Fabrication and Characterization of Polymer Composites Reinforced with Recycled Printed Circuit Board (PCB) Fillers

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ABSTRACT

The rapid growth of electronic waste has encouraged the reuse of non-metallic printed circuit board (PCB) residues as fillers in polymer composites. This work investigates high-density polyethylene (HDPE) composites reinforced with 10–30 wt% PCB powder, focusing on their mechanical and structural response. Experimental results show a substantial enhancement in stiffness, with tensile and flexural moduli increasing by up to 176% and 85%, respectively, as PCB content increases. In contrast, tensile strength and impact toughness decline, primarily due to weak filler–matrix bonding and the formation of micro-voids. SEM observations reveal irregular PCB particle morphology and interfacial defects that govern the observed mechanical degradation. FTIR and XRD analyses indicate no new phase formation but suggest constrained polymer chain mobility in the presence of rigid PCB fillers. Micromechanical predictions based on rule-of-mixtures bounds agree well with the experimental modulus values. Overall, the study demonstrates a stiffness–toughness trade-off and identifies HDPE/PCB composites as suitable for non-load-critical applications where high bending rigidity is required, offering a sustainable pathway for PCB waste utilization.

1. Introduction

As electronic devices have become increasingly prevalent in modern society, the volume of electronic waste (e-waste) has risen sharply, creating an urgent need for innovative and sustainable management strategies. A practical solution to this escalating issue is e-waste recycling, which involves recovering valuable materials from discarded electronic products [1]. Solid waste sources like electronic garbage, or e-waste, are expanding at a comparatively rapid pace with an annual growth between3% to 5%. Even though international regulations have been developed to better restrict the cross-border movement of hazardous waste worldwide, the illegal trade and informal recycling have made the recycling of e-waste more widespread. However, a lot of low-income neighborhoods continue to dispose of e-waste illegally and without using science in order to make money out of it. The production of toxic and hazardous materials has an impact on the global ecological environment via the geochemical cycle [2]. Electronic waste is recycled globally by both the formal and informal sectors to recover precious materials [3]. Approximately 30,000 million metric tons of precarious e-waste, mainly Printed Circuit Boards (PCBs), are produced per annum globally [4]. Faulty recycling techniques, mainly in the developing nations, lead to excessive levels of environmental pollution in the locality of chief recycling regions [5]. Metallurgical processes, plastic snick and render, and hand disassembly are examples of non-formal e-waste recycling methods [6]. These processes can release dirt particles containing flame retardants and heavy metals into the environment, thereby contributing to pollution and spreading contamination across wider areas. [7-8]. The innovative and environmentally responsible methods of e-waste management and recycling are desperately needed in order to significantly boost material recovery and reduce associated environmental contaminants [9]. The majority of printed circuit boards (PCBs) are composed of composite materials, which include modest amounts of glass reinforcement and thermoset epoxies or polyamide resins. When electrical devices are no longer in use, their polymeric component is usually burned, disposed of in landfills, or discarded. The non-recyclable nature of thermoset polymers poses a major challenge in the disposal of e-waste. Currently, only certain polymeric materials—specifically thermoplastics such as HDPE, PET, and PP can be effectively recycled [10]. Although synthetic plastics are widely utilized in electronic devices for components like printed circuit boards, instrument casings, and housings, they are seldom recovered in a reusable form due to the complexities involved in their sorting, collection, and separation. Recovered plastics are either disposed of in landfills or used in low-value applications since the costs of recycling may exceed the value of the reclaimed product or material [11]. E-waste disposal is a major risk to both the environment and garbage collection services. Printed circuit boards (PCBs), often regarded as the "brains" of numerous electronic devices, exist in a wide range of compositions. Found in products such as mobile phones, computers, televisions, laptops, and tablets, PCBs contain a mix of metals, polymers, and ceramics. Due to the growing demand for electronics and their short lifespans and limited reusability, these devices also contribute significantly to e-waste. Moreover, many PCBs contain hazardous or toxic substances [12].

In recent years, extensive research has focused on developing more sustainable and economically viable methods for recycling the nonmetallic components of PCBs. Guo et.al. reported that the flexural strength of Wood Plastic Composites (WPCs) incorporating nonmetallic materials was slightly higher than that of the control samples [13]. Similarly, Wang et al. observed that incorporating 20 wt% of PCB nonmetallic powder into a PVC matrix improved its bending strength compared to pure PVC [14]. According to Franz, the most effective way to recycle nonmetallic PCBs is by utilizing them in thermoplastic composites, as approximately 72% of all plastics used in packaging are high-density polyethylene (HDPE)—a thermoplastic commonly found in bottles, films, and various products [15,25]. Waste PCBs can thus be transformed into thermoset polymers that serve as fillers for producing HDPE-based composites with specific and desirable properties. Typically, printed circuit boards are composite structures made of polyamide resins or thermoset epoxies reinforced with small amounts of glass fibers [16–17].

The authors demonstrated that the geometric arrangement and load distribution significantly influence stiffness and stability, highlighting the importance of optimized composite architectures for improved mechanical response [18].

The work provided insights into how structural topology, design parameters, and loading conditions affect mechanical behavior. The results emphasized the role of data-driven modelling in enhancing composite structural performance and tailoring stiffness-to-weight ratios for advanced applications. [19].

Current work has been conducted with a focus on reducing the environmental impact of PCB recycling while finding sustainable ways to repurpose the recovered non-metallic components. In this study, composites of High-Density Polyethylene (HDPE) reinforced with nonmetallic fractions of waste PCBs were fabricated and analyzed. The research offers a detailed evaluation of utilizing the nonmetallic polymeric portion of discarded PCBs in reinforced HDPE composites. It aims to establish a fundamental understanding of the relationship between the polymeric content of PCB waste and the resulting composite properties—specifically fracture morphology, tensile, flexural, and impact strength—under varying proportions of PCB waste filler.

Scanning Electron Microscopy (SEM) was used to examine the morphological features of the waste-derived composites. Fourier Transform Infrared Spectroscopy (FTIR) and X-ray Diffraction (XRD) were employed to investigate changes in chemical structure, crystallinity, and peak characteristics of the HDPE/PCB composites, as well as to evaluate degradation effects associated with weathering. The outcomes of this study support the development of an environmentally sustainable strategy for the reuse and management of polymeric PCB waste, while offering a cost-effective approach to improve the performance of HDPE-based composites through the substitution of conventional fillers with waste-derived alternatives.

2. Materials and methods

2.1 Compositional analysis of nonmetallic PCBs

Table 1 lists all the elemental chemical compositions observed in PCB powder. Chemical element identification of non-metallic PCBs can be facilitated by data analysis obtained from Energy Dispersive Spectroscopy (EDS) testing. From table 1, it can be observed that the non-metallic component of the PCB sample consist of epoxy resin, glass fibers, and some metal content. Glass fiber materials including SiO_2, Al_2O_3, CaO, MgO, BaO, and SrO roughly account for 70.63% of the non-metallic PCB material composition while that CuO, SnO_2, Fe_2O_3 make up 8.35% of metallic components and some other elements. The components reported in Table 1 match with earlier studies. One could conclude that glass fibers reinforced epoxy resin accounts for a considerable amount of the non-metallic material of printed circuit boards [20].

To further enhance the performance of HDPE/PCB composites, several strategies can be adopted to improve filler–matrix adhesion. The use of compatibilizers such as maleic-anhydride-grafted polyethylene (PE-g-MA) can promote stronger interactions between the non-polar HDPE matrix and the polar glass-fiber/epoxy components of PCB waste. Additionally, surface treatments of PCB particles, including silane coupling agents or mild chemical/physical activation (e.g., alkali treatment, plasma exposure), can increase surface functionality and mechanical interlocking. Improving adhesion at the interface has the potential to mitigate strength loss and enhance both tensile and impact properties. Future work may incorporate these treatments to further optimize composite performance.

Table 1. Chemical composition of non-metallic elements in PCB

Elements	Percentage (%)	Elements	Percentage(%)
Al_2O_3	8.76	MgO	0.41
SiO_2	39.04	P_2O_5	0.60
K_2O	1.14	SrO	1.52
Cl	4.56	CuO	5.33
CaO	20.90	ZnO	0.68
SnO_2	1.41	Br	7.35
MnO	1.34	BaO	0.60
TiO_2	0.43	Cr_2O_3	-
Sb_2O_3	0.12	Rb_2O	-
Fe_2O_3	1.61	MoO_3	-

2.2 Preparation of composite samples

In this study, HDPE polymer of grade M6405 (granular form) was purchased from M/s GAIL India. The molded grade plastic M6405 has a melt flow index of 5g/10min and a density of 0.964 g/cm^3 at 190 ^{0}C. Table 2 lists HDPE's fundamental attributes.

Table 2. Basic characteristics and properties of HDPE

Material	Property	Value
High-Density Polyethylene (HDPE)	Melt Flow Index (190 ^{0}C / 2.16 kg)	5g/10 min.
	Density	0.964g/cm^3
	Tensile Strength	28 MPa
	Flexural Modulus	900 MPa
	Impact Strength(23 ^{0}C)	80 J/m
	Heat Deflection Temperature (455 kPa)	85^{o}C

Cutting several discarded PCBs on a lathe machine generated the waste PCB powder particles. The resulting powder particles are sieved in accordance with Part 103: Section 1 of the BS 812 sieve test [BSI, 1989]. The PCB powder is manually sieved and consolidated into distinct particles with a size range of approximately 0.03 to 0.15 mm. In order to remove moisture, these powder particles are dried in an oven. PCB waste powder was dried for four hours at 80°C in a vacuum oven before being mixed with HDPE in a sealed container and shaken by hand to create HDPE polymer for the fabrication of composites. Thus, dried waste PCB powder particles are used as filler in the HDPE polymer for fabricating a polymer composite. The non-metallic PCB powder particles will be blended with HDPE powder in varying concentrations (10%, 20%, and 30%). The choice of matrix and the kind of reinforcement applied greatly affect the mechanical behavior of polymer composites. Figure 1 shows the powder particle fabrication process.

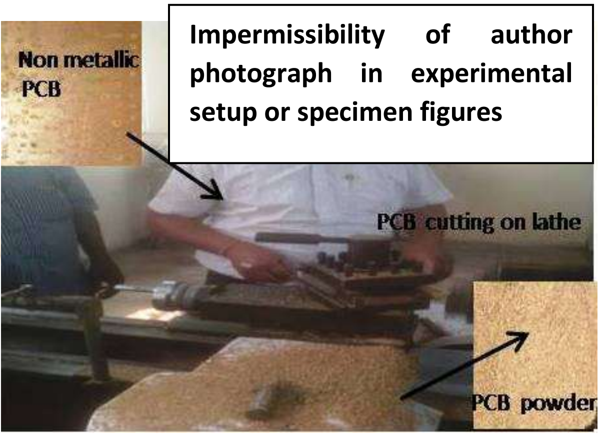

Fig.1. Images of the waste PCB powder particle fabrication process

Samples of PCB filler reinforced HDPE composite for tensile, flexural, and impact testing were developed as per standard ASTM D638, ASTM D790, and ASTM D256, respectively. Figure 2(a-d) shows samples for tensile testing, Figure 3(a-d) shows samples for Flexural testing, and Figure 4(a-d) shows samples for impact testing. Five samples for each composition were tested, and the average value of them. Figure 5 shows the mechanical characterization and morphological testing equipment employed for the present work.

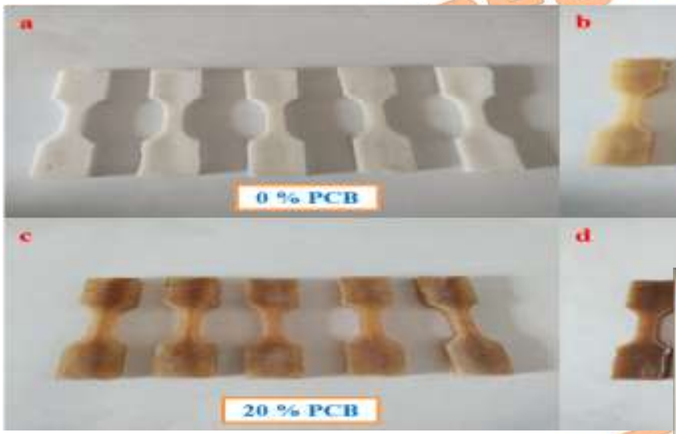

Fig. 2. (a-d). Tensile test specimens of HDPE/PCB composite with various content % of PCB

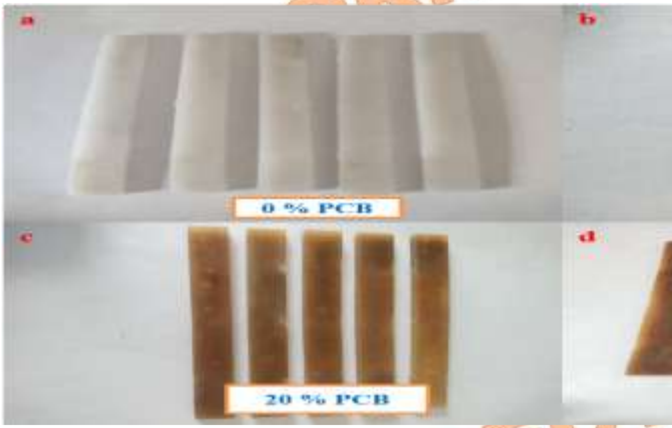

Fig. 3. (a-d). Flexural test specimens of HDPE/PCB composite with various content % of PCB

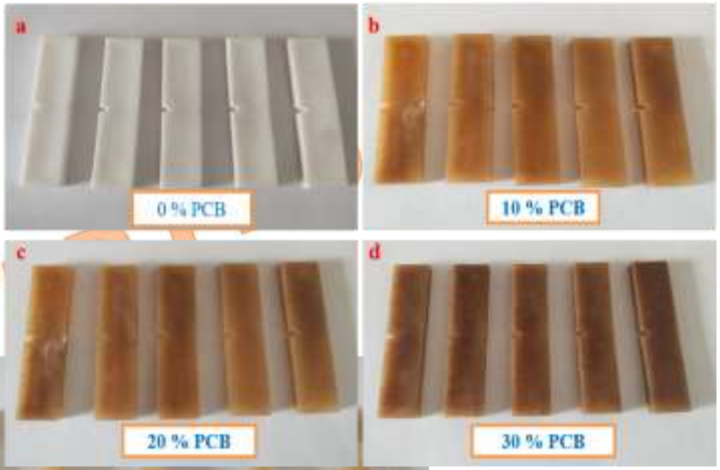

Fig. 4. (a-d). Impact test specimens of HDPE/PCB composite with various content % of PCB

Fig. 5. Images of characterization apparatus (a) Tensile, (b) Flexural, and (c) Impact testing machine, (d) EDAX-SEM apparatus

3. Results and Discussion

3.1 Phase characterization by using FTIR and XRD

Fourier Transform Infrared Spectroscopy (FTIR) was performed to investigate the chemical structure and weathering-induced degradation of HDPE/PCB composites, as shown in Figure 6. The spectra were recorded in the range of 4000–500 cm^{-1} for both unexposed and weathered samples. The unexposed HDPE/PCB composite samples showed characteristic absorption peaks of HDPE at ~2915 cm^{-1} and ~2848 cm^{-1} due to asymmetric and symmetric –CH$_2$ stretching,~1472 cm^{-1} and ~720 cm^{-1} attributed to –CH$_2$ bending and rocking vibrations. Upon incorporation of PCB waste, no major shifts in HDPE peaks were observed, indicating no significant chemical interaction between the matrix and the filler. However, minor peaks attributable to epoxy residues or flame-retardant compounds in PCB may occur, indicating the complicated composition of the PCB filler. The carbonyl absorption bands at 1718 cm^{-1} show an increase in intensity. This carbonyl band is associated with the formation of oxidation products such as ketones, aldehydes, and carboxylic acids, suggesting degradation of the polymer backbone. The increase in carbonyl-index bands (≈1718 cm^{-1}) in terms of oxidative degradation pathways and the catalytic effect of metal oxides present in PCB fillers, rather than assuming general "degradation." It has been clarified how specific functional groups in the filler (epoxy fragments, brominated residues, glass-fiber sizing) may influence HDPE chain scission or surface oxidation. The extent of oxidation varied with PCB content, implying that the presence of certain metal oxides or fillers in the PCB may catalyze the degradation process [21].

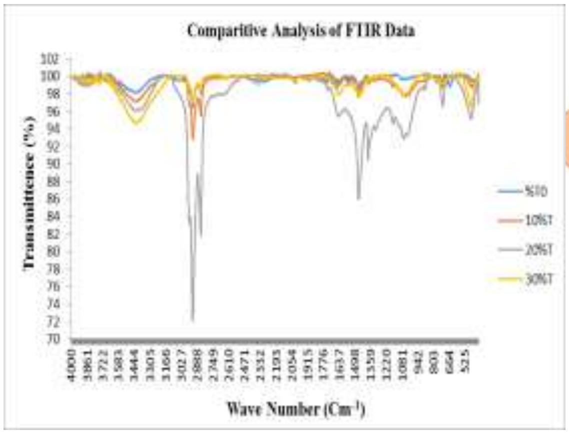

Fig. 6. Comparative data plot of FTIR

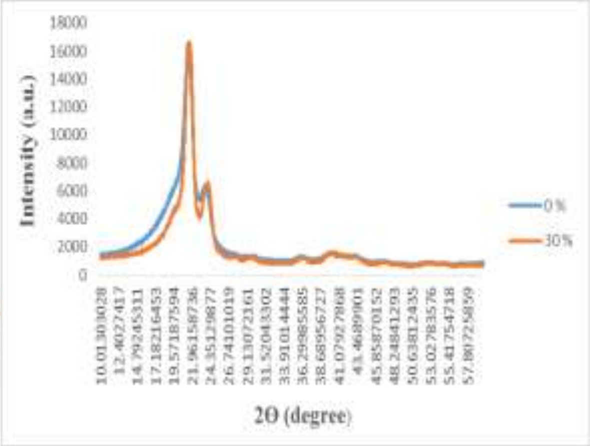

Fig. 7. Comparative data plot of XRD

To describe the peak shifts and crystallinity, Cu Ka radiation (40 kV, 40 mA) was used for the X-ray diffraction analysis. The composites' crystallinity was discovered to be within the 10° to 60° angular range. Figure 7 displays the HDPE/PCB waste composites X-ray diffraction data. Several unique peaks were seen at 2Θ angles.

There is no polymorphic crystalline transition in HDPE, as shown by the XRD comparison graphs for HDPE and PCB (filler at the 30% level), as shown in Fig. 7. A sharp peak at 19.57 ° is observed, indicating strong diffraction attributed to the crystalline phase in HDPE. When PCB filler is added, a mound region is seen, which causes peaks to be suppressed. Furthermore, no new phases are discovered, confirming that no reaction phases have developed during rectification [24]. The suppression and broadening of HDPE crystalline peaks, the absence of new diffraction peaks, and the formation of a "mound region" upon filler addition collectively indicate restricted crystal growth, partial reduction in crystallite perfection, and increased amorphous content, rather than implying a polymorphic transition. These interpretations are now supported with references to polymer crystallization literature.

3.2 Morphology of the composites

This investigation was conducted using a Philips XL 40 Scanning Electron Microscope. The materials were analyzed using SEM-EDAX techniques for non-metallic PCB powder particles ranging from 0.03 to 0.15 mm. A proper dispersion of PCB powder within the HDPE matrix was ensured by using a controlled sieve size range of 0.03–0.15 mm, which is consistent with earlier studies reporting that fine, uniformly sieved non-metallic PCB particles disperse more effectively in thermoplastic matrices. This approach follows the methodology adopted by Muniyandi et al. (2013)[23], who demonstrated that sieved PCB particles (below 150 μm) exhibit improved distribution and interfacial contact when blended with recycled HDPE.

and 1.0 cm × 1.0 cm pieces for the cracked surface of HDPE/PCB composites. Gold coating was applied to the samples to provide a smooth surface. To obtain the intended results, the study required meticulous selection of the proper focus, magnification range, working distance, and other pertinent aspects. Figures 8 (a-d) and 9 (a-d) show SEM images of non-metallic PCB powder particles and cracked surfaces of HDPE/PCB composites, respectively. Figure 8(a) illustrates the presence of elongated glass fiber in PCB powder particles, while Figure 8(b) displays the presence of resin in glass fiber at a higher magnification. The nonmetallic PCB powder is undoubtedly made of glass fibers, the majority of which are encased in thermosetting resin, as seen by the shine in Fig.8(c). A thermoset resin is a type of polymer that becomes permanently hard when it is cured. After curing, it cannot be melted or reshaped. Thermoset resins provide high thermal stability, good chemical resistance, and a rigid structural network within the composite. A portion of the thermosetting resins adheres to the surfaces of the glass fibers. A sheet of non-metal sand fiber bundles in Figure 8(d) demonstrated the matrix's adherence between glass fibers, and non-metallic PCBs clearly display a rough surface characterized by an extended form and sharp structure. Strong interfacial adhesion between the glass fibers in non-metallic PCBs was demonstrated by a matrix that was inserted into the space between the glass fibers. Using ImageJ's particle analysis tool, individual PCB particles were segmented and measured, and quantitative parameters such as particle area, equivalent length, minimum and maximum Feret diameters, and orientation angle were extracted. The analysis shows that the PCB filler particles exhibit a broad but controlled size distribution, with measured particle lengths ranging from approximately 53 μm to 150 μm, and an average particle length of about 117 μm, which is consistent with the selected sieve size range (0.03–0.15 mm). The standard deviation in particle length (~39 μm) indicates moderate size variability, while the absence of very large agglomerates suggests reasonably uniform dispersion at the powder stage.

These ImageJ-derived quantitative results have now been included in the manuscript to support the discussion on filler dispersion quality. The numerical particle size statistics strengthen the SEM analysis and provide objective evidence to complement the qualitative morphological observations.

There is a separation between HDPE polymer and non-metallic PCBs as a result of the fillers and matrix not properly adhering. The superior degree of adhesion between the glass fibers and matrix enhances the composite's mechanical characteristics. At increased magnification, the adhesion between the matrix and glass fiber was seen in the figure. 9(a), suggesting that HDPE and glass fiber in non-metallic PCB have a strong interfacial bond. As illustrated in the figure. 9(b-c), a few void holes in the bonding of the non-metallic PCB and HDPE polymer suggest a poor elastomeric phase that begins to degrade the mechanical properties of the composite. The elastomeric phase refers to the rubber-like portion of the material that can stretch and return to its original shape. This phase improves the flexibility, impact resistance, and overall toughness of the composite.

The mechanical characteristics of the composites are improved by the strong link between glass fibers and the matrix, and microstructure analysis of non-metallic PCB trash. SEM analysis of the sample helped to evaluate particle size, microstructure, surface pattern, and non-metallic PCB powder arrangement [23].

Irregular, sharp PCB particles (seen in SEM) create local stress concentrators, which directly contribute to the observed drop in tensile strength and brittle fracture behavior. Increasing pore density and interfacial voids with higher filler content (Figures 9b–9d) explain the progressive loss in toughness and impact strength, as these voids reduce energy-absorbing capability.

Areas of good mechanical interlocking between HDPE and embedded glass-fiber fragments are consistent with the increase in flexural modulus and strengthening under bending, because bending loads are less sensitive to interfacial debonding than tensile or impact loads.

Poor wetting at the filler–matrix interface, visible as debonded regions, correlates with reduced load transfer efficiency in tension, explaining why stiffness increases (because of rigid fillers) but tensile strength decreases (because the interface fails prematurely).

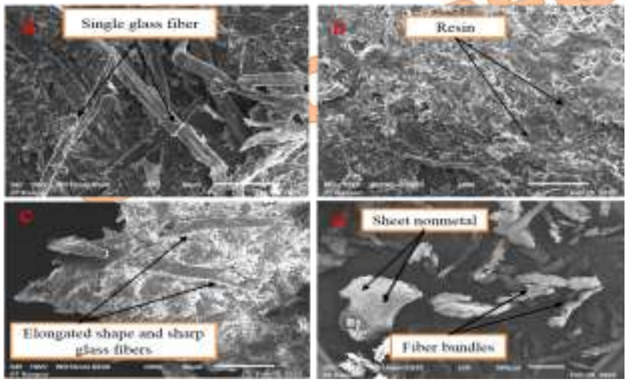

Fig. 8. (a-d). Showing SEM images of non-metallic PCB powder particles

8a) Single glass fibre, 8b) resin, 8c) Elongated shape and sharp glass fibres, 8d) Sheet non-metal

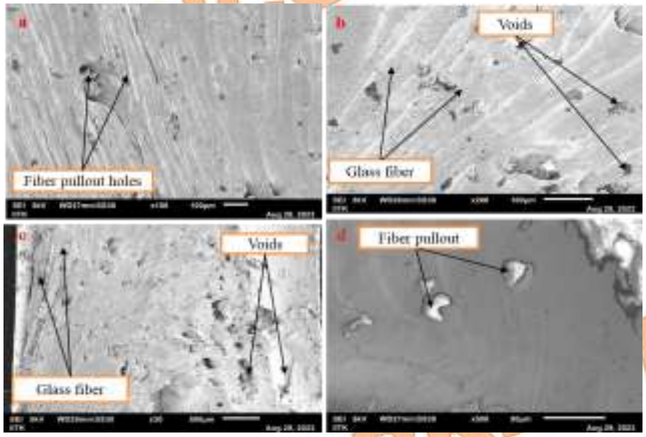

Fig. 9. (a-d). Showing SEM images of cracked surfaces of HDPE/PCB composites

9a) Fibre pull out, 9b) glass fibre and voids at 100μm, 9c) glass fibre and voids at 500μm, 9d) Fibre pullout at 50μm

3.3 Mechanical Properties

Results of tensile strength, tensile modulus, flexural resistance, flexural modulus, and impact strength of composite samples have been reported in this study. Mechanical characteristics have demonstrated substantial improvement when printed circuit board (PCB) waste is included in composites. Table 3 shows the results of tensile, flexural, and impact parameters.

Table 3. Mechanical characteristics of HDPE composites with different contents of PCB

PCB Content (wt %)	0%	10%	20%	30%
Tensile testing				
Modulus of elasticity (MPa)	635	875.5	1197.5	1752.5
Tensile strength (MPa)	21.72	11.55	13.46	17.06
Flexural testing				
Flexural modulus (MPa)	2382.5	3262.5	3610	4410
Flexural strength (MPa)	11.04	11.61	14.46	17.52
Impact strength (J/m^2)	119.394	109.974	73.222	44.381

3.3.1 Tensile testing

Tensile characteristics, including modulus of elasticity and tensile strength of HDPE and PCB-filled HDPE/PCB composites, are impacted by the filler weight percentage, as illustrated in Figures 10 and 11. Figure 10 illustrates how the tensile strength of the HDPE/PCB composite dropped from 21.72 to 17.06 MPa when PCB was added to HDPE. Several reasons, including poor filler dispersion, poor adhesion between the filler and matrix, and inadequate wetting of the filler with the matrix, can be blamed for the composite's lower tensile strength when compared to virgin polymer. Furthermore, adding more glass fibers to non-metallic PCBs could decrease component dispersion and composite flowability, which could result in poor interfacial adhesion. Additionally, referring to Figure 11, it was noted that the

Young's modulus of the HDPE/PCB composites rises from 635 to 1752.5 MPa when PCB filler is added to HDPE at weight fractions of 10, 20, and 30%, respectively. The interfacial bonding between the glass fibers and the resin is particularly important. Strong adhesion at the fiber–matrix interface ensures effective stress transfer, delaying fiber pull-out and crack propagation. Conversely, poor interfacial bonding can lead to premature failure, as cracks may easily propagate along the interface, reducing the composite's strength and toughness. The resin's viscoelastic properties also influence energy absorption during deformation, contributing to impact resistance and fatigue performance. Therefore, the overall mechanical behavior of the composite arises from a balance between the stiffness and strength of the glass fibers, the toughness and ductility of the resin, and the quality of the interfacial bonding between them.

When non-metallic parts from a Printed Circuit Board (PCB) are added to a High-Density Polyethylene (HDPE) composite, the tensile strength decreases while the tensile modulus increases. This is primarily due to the PCB's non-metallic components acting as a filler material within the HDPE matrix. The PCB fillers stiffen the composite, leading to an increase in the Young's modulus (tensile modulus), but they also create weak interfaces or micro-defects that reduce the overall ability of the material to withstand tensile stress and fracture, thus decreasing tensile strength. As we can observe in the SEM images of PCB powder particles used as filler (figure 8) and of the fractured composite surface (figure 9). It can clearly be summarized that having sharp-edged filler particles and the presence of voids in the fabricated composites can lead to such behavior. In addition, the relatively brittle nature of the PCB filler and potential poor interfacial adhesion with the HDPE matrix can create stress concentrations during tensile loading, leading to reduced tensile strength at higher filler content. When filler particles are included, the limited mobility and deformability of macromolecules may be the cause of the composites' elevated Young's modulus [13].

Supplementary Table 1 represents a comparison of Voigt and Reuss with experimental data. To interpret the experimentally measured elastic moduli of the HDPE/PCB composites, classical micromechanical bounds were applied to estimate the theoretical limits of composite stiffness. These bounds are commonly expressed using the Voigt (upper bound) and Reuss (lower bound) models, which represent idealized load-sharing conditions between the matrix and the filler phases. The Voigt model assumes uniform strain in both phases (iso-strain condition), corresponding to perfectly aligned reinforcement and ideal load transfer, and therefore provides an upper limit for the composite modulus. In contrast, the Reuss model assumes uniform stress in both phases (iso-stress condition), representing poor load transfer and weak interfacial bonding, and thus defines the lower limit of stiffness. In real particulate-filled polymer composites, the experimentally measured modulus is expected to lie between these two bounds. Comparing experimental results with these theoretical limits provides insight into the effectiveness of filler reinforcement and the role of interfacial adhesion in governing the mechanical response of the composite.

The PCB contents of 10, 20, and 30 wt % were first converted to volume fraction using the densities of HDPE and PCB filler. The filler volume fraction V_f is calculated from the weight fraction w_f as shown in Equation 1.

[illegible] … (1)

Where ρ_m = 0.964 g/cm^3 is the density of HDPE and ρ_f = 1.85 g/cm^3 is the density of the non-metallic PCB filler. Substituting the values:

Now,

The volume fraction of the matrix Vm is calculated by using Equation 2.

$$V_m = 1 - V_f \qquad \text{......} (2)$$

Now, the Estimation of the effective filler modulus from the Rule of Mixtures

The tensile modulus of neat HDPE is $E_m = 0.635\ \text{GPa}$ (635 MPa), and the tensile modulus of the 30 wt% composite is $E_c = 1.7525\ \text{GPa}$ (1752.5 MPa).

Using the Voigt (upper-bound) Rule of Mixtures using Equation 3 as shown below.

$$E_c = V_m E_m + V_f E_f \quad \text{……} \ (3)$$

Now, using Equation 4 for the Reuss (lower) bound as shown below.

Ec lower = 1 / [(Vm / Em) + (Vf / Ef)] …… (4)

where:
E_m = matrix modulus = 0.635 GPa, E_f = filler modulus = 6.8 GPa,

The experimental tensile moduli lie between the Reuss (0.67–0.76 GPa) and Voigt (0.97–1.76 GPa) bounds and approach the upper bound at higher PCB contents. Thus, experimental moduli therefore lie between the Reuss lower bound and the Voigt upper bound and are close to the upper bound at higher filler contents, confirming that the rigid PCB filler significantly reinforces the HDPE matrix. These provide a quantitative theoretical framework that supports the experimentally observed stiffness enhancement in HDPE/PCB composites.

Chemical surface treatment of PCB particles, such as silane coupling agents on the glass-fibre-rich non-metallic fraction, to form covalent or hydrogen bonds between the hydroxylated glass surface and the HDPE-compatible end groups. This can improve interfacial adhesion, reduce interfacial voids and micro-cracks, and thereby enhance tensile strength. Use of compatibilizers in the HDPE matrix, for example, maleic-anhydride-grafted polyethylene (PE-g-MA), which can interact with polar groups present in the epoxy/glass phase of the PCB waste while remaining compatible with the nonpolar HDPE chains. Such reactive or polar compatibilizers are expected to improve stress transfer across the interface and partially recover the loss in tensile and impact strength. Physical treatments (e.g., mild alkali etching, plasma or corona treatment) of PCB powder surfaces to increase roughness and introduce polar functional groups, promoting mechanical interlocking and chemical affinity with the compatibilized HDPE matrix. Future work could implement and compare these treatments to quantify their effect on tensile and impact properties, thereby providing a pathway to overcome the strength–stiffness trade-off observed in the present, untreated HDPE/PCB composites.

3.3.2 Flexural Testing

Figures 12 and 13 show how the filler weight percentage affects the HDPE/PCB composites' flexural parameters, such as their flexural strength and flexural modulus. Referring to Fig.12 and Fig.13, the flexural strength and flexural modulus values of the composite came out to be 17.52 and 4410 MPa, respectively. HDPE/PCB composites using PCB filler up to 30%, the composites' flexural strength and modulus increase as PCB weight fraction rises.

In HDPE/PCB composites, increasing the PCB filler content generally enhances flexural strength and modulus, but reduces tensile strength. This is because the PCB filler, particularly its glass fiber component, provides stiffness and rigidity, increasing the composite's resistance to bending (flexural strength and modulus). These findings are in line with earlier research; Guo et al. (2010) found that wood polymer composites (WPC) with nonmetallic PCBs had somewhat higher flexural strengths than control samples. The reason behind this is that the glass fibers in non-metallic printed circuit boards improved the composite's qualities. Zhen et al. (2009) have noted similar outcomes in nonmetallic printed circuit boards and polypropylene blends. A further study by Wang et al. (2010) found that a PVC substrate's bending strength increased by up to 39.83 MPa when nonmetallic PCB particles were added, which is 123.1% superior to pure PVC. They discovered that improving the nonmetallic PCB filler fraction from 10 to 30 weight percent enhanced the flexural qualities of the composites.

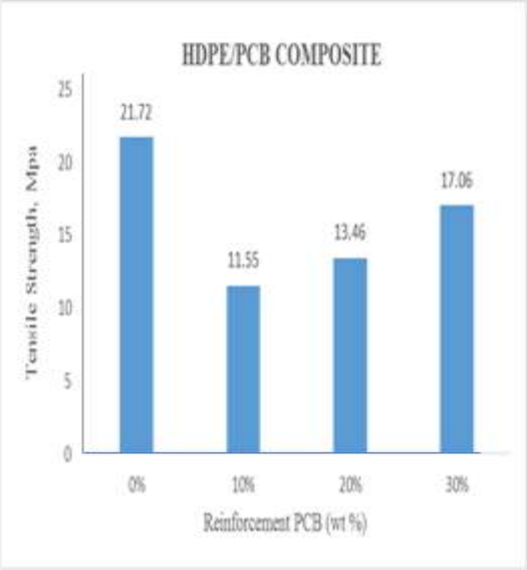

Fig. 10. Effect of reinforcement wt. (%) on Tensile strength

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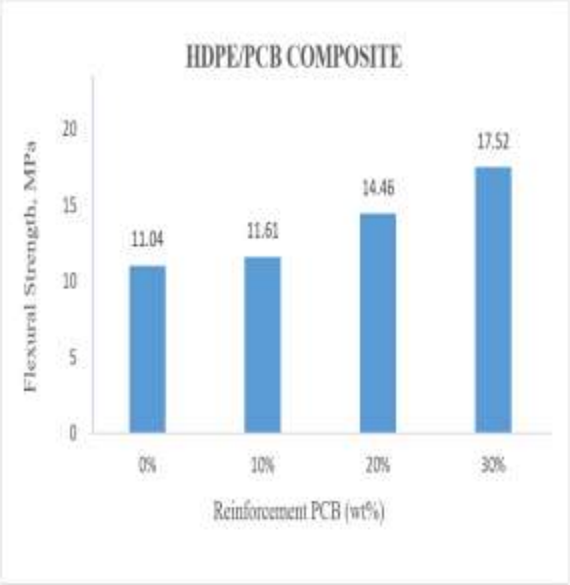

Fig. 12. Effect of reinforcement wt. (%) on Flexural strength

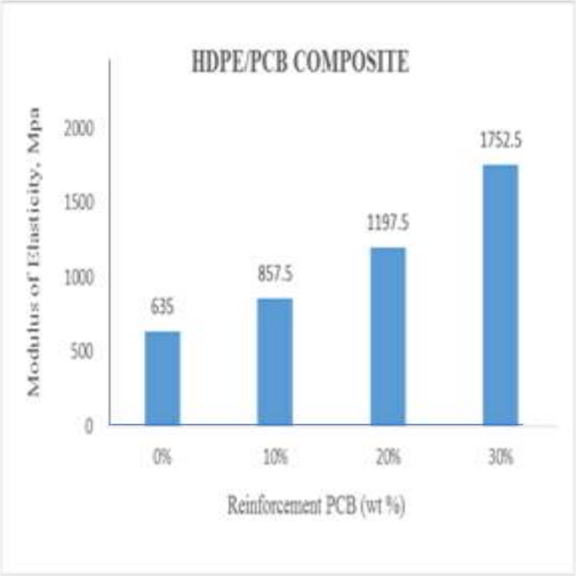

Fig. 11. Effect of reinforcement wt. (%) on Modulus of elasticity

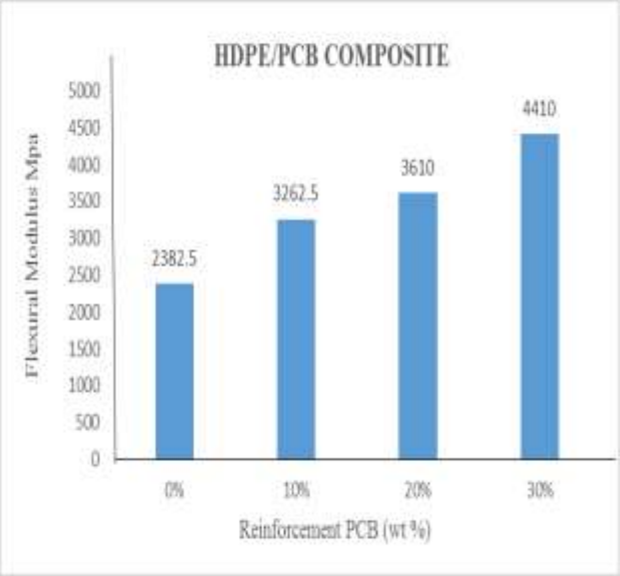

Fig. 13. Effect of reinforcement wt. (%) on Flexural modulus

Figures 12 and 13 exhibit that the flexural strengths and flexural modulus of HDPE/PCB composites vary with filler weight fraction. The great compatibility and appropriate interfacial adhesives given by glass fibers in the reinforcement between the non-metallic PCBs and the matrix explain the expected rise in flexural properties. The findings align with prior research demonstrating that the distinctive feature of non-metallic materials in PCBs is their flexural characteristics. As such, they concluded that this quality is beneficial for objects mostly used under bending loads [17].

3.3.3 Impact testing

In addition, Fig. 14 indicates the influence of filler weight fraction on the impact parameters, including impact strength of HDPE and PCB-filled HDPE/PCB composites, illustrating that impact strength reduces from 119.394 to 44.381 J/m^2, when 10 to 30 weight percent nonmetallic PCB component is added. It suggests that adding more filler may limit the polymer chain's mobility and movement. Lower impact strength is the result of the reinforcement's brittle nature and tendency to stress concentration. According to these results, glass fibers in nonmetallic PCB increased the stiffness of the composites while decreasing their toughness [23, 24]. Additionally, because the HDPE matrix and PCB filler do not adhere well to one another, which creates stress concentration regions like voids, as can be seen in Figure 9b, assisted in making the composite more prone to fracture. This led to a decrease in the toughness of the composite, making it more brittle and less able to absorb energy during impact.

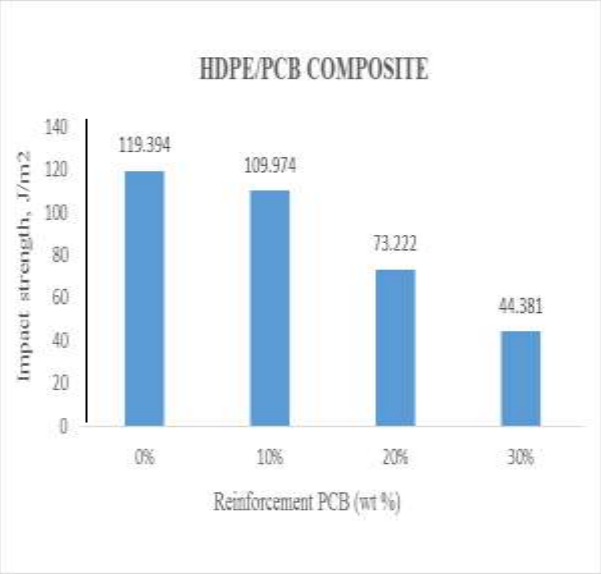

Fig. 14. Effect of reinforcement wt. (%) on impact strength

These results show a decrease in tensile and impact strength with increasing PCB content. Several studies on polymer/PCB and related waste-filled composites [13, 14, 20, 23] reported either maintained or improved strength when better interfacial adhesion and optimized particle morphology were achieved. It explicitly contrasts our tensile and impact behavior with these works and attributes the discrepancy to factors such as (i) absence of compatibilizers, (ii) relatively sharp, irregular PCB particles, and (iii) voids/poor wetting observed in our SEM micrographs. At the same time, it is noted that flexural modulus and strength trends are consistent with reports where the glass-fibre-rich nonmetallic PCB fraction primarily enhances stiffness under bending.

4. Conclusions

The feasibility of waste printed circuit boards (PCBs) as reinforcing fillers in polymer composites is explored in this work. Especially printed circuit boards, the growing volume of electronic trash raises serious environmental problems.

- The addition of PCB filler to composites reduces their tensile strength as compared to virgin polymers. This can be attributed to insufficient adhesion between the matrix and filler, poor dispersion of fillers, and insufficient soaking of the matrix and filler. Also, adding more glass fiber to non-metallic PCBs can diminish the flowability of composites and the dispersion of components, which could result in interfacial adhesion. Additionally, with the addition of PCB filler, the Young's modulus elevated, suggesting enhanced stiffness as a result of the filler particles limiting macromolecular mobility and deformability.

- By including PCB filler, the great compatibility and appropriate interfacial adhesives given by glass fibers in the reinforcement between the non-metallic PCBs and the matrix explain the expected rise in flexural properties. The flexural strength and modulus increased, suggesting that the glass fibers inside the

PCB gave reinforcement and enhanced bending resistance.

- Higher PCB concentration indicated higher brittleness as the impact strength dropped. The reductions in impact strength seen when 10 to 30 weight percent nonmetallic PCB component was added, suggesting that the reinforcements will also result in stress concentrations and brittleness, which will reduce impact strength.
- Insufficient adhesion and voids between the HDPE matrix and PCB filler observed by the SEM study indicated incompatibility. However, there was noticeable adhesion between the HDPE matrix and the glass fibers of the PCB, hence enhancing the tensile and flexural characteristics. Within thermosetting resin, the PCB filler shows irregular surfaces, elongated forms, and encased glass fibers.
- Including PCB filler into HDPE produced a compromise between tensile parameter and stiffness. The flexural characteristics and modulus got better, suggesting the composites grew more rigid and bent-resistant. The fall in impact strength points to a material's brittleness rising. The SEM images provide important new perspectives on the composite's form and the filler-matrix interaction.
- By utilizing copious amounts of PCB waste that is rich in polymers as fillers in the production of polymer-based composites, this study has contributed to the development of an environmentally acceptable method. This strategy might contribute to the opening of new and different avenues for the environmentally sustainable use of garbage.
- Considering the trade-off between increased stiffness/flexural performance and reduced tensile and impact strength, the developed HDPE/PCB composites are most suitable for semi-structural or non-structural applications where bending rigidity and dimensional stability are required, but the components are not subjected to severe tensile or impact loads.

Future Scope

The potential use of compatibilizers (e.g., PE-g-MA), surface treatments for PCB fillers (such as silane or alkaline treatment), and hybrid reinforcement approaches combining PCB waste with other fillers to enhance adhesion, toughness, and overall mechanical performance. These strategies will be mentioned to show clear directions for advancing the current composite system.

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Conflicts of Interest

The authors declared no potential conflict of interest in the publication of this article.

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