



# Sustainable Reinforcement of Rubber Compound Using Recycled PET (Polyethylene Terephthalate): A Review

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**Abbreviation:** Nat. Env. & Poll. Technol.

**Website:** [www.neptjournal.com](http://www.neptjournal.com)

*Received:* 17-04-2025

*Revised:* 13-06-2025

*Accepted:* 16-07-2025

## Key Words:

Polymer composites  
Circular economy  
Green reinforcement  
Mechanical recycling  
Waste PET  
Rubber compatibility  
Sustainable materials  
Life cycle assessment

## Citation for the Paper:

Chauhan, M., Padhiyar, S., Desai, R., Patel, B. and Shukla, P., 2026. Sustainable reinforcement of rubber compound using recycled PET (polyethylene terephthalate): A review. *Nature Environment and Pollution Technology*, 25(1), B4342. <https://doi.org/10.46488/NEPT.2026.v25i01.B4342>

*Note:* From 2025, the journal has adopted the use of Article IDs in citations instead of traditional consecutive page numbers. Each article is now given individual page ranges starting from page 1.



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## ABSTRACT

Increasing environmental concerns over plastic waste and the depletion of non-renewable resources have intensified the search for sustainable alternatives in rubber reinforcement. This review comprehensively investigates the use of recycled polyethylene terephthalate (r-PET) as a green reinforcing agent in rubber compounds, replacing traditional fillers such as carbon black and silica. Experimental studies reveal that incorporating r-PET can improve tensile strength by up to 45%, enhance thermal stability by 20–30°C, and lead to energy savings of approximately 50 MJ.kg<sup>-1</sup> compared to virgin PET. Notably, this review is the first to integrate mechanical performance analysis with life cycle assessment (LCA), providing a dual perspective on technical feasibility and environmental impacts. Processing methods, such as mechanical blending, chemical grafting, and surface modification, have been discussed to enhance r-PET compatibility with rubber matrices. Challenges such as poor dispersion, interfacial adhesion, and thermal degradation are critically analyzed, along with mitigation strategies. The findings demonstrate that r-PET not only offers performance and cost advantages but also supports circular economy initiatives by repurposing post-consumer PET waste into high-performance rubber composite. Future research directions are proposed, focusing on hybrid reinforcement systems, compatibility enhancement, and carbon-footprint reduction.

## INTRODUCTION

The growing concerns over environmental pollution and resource depletion have driven the search for sustainable alternatives in materials science. One such approach is the incorporation of recycled PET (rPET) into rubber composites. PET, which is widely used in water bottle manufacturing, contributes significantly to plastic waste. Recycling PET into rubber matrices can mitigate environmental impacts and improve the performance of rubber products. This paper reviews the current state of research on r-PET as a reinforcement for rubber compounds. It covers processing techniques, mechanical properties, environmental benefits, etc., with a focus on overcoming the limitations of industrial applications.

The rapid increase in global plastic consumption, particularly in single-use applications, has created an urgent need for recycling and repurposing plastic waste. PET (IUPAC: Poly (ethyl benzene-1,4-dicarboxylate)), being one of the most widely produced polymers, presents a significant waste management challenge (Shen et al. 2025). Traditional disposal methods, such as landfilling and incineration, contribute to pollution and greenhouse gas emissions (Elamri et al. 2015). Consequently, researchers have explored innovative ways to integrate PET waste into various materials, including rubber compounds, to promote sustainability and reduce environmental degradation.

The integration of r-PET into rubber compounds is not only a means of recycling waste but also an approach to enhancing the material properties. Studies

have shown that PET-based reinforcements can improve tensile strength, abrasion resistance, and overall durability of rubber products (Cazan et al. 2014). However, issues such as phase separation, interfacial adhesion, and compatibility between r-PET and rubber matrices need to be addressed through various modifications and processing techniques (Zhang 2024).

Moreover, research has highlighted the potential of converting PET waste into value-added products rather than discarding it. Given that PET is a thermoplastic material with excellent mechanical properties, it has the potential for reuse in various engineering applications. The recycling of PET (Rung et al. 2023) into rubber composites is not only environmentally beneficial but also cost-effective, as it reduces dependency on expensive virgin raw materials as well as Carbon Black. Additionally, the growing regulations on plastic waste management worldwide are encouraging industries to adopt more sustainable practices, making the use of r-PET in rubber a viable solution in the future.

### Chemical Structure of PET

Polyethylene terephthalate (PET) is a polyester derived (Vitkauskienė & Makuška 2008) from the polymerization of terephthalic acid ( $C_6H_4(CO_2H)_2$ ) and ethylene glycol ( $HOCH_2CH_2OH$ ). The repeating unit of PET is shown in Fig. 1.

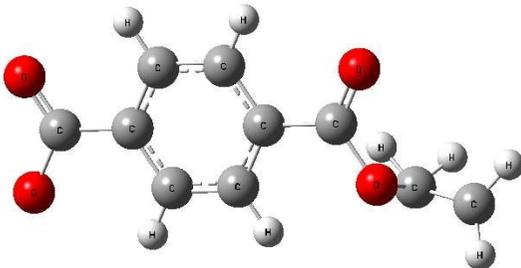


Fig. 1: PET Chemical Structure.

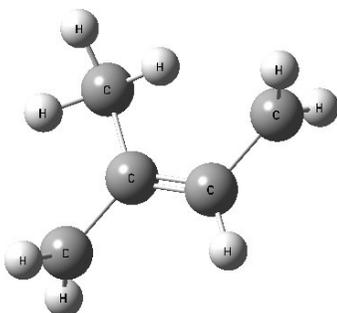


Fig. 2: Natural Rubber Chemical Structure.

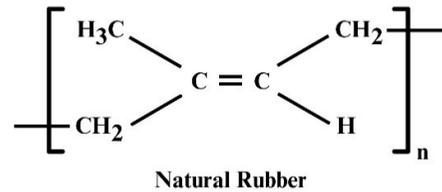


Fig. 3: Monomer of Natural Rubber.

The ester functional groups ( $-COO-$ ) present in PET provide rigidity and resistance to degradation, making it a durable reinforcement material (Bagadiya et al. 2016, Quintero et al. 2019).

### Natural Rubber Structure

Natural rubber (NR) is primarily composed of cis-1,4-polyisoprene, which imparts high elasticity and flexibility. The molecular formula of natural rubber is shown in Figs. 2 and 3. The presence of double bonds in the polymer chain makes NR reactive to chemical modifications, which can be exploited to enhance compatibility with r-PET (Hashim & Kohjya 1994).

The chemical reaction between polyethylene terephthalate (PET) and natural rubber (NR) chains typically involves the interaction of their respective polymer chains through a process known as cross-linking or grafting.

In such reactions, PET, a polyester, and NR, a polyisoprene-based elastomer, can undergo various chemical modifications when subjected to specific conditions, such as heat, radiation, or the presence of catalysts. This results in the formation of covalent bonds between the polymer chains, leading to crosslinking of the NR chains or grafting of PET onto the NR structure. The reaction often involves the use of initiators or curing agents to facilitate the chemical bonding, which improves the mechanical properties and durability of the material (Nabil et al. 2011). The reaction between PET and NR can be used to enhance the strength, elasticity, and

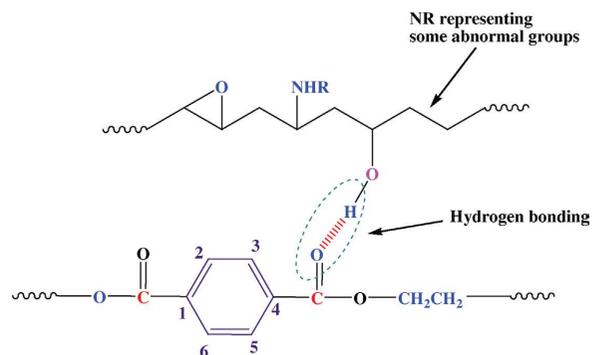


Fig. 4: Proposed interaction via hydrogen bonding between the carbonyl group of PET with abnormal groups, such as the hydroxyl functional group in NR (Reddy et al. 2015).

chemical resistance of the resulting composite material, making it suitable for various industrial applications, such as the production of advanced elastomers or hybrid materials.

## RECYCLED PET AS A REINFORCEMENT IN RUBBER

Recycled polyethylene terephthalate (r-PET) is increasingly used as a reinforcing material in rubber composites owing to its superior mechanical properties, environmental benefits, and cost-effectiveness. The reinforcement of rubber (Bagadiya et al. 2016) with r-PET has shown promise in improving tensile strength, durability, and thermal stability while reducing dependency on traditional fillers such as carbon black and silica (Nabil et al. 2011). This section explores the various types of rubber in which r-PET can be incorporated, its effects on different properties, and its real-world applications.

### PET Reinforcement in Different Rubber Types

Recycled PET can be incorporated into various types of rubber in different forms, such as fiber, powder, and flake. It has been successfully integrated into natural rubber (NR), styrene-butadiene rubber (SBR), ethylene-propylene-diene monomer (EPDM), and nitrile-butadiene rubber (NBR). In natural rubber, PET reinforcement enhances the tensile strength and wear resistance but may slightly reduce the elongation at break owing to its rigid structure. Similarly, in SBR, which is widely used in tire and industrial applications, PET reinforcement significantly improves the resistance to wear and oxidation, contributing to a longer service life. When added to EPDM, which is commonly used in automotive seals and gaskets, PET enhances thermal stability and resistance to ultraviolet (UV) radiation, increasing its longevity in outdoor applications. In oil-resistant applications such as NBR, PET-reinforced composites exhibit superior mechanical strength and enhanced chemical resistance, making them more durable in harsh environments (Cazan et al. 2014, Hashim & Kohjiy 1994, Padhan & Gupta 2015, Popa 2011, Reddy et al. 2015, Sanchez et al. 2021, Vallejos et al. 2024).

The effectiveness of PET reinforcement in different rubber matrices depends on factors such as dispersion quality,

interfacial bonding, and processing techniques used. Proper modification and compatibilization strategies can improve the overall mechanical properties of these composites, enabling their use in a wide range of industries, including automotive, construction, and industrial applications.

### Effects of PET Reinforcement on Rubber Properties

The inclusion of recycled PET (r-PET) in rubber significantly alters its mechanical, thermal, and dynamic properties of rubber. From a mechanical perspective, PET reinforcement increases tensile and tear strength due to its rigid crystalline structure, making the rubber more resistant to deformation under stress (Cosnita et al. 2017). Additionally, it enhances abrasion resistance, making it particularly suitable for high-wear applications, such as tires and industrial belts. However, incorporating PET can reduce the elongation at break, potentially affecting the rubber's flexibility. This drawback can be mitigated by incorporating plasticizers or modifying the rubber matrix to maintain an optimal balance between strength and flexibility.

In terms of thermal properties, PET reinforcement contributes to improved thermal stability, enabling rubber products to withstand higher operating temperatures without significant degradation. The presence of PET also enhances flame retardancy by reducing the flammability of the composite, making it suitable for applications that require enhanced fire resistance. These thermal improvements extend the lifespan of rubber products, particularly in environments exposed to high heat and harsh conditions (Nabil et al. 2011a).

The dynamic and aging properties of PET-reinforced rubber also exhibited notable enhancements. The inclusion of PET reduces oxidative degradation and aging effects by creating a more stable composite structure that is less susceptible to environmental factors, such as moisture, heat, and UV radiation. This results in improved durability and a longer service life, particularly for outdoor applications, where rubber is exposed to weathering. Increased resistance to UV radiation further contributes to the longevity of rubber components used in construction, automotive, and industrial applications. By incorporating PET reinforcement, manufacturers can enhance the performance and sustainability of rubber products, ensuring they meet stringent

Table 1: Effect of PET Content on Mechanical Properties Across Rubber Types.

Rubber Type	PET Form	PET Content [% by wt]	Tensile Strength Change	Elongation at Break	Hardness
NR	Powder	10%	↑ 25–30%	↓ 10–15%	↑ (Nabil et al. 2011)
SBR	Fiber	15%	↑ 35–40%	↓ Slight	↑ (Cazan et al. 2014)
EPDM	Flake	20%	↑ 20–25%	No significant change	↑ (Vallejos et al. 2024)
NBR	Powder	12%	↑ 30%	↓ 10%	↑ (Reddy et al. 2015)

industry standards and environmental regulations (Zhang 2024).

### Processing and Dispersion Challenges

Although r-PET offers significant benefits, several challenges must be addressed to optimize its use in rubber matrices. One of the primary concerns is poor compatibility

due to PET's high crystallinity and polarity (Zekriardehani et al. 2017), which makes it inherently incompatible with most rubber matrices. This incompatibility can lead to phase separation, affecting the uniformity of the composite (Cosnita et al. 2017). To counter this, various compatibilization techniques, such as chemical modifications and the use of compatibilizing agents such as maleic anhydride or ethylene

Table 2: Comparative Life Cycle Metrics of Virgin vs. Recycled PET (Duan et al. 2024, Gracida-Alvarez et al. 2023, Zheng & Suh 2019).

Parameter	Virgin PET	Recycled PET	Benefit of r-PET
Carbon Emission [kg CO <sub>2</sub> .kg <sup>-1</sup> ]	4.5	1.8	~60% reduction
Energy Consumption [MJ.kg <sup>-1</sup> ]	80	30	~63% energy saving
Waste Diversion	0%	~100%	Prevents landfill waste
Water Usage	High	Low	Reduced environmental load
Cost (Industrial Estimate)	High	Moderate-Low	More economical

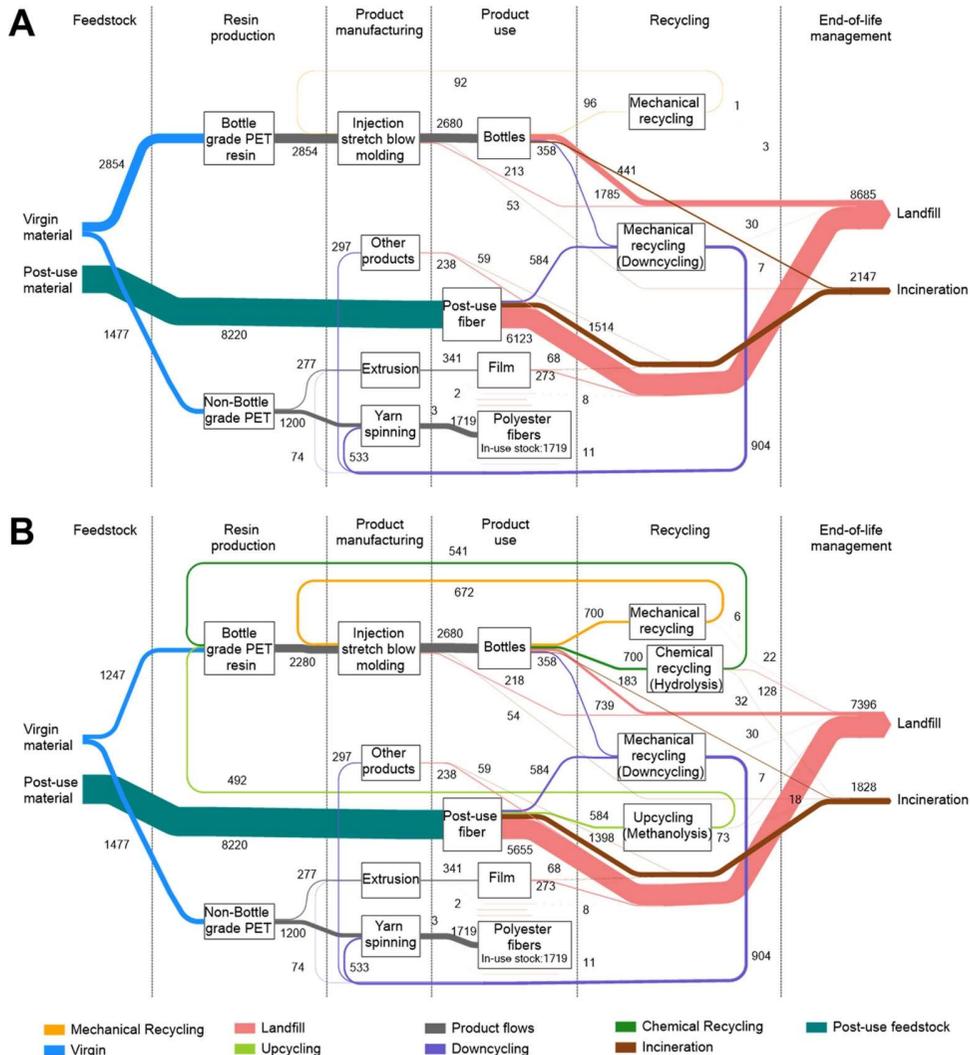


Fig. 5: Sankey diagrams of the U.S. PET bottle supply chain in 2017 for (A) the current state scenario and (B) mechanical, chemical, and upcycling scenarios. The numbers indicate thousand tonnes per year. (Gracida-Alvarez et al. 2023).

vinyl acetate (EVA) copolymers, have been employed to enhance the interfacial adhesion between PET and rubber.

Another significant challenge is the agglomeration of PET particles, which can lead to uneven dispersion within the rubber matrix. When PET particles cluster, the mechanical properties of the final composite become inconsistent, reducing overall performance (Sanchez et al. . n.d.). Effective dispersion techniques, such as high-shear mixing, ultrasonic dispersion, and mechanical milling, can help achieve a more uniform distribution of PET within the rubber.

Processing difficulties also arise because of PET's high melting point of PET (~260°C), which can degrade the rubber properties during blending. The high processing temperature required for PET can lead to the thermal degradation of the rubber matrix, negatively impacting its elasticity and flexibility. To overcome this, processing aids such as plasticizers, stabilizers, and processing oils are used to lower the processing temperature while maintaining the integrity of both the PET and rubber components.

Optimizing the formulation of r-PET-reinforced rubber composites is crucial for achieving the desired balance between their strength, flexibility, and durability. Factors such as PET content, particle size, and surface treatment methods must be carefully adjusted to enhance the compatibility and mechanical performance. By addressing these processing and dispersion challenges, the application of PET-reinforced rubber composites can be expanded across various industries, including automotive, construction, and industrial manufacturing.

### **Real-World Applications of PET-Reinforced Rubber**

Recycled PET-reinforced rubber is gaining traction across multiple industries because of its ability to enhance mechanical performance, reduce material costs, and promote sustainability. One of the most significant applications (Gracida-Alvarez et al. 2023) is in the tire manufacturing industry, where the addition of r-PET improves rolling resistance, tread wear performance, and fuel efficiency. By integrating PET-reinforced rubber into tire treads and sidewalls, manufacturers can produce longer-lasting tires that contribute to lower carbon emissions and improved fuel economy.

In the automotive sector, r-PET-reinforced rubber is used in various components, such as door seals, gaskets, and vibration-damping materials. These parts benefit from enhanced durability, chemical resistance, and improved wear performance. The addition of PET provides better thermal stability, making the material suitable for under-the-hood applications, where exposure to heat and oil is common.

Another prominent application is in industrial belts and hoses, where PET reinforcement improves the mechanical strength and abrasion resistance. Conveyor belts, transmission belts, and hydraulic hoses require materials that can withstand high levels of stress and wear. PET-infused rubber composites offer better load-bearing capacity and extend the service life of these components, thereby reducing maintenance costs and downtime.

In the footwear and sporting goods industries, PET-reinforced rubber is used to manufacture shoe soles and sports equipment. The improved impact resistance and tensile strength make it an ideal material for high-performance athletic footwear and protective gear. Additionally, its ability to enhance energy return and flexibility makes it suitable for products that require high durability and elasticity.

The construction and roofing materials sector has adopted r-PET-infused rubber for applications such as flexible roofing sheets and waterproofing membranes. The incorporation of PET enhances UV resistance, water impermeability, and overall longevity, making it an excellent choice for building materials that are exposed to harsh environmental conditions. Furthermore, PET-based rubber composites are used in vibration isolation pads and shock-absorbing materials in buildings and bridges, where enhanced damping properties are required.

These applications demonstrate the versatility of PET-reinforced rubber and its potential to replace conventional materials while offering superior mechanical properties, cost savings, and environmental benefits (Reddy et al. 2015). As industries continue to seek sustainable alternatives, the adoption of PET-reinforced rubber is expected to expand, thereby driving innovation and efficiency in multiple sectors.

### **Future Prospects**

The use of r-PET in rubber reinforcement is expected to increase with advancements in processing technology and material modifications. Researchers are focusing on improving PET dispersion, developing new compatibilizers, and optimizing processing conditions to maximize the benefits of rPET in rubber applications. As industries move towards sustainability, PET-reinforced rubber will play a crucial role in reducing environmental impact while maintaining high-performance standards.

### **MECHANISMS OF MIXING PET SCRAP WITH RUBBER**

Mixing recycled PET (r-PET) scrap with rubber involves complex physical and chemical interactions that determine the final properties of the composite material. The key challenges in mixing PET with rubber include compatibility,

dispersion, interfacial adhesion, and processing difficulties of the resulting composites. Several mechanisms have been employed to effectively integrate PET into rubber matrices.

### Compatibility Factors

One of the primary challenges in mixing PET with rubber is their inherent incompatibility owing to differences in polarity, crystallinity, and thermal properties (Vallejos et al. 2024). PET is a polar, high-melting thermoplastic, whereas rubber is generally non-polar and elastomeric. This mismatch leads to phase separation, negatively affecting the mechanical properties and reducing the efficiency of PET as a reinforcing material. To address this issue, several techniques have been explored to improve the compatibility of PET and the rubber matrices.

Surface modification is an effective approach to enhance compatibility. PET surfaces can be treated with silane coupling agents, maleic anhydride, or other reactive chemicals to improve their adhesion to rubber. Functionalized rubber, where specific functional groups such as carboxyl, hydroxyl, or amine groups are incorporated, can also enhance interfacial bonding with PET (Coniglio et al. 2019). Additionally, blending with compatibilizers, such as styrene-butadiene-styrene (SBS) and ethylene-vinyl acetate (EVA), has been shown to improve interfacial interactions, reduce phase separation, and increase overall mechanical stability.

Despite these efforts, achieving a uniform dispersion of PET within the rubber matrix remains challenging. The agglomeration of PET particles can occur, leading to inconsistencies in the mechanical properties. Effective dispersion techniques, such as high-shear mixing, ultrasonic dispersion, and mechanical milling, help achieve a more uniform distribution of PET within the rubber matrix. Furthermore, optimizing the processing parameters, such as temperature, shear rate, and mixing time, can further enhance the interaction between PET and rubber, thereby improving the composite performance.

By implementing these strategies, the incorporation of PET into rubber matrices can be optimized, resulting in improved mechanical properties, durability, and sustainability of the PET-reinforced rubber composites. As research in this area continues, advanced modification techniques and novel compatibilizers are expected to further enhance the compatibility between PET and rubber, thereby expanding their applications in various industrial sectors.

One of the primary challenges in mixing PET with rubber is their inherent incompatibility owing to differences in polarity, crystallinity, and thermal properties. PET is a polar,

high-melting thermoplastic (Bhatt et al. 2015), while rubber is generally nonpolar and elastomeric. This mismatch leads to phase separation, which negatively affects the mechanical properties.

### Challenges in Mixing

Several challenges must be addressed to achieve a uniform dispersion of PET in rubber matrices. This leads to inconsistencies in the mechanical properties, which negatively affect protection. This leads to inconsistencies in mechanical properties, negatively affecting strength, elasticity, and durability (Dimitrov et al. 2013). Effective dispersion techniques, such as high-shear mixing, ultrasonic dispersion, and mechanical milling, can help achieve better distribution and uniformity in the composite material.

Another challenge is the high melting point of PET, which requires elevated temperatures for processing. The high processing temperatures (~260°C) required to melt PET can degrade the rubber matrix, leading to a loss of elasticity and mechanical integrity. This problem can be mitigated by using processing aids, plasticizers, or compatibilizers to lower the processing temperature while maintaining the desired mechanical properties of PET and rubber.

Phase separation is another major issue in the mixing of PET with rubber. Owing to differences in polarity and solubility parameters, PET and rubber have limited miscibility, causing phase separation, which weakens interfacial adhesion and reduces overall mechanical performance. Various strategies, such as chemical grafting, surface modifications, and the use of compatibilizers such as maleic anhydride or silane coupling agents, can improve interfacial bonding and enhance the mechanical strength of the composite.

Additionally, PET's crystalline nature presents difficulty in achieving proper adhesion and bonding with rubber matrices. Modifying PET through controlled degradation, glycolysis (Vitkauskienė & Makuška 2008), or reactive blending can enhance its compatibility with rubber, resulting in better dispersion and improved mechanical properties (Luo & Van Ooij 2002).

Addressing these challenges through innovative processing techniques, compatibilization strategies, and optimized formulation methods can significantly enhance the performance and viability of PET-reinforced rubber composites in industrial applications.

### Modification Techniques

The modification of recycled polyethylene terephthalate (R-PET) composites is essential for enhancing their mechanical, thermal, and structural properties. Various

techniques have been explored to optimize their performance for industrial use. Chemical modification involves surface functionalization using chemical agents, such as silane coupling agents, which enhance the adhesion between PET and fillers. The incorporation of compatibilizers, such as maleic anhydride (MAH) or glycidyl methacrylate (GMA), improves interfacial bonding, whereas chemical treatments, such as alkaline hydrolysis, modify the polymer's surface energy, increasing its interaction with reinforcements.

Physical modification includes melt blending with reinforcing materials such as silica, carbon fibers, or nanoclays to enhance mechanical properties. Plasma treatment alters the surface characteristics, improving the wettability and adhesion properties of PET, and heat treatment techniques, such as annealing, increase the crystallinity and thermal stability of PET composites. Mechanical modification focuses on grinding and reprocessing to improve the particle size distribution and uniformity in composite blends. Mixing PET with impact modifiers, such as elastomers or rubber, enhances its toughness and ductility, whereas fiber reinforcement techniques using natural or synthetic fibers increase the tensile and compressive strengths of PET composites (Li et al. 1998).

To better evaluate the effectiveness of different PET modification strategies, Table 3 summarizes their functional benefits, drawbacks, and industrial applicability. Although silane treatments and chemical grafting agents such as MAH and GMA exhibit excellent bonding performance, they can be prohibitively expensive for large-scale use. Conversely, physical methods, such as alkaline hydrolysis and plasma treatment, are more environmentally favorable but may compromise molecular integrity or require complex infrastructure. Thus, the selection of an appropriate technique depends on the intended application, cost constraints, and environmental compliance.

Table 3: Comparison of Key PET Modification Techniques.

Technique	Improvement Achieved	Limitation	Application Area
Silane Coupling Agent	Enhances interfacial adhesion, improves tensile strength	Costly, sensitive to moisture, limited shelf life	Automotive parts, construction
Maleic Anhydride (MAH)	Improves compatibility via grafting	May cause discoloration, not biodegradable	Footwear, hoses, seals
Glycidyl Methacrylate (GMA)	Strong chemical bonding, improves elasticity	Expensive, processing requires peroxide initiator	Tire treads, dynamic components
Alkaline Hydrolysis	Increases surface roughness, low cost	Degrades molecular weight, harsh chemicals	Eco-building materials
Plasma Treatment	Eco-friendly, increases surface energy	Requires specialized equipment, low scalability	Medical packaging, electronics
Compatibilizer (EVA/SBS)	Improves blend uniformity, widely available	Moderate effectiveness, may affect thermal stability	General rubber goods

Hybrid modifications combine chemical and mechanical techniques, such as coupling agents with fiber reinforcements, to yield composites with superior mechanical and environmental resistance. Nano-enhancements using graphene or carbon nanotubes further improve the electrical conductivity and structural integrity.

### Case Studies and Applications

Several case studies have highlighted the successful implementation of R-PET composites in various industries. These applications demonstrate the potential of modified PET composites for sustainable construction and engineering solutions. In the construction industry, modified R-PET composites have been tested for use in pavement blocks, demonstrating improved durability and resistance to environmental degradation. Blended PET with sand and other reinforcements has been used to manufacture lightweight and eco-friendly architectural panels.

In the automotive sector, R-PET mixed with carbon or glass fibers is employed in vehicle interiors for lightweight and durable panels. Studies have explored PET-based composites for under-the-hood applications, where thermal stability and impact resistance are critical properties. In the packaging industry, chemically modified PET is used in food containers to improve barrier properties and recyclability. Nanocomposite enhancements have led to PET films with improved mechanical strength and resistance to permeation.

In the textile and fashion industries, PET is extensively used to produce sustainable textiles for clothing and upholstery. PET-based composites are also used in technical textiles for geotextiles and industrial applications. In electronics and electrical applications, PET composites with enhanced thermal conductivity and insulation properties are used in electronic device casings, and the integration of conductive fillers with PET matrices has led

to the development of lightweight and flexible electronic components.

These case studies demonstrate that effectively modified R-PET composites can significantly contribute to sustainable material development and circular economy initiatives across various industries.

## PROCESSING TECHNIQUES AND COMPOSITE FORMULATIONS

The processing of recycled PET (r-PET) in rubber matrices involves several techniques that influence the properties of the final composite. The selection of a suitable processing technique depends on factors such as PET content, rubber type, processing temperature, and required end-use properties. This section elaborates on the major processing techniques, key parameters, material modifications, and their effects on the mechanical, thermal, and morphological properties.

### Processing Techniques

The processing of recycled polyethylene terephthalate (R-PET) composites involves several techniques that optimize their structural and mechanical properties. Melt blending is one of the most common techniques, in which PET is heated and mixed with reinforcing fillers such as silica, carbon fibers, or nanoclays to improve its mechanical strength. Extrusion is widely used to process PET composites into sheets, fibers, or molded components, providing a uniform distribution of fillers. Injection molding allows the creation of intricate composite structures with high precision and high reproducibility. Compression molding is another method in which heat and pressure are applied to form durable and high-strength composite panels (Luo & Van Ooij 2002). Advanced processing techniques, such as electrospinning and 3D printing, have also been explored for fabricating PET-based composites with enhanced functionalities (Jamshidi et al. 2005).

### Composite Formulations and Key Parameters

The formulation of R-PET composites depends on several key parameters, including the type and proportion of fillers, matrix modification, and processing conditions. The selection of fillers, such as glass, carbon, or natural fibers, influences the mechanical, thermal, and barrier properties of the composite. The incorporation of coupling agents like silane or compatibilizers such as maleic anhydride improves the interfacial adhesion between PET and fillers, leading to enhanced composite performance (Razavizadeh & Jamshidi 2016). Processing parameters, such as temperature, shear rate,

and cooling rate, affect the crystallinity and phase dispersion of the composites. The addition of impact modifiers can enhance toughness, whereas stabilizers improve thermal resistance, ensuring longevity in various applications.

### Impact on Final Properties

The final properties of R-PET composites are significantly influenced by the processing techniques and formulations used to produce them. The mechanical properties, such as tensile strength and impact resistance, depend on the type of reinforcement and processing conditions (Nabil et al. 2011). The improved dispersion of the fillers enhanced the thermal stability, making the PET composites suitable for high-temperature applications. The addition of nanofillers or compatibilizers increases the resistance of the composite to moisture and chemical degradation, thereby improving its durability. Furthermore, proper processing techniques minimize void formation and enhance density, leading to better load-bearing capabilities in structural applications (Phetphaisit et al. 2015). The ability to fine-tune these properties renders R-PET composites versatile across various industries.

### Case Studies and Industrial Applications

R-PET composites have found applications in various industries owing to their sustainable and high-performance characteristics. In the construction industry, they are used in pavement blocks, roofing tiles, and structural panels, offering a lightweight and durable alternative to conventional materials. The automotive industry employs PET composites in interior panels, bumpers, and under-the-hood components because of their excellent strength-to-weight ratio and thermal stability. In packaging, PET-based composites improve barrier properties, ensuring better food preservation and sustainability of the packaging. The textile sector benefits from R-PET fibers, which are used in clothing, upholstery, and non-woven fabrics (Popa 2011). Electronics and electrical applications include PET composites in circuit boards, insulating materials and casings for electronic devices. These case studies illustrate the adaptability of R-PET composites in various high-performance and eco-friendly applications.

## MECHANICAL PROPERTIES OF PET-REINFORCED RUBBER

Experimental studies on PET-reinforced rubber composites have demonstrated significant improvements in their mechanical properties, making them suitable for various engineering applications. Research indicates that incorporating PET fibers into rubber matrices enhances the tensile strength, elongation at break, and impact resistance.

Studies have also shown that the dispersion of PET in rubber affects stress distribution, leading to more durable and resilient composites (Cosnita et al. 2014). Additionally, crosslinking techniques, such as sulfur or peroxide curing systems, play a crucial role in defining the mechanical performance of these composites.

Several factors contribute to the property enhancement of PET-reinforced rubber. The selection of reinforcement materials, particle size, and fiber orientation significantly influences the mechanical strength. The addition of coupling agents, such as silane treatments, improves the interfacial bonding between PET and rubber, reducing stress concentration points and enhancing toughness. Furthermore, the degree of crystallinity of PET fibers affects the stiffness and energy absorption capabilities of the final composite (Vallejos et al. 2024).

Material testing techniques are essential in evaluating the mechanical properties of PET-reinforced rubber. Tensile tests determine the strength and elasticity, while dynamic mechanical analysis (DMA) assesses viscoelastic behavior under different temperature conditions. Scanning electron microscopy (SEM) is used to examine the dispersion and adhesion of PET fibers within the rubber matrix (Vallejos et al. 2024). Additionally, thermogravimetric analysis (TGA) provides insights into the thermal stability of the composite, crucial for high-temperature applications.

The performance of PET-reinforced rubber under real-world conditions has been investigated across multiple industries. In automotive applications, these composites exhibit superior resistance to wear and tear, making them ideal for tire treads and suspension components (Cosnita et al. 2017). In construction, PET-reinforced rubber is used in shock-absorbing materials and flexible pavement structures (Cosnita et al. 2014). Additionally, in sports and safety equipment, these composites provide enhanced impact resistance, ensuring durability and protection of the equipment. These real-world applications highlight the versatility and efficiency of PET-reinforced rubber, further establishing its potential for sustainable material development.

## **THERMAL AND MORPHOLOGICAL ANALYSIS**

Advanced thermal studies of PET-reinforced composites are crucial for understanding their behavior under varying temperature conditions. Thermogravimetric analysis (TGA) revealed that R-PET composites exhibited enhanced thermal stability compared to virgin PET, primarily owing to the presence of reinforcing fillers and improved interfacial bonding. Differential scanning calorimetry (DSC) was employed to evaluate the melting and crystallization behaviors

of these composites, revealing that the incorporation of nanofillers and compatibilizers can significantly modify the thermal transitions and enhance the heat resistance.

The material decomposition behavior is an essential factor in assessing the longevity and performance of PET-based composites. Studies have indicated that PET decomposition occurs in multiple stages, beginning with the breakdown of weaker polymer chains and followed by more complex degradation reactions (Padhan & Gupta 2015). The presence of stabilizers and flame retardants in PET composites can delay thermal degradation, ensuring enhanced durability for high-temperature applications (Pacheco-Torgal et al. 2012). Additionally, pyrolysis studies have demonstrated that PET composites can be effectively recycled through controlled thermal decomposition processes, thereby minimizing their environmental impact.

Surface morphology analysis plays a pivotal role in determining the structural integrity of PET composite materials. Scanning electron microscopy (SEM) is widely used to examine the dispersion of fillers, detect microstructural defects, and assess fiber-matrix adhesion. Atomic force microscopy (AFM) provides insights into the surface roughness and interfacial interactions, aiding in the optimization of composite formulations (Phinyocheep et al. 2007). Well-dispersed reinforcements within the polymer matrix lead to enhanced mechanical properties and thermal stability, ensuring superior performance in practical applications.

The impact of PET content on thermal stability has been extensively studied to identify optimal compositions for various applications. Increasing the PET content generally improves the heat resistance of the composites; however, excessive PET concentrations may lead to brittleness and reduced toughness. Balancing PET with other polymers or elastomers ensures synergy between mechanical strength and thermal endurance. The experimental results highlighted that composites with controlled PET content and appropriate fillers demonstrated superior resistance to thermal degradation, making them suitable for demanding industrial applications.

## **ENVIRONMENTAL AND SUSTAINABILITY ASPECTS**

The incorporation of R-PET in composite formulations presents significant environmental and sustainability benefits (Vallejos et al. 2024). The use of recycled materials reduces plastic waste, minimizes landfill accumulation, and decreases dependency on virgin petroleum-based resources (Miranda Vidales et al. 2014). Regulatory frameworks, such as extended producer responsibility (EPR) programs

and environmental directives, encourage industries to adopt sustainable materials and ensure compliance with eco-friendly manufacturing practices. Industry adaptation has been steadily increasing, with sectors like automotive, construction, and packaging integrating PET-based composites to meet sustainability goals (Zhang 2024). Compared with conventional rubber reinforcement methods, PET composites offer superior recyclability, a reduced carbon footprint, and enhanced durability. The long-term benefits of PET-reinforced composites include improved lifecycle performance, lower production costs, and alignment with circular economy principles, making them viable alternatives to traditional reinforcement materials.

## ENVIRONMENTAL IMPACT CALCULATION

A detailed life cycle assessment (LCA) of PET-reinforced (Duan et al. 2024) composites highlights their significant environmental advantages over conventional materials. LCA studies have shown that incorporating ET in composite formulations results in lower greenhouse gas emissions, reduced energy consumption, and minimized resource depletion (Phetphaisit et al. 2015). Emissions data indicate that PET composites emit fewer carbon dioxide equivalents per kilogram compared to virgin plastics and conventional rubber reinforcements. The use of recycled PET also contributes to waste reduction by diverting plastic waste from landfills and reducing reliance on virgin polymer production.

### Carbon Footprint Reduction:

- Virgin PET production emits approximately 4.5 kg CO<sub>2</sub> per kg of PET produced (Zheng & Suh 2019).
- Recycling PET reduces emissions by up to 60%, leading to a net reduction of approximately 2.7 kg CO<sub>2</sub> per kg of recycled PET used in rubber composites.

### Energy Savings:

- Manufacturing virgin PET requires 80 MJ.kg<sup>-1</sup> of energy.
- Recycled PET requires only 30 MJ.kg<sup>-1</sup>, leading to a significant reduction in energy consumption.

### Waste Diversion:

- Incorporating r-PET into rubber reduces landfill waste and extends the lifecycle of plastic materials.

Waste reduction benefits of PET composites are evident in their recyclability and reusability, promoting a circular economy. By using post-consumer PET waste, industries can significantly lower their environmental footprint while maintaining high material performance. Economic impact assessments demonstrate that adopting PET-based composites can lead to cost savings in material procurement, processing, and waste management. (Zhang 2024). Additionally, regulatory incentives and sustainability goals encourage industries to transition towards PET composites, further solidifying their role in eco-friendly material innovation.

## Comparison with Carbon Black-Reinforced Rubber

To evaluate the environmental advantage of PET-reinforced rubber, it is essential to compare it with the most commonly used conventional filler, carbon black (CB). Carbon black is a fossil fuel-derived reinforcing agent widely used in rubber compounding, particularly for tires and industrial goods. However, its production is highly energy-intensive and generates significant greenhouse gas (GHG) emissions.

A direct life cycle comparison between CB- and r-PET-reinforced rubber composites reveals considerable environmental benefits in favor of r-PET, as shown in Table 4.

In addition to lower GHG emissions and energy use, r-PET provides circular economy benefits by diverting plastic waste from landfills and reducing dependency on virgin fossil resources. While carbon black remains technically superior in some reinforcement metrics, the environmental trade-offs strongly favor r-PET, particularly for non-critical or semi-dynamic applications where sustainability is prioritized.

## CHALLENGES AND FUTURE PROSPECTS

Despite the numerous benefits of PET-reinforced composites, several challenges limit their widespread adoption. One

Table 4: Life Cycle Comparison – Carbon Black vs. r-PET as Reinforcement in Rubber.

Metric	Carbon Black (CB) Reinforcement	Recycled PET (r-PET) Reinforcement	Relative Benefit
GHG Emissions [kg CO <sub>2</sub> .kg <sup>-1</sup> filler]	~2.4	~1.8	~25% reduction
Energy Use [MJ.kg <sup>-1</sup> filler]	~100	~30	~70% reduction
Waste Diversion	None	High (from post-consumer PET)	Strong benefit
Carbon Source	Fossil	Recycled polymer (plastic waste)	Renewable-based
Circular Economy Value	Low	High	√

major limitation is the difficulty in achieving consistent mechanical properties due to variability in recycled PET feedstocks. Addressing this issue requires advanced sorting and purification techniques to enhance the quality of recycled materials. Another challenge is the relatively high processing cost associated with modifying PET composites for specific applications. Innovations in processing technologies, such as improved compatibilization methods and additive manufacturing, can help mitigate these costs.

Future innovations in PET-reinforced composites will likely focus on developing bio-based (Bhatt et al. 2016) and hybrid reinforcements to enhance sustainability and performance. Research into self-healing materials and smart composites with adaptive properties can further expand the applications of PET composites. Large-scale adoption of PET composites can be facilitated through industry collaborations, policy incentives, and advancements in recycling infrastructure. Establishing standardized testing and certification protocols will also play a crucial role in ensuring the reliability and acceptance of these materials across various industries. With continued advancements, PET-reinforced composites are poised to become a key component in next-generation sustainable materials.

## CONCLUSIONS

Recycled PET presents a sustainable and effective reinforcement for rubber compounds, offering improved mechanical and thermal properties while reducing environmental impact. Through various mixing mechanisms, PET scrap can be effectively incorporated into rubber, enhancing its durability and reducing reliance on virgin raw materials. Chemical modifications, such as glycolysis and compatibilization, further enhance the feasibility of PET-rubber composites.

However, challenges such as optimizing processing conditions, ensuring homogeneous dispersion, and improving interfacial adhesion remain critical areas of research. Addressing these challenges will facilitate broader industrial adoption of PET-reinforced rubber composites.

Future advancements in chemical recycling techniques, including depolymerization and reactive extrusion, hold great promise for enhancing the performance of r-PET in rubber matrices. Additionally, more in-depth environmental assessments can provide clearer insights into the long-term sustainability benefits of such materials.

Overall, continued research and innovation in this field will pave the way for greener, more sustainable rubber products, contributing to a circular economy and reducing the environmental burden of plastic waste.

## ACKNOWLEDGMENTS

The author gratefully acknowledges the support of the Department of Rubber Technology, L. D. College of Engineering, for providing the necessary laboratory infrastructure and guidance during the project. The author also wishes to thank all the staff and faculty members who contributed indirectly through their administrative and technical support.

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