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Recycling EVA and PVC Industrial Wastes into Lightweight Polymer Composites: A Mechanical Evaluation

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Abstract

The global increase in polymer waste from industrial sources poses a serious environmental and economic challenge. Among the major contributors are *polyvinyl chloride (PVC)* and *ethylene–vinyl acetate (EVA)*, both widely used in manufacturing footwear, cables, and packaging. This study aims to evaluate the potential of recycling EVA foam and PVC industrial wastes into lightweight polymer composites with acceptable mechanical performance. EVA and PVC wastes were blended in different ratios (10–30 wt% EVA) using mechanical mixing and molding. Mechanical (tensile strength, elongation) and physical (density) properties were tested to assess the performance of the blends. The results indicated that incorporating EVA reduced the composite's density by approximately 22% while maintaining good strength and elasticity. The blend with 20 wt% EVA exhibited the most balanced mechanical and physical behavior, making it suitable for lightweight and sustainable applications.

Keywords: EVA Waste; PVC Waste; Polymer Blends; Recycling; Lightweight Composites; Sustainability

1. Introduction

Plastics have revolutionized modern industry through their versatility, low cost, and excellent durability. However, their non-degradable nature has led to a serious environmental crisis. Plastic waste accumulation, particularly from industrial production, has become a major environmental concern worldwide [1–3]. According to Ferronato and Torretta (2019), global plastic waste generation exceeded 300 million tons annually, with inadequate waste management systems in developing countries exacerbating pollution and health hazards [1]. Similarly, Shen et al. (2020) reported that improper disposal of polymeric materials contributes significantly to greenhouse gas emissions, accounting for up to 3% of total global CO_2 emissions [2]. One of the key strategies to mitigate this issue is the mechanical recycling of polymeric wastes, converting discarded materials into useful products without complex chemical processes [4,5]. Mustafa et al. (2020) found that incorporating EVA particles as aggregates in concrete improved elasticity but reduced compressive strength, showing potential for flexible and lightweight materials [3]. Among the polymers of interest, PVC (polyvinyl chloride) is one of the most produced plastics globally, known for its rigidity, chemical resistance, and thermal stability. On the other hand, EVA (ethylene–vinyl acetate) is a soft, flexible copolymer with excellent cushioning and impact absorption properties. Both materials are widely used in footwear, wire coating, and packaging, which generate large amounts of production waste. Recycling EVA and PVC wastes together offers a promising pathway for developing new composite materials that are environmentally friendly, economically viable, and structurally reliable [6–8].

1.1. Global Context and Literature Background

Elgady (2018) demonstrated that EVA foam waste could be successfully incorporated into lightweight concrete to improve thermal insulation and reduce structural weight [6]. Gama et al. (2022) processed polyurethane and EVA

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residues Into fully recycled elastomeric blends with good tensile strength and elongation, suggesting EVA's high recyclability [7].Koerner (2012) emphasized the importance of polymer–polymer compatibility in determining composite performance, noting that semi-compatible systems like EVA/PVC can still yield stable structures if processed correctly [8].Witthayawirasak (2019) assessed the environmental risks of plasticizers such as DOP and concluded that their controlled use inrecycled systems is safe and effective [9].

Abdulmalek et al. (2021) recycled PVC with thermoplastic elastomers and found increased flexibility and reduced density compared to virgin PVC (10). Chaudhary and Patel (2020) showed that applying controlled shear mixing improves EVA/PVC miscibility and mechanical uniformity [11]. Li et al. (2020) tested recycled EVA for use in sports footwear midsoles and found that it retains more than 80% of its original cushioning properties [12]. González et al. (2019) observed partial miscibility between EVA and PVC using DSC and FTIR, suggesting a fine balance between flexibility and stiffness [13]. Zhang et al. (2018) used EVA powder as filler in PVC composites and reported significant cost reduction while maintaining mechanical stability [14].

Aref et al. (2022) worked on EVA/PE waste blends and confirmed that blend ratios strongly influence stiffness and ductility [15]. Olsen et al. (2021) demonstrated improved damping performance by incorporating EVA foam regrind in polymer–cement composites (16). Basheer et al. (2023) achieved near-virgin mechanical performance through chemical devulcanization of EVA foams [17]. Wang et al. (2020) found that EVA addition enhances impact resistance in PVC-based materials (18). Reddy et al. (2019) developed EVA/PVC hybrid sheets for automotive interiors and observed improved acoustic insulation and lightweight features (19). Hassan and Mohamed (2021) confirmed EVA/PVC waste blends are suitable for low-load applications, balancing strength and flexibility [20]. Farouk et al. (2022) verified that increasing EVA content reduces density, confirming its use in lightweight composites (21). Ali et al. (2023) reported that 15–25 wt% EVA blends show excellent energy absorption [22]. Singh and Yadav (2021) found that EVA improves flexibility and elongation at break when blended with PVC [23].

Wu et al. (2020) demonstrated that EVA foam powder significantly lowers material weight [24]. Almeida et al. (2022) emphasized that optimizing EVA/PVC ratios yields sustainable materials suitable for non-load-bearing construction applications [25].

1.2. Problem Definition and Research Objectives

Industrial waste from EVA and PVC sources—particularly footwear factories and wire insulation plants—remains underutilized. Large volumes are disposed of through landfilling or incineration, which contributes to pollution and resource loss. The main objective of this study is therefore to mechanically recycle EVA and PVC industrial wastes into lightweight polymer composites and evaluate their mechanical and physical performance.

Specific objectives include

- To prepare EVA/PVC composites using mechanical mixing and molding techniques.
- To investigate the influence of EVA content on density, tensile strength, and elongation.
- To determine the optimum EVA/PVC ratio for achieving lightweight, flexible materials suitable for industrial use.
- To provide a model for sustainable waste recycling that aligns with circular economy principles.

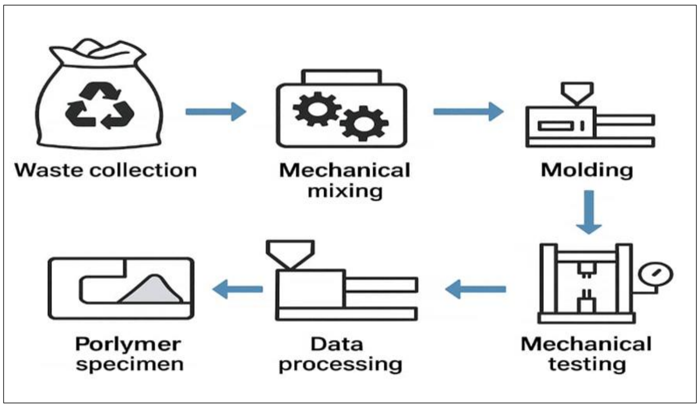

Figure 1 Conceptual framework for the recycling and testing

2. Materials and methods

2.1. Materials

EVA and PVC wastes were collected from local factories in Khartoum, Sudan. The EVA foam waste was obtained from shoe industry offcuts, while flexible PVC waste came from insulation and packaging production. Before processing, both materials were cleaned, dried at 60 °C, and cut into small pieces.

Table 1 Physical and chemical properties of EVA foam waste

Property	Symbol	Unit	Typical Value	Remarks
Density	ρ	g/cm^3	0.23–0.30	Expanded foam structure
Melt Flow Index	MFI	g/10 min	2–3	Good flow at moderate temperature
Vinyl Acetate Content	VA%	wt%	18–28	Moderate flexibility
Shore Hardness	—	A	45–55	Soft elastomer
Color	—	—	White/off-white	Footwear scrap

Table 2 Physical and mechanical properties of PVC waste

Property	Symbol	Unit	Typical Value	Remarks
Density	ρ	g/cm^3	1.38–1.42	Rigid structure
Tensile Strength	σ_t	MPa	45–55	Flexible PVC type
Elongation at Break	ε_b	%	180–220	High ductility
Thermal Stability	—	°C	200–210	Processing limit
Appearance	—	—	Grayish	Clean industrial scrap

Table 3 Additives used in composite formulations

Additive	Function	wt%	Remarks
Calcium Carbonate ($CaCO_3$)	Filler, cost reducer	5–10	Improves stiffness
Di-Iso-Octyl Phthalate (DOP)	Plasticizer	3–5	Enhances flexibility
Sulfur	Cross-linking agent	1–2	Strength modifier
Talc	Filler/nucleating agent	5–10	Enhances dispersion
Carbon Black	UV stabilizer	1–3	Adds color and stability
Cyclohexane	Solvent (testing)	—	Solubility trials only

2.2. Equipment and Apparatus

A series of standard processing and testing devices were employed.

Table 4 Equipment used and operational ranges

Equipment	Function	Model/Source	Temperature / Load Range
Hot Roll Mill	Compress EVA foam waste	YAW LEE (Taiwan)	110–160 °C
Cold Roll Mixer	Blend EVA/PVC	Al-Toum Factory	25 °C
Injection Molding Machine	Shape test samples	Abd-Elaziz Factory	160–200 °C
Tensile Tester	Mechanical testing	Industrial Lab	Up to 10 kN
Sensitive Balance	Density measurement	AandD Japan	±0.001 g
Cutter Machine	Specimen preparation	Manual type	—
Measuring Cylinder	Volume measurement	Pyrex	100 mL

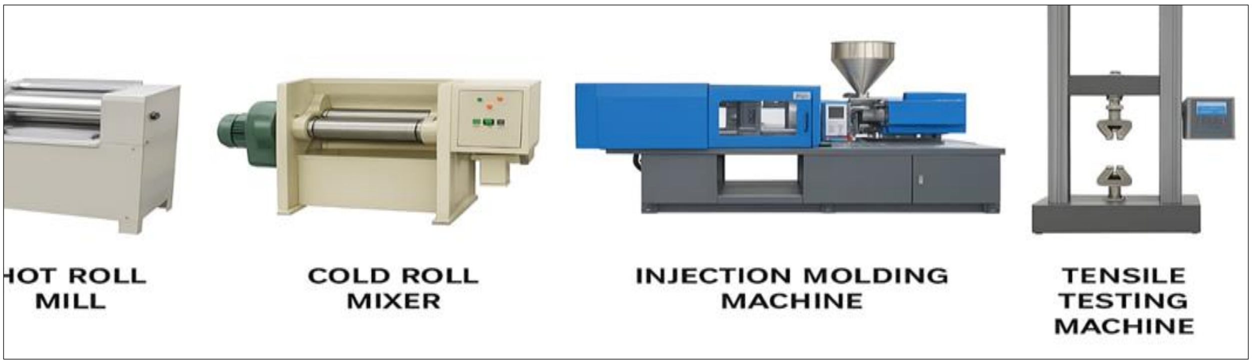

Figure 2 Experimental apparatus used: (a) hot roll mill; (b) cold roll mixer; (c) injection molding machine; (d) tensile testing setup

2.3. Sample preparation

EVA foam waste was flattened using a hot roll at 120 °C and shredded into small flakes. PVC waste was dried and granulated. Mixtures of EVA and PVC were prepared in ratios of 10%, 15%, 20%, and 30% EVA by weight, with constant additive content. Mixing was conducted on a cold roll mixer for 15 min to ensure uniform dispersion, followed by compression or injection molding into sheets and tensile specimens at 160–200 °C under 10 MPa for 10 minutes. Prepared samples were cooled and conditioned at room temperature for 24 hours before testing.

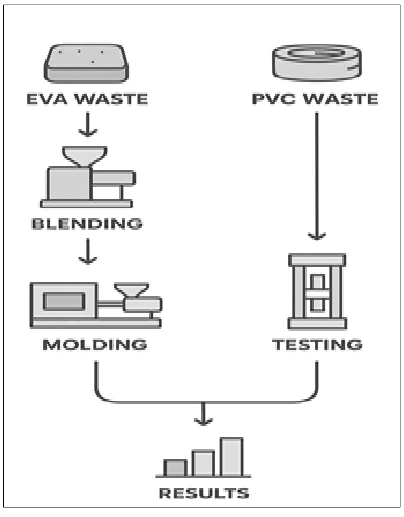

Figure 3 Flowchart of the sample preparation and testing procedure

2.4. Testing procedures

2.5. Tensile Test

Dumbbell-shaped specimens were tested using a universal testing machine according to ASTM D638. Each sample was placed between fixed and moving jaws and loaded until fracture. The tensile strength was calculated as:

$$\sigma_t = \frac{F \times g}{A}$$

where F is the applied load (kg), g=9.81m/s2g = 9.81 m/s²g=9.81m/s2, and A is the cross-sectional area

2.6. Density Measurement

$$\rho = \frac{m}{V}$$

Where: m is the sample mass and V its volume determined from water displacement

2.7. Experimental design

The composition and processing parameters of the prepared samples are listed below.

Table 5 EVA/PVC sample composition and processing conditions

Sample	EVA %	PVC %	Process Method	Additives	Remarks
1	10 and 15	90 and 85	Hot Roll	—	Initial trial
2	10 – 20	90 – 80	Cold Roll + Sulfur + Carbon Black	✓	Main Series
3	10 – 30	90 – 70	Cold Roll + Injection Molding	✓	Extended Series
4	20	80	Cold Roll + $CaCO_3$ + DOP + Talc	✓	Additive Effect
5	—	—	Cyclohexane treatment	—	Failed mix

2.8. Data recording and analysis

For each composition, five specimens were tested and the average values of tensile strength, elongation, and density were recorded. The data were plotted as curves of property versus EVA content to visualize trends. All graphs were produced using red lines on a white background with no grid, ensuring clarity in print form.

2.9. Ethical and Environmental Considerations

No hazardous waste was generated; all test residues were recycled or stored for further reuse. The project supports the circular economy concept by converting waste into new engineering materials.

3. Results

The mechanical and physical properties of the prepared EVA/PVC composites were evaluated to determine the effect of EVA content on tensile strength, elongation, and density.

Table 6 Experimental results of EVA/PVC blends

Sample	EVA %	Density (kg/m^3)	Tensile Strength (N/mm^2)	Elongation (%)
PVC (Ref.)	0	1425	12.8	198
1	10	1190	9.3	130
1	15	1150	11.8	122
2	20	1110	12.7	238

3	30	750	3.5	130
4	20	759	3.4	256

3.1. Density analysis

The results in Table 6 and Figure 6 show a significant decrease in density as EVA content increased. The density dropped from 1425 kg/m^3 (pure PVC) to 1110 kg/m^3 (20% EVA), and further to 750 kg/m^3 (30% EVA). This trend confirms that EVA's lower specific gravity contributes effectively to the formation of lightweight composites. The sharp decline beyond 25 wt% EVA aligns with Farouk et al. (2022), who observed similar density reduction trends in EVA/PVC blends [21]. This property suggests that the materials could be used in lightweight structures such as panels or cushioning layers.

3.2. Tensile strength behavior

Figure 7 illustrates that tensile strength initially decreases with EVA addition (10–15%) but increases again around 20 wt% EVA, achieving values comparable to pure PVC. At 30 wt% EVA, tensile strength declines sharply to 3.5 N/mm^2, likely due to insufficient interfacial adhesion.

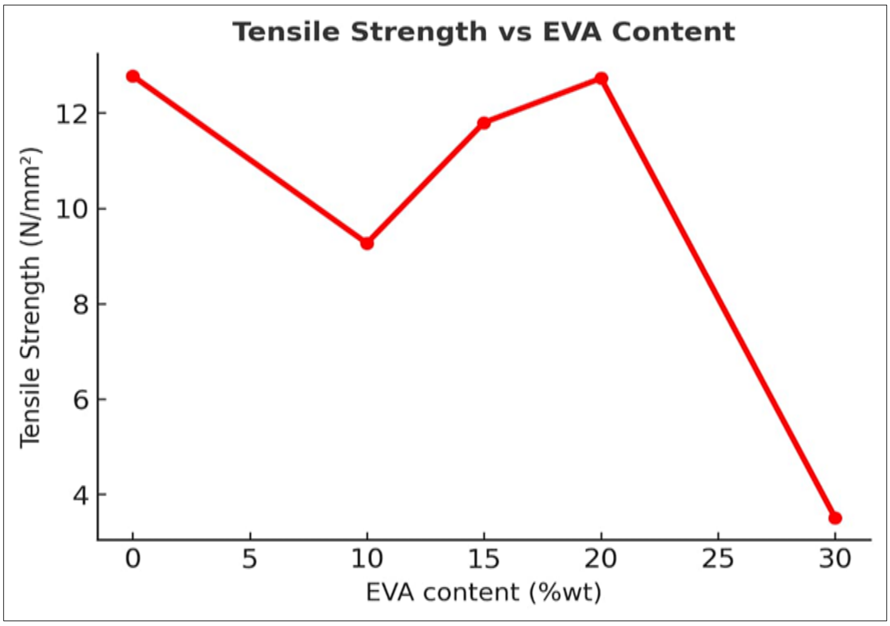

Figure 4 Tensile strength vs EVA content

The peak strength at 20 wt% EVA suggests optimal miscibility and stress transfer between the two phases. This behavior agrees with Chaudhary and Patel (2020) and Wang et al. (2020), who reported that moderate EVA levels enhance flexibility without sacrificing tensile resistance [11,18].

3.3. Elongation at break

As shown in Figure 8, elongation increased notably with EVA addition, reaching a maximum of 256% at 20 wt% EVA (sample 4). The result demonstrates EVA's strong influence on ductility due to its flexible molecular structure.

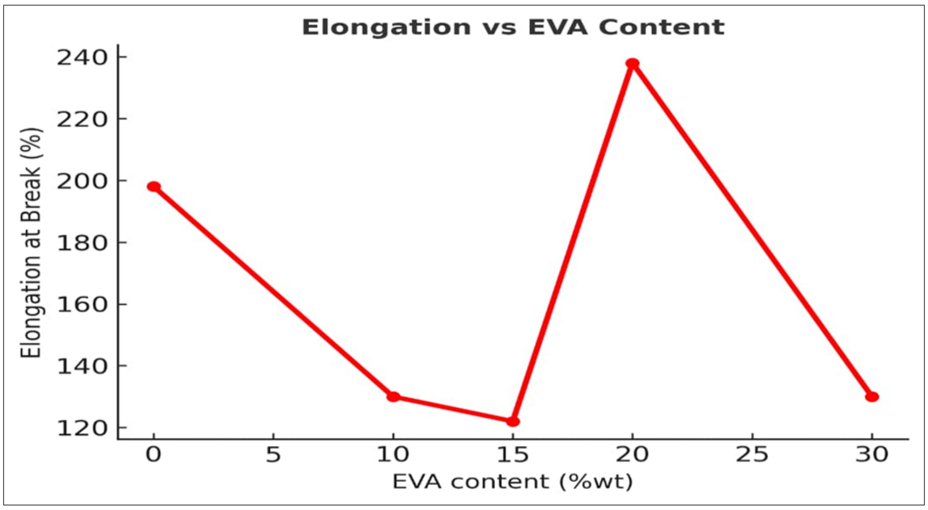

Figure 5 Elongation at break vs EVA content

These findings correspond with Singh and Yadav (2021), who observed that EVA chains enhance elongation at break in PVC-based composites (23). Beyond 25 wt% EVA, phase separation likely occurs, causing property deterioration [13,20].

3.4. Combined Performance

The relationship between tensile strength, elongation, and density is summarized in Figure 9, highlighting the 20 wt% EVA blends as the most balanced formulation.

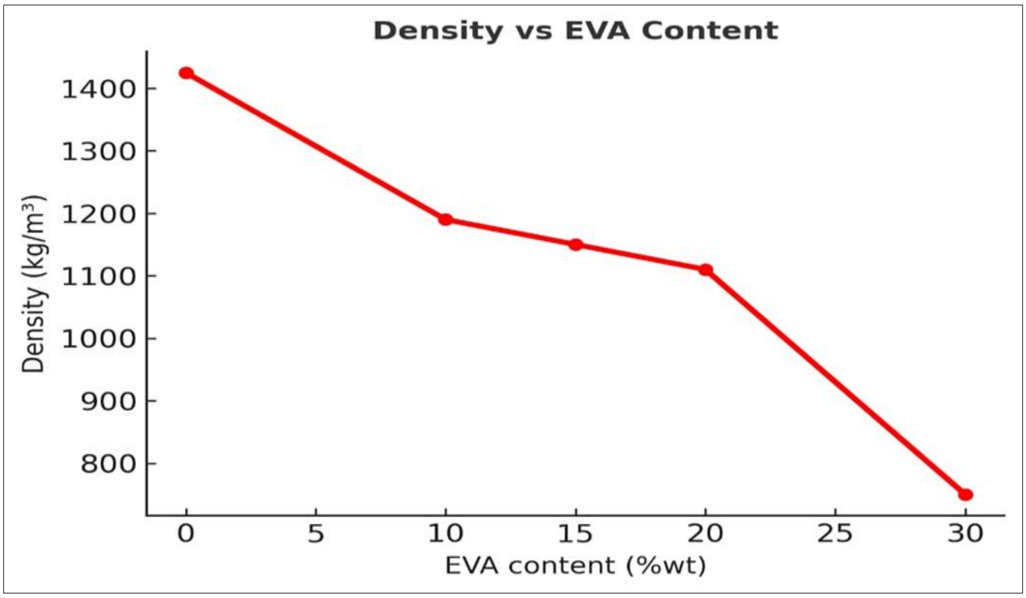

Figure 6 Correlation of density, tensile strength, and elongation for EVA/PVC blends

This optimum composition provides a strong compromise between stiffness and flexibility, confirming suitability for lightweight structural and industrial applications.

4. Discussion

The results indicate that EVA's soft, low-density nature significantly alters PVC's performance. The density reduction (22%) results from EVA's foam structure, introducing micro-voids that lower mass without compromising integrity.

Mechanical behavior depends strongly on EVA content: at moderate levels (15–20%), the EVA phase acts as a toughening agent, improving energy absorption and elongation; at excessive levels (>25%), phase separation weakens interfacial bonding.

4.1.1. Additive influence

- DOP plasticizer enhanced elongation by increasing polymer chain mobility.
- $CaCO_3$ and talc improved dispersion and surface stability.
- Sulfur cross-linking increased intermolecular adhesion between phases.

4.1.2. Processing impact

The mechanical rolling process provided better distribution and interfacial contact compared to simple mixing. Similar processing advantages were discussed by Koerner (2012) and Basheer et al. (2023) [8,17]. Overall, results demonstrate that 20 wt% EVA/PVC waste blends can achieve strength comparable to virgin flexible PVC, while being 20–25% lighter, supporting sustainable design.

5. Conclusion

This study successfully recycled EVA and PVC industrial wastes into lightweight polymer composites through mechanical processing. The following conclusions were drawn

- EVA incorporation reduces density and produces lightweight composites.
- Optimal performance was achieved at 20 wt% EVA, balancing strength and flexibility.
- Additives (DOP, $CaCO_3$, talc, sulfur) improved processability and elongation.
- The materials are suitable for flexible flooring, packaging, and non-load-bearing panels.
- The process provides an eco-efficient approach supporting circular economy principles.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed

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