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

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ABSTRACT

The 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 like carbon black, silica, etc. 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 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 impact. Processing methods such as mechanical blending, chemical grafting, and surface modifications are 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 composites. 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 material science. One such approach is the incorporation of recycled PET (r-PET) into rubber composites. PET, widely used in water bottle manufacturing, contributes significantly to plastic waste. Recycling PET into rubber matrices can mitigate environmental impacts while improving the performance of rubber products. This paper reviews the current state of research on r-PET as a reinforcement in rubber compounds. It covers processing techniques, mechanical properties, environmental benefits, etc, with a focus on overcoming limitations to industrial applications.

The rapid increase in global plastic consumption, particularly in single-use applications, has led to 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, Abid, Harzallah, & Lallam, 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 enhance material properties. Studies have shown that PET-based reinforcements can improve tensile strength, abrasion resistance, and overall durability of rubber products (Cazan, Cosnita, Visa, & Duta, 2014a). 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 et al., 2024).

Moreover, research has highlighted the potential of PET waste conversion into value-added products rather than being discarded as waste. Given that PET is a thermoplastic material with excellent mechanical properties, it has the potential to be reused 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 for the future.

1.1 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 represented as per Fig. 1.

The ester functional groups (-COO-) present in PET provide rigidity and resistance to degradation, making it a durable reinforcement material (Bagadiya, Desai, & Padhiyar, 2016a; Quintero, Figueroa, Gil, & Zuleta, 2019).

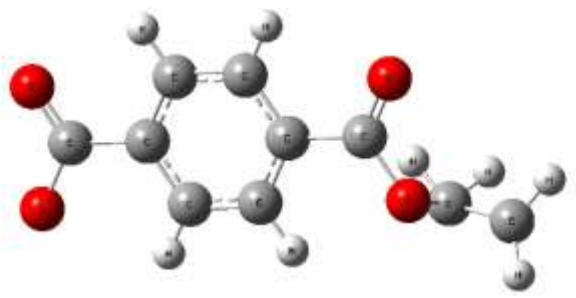

Fig. 1: PET Chemical Structure

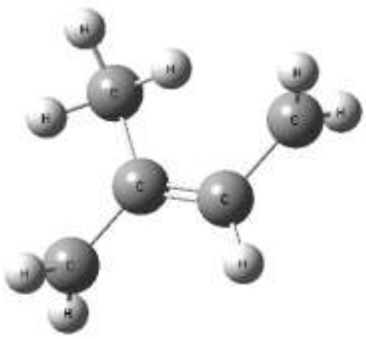

Fig. 2: Natural Rubber Chemical Structure

1.2 Natural Rubber Structure

Natural rubber (NR) is primarily composed of cis-1,4-polyisoprene, which gives it its high elasticity and flexibility. The molecular formula of natural rubber can be expressed as per Fig. 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'" & Kohjiya, n.d.).

Fig. 3: Monomer of Natural Rubber

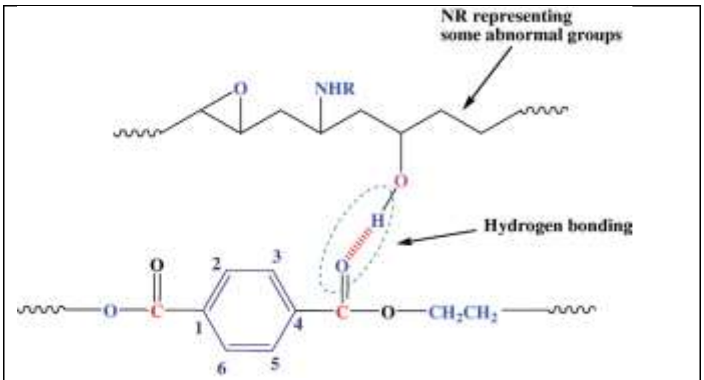

Fig 4: Proposed interaction via hydrogen bonding between the carbonyl group of PET with abnormal groups, such as the hydroxyl functional group in NR (Reddy et al., 2015a).

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 crosslinking or grafting.

In such reactions, PET, which is a polyester, and NR, which is 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 the crosslinking of the NR chains or the 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, Ismail, & Azura, 2011a). The reaction between PET and NR can be used to enhance the strength, elasticity, and chemical resistance of the resulting composite material, making it suitable for various industrial applications, such as in the production of advanced elastomers or hybrid materials.

2. RECYCLED PET AS A REINFORCEMENT IN RUBBER

Recycled polyethylene terephthalate (r-PET) is increasingly being used as a reinforcing material in rubber composites due to its superior mechanical properties, environmental benefits, and cost-effectiveness. The reinforcement of rubber (Bagadiya, Desai, & Padhiyar, 2016b) 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., 2011a). This section explores the various types of rubber in which r-PET can be incorporated, its effects on different properties, and real-world applications.

2.1 PET Reinforcement in Different Rubber Types

Recycled PET can be incorporated into various types of rubber in different forms, such as fibers, powders, and flakes. It has been successfully integrated into natural rubber (NR), styrene-butadiene rubber (SBR), ethylene-propylene-diene monomer (EPDM), and nitrile butadiene rubber (NBR), among others. In natural rubber, PET reinforcement enhances tensile strength and wear resistance but may slightly reduce elongation at break due to its rigid structure. Similarly, in SBR, which is widely used in tire and industrial applications, PET reinforcement significantly improves resistance to wear and oxidation, contributing to longer service life. When added to EPDM, 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., 2014a; Hashim’" & Kohjiya, n.d.; Padhan & Gupta, 2015; Popa, 2011; Reddy et al., 2015a; SANCHEZ-SOLfS, Estrada J Cruz, Znstituto de Znuestigaciones en Materiales, & P, n.d.; Vallejos, Montenegro, Muñoz, & García, 2024a).

The effectiveness of PET reinforcement in different rubber matrices depends on factors such as dispersion quality, interfacial bonding, and processing techniques. 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.

2.2 Effects of PET Reinforcement on Rubber Properties

The inclusion of recycled PET (r-PET) in rubber significantly alters its mechanical, thermal, and dynamic properties. 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, Cazan, & Duta, 2017). Additionally, it enhances abrasion resistance, making it particularly suitable for high-wear applications such as tires and industrial belts. However, the incorporation of PET can also reduce the elongation at break, potentially affecting the flexibility of the rubber. 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 requiring 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 exhibit 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. The 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 industry standards and environmental regulations (Zhang et al., 2024).

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, Ismail, & Azura, 2011b)
SBR	**Fiber**	**15%**	**↑ 35–40%**	**↓ Slight**	↑ (Cazan, Cosnita, Visa, & Duta, 2014b)

EPDM	**Flake**	**20%**	**↑ 20–25%**	**No significant change**	↑ (Vallejos, Montenegro, Muñoz, & García, 2024b)
NBR	**Powder**	**12%**	**↑ 30%**	**↓ 10%**	↑ (Reddy et al., 2015b)

2.3 Processing and Dispersion Challenges

While 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, Jabarin, Gidley, & Coleman, 2017), which make 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 like maleic anhydride or EVA copolymers are employed to enhance 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

Table 2: Comparative Life Cycle Metrics of Virgin vs. Recycled PET (Duan, Wang, Zhou, & Yao, 2024; Gracida-Alvarez, Xu, Benavides, Wang, & Hawkins, 2023; Zheng & Suh, 2019)

Parameter	Virgin PET	Recycled PET	Benefit of r-PET
Carbon Emission (kg CO_2/kg)	4.5	1.8	~60% reduction
Energy Consumption (MJ/kg)	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

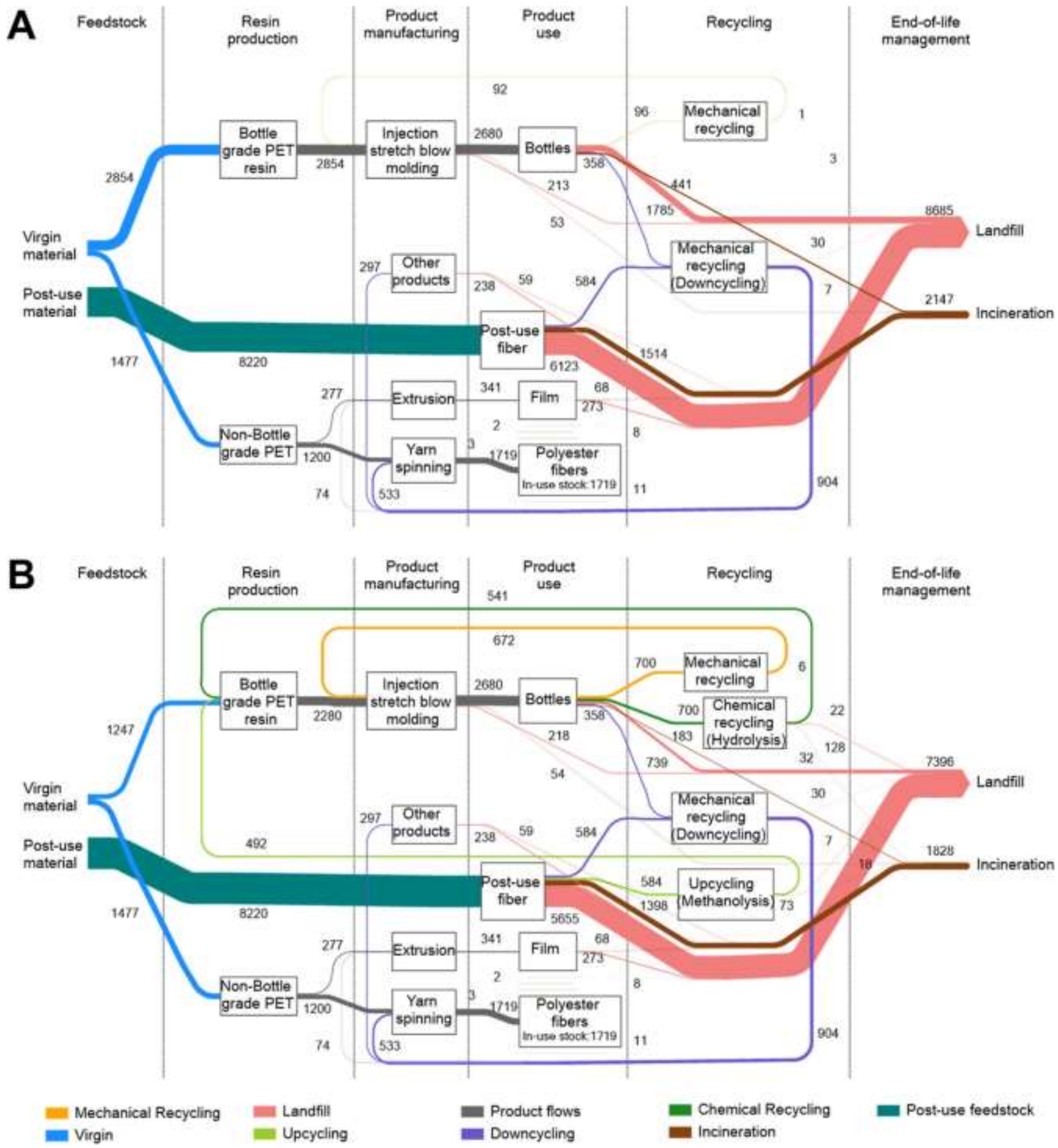

Fig. 5: Sankey diagrams of the U.S. supply chain of PET bottles in 2017 for the (A) current state scenario and (B) mechanical, chemical, and upcycling scenario. Numbers indicate thousand tonnes per year. (Gracida-Alvarez et al., 2023)

inconsistent, reducing overall performance (SANCHEZ-SOLfS 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 rubber.

Processing difficulties also arise due to PET's high melting point (~260°C), which can degrade rubber properties during blending. The high processing temperature required for PET can lead to thermal degradation of the rubber matrix, negatively impacting 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 PET and rubber components.

Optimizing the formulation of r-PET-reinforced rubber composites is crucial for achieving the desired balance between strength, flexibility, and durability. Factors such as PET content, particle size, and surface treatment methods must be carefully adjusted to enhance 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.

2.4 Real-World Applications of PET-Reinforced Rubber

Recycled PET-reinforced rubber is gaining increasing traction across multiple industries due to 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 greater 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 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, reducing maintenance costs and downtime.

In the footwear and sporting goods industry, 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 requiring high durability and elasticity.

The construction and roofing materials sector has also 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 exposed to harsh environmental conditions. Furthermore, PET-based rubber composites are being 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., 2015a). As industries continue to seek sustainable alternatives, the adoption of PET-reinforced rubber is expected to expand, driving innovation and efficiency in multiple sectors.

2.5 Future Prospects

The use of r-PET in rubber reinforcement is expected to grow 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 r-PET 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.

3. 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. Several mechanisms are employed to integrate PET into rubber matrices effectively.

3.1 Compatibility Factors

One of the primary challenges in mixing PET with rubber is their inherent incompatibility due to differences in polarity, crystallinity, and thermal properties (Vallejos et al., 2024a). PET is a polar, high-melting thermoplastic, whereas rubber is generally nonpolar and elastomeric. This mismatch leads to phase separation, negatively affecting 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 rubber matrices.

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

Despite these efforts, achieving uniform dispersion of PET within the rubber matrix remains a challenge. Agglomeration of PET particles can occur, leading to inconsistencies in mechanical properties. Effective dispersion techniques such as high-shear mixing, ultrasonic dispersion, and mechanical milling help to 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, leading to improved 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 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, expanding its applications in various industrial sectors.

One of the primary challenges in mixing PET with rubber is their inherent incompatibility due to differences in polarity, crystallinity, and thermal properties. PET is a polar, high-melting thermoplastic (G. G. Bhatt, Desai, & Padhiyar, 2015), while rubber is generally nonpolar and elastomeric. This mismatch leads to phase separation, which negatively affects mechanical properties.

3.2 Challenges in Mixing

Several challenges must be addressed to achieve a uniform dispersion of PET in rubber matrices. One of the primary issues is agglomeration, where PET particles tend to cluster together, resulting in an uneven distribution within the rubber matrix. This leads to inconsistencies in mechanical properties, negatively affecting strength, elasticity, and durability (Dimitrov, Kratofil Krehula, Ptiček Siročić, & Hrnjak-Murgić, 2013). Effective dispersion techniques, such as high-shear mixing, ultrasonic dispersion, and mechanical milling, can help achieve better distribution and uniformity within the composite material.

Another challenge is PET's high melting point, which requires elevated temperatures for processing. The high processing temperatures (~260°C) needed 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 both PET and rubber.

Phase separation is another major issue in mixing PET with rubber. Due 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 like maleic anhydride or silane coupling agents can improve interfacial bonding and enhance the mechanical strength of the composite.

Additionally, PET's crystalline nature presents difficulties 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 for industrial applications.

3.3 Modification Techniques

The modification of recycled polyethylene terephthalate (R-PET) composites is essential to enhance their mechanical, thermal, and structural properties. Various techniques have been explored to optimize their performance for industrial applications. 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 like maleic anhydride (MAH) or glycidyl methacrylate (GMA) improves interfacial bonding, while 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 like 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 particle size distribution and uniformity in composite blends. Mixing PET with impact modifiers like elastomers or rubber enhances toughness and ductility, while fiber reinforcement techniques using natural or synthetic fibers increase the tensile and compressive strength of PET composites (Li, White, & Lee Peyton, 1998).

To better evaluate the effectiveness of different PET modification strategies, Table summarizes their functional benefits, drawbacks, and industrial applicability. While silane treatments and chemical grafting agents like MAH and GMA show excellent bonding performance, they can be cost-prohibitive 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. Selection of an appropriate technique thus 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 properties. Nano-enhancements using graphene or carbon nanotubes further improve electrical conductivity and structural integrity.

3.4 Case Studies and Applications

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

In the automotive sector, R-PET mixed with carbon fibers 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. In the packaging industry, chemically modified PET is used in food containers, improving barrier properties and recyclability. Nanocomposite enhancements have led to PET films with better mechanical strength and resistance to permeation.

In the textile and fashion industry, PET is extensively used in producing sustainable textiles for clothing and upholstery. PET-based composites are also utilized 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, while the integration of conductive fillers with PET matrices has led to the development of lightweight and flexible electronic components.

Through these case studies, it is evident that R-PET composites, when effectively modified, can significantly contribute to sustainable material development and circular economy initiatives across various industries.

4. PROCESSING TECHNIQUES AND COMPOSITE FORMULATIONS

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

4.1 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, where PET is heated and mixed with reinforcing fillers such as silica, carbon fibers, or nanoclays to improve mechanical strength. Extrusion is widely used to process PET composites into sheets, fibers, or molded components, providing uniform distribution of fillers. Injection molding allows the creation of intricate composite structures with high precision and reproducibility. Compression molding is another method where 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 to fabricate PET-based composites with enhanced functionalities (Jamshidi, Afshar, Mohammadi, & Pourmahdian, 2005).

4.2 Composite Formulations and Key Parameters

The formulation of R-PET composites depends on several key parameters, including the type and proportion of fillers, matrix modifications, and processing conditions. The selection of fillers such as glass fibers, carbon fibers, or natural fibers influences the composite's mechanical, thermal, and barrier properties. 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 like temperature, shear rate, and cooling rate affect the crystallinity and phase dispersion of the composites. The addition of impact modifiers can enhance toughness, while stabilizers improve thermal resistance, ensuring longevity in various applications.

4.3 Impact on Final Properties

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

4.4 Case Studies and Industrial Applications

R-PET composites have found applications in various industries due 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 yet durable alternative to conventional materials. The automotive industry employs PET composites in interior panels, bumpers, and under-the-hood components due to their excellent strength-to-weight ratio and thermal stability. In packaging, PET-based composites improve barrier properties, ensuring better food preservation and sustainability. 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.

5. MECHANICAL PROPERTIES OF PET-REINFORCED RUBBER

Experimental studies on PET-reinforced rubber composites have demonstrated significant improvements in mechanical properties, making them suitable for various engineering applications. Research indicates that incorporating PET fibers into rubber matrices enhances 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, Cazan, & Duta, 2014). Additionally, crosslinking techniques, such as the use of sulfur or peroxide curing systems, play a crucial role in defining the mechanical performance of these composites.

Several factors contribute to property enhancement in PET-reinforced rubber. The selection of reinforcement materials, particle size, and fiber orientation significantly influence mechanical strength. The addition of coupling agents, such as silane treatments, improves 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., 2024a).

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., 2024a). 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. These real-world applications highlight the versatility and efficiency of PET-reinforced rubber, further establishing its potential in sustainable material development.

6. THERMAL AND MORPHOLOGICAL ANALYSIS

Advanced thermal studies of PET-reinforced composites are crucial for understanding their behavior under varying temperature conditions. Thermogravimetric analysis (TGA) has shown that R-PET composites exhibit enhanced thermal stability compared to virgin PET, primarily due to the presence of reinforcing fillers and improved interfacial bonding. Differential scanning calorimetry (DSC) has been employed to evaluate the melting and crystallization behavior of these composites, revealing that the incorporation of nanofillers and compatibilizers can significantly modify thermal transitions and enhance heat resistance.

Material decomposition behavior is an essential factor in assessing the longevity and performance of PET-based composites. Studies indicate that the decomposition of PET 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, Ding, & Jalali, 2012). Additionally, pyrolysis studies have demonstrated that PET composites can be effectively recycled through controlled thermal decomposition processes, minimizing environmental impact.

Surface morphology analysis plays a pivotal role in determining the structural integrity of PET composites. Scanning electron microscopy (SEM) has been 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, Saelao, & Buzaré, 2007). Well-dispersed reinforcement within the polymer matrix leads 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 the optimal composition for various applications. Increasing PET content generally improves the heat resistance of composites, but excessive PET concentrations may lead to brittleness and reduced toughness. Balancing PET with other polymers or elastomers ensures a synergy between mechanical strength and thermal endurance. Experimental results highlight that composites with controlled PET content and appropriate fillers demonstrate superior resistance to thermal degradation, making them suitable for demanding industrial applications.

7. ENVIRONMENTAL AND SUSTAINABILITY ASPECTS

The incorporation of R-PET in composite formulations presents significant environmental and sustainability benefits (Vallejos et al., 2024a). The use of recycled materials reduces plastic waste, minimizes landfill accumulation, and decreases dependency on virgin petroleum-based resources (Miranda Vidales, Narváez Hernández, Tapia López, Martínez Flores, & Hernández, 2014). Regulatory frameworks such as extended producer responsibility (EPR) programs and environmental directives encourage industries to adopt sustainable materials, ensuring 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 et al., 2024). Compared to conventional rubber reinforcement methods, PET composites offer superior recyclability, 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 a viable alternative to traditional reinforcement materials.

8. 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 the incorporation of R-PET 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_2 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_2 per kg of recycled PET used in rubber composites.

Energy Savings:

- Manufacturing virgin PET requires 80 MJ/kg of energy.
- Recycled PET requires only 30 MJ/kg, 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 et al., 2024). Additionally, regulatory incentives and sustainability goals encourage industries to transition towards PET composites, further solidifying their role in eco-friendly material innovation.

8.1 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.

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_2/kg filler)	~2.4	~1.8	~25% reduction
Energy Use (MJ/kg 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	✓

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.

9. CHALLENGES AND FUTURE PROSPECTS

Despite the numerous benefits of PET-reinforced composites, several challenges limit their widespread adoption. One 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 (H. M. Bhatt, Desai, & Sunil Padhiyar, n.d.) 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.

10. CONCLUSION

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.

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REFERENCES

[1] X. Shen *et al.*, "Investigating Polyethylene Terephthalate Beverage Packaging: Impact of Recycled Content on Acetaldehyde, Benzene, and Other Contaminants," *J Polym Environ*, Mar. 2025, doi: 10.1007/s10924-025-03544-1.

[2] A. Elamri, K. Abid, O. Harzallah, and A. Lallam, "Characterization of Recycled/ Virgin PET Polymers and their Composites," *American Journal of Nano Research and Application. Special Issue: Nanocomposites Coating and Manufacturing*, vol. 3, no. 1, pp. 11–16, 2015, doi: 10.11648/j.nano.s.2015030401.13.

[3] C. Cazan, M. Cosnita, M. Visa, and A. Duta, "Novel Rubber—Plastics Composites Fully Based on Recycled Materials," 2014, pp. 503–519. doi: 10.1007/978-3-319-09707-7_38.

[4] Y. L. Zhang *et al.*, "Microplastics in landfast sea ice of Alaskan Arctic: Characteristics and potential sources," *Research in Cold and Arid Regions*, 2024, doi: 10.1016/j.rcar.2024.12.001.

[5] C. Rung, F. Welle, A. Gruner, A. Springer, Z. Steinmetz, and K. Munoz, "Identification and Evaluation of (Non-)Intentionally Added Substances in Post-Consumer Recyclates and Their Toxicological Classification," *Recycling*, vol. 8, no. 1, Feb. 2023, doi: 10.3390/recycling8010024.

[6] I. Vitkauskienė and R. Makuška, "Glycolysis of industrial poly(ethylene terephthalate) waste directed to bis(hydroxyethylene) terephthalate and aromatic polyester polyols," 2008.

[7] Y. G. Quintero, D. R. Figueroa, H. Gil, and A. A. Zuleta, "PHYSICAL AND MECHANICAL PROPERTIES OF RECYCLED PET COMPOSITES," *Stavební obzor - Civil Engineering Journal*, vol. 28, no. 4, Dec. 2019, doi: 10.14311/cej.2019.04.0045.

[8] M. Bagadiya, R. N. Desai, and S. J. Padhiyar, "REINFORCEMENT OF NATURAL RUBBER BY USING HUMAN HAIR," 2016. [Online]. Available: www.ijariie.com

[9] A. S. Hashim'" and S. Kohjiya, "Curing of Epoxidized Natural Rubber with p-Phenylenediamine."

[10] A. B. Reddy *et al.*, "Polyethylene Terephthalate-Based Blends: Natural Rubber and Synthetic Rubber," in *Poly(Ethylene Terephthalate) Based Blends, Composites and Nanocomposites*, Elsevier Inc., 2015, pp. 75–98. doi: 10.1016/B978-0-323-31306-3.00005-1.

[11] H. Nabil, H. Ismail, and A. R. Azura, “Recycled polyethylene terephthalate filled natural rubber compounds: Effects of filler loading and types of matrix,” *Journal of Elastomers and Plastics*, vol. 43, no. 5, pp. 429–449, Sep. 2011, doi: 10.1177/0095244311405503.

[12] M. Bagadiya, R. N. Desai, and S. J. Padhiyar, “Utilize Natural Fiber: Treated Human Hair to Improve Rubber Physical Properties,” 2016.

[13] G. A. . Popa, *Recycled Rubber: Composite Matrix*. Nova Science Publishers, Inc., 2011.

[14] J. Vallejos, M. Montenegro, S. Muñoz, and J. García, “Mechanical and Microstructural Properties of Environmentally Friendly Concrete Partially Replacing Aggregates with Recycled Rubber and Recycled PET,” *Journal of Sustainable Architecture and Civil Engineering*, vol. 36, no. 3, pp. 94–110, Oct. 2024, doi: 10.5755/j01.sace.36.3.33836.

[15] R. K. Padhan and A. A. Gupta, “Polyethylene Terephthalate-Based Blends: Thermoplastic and Thermoset,” in *Poly(Ethylene Terephthalate) Based Blends, Composites and Nanocomposites*, Elsevier Inc., 2015, pp. 65–73. doi: 10.1016/B978-0-323-31306-3.00004-X.

[16] A. SANCHEZ-SOLfS, M. R. Estrada J Cruz, M. Znstituto de Znuestigaciones en Materiales, and L. A. P, “On the Properties and Processing of Polyethylene Te r e p h t h a I at e/S ty r e n e-B u t a d i en e R u b b e r B I end.”

[17] M. Cosnita, C. Cazan, and A. Duta, “Effect of waste polyethylene terephthalate content on the durability and mechanical properties of composites with tire rubber matrix,” *J Compos Mater*, vol. 51, no. 3, pp. 357–372, Feb. 2017, doi: 10.1177/0021998316645850.

[18] S. Zekriardehani, S. A. Jabarin, D. R. Gidley, and M. R. Coleman, “Effect of Chain Dynamics, Crystallinity, and Free Volume on the Barrier Properties of Poly(ethylene terephthalate) Biaxially Oriented Films,” *Macromolecules*, vol. 50, no. 7, pp. 2845–2855, Apr. 2017, doi: 10.1021/acs.macromol.7b00198.

[19] U. R. Gracida-Alvarez, H. Xu, P. T. Benavides, M. Wang, and T. R. Hawkins, “Circular Economy Sustainability Analysis Framework for Plastics: Application for Poly(ethylene Terephthalate) (PET),” *ACS Sustain Chem Eng*, vol. 11, no. 2, pp. 514–524, Jan. 2023, doi: 10.1021/acssuschemeng.2c04626.

[20] M. A. Coniglio, C. Fioriglio, and P. Laganà, “SPRINGER BRIEFS IN MOLECULAR SCIENCE CHEMISTRY OF FOODS.” [Online]. Available: http://www.springer.com/series/11853

[21] G. G. Bhatt, P. R. N. Desai, and P. S. J. Padhiyar, “New Era Of Thermoplastic Vulcanizate Alloy For Sponge Application,” 2015. [Online]. Available: http://www.ptsuk.com/powerpoints/

[22] N. Dimitrov, L. Kratofil Krehula, A. Ptiček Siročić, and Z. Hrnjak-Murgić, “Analysis of recycled PET bottles products by pyrolysis-gas chromatography,” *Polym Degrad Stab*, vol. 98, no. 5, pp. 972–979, May 2013, doi: 10.1016/j.polymdegradstab.2013.02.013.

[23] S. Luo and W. J. Van Ooij, “Surface modification of textile fibers for improvement of adhesion to polymeric matrices: A review,” 2002. doi: 10.1163/156856102320396102.

[24] Y. Li, D. J. White, and R. Lee Peyton, “Composite material from fly ash and post-consumer PET,” 1998.

[25] M. Jamshidi, F. Afshar, N. Mohammadi, and S. Pourmahdian, “Study on cord/rubber interface at elevated temperatures by H-pull test method,” *Appl Surf Sci*, vol. 249, no. 1–4, pp. 208–215, Aug. 2005, doi: 10.1016/j.apsusc.2004.11.081.

[26] M. Razavizadeh and M. Jamshidi, “Adhesion of nitrile rubber (NBR) to polyethylene terephthalate (PET) fabric. Part 1: PET surface modification by methylenediphenyl di-isocyanate (MDI),” *Appl Surf Sci*, vol. 360, pp. 429–435, Jan. 2016, doi: 10.1016/j.apsusc.2015.10.137.

[27] C. W. Phetphaisit, J. Namahoot, K. Saengkiettiyut, J. Ruamcharoen, and P. Ruamcharoen, "Green metal organic coating from recycled PETs and modified natural rubber for the automobile industry," *Prog Org Coat*, vol. 86, pp. 181–189, Sep. 2015, doi: 10.1016/j.porgcoat.2015.04.025.

[28] M. Cosnita, C. Cazan, and A. Duta, "Interfaces and mechanical properties of recycled rubber-polyethylene terephthalate-wood composites," *J Compos Mater*, vol. 48, no. 6, pp. 683–694, Mar. 2014, doi: 10.1177/0021998313476561.

[29] F. Pacheco-Torgal, Y. Ding, and S. Jalali, "Properties and durability of concrete containing polymeric wastes (tyre rubber and polyethylene terephthalate bottles): An overview," May 2012. doi: 10.1016/j.conbuildmat.2011.11.047.

[30] P. Phinyocheep, J. Saelao, and J. Y. Buzaré, "Mechanical properties, morphology and molecular characteristics of poly(ethylene terephthalate) toughened by natural rubber," *Polymer (Guildf)*, vol. 48, no. 19, pp. 5702–5712, Sep. 2007, doi: 10.1016/j.polymer.2007.07.016.

[31] J. M. Miranda Vidales, L. Narváez Hernández, J. I. Tapia López, E. E. Martínez Flores, and L. S. Hernández, "Polymer mortars prepared using a polymeric resin and particles obtained from waste pet bottle," *Constr Build Mater*, vol. 65, pp. 376–383, Aug. 2014, doi: 10.1016/j.conbuildmat.2014.04.114.

[32] C. Duan, Z. Wang, B. Zhou, and X. Yao, "Global Polyethylene Terephthalate (PET) Plastic Supply Chain Resource Metabolism Efficiency and Carbon Emissions Co-Reduction Strategies," *Sustainability (Switzerland)* , vol. 16, no. 10, May 2024, doi: 10.3390/su16103926.

[33] J. Zheng and S. Suh, "Strategies to reduce the global carbon footprint of plastics," May 01, 2019, *Nature Publishing Group*. doi: 10.1038/s41558-019-0459-z.

[34] H. M. Bhatt, R. N. Desai, and A. Sunil Padhiyar, "Bio Degradability test of blend of PLA and modified starch." [Online]. Available: www.ijariie.com