Unnicked specimens having a 90° central angle and an overall length of 102 mm were carefully prepared for the evaluation. Before testing, all specimens were conditioned at a temperature of 23 ± 2℃ for a minimum duration of 3 hours to ensure uniform testing conditions. For each composite formulation, at least three specimens were tested, and the tear strength values were recorded accordingly.

X-ray Properties: To evaluate the X-ray shielding performance of the developed composites, X-ray examination was carried out using a SENSUS X-ray machine. The samples were tested at a tube voltage of 40 kV and a tube current of 6 mA. The distance between the X-ray tube and the samples under investigation was maintained at 100 cm throughout the study. During the measurements, the samples were placed on the X-ray table, and a detector was used to capture the transmitted X-ray radiation. The resulting X-ray images were acquired and subsequently displayed on a digital computer system for detailed observation and analysis.

Surface Analysis by SEM-EDS: The surface morphology and elemental composition of the e-waste residue were examined using Scanning Electron Microscopy (SEM; SEC SNE-4500M Plus A, Suwon, South Korea).

Density and Water Absorption: The density of E-waste residue-rubber composite was determined in accordance with IS 3400[30], while the water absorption was calculated as per IS 5382[31].

RESULT AND DISCUSSION

Characterization of E-Waste Residue

Compositionof E-Waste Residue

It can be seen from (Table 1) that the major metal constituents of the dry ash of the sample. The copper, iron, lead, tin and silica oxide content in the sample were found to be 46.92%. The other metals like zinc, aluminum, titanium, manganese, nickel, barium, boron, cadmium, chromium, antimony, magnesium, and tungsten oxides were also found in significant amounts, which can be utilized in different applications or to make a suitable useful product from embankment blocks, pavement bricks, and radiation shielding material.

Table 1. Chemical Composition of E Waste Residue

Components	CuO	Fe_2O_3	PbO	SnO_2	SiO_2	NiO	ZnO	Al_2O_3	MnO_2	MgO	Sb_2O_3	CaO
wt.%	28.27	7.35	2.95	3.21	5.14	2.01	1.87	1.78	0.75	0.30	0.47	23.64

Carbon Black Content

Carbon Black is a high-purity form of elemental carbon commonly used as a reinforcing filler to improve the mechanical strength and abrasion resistance of rubber composites. Determination of carbon black is the primary step for specific elemental analysis. The test was performed in combustion boat in the presence of nitrogen gas. The Carbon Black was calculated by determining the weight loss of the sample. It can be observed from the results that e-waste residue have carbon black content as ~ 10%.

Particle Size Analysis

Particle size analysis of e waste residue was carried out using a particle size analyser. D 50 value of the particles was found to be 175.8 µm, that means 50% of the particles were smaller and 50% of the particles were larger than 175.8 µm. D 10 and D 90 values were found to be 8.56 µm, and 427.0 µm, respectively. Particle size distribution table of e-waste residue is shown in Fig. 1and Table 2

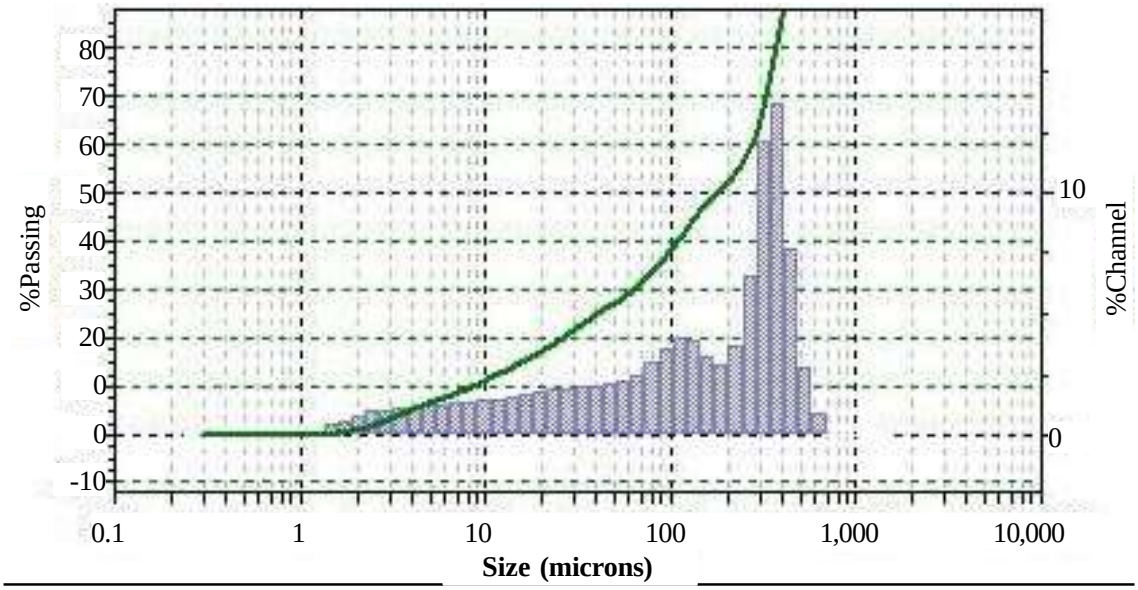


Figure 1. Particle Size Distribution Curve of E-Waste Residue

Table 2. Particle Size Analysis Table f E-Waste Residue

% Tile	D10	D50	D90
Size (µm)	8.56	175.8	427.0

CHNS Analysis

The CHNS elemental contents are reported in weight percent. The result of elemental analysis of e-waste residue are presented in (Table 3), Carbon content in e-waste residue was found to be 30.0 %, hydrogen 3.56%, nitrogen 1.18% and Sulphur 0.16%.

Table 3. CHNS analysis of e-waste residue

Material	C (%)	H (%)	N (%)	S (%)
e-waste residue	30.0	3.56	1.18	0.16

Thermal Degradation of E-Waste Residue

The TGA curve of the e-waste residue (Fig. 2) shows a gradual decrease in mass with increasing temperature, reflecting the thermal decomposition behavior of the sample. In the first region, a small mass loss occurs due to the release of moisture and light volatiles. By 250℃, the volatile content accounted for approximately 2.1 % of the total mass. The second decomposition region, corresponds to the breakdown of more thermally labile organic components, resulting in an additional 8.01 % mass loss at 500℃. Beyond this temperature, the mass stabilizes representing the inorganic fraction of the e-waste residue. The smooth mass reduction observed in the curve indicates the material's high thermal stability, making it suitable as a filler for reinforcing rubber composites.

Density

Density of e-waste residue was determined as 2.58 g/cc. The Specific gravity depends on its chemical composition. Electronic waste with higher content of copper has relatively higher specific gravity.

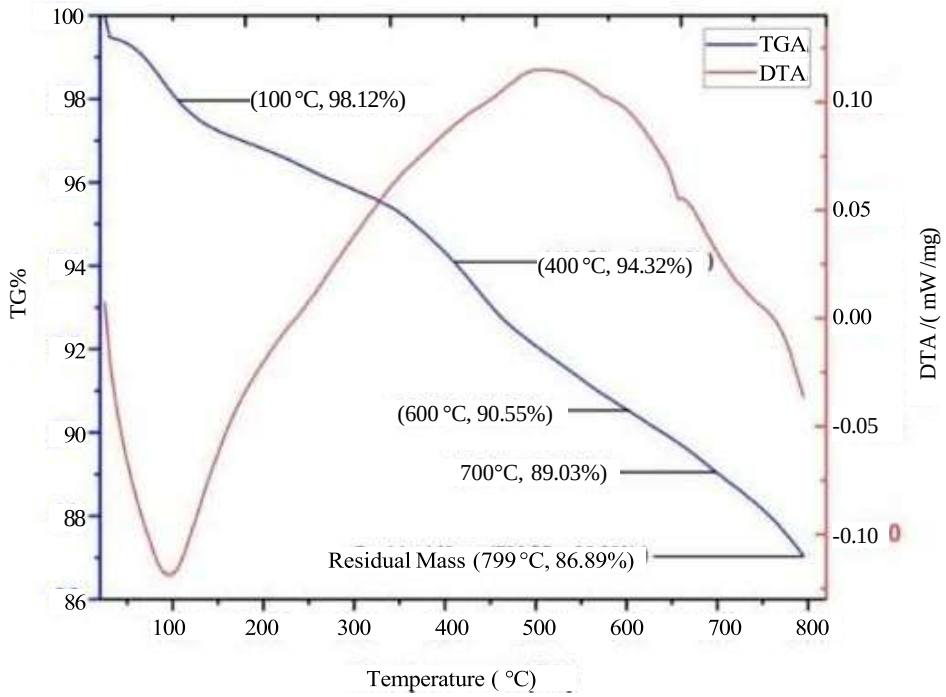


Figure 2. TGA-DTG Thermogram of E-Waste Residue

EDS Analysis of E Waste Residue

The corresponding EDS spectrum (Fig 3) confirms the elemental composition of the residue, indicating the presence of Cu, Fe, Zn, Ti, Mn, Al, Si, Mg, Ca, K, and O. Among these, copper appears as one of the predominant metallic constituents. The detection of carbon and oxygen suggests the presence of residual organic components or oxidized by-products resulting from epoxy resin degradation, which may contribute to improved filler–matrix interaction. Overall, the EDS results demonstrate that the e-waste residue comprises a combination of metallic and non-metallic components originating from printed circuit boards. The exposed, irregular morphology and increased surface area of these particles are advantageous for forming a dense and compact structure, making the residue suitable for X-ray shielding applications.

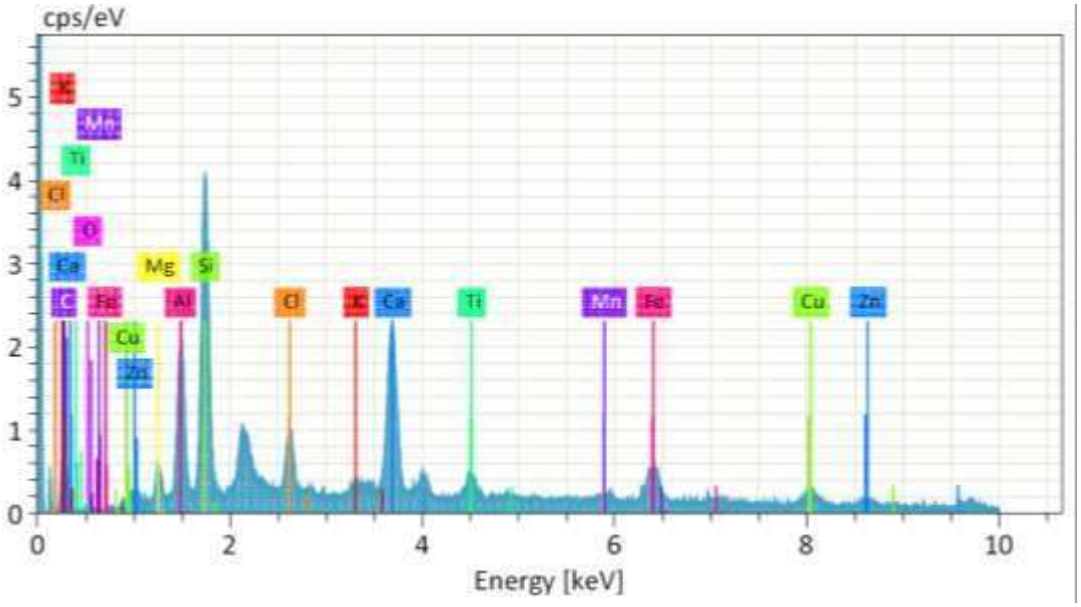


Figure 3. EDS of E-Waste Residue

Characterization of E-Waste-Rubber Composite

As shown in Table 4, hardness of the rubber composite increases steadily from 45 Shore A for unfilled rubber to 87 Shore A at 600 phr e-waste residue loading. This progressive increase in hardness is attributed to the incorporation of rigid filler particles, which restrict the mobility of rubber chains and reduce the elastic deformation of the matrix, resulting in stiffer vulcanizates.

The density of the composites also increases significantly with increasing residue loading, rising from 0.89 g/cm³ for neat rubber to 2.42 g/cm³ at 600 phr. This increase is mainly due to the high density of the metal-rich e-waste residue and the progressive filling of void spaces within the rubber matrix. The increase in density further supports the formation of compact composite structures at higher filler contents.

In contrast, tensile strength decreases continuously with increasing e-waste residue loading, dropping from 13.0 N/mm² for unfilled rubber to 2.0 N/mm² at 600 phr. This reduction is associated with weak interfacial adhesion between the hydrophilic e-waste residue and the hydrophobic natural rubber matrix, which limits efficient stress transfer during tensile deformation [32]. Additionally, at higher filler loadings, filler–filler interactions and particle agglomeration dominate, further reducing the reinforcing efficiency.

A similar decreasing trend is observed for tear strength, which declines from 38.0 N mm for neat rubber to 12.1 N mm at 600 phr. The presence of rigid filler particles acts as stress concentration sites, facilitating crack initiation and propagation under tearing forces. Abrasion resistance, expressed as weight loss, shows a clear deterioration with increasing filler content. Weight loss increases from 0.001 g for unfilled rubber to 0.40 g at 600 phr, indicating reduced abrasion resistance. This behavior is attributed to poor filler–matrix bonding and the tendency of loosely bound filler particles to detach from the rubber surface during abrasion.

Water absorption of the composites increases gradually from 0.13% to 0.86% with increasing residue loading. This trend is mainly due to the hydrophilic nature of the e-waste residue and the increased availability of polar sites that facilitate moisture uptake at higher filler concentrations.

Table 4. Summary of Physico-Mechanical Properties of E-Waste Residue-Rubber Composite at Different Concentration of E-Waste Residue.

E-waste residue (phr)	Hardness, (Shore A)	Density, (g/cm^3)	Tensile Strength, N/mm^2	Tear Strength, N/mm	Weight Loss, (g)	Water Absorption (%)
0	45	0.89	13.0	38.0	0.001	0.13
100	57	1.49	8.0	29.6	0.019	0.49
200	72	1.86	6.5	20.1	0.15	0.58
300	78	2.11	4.4	15.2	0.20	0.62
400	83	2.34	4.0	14.2	0.27	0.69
500	85	2.39	3.2	13.5	0.33	0.80
600	87	2.42	2.0	12.1	0.40	0.86

The effect of particle size at constant filler loading is summarized in Table 5. Hardness decreases from 83 Shore A for 25 µm particles to 75 Shore A for 150 µm particles, indicating superior reinforcement by smaller particles due to their higher surface area and improved filler–rubber interaction, which promotes a more compact composite structure.

A similar trend is observed for density, which decreases from 1.73 to 1.42 g cm^{-3} with increasing particle size. The presence of larger particles leads to increased interfacial voids and reduced packing

efficiency within the rubber matrix. Tensile strength declines from 3.5 to 1.4 N mm^{-2} as particle size increases from 25 to 150 µm, owing to the lower specific surface area of coarse particles and the resulting reduction in effective stress transfer. Tear strength follows the same trend, further confirming the lower reinforcing efficiency of larger particles.

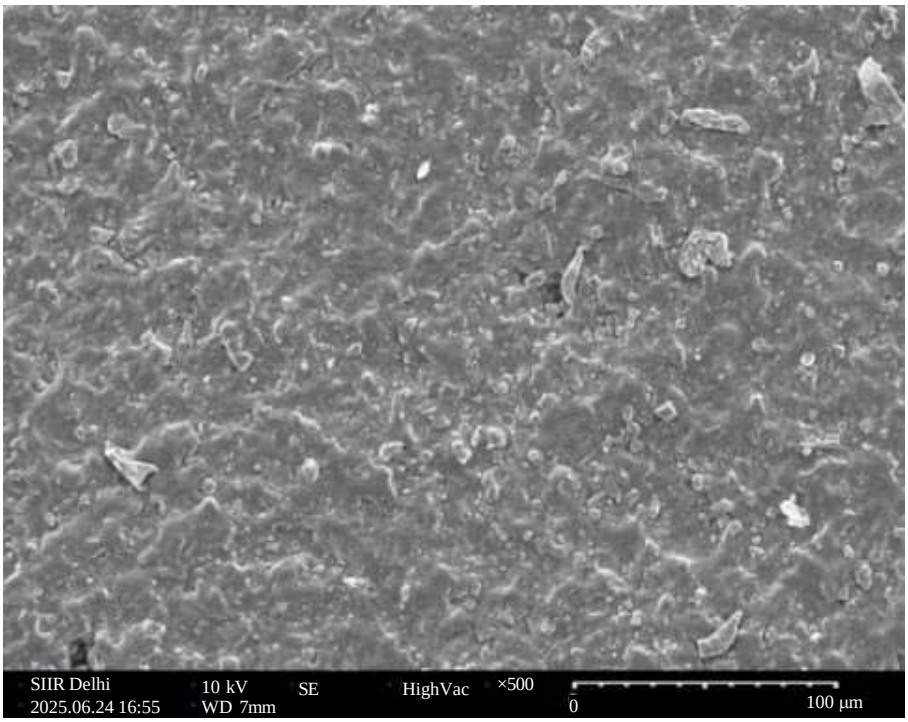
Abrasion resistance deteriorates with increasing particle size, as reflected by the rise in weight loss from 0.29 to 0.51 g, which is attributed to weaker interfacial bonding and increased particle pull-out during abrasion. Water absorption also shows a slight increase, from 0.53% to 0.80%, due to reduced filler–matrix interaction and the presence of more exposed hydrophilic sites and micro-voids in composites containing coarser particles.

Table 5. Summary of Physico-Mechanical Properties of E-Waste Residue-Rubber Composite at Different Particle Size of E-Waste Residue

Particle size (µ)	Hardness, (Shore A)	Density, (g/cm^3)	Tensile Strength, N/mm^2	Tear Strength, N/mm	Weight Loss, (g)	Water Absorption (%)
Upto25	83	1.73	3.5	12.8	0.29	0.53
Upto75	80	1.62	2.4	11.2	0.32	0.60
Upto100	78	1.54	2.0	10.0	0.44	0.66
Upto150	75	1.42	1.4	8.1	0.51	0.80

SEM Analysis

The SEM micrographs (Fig 4) of the e-waste residue–rubber composite reveals a relatively uniform and compact surface morphology with good dispersion of filler particles within the rubber matrix. The absence of large cracks or voids indicates effective incorporation of the residue into the elastomeric phase. Irregularly shaped e-waste particles are embedded in the rubber matrix, suggesting mechanical interlocking between the filler and rubber chains. The rough surface texture enhances filler–matrix contact and is consistent with the increased hardness and density observed experimentally. Overall, the SEM results confirm the formation of a dense composite structure suitable for functional applications such as radiation shielding.



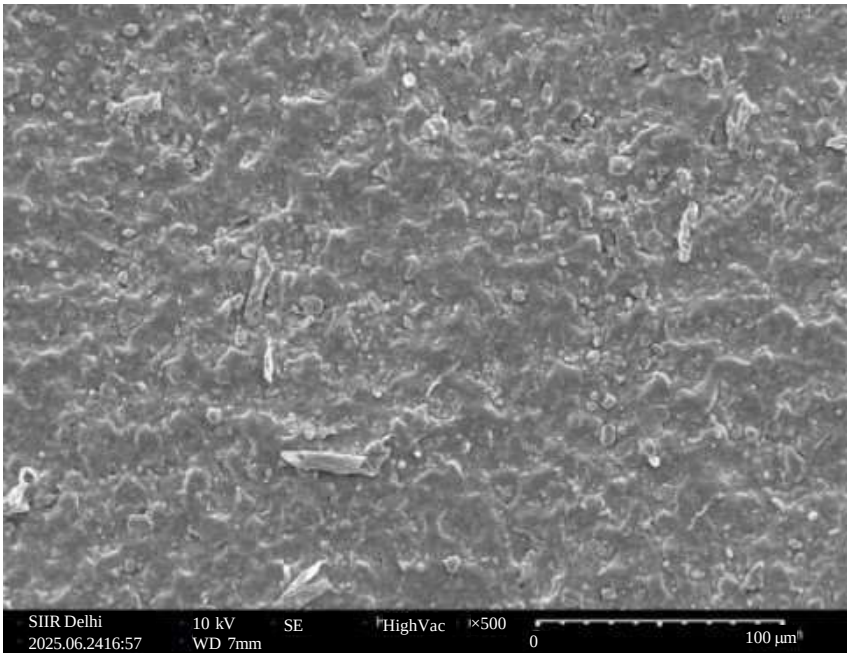


Figure 4. SEM Micrographs of E-Waste Rubber Composite

X-Ray Radiograph

The radiographic image (Figure 5) obtained at 40 kVp clearly shows the difference in X-ray attenuation among the tested samples. Neat natural rubber (NR 1) appears transparent to X-rays, indicating poor shielding ability. In contrast, the rubber composites containing e-waste residue (NR 2–NR 6) display progressively darker regions, suggesting improved X-ray absorption with increasing residue content. This enhancement is due to the presence of metal-rich components such as copper, iron, and zinc in the e-waste residue, which increase the density and effective atomic number of the composites. The potential applications of these are commercially available protective materials such as market gloves and head shields. These results indicate that e-waste–rubber composites can serve as promising, eco-friendly alternatives for lead-free X-ray shielding applications.

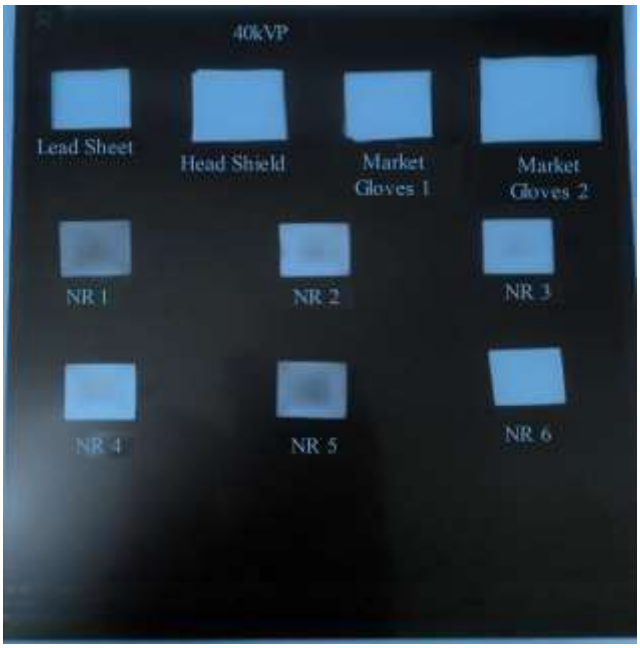


Figure 5. X-ray Radiograph of E-Waste-Rubber Composite

CONCLUSION

The developed e-waste residue-rubber composites show significant improvements in hardness, density, and X-ray shielding performance as the filler content increases. This study demonstrates that incorporating e-waste with sufficient metallic constituents into rubber not only enhances the mechanical and functional properties of the resulting composite but also offers a sustainable alternative for practical applications.

From a sustainability perspective, the study highlights the potential of using waste residue materials as alternative fillers for the development polymer composites. The integration of PCB-derived residues into elastomeric matrices promotes resource recovery and supports circular material utilization by converting hazardous waste streams into useful materials. Overall, this work demonstrates a practical and scalable approach for the valorization of e-waste within polymer composite technology, contributing to the development of sustainable and functional materials for protective and structural applications.

DECLARATION OF INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

ACKNOWLEDGEMENTS

The authors express their gratitude to the management of the Shriram Institute for Industrial Research in Delhi, India, for providing the required facilities for conducting the research and also thanks to the Department of Science & Technology, Government of India, for their financial support. The manuscript is SRI communication SRI-MS#20260313-01.

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