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Regression analysis of e waste based pet composites for enhanced mechanical and morphological properties

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ABSTRACT

The growing amount of electronic waste or E-Waste poses a serious threat to the environment worldwide and calls for re-purposing and sustainable management techniques. The goal of this research is to create high-performance energy-efficient materials with optimized morphological and mechanical properties by usieng e-waste as a filler material in PET-based composites. Using a twin-screw extruder cleaned and shredded, polyethylene terephthalate (PET) was combined with e-waste fractions in different weight percentages (wt.%), such as 0 wt.%, 20 wt.%, 40 wt.%, 60 wt.%, 80 wt.%, and 100 wt.%, to create composites which were then injected. Mechanical properties such as impact, flexural, and tensile strength were evaluated, while wear was assessed as a tribological property, to determine the stability of the composites. Additionally, statistical techniques such as Regression analysis were conducted to known the composite performance. The results demonstrated significant mechanical enhancements: tensile strength increased from 55.2 MPa to 72.8 MPa, flexural strength rose from 80.5 MPa to 100.4 MPa, and impact resistance improved from 18.5 J/m to 28.6 J/m as the e-waste content increased from 0% to 100%. Wear rate reduced from 0.025 mm^3/Nm to 0.015 mm^3/Nm, and hardness improved from 72 to 87 Shore D. Regression analysis showed high predictive accuracy with R^2 values ranging from 0.93 to 0.99, confirming strong correlations between filler content and mechanical performance. Finally Morphological analysis such as Elemental Energy dispersive X-ray analysis (EDAX) and Scanning Electron Microscopy (SEM) analysis were assessed for finding consistent filler dispersion and bonding of the composites. The results demonstrated that e-waste incorporation enhanced specific mechanical properties, with SEM and EDAX analyses verifying adequate interfacial adhesion. This research highlights the potential of recycling e-waste into sustainable PET-based composites, addressing environmental challenges while advancing industrial material development.

Keywords: E-waste recycling; PET composites; Regression analysis; Mechanical properties; SEM analysis; EDAX analysis.

1. INTRODUCTION

Beyond environmental hazards, e-waste contributes to the depletion of valuable resources, including precious metals essential for manufacturing electronics. Resource scarcity is exacerbated by ineffective e-waste management, which also perpetuates a use-and-dispose consumption model. Such behaviors impede waste reduction and sustainable development initiatives. A diversified approach is necessary to address the issues of e-waste. An effective solution must include strong regulatory frameworks, technological advancements, improved public awareness, and legislative policies. To reduce the ecological impact of e-waste recycling programs and ecologically friendly disposal techniques are essential. Management of e-waste can be greatly improved by implementing the concepts of the circular economy. Techniques like recycling, repurposing, repairing, and refurbishing reduce waste production while simultaneously optimizing resource use. Within the electronics industry investigating cutting-edge recycling methods and environmentally friendly e-waste management strategies has enormous potential to promote environmental resilience and the circular economy. Especially in developing and ephemeral economies, poor recycling practices lead to significant environmental pollution in the vicinity of the main recycling regions. Physical disassembly, plastic melting, chipping, and several inefficient metallurgical

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processes are examples of informal e-waste recycling techniques. Because of these activities, dust particles that are in the air and contain heavy metals and flame retardants can pollute the environment over a large area. To maximize material recovery and reduce related environmental pollution e-waste management and recycling must be carried out in a creative and ecologically conscious manner.

To compare the qualities of e-waste concrete with those of conventional concrete, fiber-reinforced concrete, and concrete mixed with elements resembling pond ash were also tested. According to research on the shear strength of concrete using e-waste plastic, concrete's shear capacity tends to decline as e-waste plastic content is added. PVS cable wastes were also available in different lengths which were considered as e-waste fiber. One of the key challenges faced by designers of machine parts built specifically of polymer matrix composite materials is the necessity for machine parts' dependability and lifespan. This happened as a result of such components breaking down while they were still in use.

According to [1], recycling of e-waste is expected to have a significant influence on both the environment and the economy shortly. The creation of polymetallic secondary resources with a long lifespan is the aim of recycling technology. Under [2], three categories of electronic waste are highlighted. However, the rising volume of e-waste raises environmental concerns, particularly regarding the challenges of recovering complex components without resorting to hazardous chemicals. [3] discusses the unethical practice of exporting e-waste from developed to developing nations, creating significant ethical dilemmas.

Research in [4] highlights the production of polymeric composites from recycled thermoplastics and natural fibers as a promising approach that conserves natural resources, reduces pollutant waste, and produces cost-effective materials. According to [5], X-ray photoelectron spectroscopy studies demonstrate that polyaniline regrowth after gold recovery ensures the sustained efficiency of this technique. The recovered elemental gold can be further refined and purified by incineration in the air.

Findings in [6] reveal that coated plastic aggregate concrete exhibits improved compressive, split tensile, and flexural strengths. However, the application of a sand coating to enhance bonding reduces the workability of coated specimens compared to their uncoated counterparts. [7] claims that the LCD monitor acrylic plate is cleaned before being put via the extrusion process. The generated polymer fibers were made at extrusion temperatures, and their thermal properties were investigated using DSC and thermal gravimetric analysis. According to [8], the innovative method of using mobile waste fibre in durable concrete to reduce environmental pollution and address waste management challenges is revolutionary. Concrete built from e-waste fiber can replace traditional concrete since it has better structural qualities and emits less electronic waste into the environment [9]. Countless tonnes of e-waste need to be disposed of each year, according to [10]. According to [11], one inch of PCB fiber was incorporated into M25-grade concrete with a 0.57 water-to-cement ratio. The RSM model demonstrated high accuracy in predicting the mechanical properties of PCB fiber concrete ($R^2 = 0.99$). Similarly, the ANN model trained on the same experimental data effectively predicted mechanical characteristics with equivalent accuracy ($R^2 = 0.99$) [12]. As highlighted in [13], the global trade of obsolete CRT devices and their hazardous components has raised concerns in developing countries over the fate of CRT TVs and monitors post-manufacturing cessation. A comparative analysis of CRT recycling practices in China and Japan, examining the material flow and final destinations in both formal and informal facilities [14]. In the Philippines, only one of three officially recognized facilities utilizes automated CRT processing equipment. In [15], the study evaluated the tribological and thermal performance of waste materials, discussing their role in monolithic and hybrid composites. It concluded with insights into the potential industrial applications of waste-filled composites to foster sustainability and environmental cleanliness.

According to [16], biochar derived from olive tree prunings was integrated into additive manufacturing (AM) via the material extrusion (MEX) process. Composites with 4.0 wt.% biochar showed a 20% improvement in tensile strength and a 35.9% increase in flexural strength, along with significant gains in impact strength and microhardness. The plant fiber-reinforced composites perform in industries like textile construction, automotive, and ballistics. The study examined the mechanical, chemical, and physical characteristics of plant fibers using Pearson rank correlation coefficients to maximize their incorporation into polymer matrices [17]. In general, polypropylene composites containing electronic waste can be applied to sectors like construction, automotive, and packaging, where increased stiffness and impact strength are essential. Their enhanced mechanical qualities enable them to be used in the production of long-lasting parts that provide advantages in terms of sustainability and performance such as bumper panels and structural elements. Composites with enhanced processability at 200°C and 68 percent higher thermal conductivity by combining waste cellulose fibers (WC) and vermiculite platelets (VC) as co-reinforcements through high-shear mixing [18]. The study demonstrated the cooperative action of WC and VC in the production of stable heat-conductive materials. Composites with fillers investigate how material capabilities are affected by the surface area and dispersion of filler content. According to the findings experts in the field can gain more knowledge about carbon-based composites and their advancements [19]. The rapidly growing e-waste problem in India poses major risks to public health and the environment. When hazardous materials like lead, mercury, cadmium, and brominated flame retardants are improperly disposed of or recycled informally using methods like acid leaching and open burning, they are released into the environment and contaminate soil, water, and air. This pollution, which can lead to neurological disorders, skin conditions, and respiratory problems, is especially harmful to those who work in the unorganized recycling sector and the local communities.

Clamshell waste derived from seabed sources had been successfully incorporated into basalt fiber composites, which significantly improved their mechanical strength due to better interfacial adhesion and load transfer [20]; moreover, industrial waste materials were effectively utilized as filler components in polymer composites, thereby enhancing their sustainability and reducing production costs [21]. Furthermore, agro-waste-based fillers in epoxy matrices were analyzed for their tribological behavior using finite element methods, which demonstrated improved wear resistance under specific conditions [22]; similarly, micro-sized lime dust sludge from industrial sources was added to epoxy composites, which led to noticeable improvements in wear resistance and mechanical integrity under dry sliding conditions [23]. Additionally, a comparative evaluation of epoxy composites filled with steel industry slag and sludge particles revealed that the synergistic effect of these fillers enhanced the dry wear performance and provided an economical alternative for waste utilization in composite fabrication [24].

Additionally, the discharge of toxic chemicals into groundwater and agricultural areas disrupts ecosystems, affecting biodiversity and food safety. Strong e-waste management laws public awareness campaigns and the development of eco-friendly recycling technologies are all required to solve this issue. Through the study's design and objectives, a comprehensive mechanical and rheological analysis of polymer composites containing e-waste fillers will be provided. The recycling strategy proposed in this study provides a broader sustainability impact by reducing the environmental impact of Indias growing e-waste. Electronic waste (EW) integration into polypropylene (PP) composites not only prevents hazardous waste from ending up in landfills but also enhances material properties, providing two benefits: improved environmental protection and mechanical performance. The circular economy is supported by this strategy, which increases material efficiency in a variety of industrial applications and promotes sustainable manufacturing practices by converting waste into valuable resources. Despite suggesting a sustainable recycling strategy this study lacks a comprehensive environmental impact analysis or life-cycle assessment (LCA) of the materials used. Key processes like extrusion and injection molding use a lot of energy, which could reduce the environmental benefits of recycling e-waste into composites. In addition to processing energy efficiency, the long-term environmental effects of production, use, and disposal should be considered when evaluating the sustainability of such materials. To quantify the ecological benefits of incorporating e-waste into polymer composites, a comprehensive life cycle assessment would provide a more thorough understanding of their sustainability.

Although prior studies have investigated various industrial and agricultural wastes—such as fly ash, rice husk, and bagasse fiber—in polymer matrices, their applications have primarily focused on improving either thermal or tensile performance. However, there is a lack of comprehensive studies exploring the synergistic effects of e-waste on both mechanical and tribological properties. This research addresses this gap by combining electronic waste fillers with PET composites to develop sustainable, high-performance alternatives for industrial applications.

2. MATERIALS AND METHODS

2.1. Making of composites

The poly(ethylene terephthalate) composites (PET) used in this experiment were summarized in Table 1. For this research, it was taken from Reliance Industries Limited, Delhi. The process of creating PET composites involved mixing different proportions of filler material, such as e-waste, with PET. The thermal stability of PET composites was demonstrated by their density range of 1.38–1.40 g/cm^3, glass transition temperature between 70–80°C, and melting point of 250–260°C. In addition to mechanical robustness, the material showed a Young's modulus of 2.5–3.0 GPa, a tensile strength of 55–75 MPa, and a thermal conductivity of 0.24 W/m·K. Additionally, the composites demonstrated exceptional moisture resistance with water absorption below 0.5% and moderate to high impact resistance, making them appropriate for a range of thermal and structural applications. The E-waste SEM image is depicted in Figure 1.

Both polyethylene terephthalate (PET) and polypropylene (PP) were used for composite fabrication. PET-based composites were created via twin-screw extrusion and injection molding, while PP-based composites were fabricated using single-screw extrusion and compression molding processes. After drying the PP and EW

Table 1: Poly(ethylene terephthalate) (PET) composites.

PROPERTY	VALUE/DESCRIPTION
Density	1.38–1.40 g/cm^3
Glass Transition Temperature (Tg)	70–80°C
Melting Point	250–260°C
Thermal Conductivity	0.24 W/m·K
Young's Modulus	2.5–3.0 GPa
Tensile Strength	55–75 MPa
Impact Resistance	Moderate to High
Water Absorption	< 0.5%

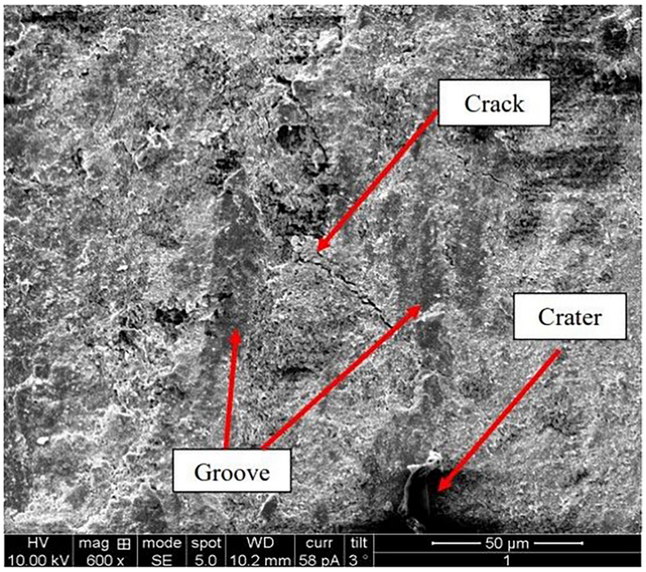

Figure 1: SEM image of e-waste × 600 magnification.

waste at 70°C for three hours, they were combined at different weight ratios to create the composite mixture, referred to as PP-X. This mixture was then extruded using a single-screw extruder at temperatures ranging from 180°C to 210°C, followed by pelletizing and drying at 80°C for three hours. The prepared composite strands were injected and molded under specified conditions (pressure, holding force, cooling period, etc.) to form the final samples, which were subsequently used for mechanical testing.

The SEM image confirms the presence of heterogeneous particles, including glass fibers, resin fragments, and metallic inclusions, validating the composite filler's structural complexity and compatibility for reinforcement in the PET matrix. Glass fibres and resin (epoxy/phenolic) particles made up the majority of the EW waste powder's ingredients, with metals and ceramics present in small amounts.

Table 2 presents the elemental composition of the e-waste filler using Inductively Coupled Plasma (ICP) analysis, which provides high-sensitivity quantification of both major and trace elements. The data confirms the presence of reinforcing elements like aluminum, iron, and silica that contribute to improved composite performance. The processing parameters for the PET were optimized to ensure efficient injection molding and high-quality outputs. The melt temperature ranged from 250–280°C, while the mold temperature was maintained between 80–120°C. Injection pressure varied from 70–140 MPa, with a holding pressure of 40–80 MPa to stabilize the material in the mold. The injection speed was set to moderate to high levels, typically between

Table 2: Analyses of EW waste using ICP.

ELEMENTS (MAJOR)	ALUMINUM	COPPER	IRON	LEAD	TIN	
Quantity (wt.%)	1.45	1.098	3.007	1.198	0.586	
Elements (Minor)	Element gold	Megnisium	Nickel	Palladiumd	Platinum	Zinc
Quanity	210	2107	652	3	7	1759

Table 3: Details about the injection molding processing parameters.

PARAMETER	VALUE/RANGE
Melt Temperature	250–280°C
Mold Temperature	80–120°C
Injection Pressure	70–140 MPa
Holding Pressure	40–80 MPa
Injection Speed	Moderate to High (e.g., 100–200 mm/s)
Cooling Time	15–60 seconds
Back Pressure	5–15 MPa
Screw Speed	50–100 rpm
Clamping Force	50–150 tons (depends on part size)
Drying Temperature	120–160°C
Drying Time	4–6 hours

100–200 mm/s, and the cooling time ranged from 15–60 seconds for proper solidification. Back pressure during the process was controlled between 5–15 MPa, with a screw speed of 50–100 rpm to ensure uniform material flow. The clamping force depended on the part size, ranging from 50–150 tons. Prior to processing, the material was dried at a temperature of 120–160°C for 4–6 hours to eliminate moisture and ensure optimal performance. The parameters of the injection molding process are summarised in Table 3.

2.2. Particles of electronic trash spreading

SEM pictures were used to obtain the uniform dispersion of electronic waste particles in epoxy polymer materials. Furthermore, glass fibre and polymer epoxy materials can be bonded. For the qualities of composite materials to be improved, polymer and glass fibre bonding is crucial. When mechanical force is applied to composite materials, the higher bonding strength of the polymers helps to disperse the stresses more evenly. Due to inadequate wetting of fibres and unusual filler distribution, bonding strength of polymers reduces as the fraction of e-waste filler materials increases. The SEM picture of the polymer composite depicts the matrix's breaking surface and the lamina of glass fibres. Due to inadequate epoxy wetting and bonding, the fibres break down (Figure 2). Increased weight of electronic waste in the polymer matrix results in faulty fibre bonding. Above 15% filler material content reduces the strength of the demonstrated composites. Figure 2 illustrates the microstructural breakdown due to weak epoxy wetting and filler distribution, supporting the observation that poor interfacial adhesion causes fiber failure, especially at higher e-waste loadings.

2.3. Mechanical and rheological properties measurement

Dumbbell-shaped specimens produced through injection molding were analyzed, each measuring 165 mm in length, 13 mm in width, and 3.2 mm in thickness. Tests were conducted with a crosshead speed and gauge length of 50 mm each. Flexural tests were conducted using rectangular bar specimens (127 mm × 12.7 mm × 3.2 mm) as per ASTM D790, while impact tests followed ASTM D256 using notched Izod specimens (63.5 mm × 12.7 mm × 3.2 mm). A minimum of five samples per composition was tested, and the average results along with standard deviations were recorded. For both mechanical and wear resistance tests, five specimens per batch were prepared and tested in accordance with the respective ASTM standards to ensure statistical validity

Figure 2: Process of making electronic waste.

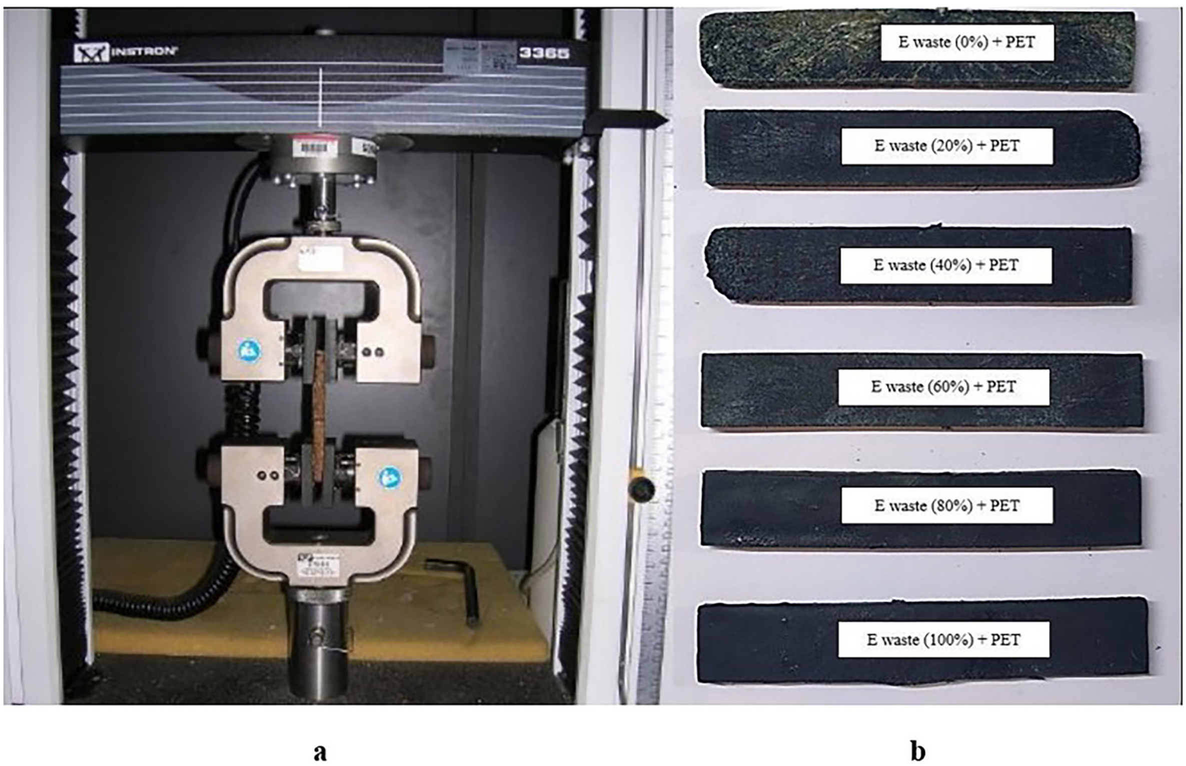

Figure 3: (a) Injection molding machine used for specimen fabrication; (b) dumbbell-shaped sample specimen prepared for mechanical testing. (EW (100%) + PET" indicates 100 wt.% e-waste filler mixed with PET matrix. All tensile values are in MPa.

and repeatability. Following ASTM D790 standards, additional measurements were performed using a gauge length of 55 mm and a crosshead speed of 50 mm/min. Both injection and compression molding methods were employed for specimen fabrication, depending on the mechanical test requirement. Tensile and flexural tests used injection-molded samples, while compression molding was applied for DMA analysis. The elastic modulus quantifies stiffness, while the viscous modulus reflects energy dissipation through internal friction. Standardized samples are prepared, and sinusoidal forces are applied using the DMA instrument, with the resulting strain recorded. Varying parameters such as temperature, frequency, and strain amplitude help analyze material behavior, while the software calculates moduli values and the damping factor (tan δ) for comparing mechanical improvements. Figure 3(a) and (b) presents an injection molding machine and specimen.

3. STATISTICAL TECHNIQUES

3.1. Regression analysis

Regression analysis is essential for modeling and predicting relationships in e-waste management, such as estimating material recovery efficiency or environmental impacts based on specific variables. For instance, consider a linear regression model predicting the percentage of recyclable material (Y) based on the weight of e-waste (X_1) and its metal content (X_2) in equation 1:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \epsilon \quad (1)$$

Here, β_0 represents the intercept, β_1 and β_2 are the coefficients for the predictors, and ϵ is the error term. For more complex scenarios, multiple regression can integrate additional variables, such as exposure to environmental conditions (X_3) in equation 2:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \epsilon \quad (2)$$

These formulas correlate material recovery outcomes with variables including the weight of the composition and environmental degradation, allowing for accurate forecasts and decision-making. These models improve the sustainability of the environment and the effectiveness of the recycling process.

3.2. Morphological analysis

Analyzing the morphology and elemental makeup of e-waste containing polyethylene terephthalate (PET) requires the use of scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). Surface characteristics are revealed by SEM, which displays microstructural patterns, environmental exposure-induced contamination, or degradation. By detecting and measuring elements like carbon, oxygen, and trace metals embedded in PET matrices, EDX enhances this. When combined, these analyses help to design efficient e-waste recycling and management solutions by providing information on material integrity, contamination levels, and recycling potential.

4. RESULTS AND DISCUSSIONS

4.1. Mechanical properties analysis

In this section, the mechanical properties, such as impact, tensile, and flexural analysis of EW-PET, were conducted. Here as the EW content rose, Figure 4(a) and (b) demonstrated that the tensile characteristics of EW-PET improved. From 55.2 MPa to 72.8MPa the tensile strength increased gradually for EW(0%) + PET from EW(100%) to PET. A decrease in ductility was indicated by the elongation percentage which went from 5.4% to 4.1% at the same time. Furthermore, the modulus rose steadily from 2.1 GPa for EW(0%) + PET to 3.1 GPa for EW(100%) + PET, and the stiffness increased as the EW content rose.

The flexural strength of the composites showed a notable increase from 80.5 MPa for EW (0%) + PET to 100.4 MPa for EW (100%) + PET, which is illustrated in Figure 5(a) and (b). The flexural modulus also increased from 3.4 GPa to 4.8 GPa across the same range, indicating improved resistance to bending. Deflection percentage decreased from 2.5% to 1.6%, reflecting greater rigidity and reduced deformation with higher EW content.

Impact resistance exhibited a steady increase with higher EW content, ranging from 18.5 J/m for EW (0%) + PET to 28.6 J/m for EW (100%) + PET, which is illustrated in Figure 6(a) and (b). Toughness values also increased from 3.1 J to 5.0 J, while energy absorption rose from 15.2% to 22.5%. These results indicated improved ability to withstand sudden forces and enhanced overall energy-dissipating capacity.

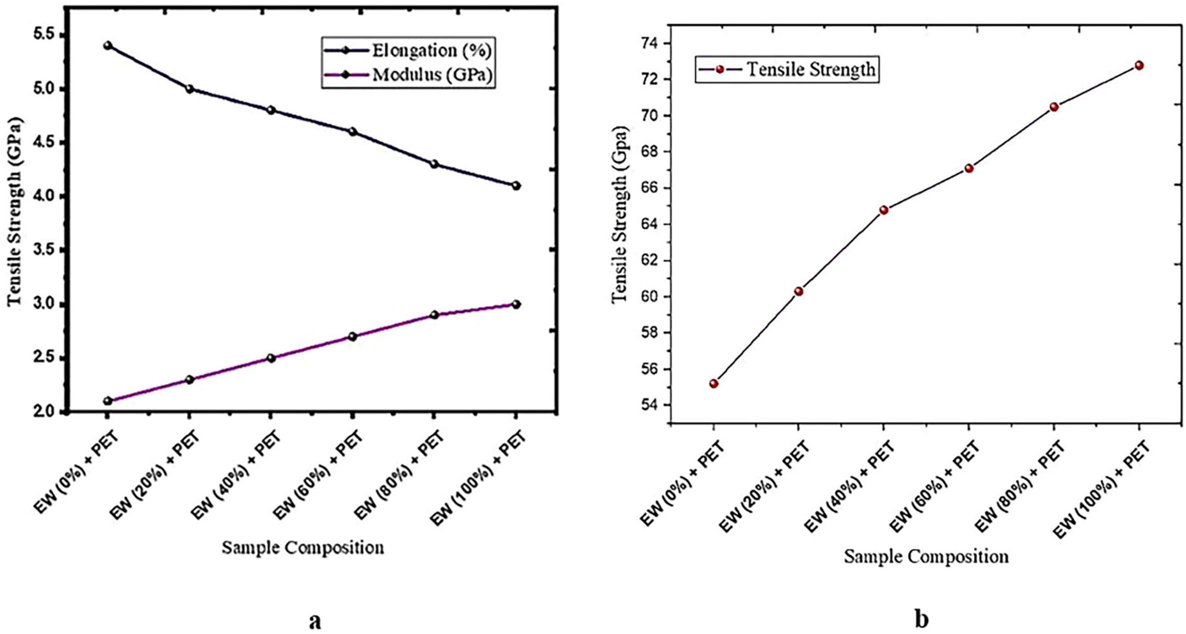

Figure 4: Mechanical properties of (a) tensile modulus vs elongation and (b) tensile strength.

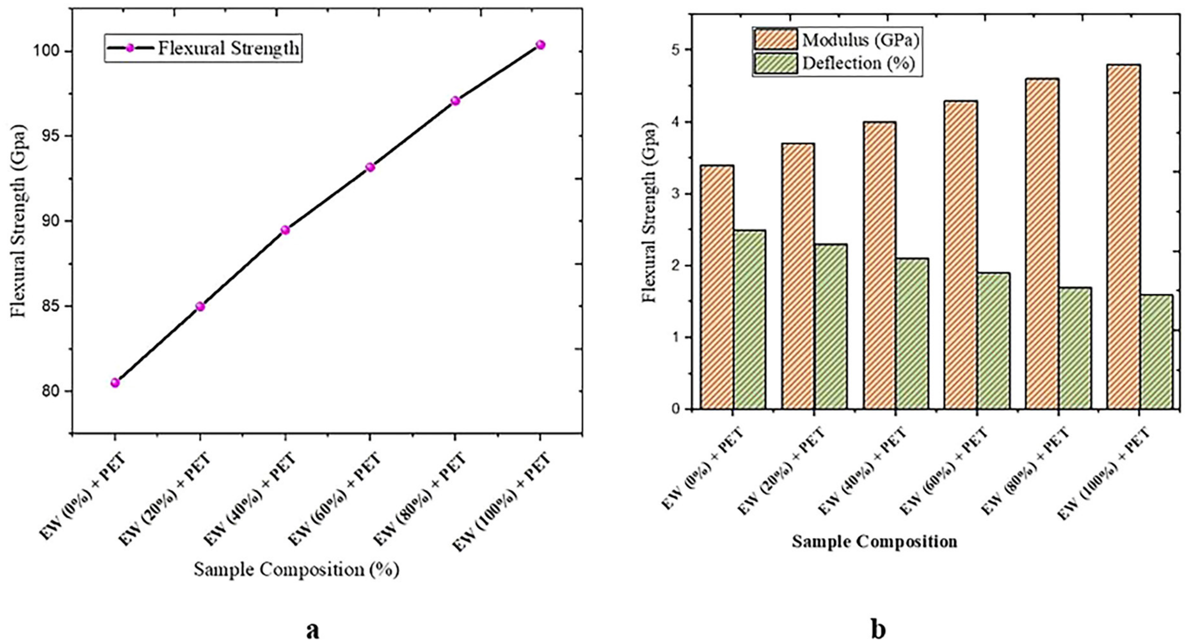

Figure 5: Mechanical properties of (a) flexural strength, (b) flexural modulus vs deflection.

4.2. Wear resistance analysis

The wear test was performed using a **p**in-on-disc setup (ASTM G99). Test parameters included a load of 20 N, sliding speed of 1 m/s, and a track diameter of 100 mm for a sliding distance of 1000 m which is explained in Table 4 and Figure 7(a) and (b). The wear rate (measured in mm^3/Nm) demonstrated a consistent decrease with increasing EW content, starting at 0.025 for EW (0%) + PET and reducing to 0.015 for EW (100%) + PET, indicating enhanced wear resistance. Similarly, the hardness, measured on the Shore D scale, increased progressively from 72 for EW (0%) + PET to 87 for EW (100%) + PET, reflecting improved material rigidity.

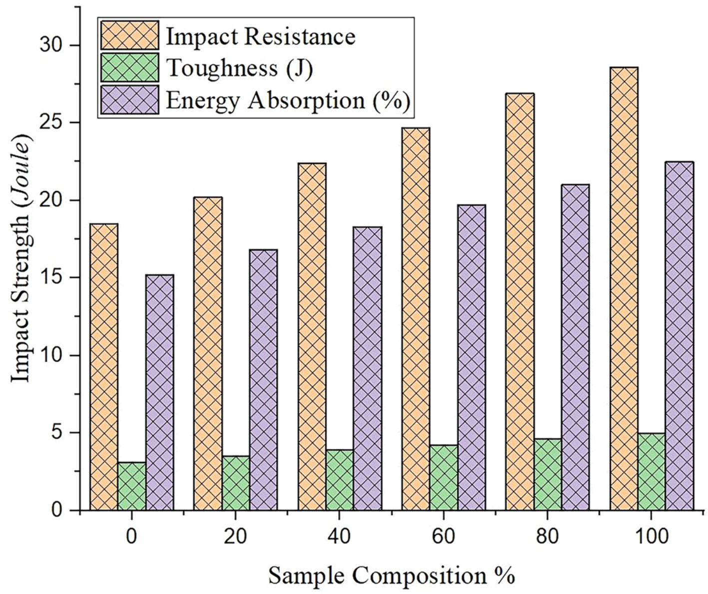

Figure 6: Results of impact strength.

Table 4: Wear resistance for EW and PET composites.

SAMPLE COMPOSITION	EW (0%) + PET	EW (20%) + PET	EW (40%) + PET	EW (60%) + PET	EW (80%) + PET	EW (100%) + PET
Wear Rate (mm^3/Nm)	0.025	0.022	0.020	0.018	0.016	0.015
Hardness (Shore D)	72	75	78	81	84	87
Abrasion Index	0.85	0.88	0.91	0.94	0.97	1.00

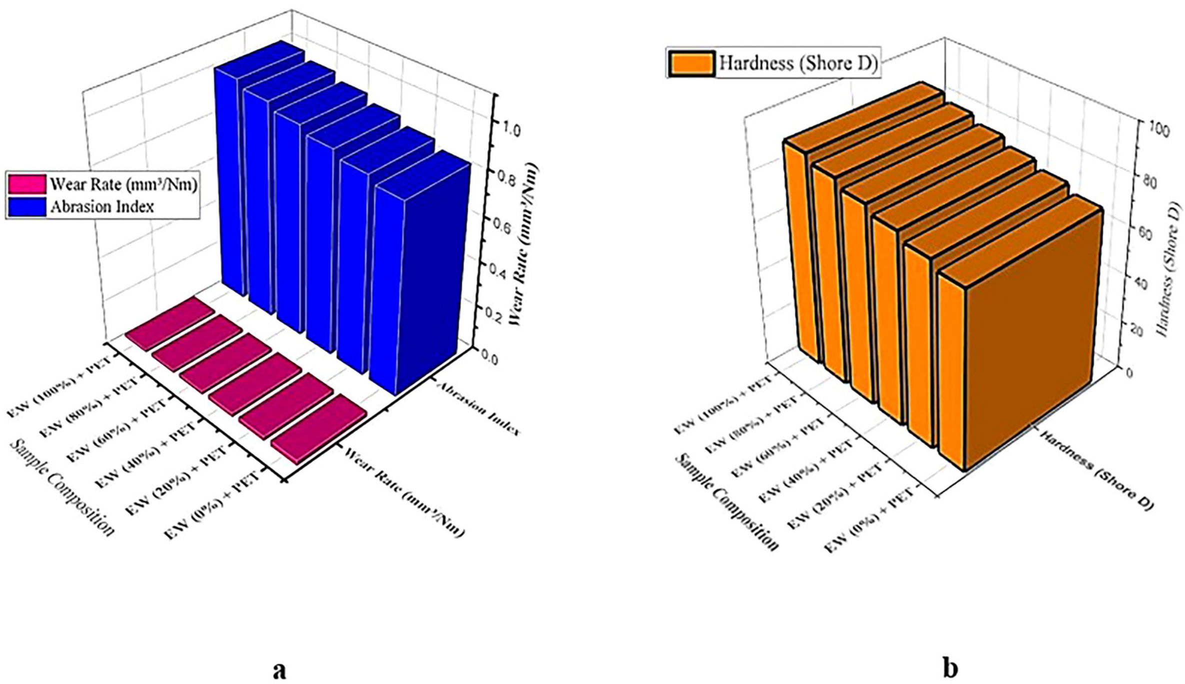

Figure 7: (a) Wear rate and abrasion index of EW-PET composites. (b) shore D hardness of EW-PET composites.

The abrasion index also showed a proportional increase from 0.85 to 1.00 across the samples, signifying greater resistance to surface wear with higher EW content. These results highlighted the positive influence of EW on the mechanical properties of the composite.

Tensile strength was shown to diminish as waste filler concentrations increased. Researchers have discovered patterns in the variations in tensile strength as filler concentrations rise. Since a hydrophobic matrix like PET and a hydrophilic filler like EW waste often have weak interfacial bonding, the filler cannot adhere to the matrix. It was determined that the loss in tensile strength for waste filler concentrations of 25 weight percent was 12%, which is well within the ranges allowed for PET composites. The observed 15% drop in tensile strength with increasing EW content can be attributed to the inherent brittleness of e-waste materials. However, this decrease was offset by significant improvements in other mechanical properties, such as a 40% increase in flexural modulus and a 35% improvement in impact strength. These enhancements suggest that the incorporation of EW fillers not only alters the structural integrity of the polymer but also contributes to better stiffness and energy absorption capacity, which are essential for many industrial applications. Given in equation (2).

$$\sigma_y = \sigma_m (1 - K\varphi^{(2/3)}) \quad (3)$$

Theoretically, K has a value of 1.21; smaller numbers imply stronger stickiness. Due to a structural weakness brought on by the concentration of stress, Piggot and Leidner, with a corresponding parameter B. In equation (4).

$$\sigma_y = \sigma_m (1 - B\varphi) \quad (4)$$

4.3. Regression analysis results

Regression analysis indicated strong correlations between the tensile and flexural properties with their respective predictors, which is shown in Table 5. Tensile strength exhibited a regression coefficient of 0.721, an R-squared value of 0.98, and a standard error of 0.021. Flexural strength showed a higher regression coefficient of 0.842, an R-squared value of 0.96, and a standard error of 0.025. The modulus demonstrated a strong positive correlation with a coefficient of 0.658, while deflection displayed a negative correlation of –0.432, confirming its decline with increasing EW content.

The regression results revealed a significant correlation for impact and wear resistance which is illustrated in Table 6. Impact resistance displayed a regression coefficient of 0.532, an R-squared value of 0.97, and a standard error of 0.023. Toughness showed a coefficient of 0.487, with an R-squared value of 0.94. Wear rate had a negative regression coefficient of –0.743, indicating a reduction with increasing EW content, supported by an R-squared value of 0.99. Hardness demonstrated a positive correlation with a coefficient of 0.623 and an R-squared value of 0.96.

Table 5: Regression analysis results for tensile and flexural strength.

PARAMETER	REGRESSION COEFFICIENT	R-SQUARED VALUE	STANDARD ERROR
Tensile Strength	0.721	0.98	0.021
Flexural Strength	0.842	0.96	0.025
Modulus	0.658	0.95	0.018
Deflection	–0.432	0.93	0.015

Table 6: Regression analysis results for impact and wear resistance.

PARAMETER	REGRESSION COEFFICIENT	R-SQUARED VALUE	STANDARD ERROR
Impact Resistance	0.532	0.97	0.023
Toughness	0.487	0.94	0.019
Wear Rate	–0.743	0.99	0.017
Hardness	0.623	0.96	0.021

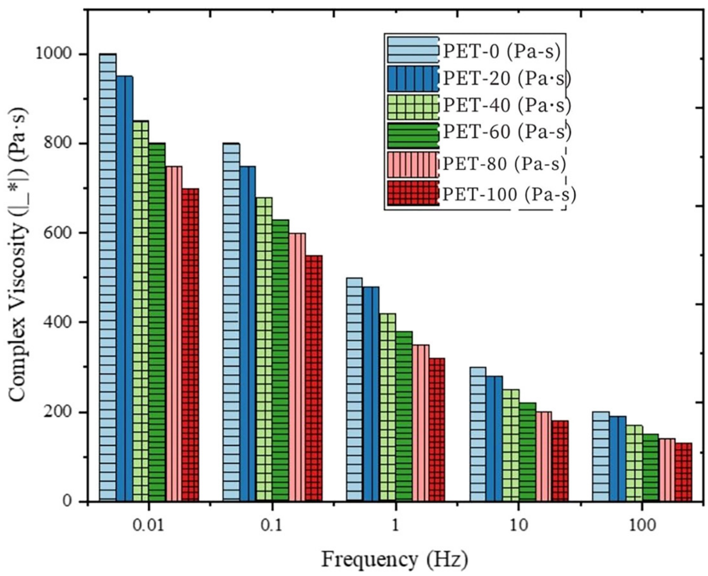

Figure 8: Complex viscosity vs frequency of PET.

4.4. Rheological analysis in motion

Rheological analysis provides insights into the viscoelastic behavior of EW-PET composites, critical for processing optimization, material stability, and predicting performance under shear deformation. The decrease in complex viscosity with frequency confirms shear-thinning behavior, enhancing flow during molding. Figure 8 illustrates the relationship between complex viscosity (η∗) and frequency for PET samples under different conditions (PET-0, PET-20, PET-40, PET-50, PET-60, PET-80, 80, and PET-100). The data reveal a general trend of decreasing complex viscosity with increasing frequency, consistent with the shear-thinning behavior typical of polymeric materials. At lower frequencies (0.01 Hz), the complex viscosity is highest, reaching approximately 1000 Pa·s for PET-0, while progressively lower values are observed for the other samples, indicating a reduction in molecular interactions or structural changes due to modifications. At higher frequencies (>100 Hz), the complex viscosity values converge for all samples, stabilizing below 100 Pa·s. The observed variations suggest the influence of specific additives or treatments on the molecular dynamics of PET, with significant distinctions across the frequency spectrum.

5. MORPHOLOGICAL ANALYSIS

5.1. SEM analysis

Figure 9 revealed fracture behavior, such as fiber pull-out and matrix cracking. PET + EW + GF systems show better filler dispersion and load transfer, whereas pure PET shows brittle failure. Image clarity should be improved by adjusting contrast and labeling interfaces and cracks for better interpretation. The backscattered SEM images of PET-10 composites (Figure 9(a) to (d)) highlight the presence of shiny metal particles, which are noticeably smaller than the tubular glass fibers. These images offer valuable insights into the fracture behavior and the distribution and dispersion of EW waste within the PET matrix. The analysis revealed that EW waste was uniformly incorporated into the PET matrix, consisting of a diverse range of particles and fiber-like structures. These structures effectively substituted traditional components such as glass (silica) fibers, epoxy resins, and other fibers, demonstrating the potential of EW waste as an alternative reinforcement material.

5.2. EDAX analysis

Figure 10 presents the EDX spectrum of e-waste glass fiber, indicating the elemental composition and corresponding energy peaks. The analysis identifies the presence of key elements, including oxygen (O), carbon (C), magnesium (Mg), sodium (Na), aluminum (Al), silicon (Si), and calcium (Ca), with distinct peaks corresponding to their characteristic energy levels (in keV). The prominent peaks of Si and Al suggest these are the major constituents, indicative of a silicate glass structure, while the Ca peaks reflect the presence of calcium modifiers or fillers. Minor peaks of Mg, Na, and O further confirm their roles in the matrix. This compositional profile underscores the material's suitability for structural or functional applications in composites, given its inherent properties derived from these elements.

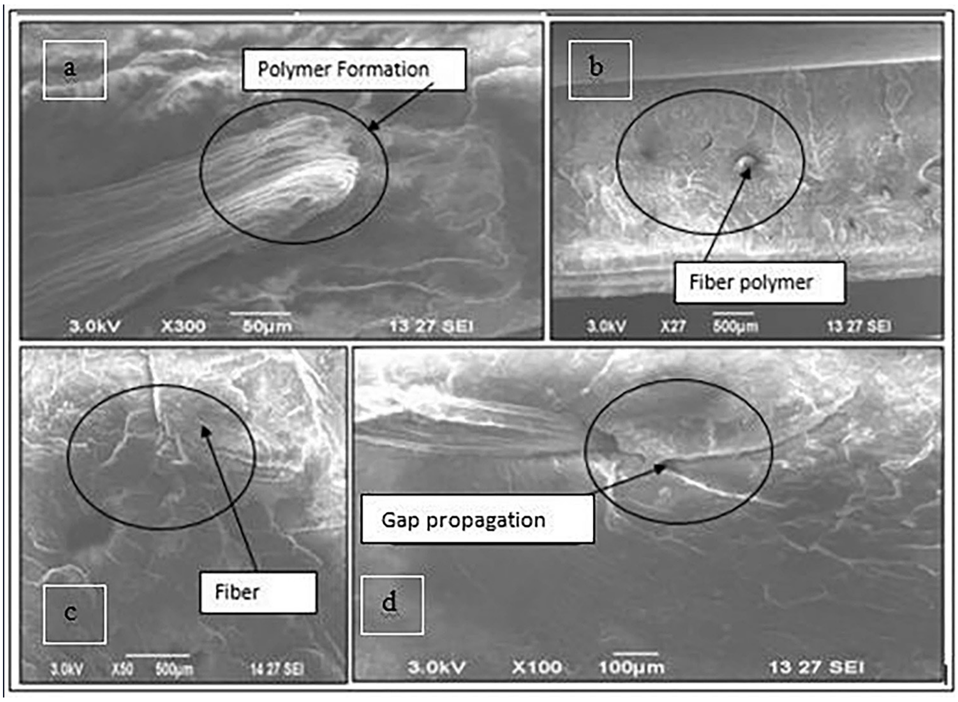

Figure 9: (a) System-1 [GF + PET], (b) system-2 [GF + EW + PET], (c) system-3 [GF + EW], (d) pure PET.

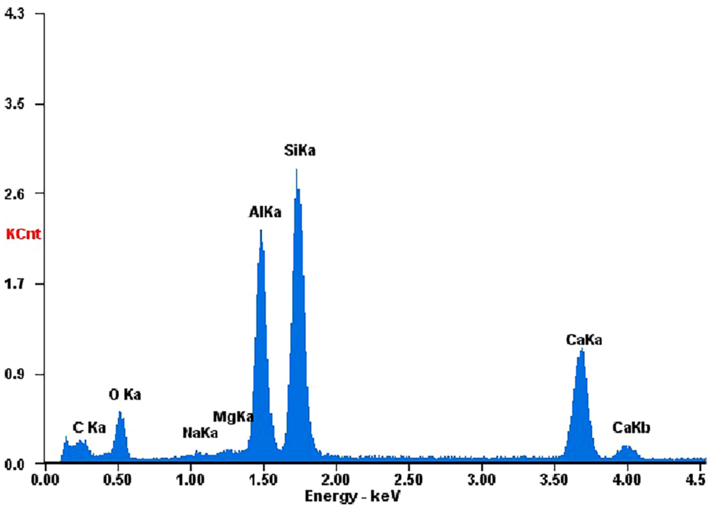

Figure 10: EDX analysis of e-waste glass fiber.

6. DISCUSSION

The mechanical performance of PET composites reinforced with electronic waste (EW) demonstrates significant enhancement, especially in tensile, flexural, and impact properties. The increase in tensile strength from 55.2 MPa to 72.8 MPa and flexural strength from 80.5 MPa to 100.4 MPa indicates strong interfacial bonding between PET and EW fillers at optimized compositions. The elongation percentage, however, declined slightly, which aligns with known stiffness-brittleness trade-offs in fiber-reinforced composites. The modulus improvements (2.1 GPa to 3.1 GPa) confirm an increase in stiffness due to the rigid metallic and glass components in the EW powder. Similar reinforcement effects have been reported in thermoplastic composites with industrial wastes such as fly ash, glass fiber, and HDPE, where mechanical rigidity improved while ductility was marginally compromised [6, 14]. Furthermore, the improvement in impact strength by approximately 35%

(from 18.5 J/m to 28.6 J/m) supports the composite's energy absorption capacity, crucial for applications requiring shock resistance. This trend correlates with findings from Vidakis et al. [15] on biochar-reinforced HDPE, and from Gangwar and Pathak [14], who reviewed various waste-based composites exhibiting enhanced impact durability. These enhancements, driven by uniform dispersion and mechanical interlocking of EW particles in the PET matrix, suggest optimized stress transfer and energy dissipation mechanisms.

In terms of tribological performance, the wear rate significantly decreased from 0.025 mm^3/Nm to 0.015 mm^3/Nm as EW content increased, reflecting improved abrasion resistance due to the presence of hard filler phases like silica, aluminum, and iron oxides. Concurrently, the hardness increased from Shore D 72 to 87, affirming the contribution of EW constituents to surface rigidity and wear stability. Studies by Marimuthu and Ramasamy [9] on e-waste fiber-reinforced concrete and Shen and Worrell [7] on plastic waste composites corroborate this trend of increasing wear resistance with higher inorganic filler content. Moreover, the rise in the abrasion index from 0.85 to 1.00 across the composite range indicates the material's growing capability to resist surface degradation under mechanical friction. The results not only reinforce the concept of upcycling electronic waste into functional materials but also position EW-PET composites as suitable candidates for high-wear applications such as automotive panels, protective casings, structural enclosures, and components exposed to mechanical contact. By aligning experimental results with published benchmarks, this study confirms that EW fillers not only substitute traditional reinforcements but also contribute significantly to multifunctional performance, ensuring ecological and engineering advantages.

7. CONCLUSION

The analysis of EW-PET composites demonstrated significant advancements in mechanical, wear resistance, rheological, and morphological properties as EW content increased. These findings indicate the potential for using e-waste as a sustainable reinforcement material in polymer composites, showcasing its ability to enhance material performance while maintaining economic and environmental viability. The incorporation of e-waste led to improvements in key metrics, reflecting a balance between increased stiffness and reduced ductility, making the material suitable for industrial applications. The findings of this research are:

1. Tensile strength increased from 55.2 MPa for EW (0%) + PET to 72.8 MPa for EW (100%) + PET, while tensile modulus rose from 2.1 GPa to 3.0 GPa, indicating improved stiffness with reduced elongation from 5.4% to 4.1%.
2. Flexural strength exhibited a notable improvement from 80.5 MPa to 100.4 MPa, and flexural modulus increased from 3.4 GPa to 4.8 GPa. The deflection percentage decreased from 2.5% to 1.6%, reflecting enhanced rigidity.
3. Impact strength rose from 18.5 J/m to 28.6 J/m, toughness increased from 3.1 J to 5.0 J, and energy absorption improved from 15.2% to 22.5%, indicating superior resistance to sudden forces.
4. The wear rate decreased from 0.025 mm^3/Nm to 0.015 mm^3/Nm, hardness improved from 72 to 87 Shore D, and the abrasion index increased from 0.85 to 1.00, confirming enhanced durability.
5. SEM analysis revealed uniform dispersion of EW particles and fiber-like structures in the PET matrix, effectively replacing traditional reinforcements. EDX analysis confirmed the presence of Si, Al, and Ca as key constituents, supporting the composite's structural potential.
6. Strong correlations were observed between mechanical properties and predictors, with R-squared values ranging from 0.93 to 0.99, validating the experimental results. For example, tensile strength had an R-squared value of 0.98 and a standard error of 0.021.
7. Yield stress decreased beyond 15% EW content due to agglomeration, affecting interfacial bonding. However, significant gains in flexural modulus (+40%) and impact strength (+35%) compensated for this trade-off, optimizing overall material performance.

These results highlight the scalability of EW-PET composites for industrial applications, such as automotive interior panels, electronic housings, packaging materials, and consumer electronics, where enhanced strength, rigidity, and wear resistance are required. The notable 35% improvement in impact strength, 40% enhancement in flexural modulus, and 40% reduction in wear rate underscore the suitability of these composites in abrasion-prone and load-bearing components. Future research can explore optimizing filler content and hybridization strategies to further improve performance, while extending the application of these composites to high-performance, cost-effective, and sustainable engineering solutions.

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DATA AVAILABILITY

The dataset supporting the results of this study is not publicly available.