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Waste Rubber-Polyethylene Composite Materials for Enhancement of Mechanical, Thermal, and Electrical Properties–A Critical Review

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Keywords:
Polyethylene; Waste tires; Recycling; Reinforcement; Environment.

Highlights:
- *Recycled materials are crucial for sustainable environmental conservation practices.*
- *Recycling reduces waste, saves energy, and lowers emissions.*
- *Recycling tires creates eco-friendly materials and products.*
- *Recycled rubber enhances polyethylene density and thermal conductivity.*

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Abstract: Scholars have redirected their attention toward the use of recycled resources as a response to the escalating environmental concerns. They demonstrated that recycled materials are essential for sustainable practices, as they contribute to environmental conservation and the effective use of resources, through the examination of their impact on waste reduction, energy saving, and the alleviation of greenhouse gas emissions. Furthermore, recycling has substantial economic and social ramifications, and rubber is one of the materials that may undergo the recycling process. Considering the significance of recycled rubber in addressing environmental issues, including excessive waste in landfills and resource depletion, it is essential to examine the process of transforming waste rubber into valuable commodities through recycling. The many uses of recycled rubber range from eco-friendly construction materials to inventive consumer goods, with a focus on its contribution to fostering a sustainable, closed-loop economy. Waste tires are a significant kind of waste rubber. Hence, the process of recycling used tires and transforming them into valuable commodities has significant ecological and financial significance. This paper reviews the reuse of scrap tires to mitigate environmental hazards. It analyzes the effect of using recycled rubber on the mechanical and physical properties of low and high-density polyethylene. It shows that the distribution of recycled rubber granules in polyethylene increases its density with improved thermal conductivity values due to the presence of carbon black. The study also shows a deterioration in the mechanical properties of polyethylene. Tensile strength, flexural strength, and hardness are examples; however, the inclusion of tire waste particles improves impact strength ratings. Nonetheless, this deterioration stays within permissible boundaries when evaluating the economic and environmental advantages it offers.

المواد المركبة من المطاط المُعاد تدويره والبولي إيثيلين لتحسين الخواص الميكانيكية والحرارية والكهربائية - مراجعة نقدية

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الخلاصة
أعاد الباحثون توجيه اهتمامهم نحو استخدام الموارد المُعاد تدويرها استجابةً للمخاوف البيئية المتزايدة. لقد أظهروا أن المواد المُعاد تدويرها أساسية للممارسات المستدامة نظرًا لمساهمتها في الحفاظ على البيئة والاستخدام الفعّال للموارد. وذلك من خلال دراسة تأثيرها على تقليل النفايات وتوفير الطاقة والتخفيف من انبعاثات الغازات الدفيئة. بالإضافة إلى ذلك، فإن إعادة التدوير لها آثار اقتصادية واجتماعية كبيرة، ويُعد المطاط أحد المواد التي يمكن أن تخضع لعملية إعادة التدوير. نظرًا لأهمية المطاط المُعاد تدويره في معالجة القضايا البيئية، بما في ذلك النفايات الزائدة في مدافن النفايات واستنزاف الموارد، فمن الضروري فحص عملية تحويل نفايات المطاط إلى سلع قيمة عبر إعادة التدوير. تتعدد استخدامات المطاط المُعاد تدويره، بدءًا من مواد البناء الصديقة للبيئة وصولًا إلى المنتجات الاستهلاكية المبتكرة، مع التركيز على مساهمته في تعزيز الاقتصاد الدائري المستدام. تُعتبر إطارات النفايات نوعًا مهمًا من نفايات المطاط، وذلك نتيجة للكميات الكبيرة التي يتم استهلاكها والمساحات الشاسعة التي تُستخدم كمكبات للنفايات. وبالتالي، فإن عملية إعادة تدوير الإطارات المستعملة وتحويلها إلى سلع ذات قيمة لها أهمية بيئية واقتصادية كبيرة. يوفر هذا البحث مراجعة لإعادة استخدام إطارات الخردة لتقليل المخاطر البيئية. يحلل البحث الحالي تأثير استخدام المطاط المُعاد تدويره على الخواص الميكانيكية والفيزيائية للبولي إيثيلين منخفض وعالي الكثافة. أظهرت هذه الدراسة أن توزيع حبيبات المطاط المُعاد تدويرها في البولي إيثيلين يزيد من كثافته مع تحسين قيم التوصيل الحراري بسبب وجود الكربون الأسود. كما أظهرت الدراسة تدهورًا في الخواص الميكانيكية للبولي إيثيلين، مثل قوة الشد، وقوة الانحناء، والصلابة، لكن قيم قوة التأثير تحسنت عند إضافة جزيئات نفايات الإطارات. ومع ذلك، يبقى هذا التدهور ضمن الحدود المقبولة عند النظر في الفوائد الاقتصادية والبيئية التي يوفرها.

الكلمات الدالة: البولي اثيلين، نفايات الاطارات، اعادة التدوير، التقسية، البيئة.

1.INTRODUCTION

The scientific community has widely acknowledged that the safe disposal of environmental waste remains a significant challenge. After reaching the end of their useful life, rubber materials can present challenges when reusing or recycling them. Currently, a unique technology is used to recycle plastic waste, including all kinds of plastic bags, food containers, fat containers, and tires; this process involves the pulverization and segregation of the fibers from vulcanized rubber. The plastic produced is then used in many industrial applications [1, 2]. Plastics and rubber are widely used in many industries, including automotive, construction, material handling, packaging, and household items. However, these materials do not decompose and remain in the environment for a long time, except when they are discarded after expiration. The global rise in the production of polymer waste materials, such as plastics and rubber, has necessitated the development of effective methods to recycle these materials and mitigate their negative environmental impact upon disposal. Incineration and landfilling are inappropriate technologies for removing polymer waste due to their many disadvantages [3–5]. The reprocessing and recycling of polymers provide inherent challenges for conventional technologies due to their chemically cross-linked structure. Managing polymer waste often requires the use of landfills, elevated temperatures, or hazardous chemicals, all of which result in significant environmental concerns. Polymers possess the ability to flow and undergo reprocessing when exposed to heat [6]. However, their resistance to solvents, as well as their thermal and mechanical properties at elevated temperatures, are inadequate. Consequently, they cannot substitute for thermosets in numerous engineering applications, particularly those demanding exceptional performance, such as the aircraft and automotive industries. Due to the increasing amount of waste generated from thermosetting polymers, numerous innovative methods for reprocessing and recycling have been proposed. A practical process involves repurposing finely pulverized thermoset waste as reinforcements for other elastomers, ceramics, and concrete to enhance their qualities or prolong their lifespan. Nevertheless, treating polymer wastes often requires surface chemical modifications before use to enhance their compatibility with the matrix. This process is expensive and financially impractical for large-scale manufacturing [7–10]. Emphasizing recent advancements in the domain of recycled rubber composites using polyethylene, and evaluating sophisticated techniques for enhancing the mechanical and thermal characteristics of these composites. The analysis examines new advancements in manufacturing techniques and compatibility strategies among various components. This review advances contemporary research trends focused on enhancing environmental sustainability through the utilization of recycled materials, highlighting current global issues in addressing environmental and industrial challenges. This thorough and current perspective renders the evaluation highly valuable to academics and producers focused on sustainable composite material applications. The objective is to examine the addition ratios and the impact of recycled rubber on the characteristics of polymers, particularly polyethylene.

2.RECYCLING OF PLASTICS

Plastic is a versatile and widely used material, considered one of the most significant discoveries of the twentieth century. Industrial processes, municipal solid waste, and service companies produce a large amount of waste materials. There has been a significant increase in the use of plastic worldwide in recent years, resulting in a corresponding rise in plastic waste of all kinds. In a recent study, the percentages of plastic waste were found, as shown in Fig. 1. Improper disposal of solid waste, including tires, is a significant contributor to environmental issues in our society. This issue is primarily due to the three-dimensional structure created by the cross-links in the tires, which undergo a natural deterioration process with no end in sight. Tires, mainly when disposed of in landfills, are very effective in storing rainwater due to their large size and thus serve as a convenient and ideal breeding ground for disease vectors. These materials are also considered to be of great intrinsic value due to their composition, technological features, and intellectual content. Technology is used in the manufacturing process. Therefore, tires must reach the end of their useful life and find new uses. As a result of the significant increase in the number of cars worldwide, numerous endeavors have been undertaken to reduce the accumulation and disposal of waste tires by utilizing them as a valuable source of sustainable resources [11–16].

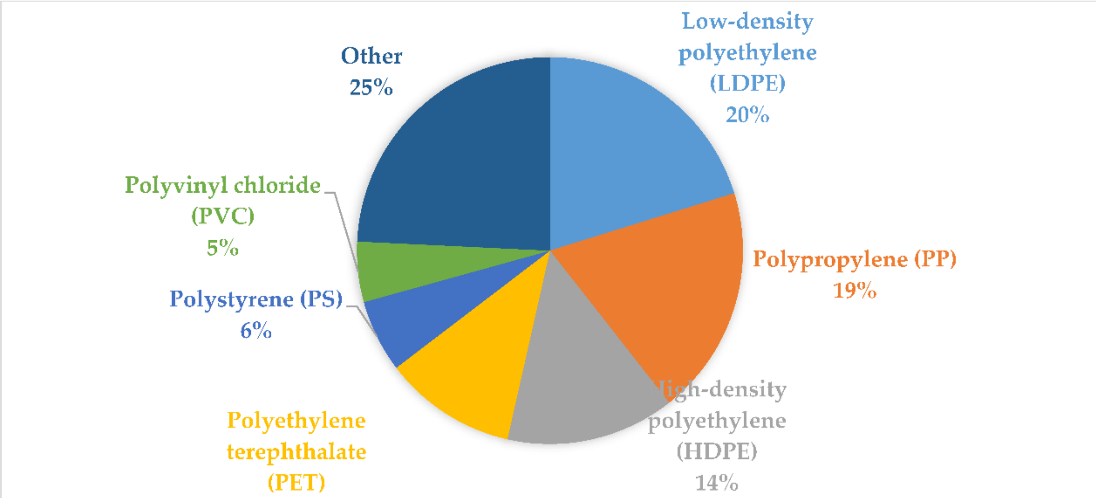


Fig. 1 The Global Distribution of Plastic Garbage Based on Type of Plastic [17].

2.1.Waste Tire Utilization

Recycled waste tires are considered a valuable resource due to their composition and properties, making them a source of essential raw materials. The effectiveness of waste tire recovery technology has enabled the efficient conversion of waste tires into energy or useful materials. Suitable waste tires can be repurposed to create practical or useful items. Waste tires are generated when worn tires are replaced with new ones before disposal. They can be classified as either partially used tires or tires that have reached the end of their maximum life. Partially worn tires are still usable on the road ; however, end-of-life tires can no longer perform their original function. Various efforts have been made to utilize waste tires by recovering them, and Fig. 2 illustrates some of the uses of recycled rubber [4, 18, 19].

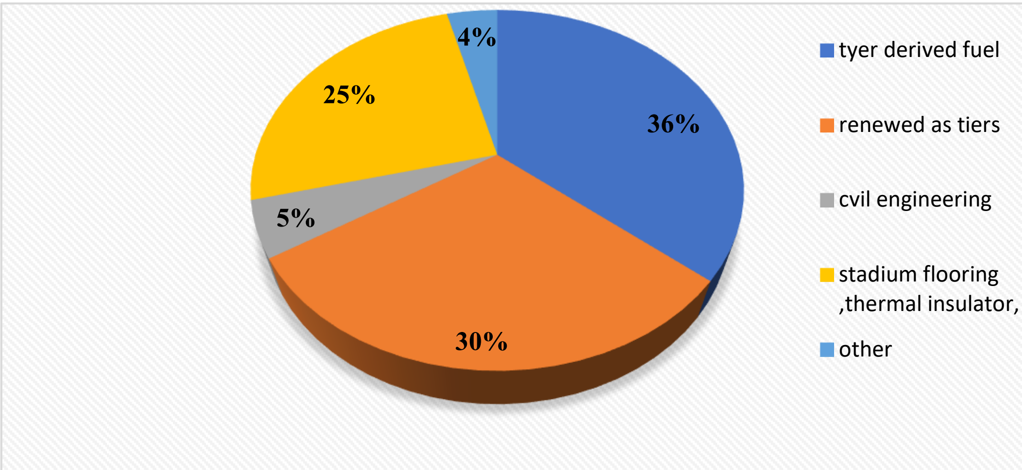


Fig. 2 Usages of Recycled Rubber [18].

Utilizing intact waste tires and shredded tires is classified as recycling. Whole abandoned tires are used in artificial reefs, playground equipment, corrosion control measures, highway crash barriers, and breakwaters. Scrap tires are broken down into smaller pieces and used in the rubber or plastic industries to manufacture playground surfaces and sports tracks (Fig. 3). Shredded tires are combined with asphalt mixtures for the construction of structures and concrete applications. Ground tire rubber (GTR), obtained by various downsizing (grinding) methods, includes many premium natural and synthetic rubbers. These rubbers may serve as excellent raw materials for integration into polymers such as thermoplastics, thermosets, and rubbers [20, 21].

2.2.Tire Composition

Tires are intricately designed and intricate assemblies of components with a diverse array of qualities. The outermost layer of the tire, which comes into direct contact with the road, comprises a significant proportion of natural and synthetic rubbers. The belts are composed of rubber, steel, and cloth, chosen according to the specific tire use, such as passenger cars, trucks, or off-the-road vehicles [22, 23]. The main challenges in recycling or recovering used tire rubber stem from its complex composition, which includes steel-reinforced cross-linked rubber and polymer fibers, such as cellulose, nylon, and polyester. Therefore, mechanical recycling is necessary to extract each component of the rubber. A passenger car tire typically consists of at least 12 components, while a truck tire comprises 20 members. Generally, styrene-butadiene rubber (SBR) is used to manufacture passenger tires, while natural rubber (NR) is mainly used to produce truck tires. The most abundant components in various tires are listed in Table 1 [24,25].

Fig. 3 Rubber Recycling Strategy [10].

Table 1 Composition of Different Tires [26].

Components	Passenger car tire	Components	Passenger car tire
Rubbers/Elastomers (natural)	16	30	31
Rubbers/Elastomers (synthetic)	31	15	16
Carbon black and silica	21.5	22	22
Metal	16.5	25	12
Textile	5.5	-	10
Zinc oxide	1	2	2
Sulfur	1	1	1
Additives	7.5	5	6

3.POLYETHYLENE

Polyethylene, produced from ethylene gas, is the most widely produced plastic on a global scale. Various manufacturing processes and a range of catalysts and comonomers can be used to produce a broad spectrum of ethylene homopolymers and copolymers. Producers can create several variations of resins, allowing them to tailor the materials to applications, such as packaging films, rigid containers, drums, and tubes. Consequently, there has been a significant advancement in polyethylene manufacturing, which now accounts for around 30% of the total plastic output, as shown in Fig. 4. All plastic outputs. The rapid growth of the global economy has fostered a favorable climate for the development of the synthetic resins sector. The polyethylene sector is expected to witness rapid growth [27,28].

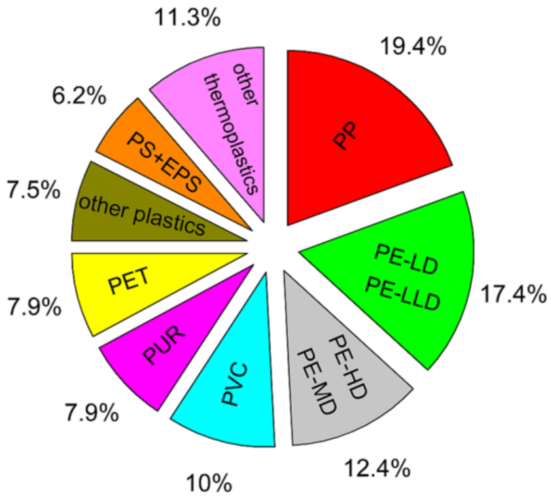


Fig. 4 Distribution of Global Plastic Production [29].

Polyethylene can be produced using various processes, including high-pressure polyethylene, medium-pressure polyethylene, and low-pressure polyethylene. Three strategies include distinct benefits and drawbacks that coexist within the sector. The qualities of polyethylene vary depending on the production technique and are closely linked to its molecular structure. Additionally, polyethylene can be categorized into two types: low-density polyethylene (LDPE) and high-density polyethylene (HDPE). It exhibits extraordinary resilience to low temperatures, outstanding resistance to chemicals, excellent electrical insulation properties, strong resistance to high pressure, and exceptional resistance to radiation. Polyethylene exhibits exceptional water resistance due to its lack of polar components, as it consists solely of carbon and hydrogen [27, 30, 31].

3.1.Polyethylene's Structure

Polyethylene (PE) is a synthetic material classified as a thermoplastic polymer. A simple example is the plastic bags found in supermarkets. Despite its basic structure, polyethylene remains the most widely used polymer material due to its ease of manufacturing [31]. It is formed by the repetition of the -CH2 unit. Polyethylene is synthesized through the process of addition polymerization of ethylene (CH2=CH2). The user's text states that polyethylene's performance is contingent upon its polymerization process. The Ziegler-Natta polymerization process was conducted using organic compound catalysts at a moderate pressure range of 15-30 atm, specifically for the production of high-density polyethylene (HDPE). Under these circumstances, the polyethylene molecules undergo polymerization, resulting in a linear molecular structure with an exceptionally long chain length and a molecular weight that may reach several hundred thousand. When subjected to high pressure (100-300 MPa), high temperature (190-210 °C), and peroxide catalytic conditions, the resulting product is low-density polyethylene (LDPE), which exhibits a branched structure [27, 31, 32]. The density of low-density polyethylene typically falls between 0.91 and 0.925 g/cm³, whereas linear low-density polyethylene has a density ranging from 0.918 to 0.94 g/cm³. High-density polyethylene, on the other hand, has a density of 0.935 to 0.96 g/cm³ and higher [33].

3.2.Utilization of Polyethylene

Polyethylene (PE) is a promising synthetic material with exceptional physical and chemical characteristics. PE has a high level of mechanical qualities and possesses an extraordinary mix of favorable dielectric properties. Furthermore, the molding technique is of high quality, and the costs are affordable. They have significant importance in the following areas: Insulation for electrical purposes. With its exceptional stability, moisture resistance, and superior dielectric properties, this material is highly suitable for use in insulating materials for both electrical and non-electrical engineering applications, as well as other related fields [28, 32, 34]. It is used in automobile parts such as upholstery, electrical components, and Liquid reservoirs [33]. Packaging Polyethylene sheets exhibit low density, softness, impermeability to water, muscular tear strength, and chemical resilience. The packaging sector highly values polyethylene film due to its essential features for packaging items. Polyethylene has a wide range of applications, including its use in various medical equipment, which offers several benefits as a biomaterial for medical implants. It has been widely used in the production of porous high-density polyethylene implants for facial and cranial reconstruction. Moreover, for spraying metal, wood, cloth, and other materials. High-density polyethylene can serve as a reinforcing agent for rubber [27, 32, 35]. Using waste polyethylene as a resource rather than discarding it as trash holds significant promise for mitigating environmental problems associated with plastic pollution while also providing economic and sustainable benefits. There are various ways to utilize waste polyethylene:

1) **Environmental impact reduction:** Reusing polyethylene waste

reduces landfill congestion and mitigates the broader environmental impacts of plastic pollution. Reusing polyethylene prevents its introduction into ecosystems, thereby protecting animals and marine life from potential harm. Reusing polyethylene plastic waste is crucial to mitigating the environmental consequences by addressing several key aspects of plastic pollution. The continued accumulation of polyethylene plastic waste in landfills, where it can take thousands of years to decompose, can result in its release into the marine environment, posing significant risks to marine life through ingestion and entanglement. Recycling polyethylene waste conserves vital natural resources, such as crude oil, the main raw material for plastics. Reducing the need for new plastics results in the gradual decomposition of plastic waste into smaller particles known as microplastics, which can permeate ecosystems and pose significant environmental and health risks. Recycling polyethylene waste reduces the volume of plastic that can degrade into microplastics. Incorporating recycled polyethylene into the production process reduces the environmental impact of plastic while maintaining the economic value of the material [36–38].

2) **Resource conservation:** Recycling waste polyethylene conserves resources by reducing the need for virgin plastic production, conserving energy and raw materials, such as crude oil, which is the primary source for producing plastic.
3) **Energy savings:** Recycling polyethylene requires less energy than producing new plastic from raw materials. This behavior is because recycling involves melting and reshaping the plastic rather than extracting, refining, and processing raw materials.
4) **Economic opportunities:** Repurposing waste polyethylene can create economic opportunities by developing recycling industries and producing recycled plastic products, which create jobs and generate revenue within local communities.
5) **Technological advances:** Ongoing advancements in recycling technologies are making it increasingly feasible to process and utilize waste polyethylene efficiently. Innovations such as advanced sorting techniques, chemical recycling, and 3D printing with recycled plastics are expanding the possibilities for its reuse.
6) **Challenges and limitations:** Despite its potential benefits, using waste polyethylene also presents challenges. Contamination, including that from other types of plastics and non-plastic materials, can compromise the quality and usability of recycled polyethylene. Furthermore, the infrastructure for collecting, sorting, and processing plastic waste requires further development and investment to fully realize its potential.
7) **Policy and regulatory frameworks:** Effective waste management policies and regulations play a crucial role in promoting the use of waste polyethylene. Governments and organizations worldwide are implementing measures such as extended producer responsibility (EPR) schemes, plastic bags, and incentives for recycling to encourage the sustainable management of plastic waste. Table 2 summarizes the utilization of waste polyethylene for different applications:

Table 2 Utilization of Waste Polyethylene for Different Applications.

Research Work	Utilization Method	Key Findings	Refs.
Recycling into New Plastic	Mechanical Recycling	- Mechanical recycling processes such as shredding, melting, and extrusion can transform waste polyethylene into new plastic products with acceptable mechanical properties.	[8–10, 14]
Pyrolysis	Thermal Conversion	- Pyrolysis, a thermal decomposition process, can convert waste polyethylene into valuable fuels, gases, and chemical feedstocks, offering an alternative to landfill disposal or incineration.	[11, 15–17]
Chemical Recycling	Chemical Conversion	- Chemical recycling techniques, including depolymerization and catalytic cracking, can break down waste polyethylene into monomers or other valuable chemicals for use in manufacturing processes.	[12, 13, 18,19]
Composite Material Production	Reinforcing Filler	- Incorporating waste polyethylene as a reinforcing filler in composite materials, such as concrete, asphalt, or polymer composites, enhances material properties and reduces the environmental impact of construction and manufacturing industries.	[20, 21, 39, 40]
Energy Recovery	Waste-to-Energy	- Waste polyethylene can be utilized as a source of energy through waste-to-energy processes such as incineration, where it is burned to generate heat and electricity, contributing to renewable energy production and waste management.	[22, 23, 41]
3D Printing	Additive Manufacturing	- Waste polyethylene can be recycled and processed into filament materials for 3D printing, enabling the fabrication of functional prototypes, customized products, and spare parts with a reduced environmental footprint compared to conventional manufacturing methods.	[24, 25, 27, 31]

4.PROPERTIES

4.1.Morphological Properties

Kakroodi and Rodrigue [42] conducted a study to investigate the impact of incorporating ground tire rubber (GRT) into high-density polyethylene (HDPE) at varying weights (ranging from 50 to 90 wt.%) on the material's characteristics. Upon investigation, scanning electron microscopy (SEM) images in Fig. 5 revealed a significant presence of contaminants in the recycled rubber powder, which is attributable to its recycled nature. Rubber particles exhibit a wide range of forms and sizes. Certain rubber particles possess porous surfaces, as seen from the provided images, which display the smoothness of their angular surfaces. This discovery suggests that the particles originate from distinct tire varieties or diverse grinding techniques. Conversely, the particles exhibit a high level of cleanliness due to the weak bonding between the matrix and the rubber. However, this bonding is still considered satisfactory.

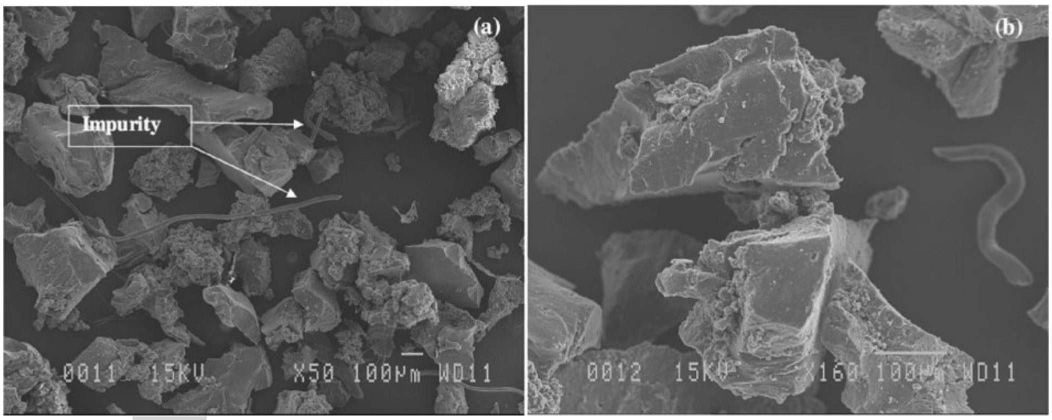


Fig. 5 Images (SEM) of GTR at Different Magnifications A&B [42].

Kazemi et al. [38] conducted a comparison between the inclusion of clean fiber (CF) and ground waste (GR) in varying weights (ranging from 0% to 30%) with recycled LDPE. The evaluation of the samples was carried out using electron microscopy. The scanning electron microscopy (SEM) analysis of the LDPE/CF composites revealed that the fibers exhibit a predominantly perpendicular alignment with respect to the cross-section. This alignment is attributed to the orientation of the fibers, which is caused by the influence of the jet flow inside the mold cavity. Injecting the mixes directly into a dog-bone-shaped mold caused the samples to align in the direction of the flow. Conversely, fiber routing pieces created by Compression Molding are mostly stochastic. Regarding LDPE/GR composites, injection molding demonstrated superior particle dispersion compared to compression molding. This behavior is caused by the secondary melt mixing process that occurs within the injection molding screw, resulting in enhanced dispersion of fillers. Shaker and Rodrigue [43] researchers combined renewable and non-renewable ground tire rubber (GTR) with LDPE to create thermoplastic rubber (TPE) for off-road (OTR) use. Specifically, the blending process used two distinct methods: molten blending, which was conducted by extrusion, and dry blending, which utilized a high-shear blender. GTR concentrations are available, namely at 0, 20, 35, and 50 weight percent. To assess the impact of the regeneration process on GTR molecules, a microscope can be used to examine their size and shape. The NRR particles have a more uniform surface than the RR particles, which display surface irregularities such as bumps and fractures. In contrast, the RR particles possess a more polished exterior but with some discernible fissures and imperfections. Moreover, mechanical regeneration can decrease the particle size by utilizing shear forces to mechanically disintegrate the particles. A decrease in particle size yields a greater surface area, facilitating substance alterations. The scanning electron microscopy (SEM) Figure 6 reveals a uniform dispersion of GTR (ground tire rubber) throughout the matrix, with a low GTR concentration ranging from 0% to 20%. Nevertheless, more bubbles and imperfections were observed as the GTR concentration increased, particularly in the case of the dry mixed samples. The increased surface area is attributed to the more excellent viscosity matrix, which results in fewer interfacial contacts between GTR-LDPE. This behavior is because no pressure is exerted during the rotational molding process. Ground tires (GTR) are combined with LDPE and HDPE. Gensca et al. [44] identified, through scanning electron microscope (SEM) images Figure 7, two distinct phases in the studied compounds. One side of the equation involves the polyethylene matrix, which is composed of LDPE and HDPE, respectively. The other aspect involves reinforcing tire particles. Thus, incorporating the reinforcement into the matrix is evident as a distinct phase, with limited integration into the polymer matrix, as evidenced by gaps between the particles and the reinforcement. These results are typical in such composite materials. Conversely, the outstanding feature is the uniform distribution of strengthening molecules in the composite, where the reinforcement is well-distributed throughout the sample, which is crucial in ensuring that no particle buildup occurs during the sample manufacturing process. Thus, the images shown reveal the presence of weak internal bonding between the two phases of the composite material, as well as the effective dispersion of the reinforcement within the composite matrix.

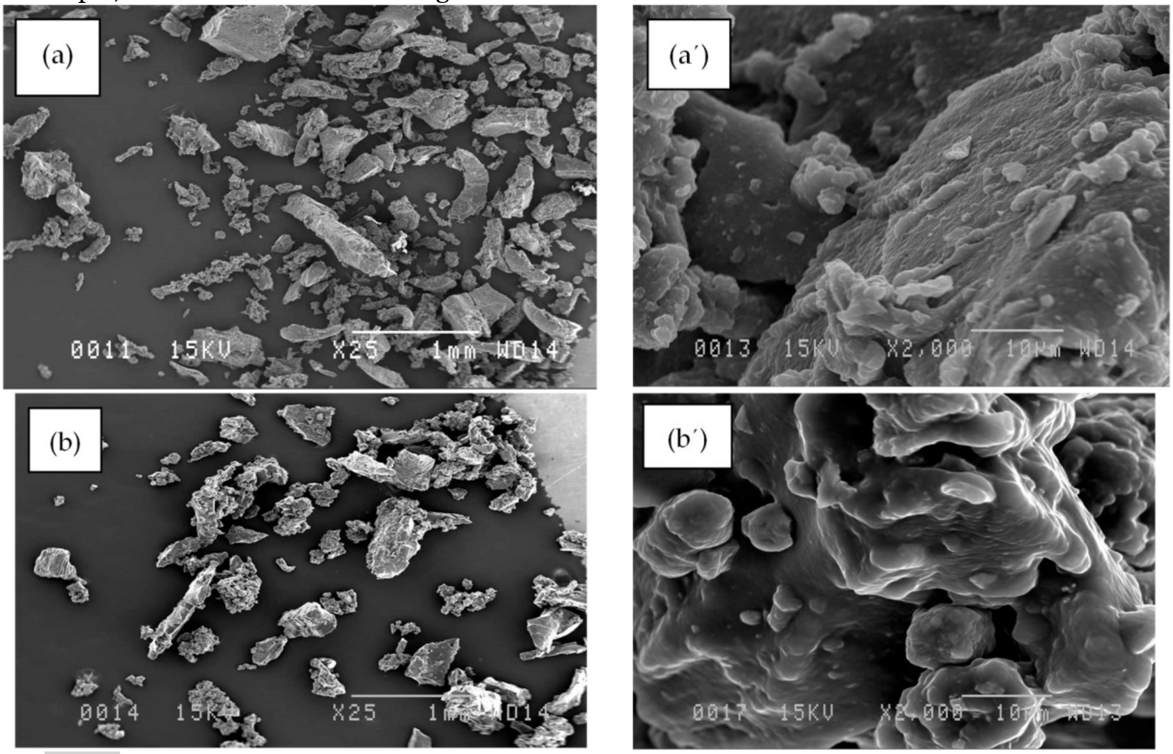
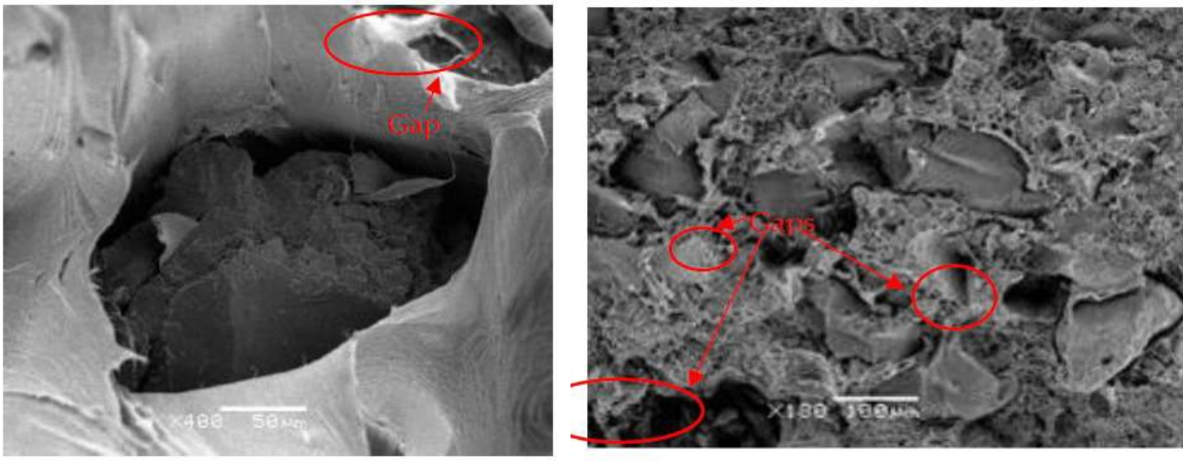


Fig. 6 (SEM) Images of the (a,a’) Non-Regenerated and (b,b’) Regenerated GTR at Different Magnifications [43].



(a) **(b)**

Fig. 7 (SEM) Micrographs of (a) LDPE/20%GTR, (b) HDPE/20%GTR [44].

A study conducted by Kiss et al. [45] utilized value-added ultra-fine ground tire recycling (uGTR). Waterjet milling is used in the rubber industry (uGTR) by evaluating the properties of different mixtures of uGTR tires and conventional small ground tires. LDPE blends were created by including rubber components (fGTR) in weight percentages of 10%, 20%, and 30%. SEM micrographs revealed that GTR had a large particle size and limited surface area. Furthermore, there was a complete lack of adhesion between the different phases. Due to the holograms, the GTR molecules are physically isolated from the LDPE matrix, preventing payload transfer. As a result, breakage occurs quickly. In contrast, the two images also show the “fibrous” fracture surface of the samples containing uGTR, indicating a positive relationship between the phases. Dispersed GTR molecules exhibit little visibility and thus contribute to the exceptional elongation at break. The scanning electron microscopy (SEM) picture depicts the microstructure of the samples, including filler additions ranging from 0% to 25%. Fillers manifest as supplementary black particles that are already present in the LD-PE. Observably, the particle size exhibits an increment as the filler ratio is augmented, and their distribution inside the matrix is mostly homogeneous. The rubber is thoroughly consolidated and uniformly dispersed throughout the matrix. Bodude et al. [46] captured these photos of LDPE manufactured from crushed rubber particles measuring 150 micrometers in size. The proportion of rubber granules used varies from 0% to 25%. The study conducted by Mastalygina et al. [47] examined low-density polyethylene (PE) samples with varying amounts of natural rubber (NR) content (10-30 wt.%). Incorporating filler into the polymeric matrix results in substantial alterations to the morphology of the composite material and the mobility of the boundary layers at the macromolecular level. The microstructure of composite materials was investigated using optical microscopy. The combination of PE and NR resulted in a system where PE acted as the core structure while NR was distributed as separate domains. Due to its elastomeric properties, NR functioned as a flexible dispersed filler inside the PE matrix. In this scenario, PE/NR systems cannot be regarded as a composite of two thermoplastic polymers. The rubber domains in the composites had a size ranging from 10 to 100 µm. It was found that as the NR concentration in the PE matrix increased, the domains exhibited a more even distribution with smaller sizes. SEM images of low-density or high-density polyethylene composites with ground tire rubber (GRT) revealed a consistent dispersion of reinforcement particles throughout the base material (PE), with a relatively moderate but satisfactory level of cross-linking between them. The scanning electron microscope (SEM) image reveals that as the particle size decreases, the bonding quality improves due to the increased surface area of the additive, thereby enhancing its ability to increase bonding strength. The research also indicated a small level of porosity, which varies depending on the manufacturing technique employed. This result is what researchers [48] to [49] agreed on. Therefore, their results are consistent with those of the researcher [46]. When incorporating natural rubber (NR) at a weight percentage of 10-30%.

4.2.Density

Different methods can enhance the density of composite plastic materials by effectively incorporating waste polyethylene, optimizing processing conditions, adjusting filler loading levels, modifying surface characteristics, and exploring hybridization with other fillers or reinforcements. Table 3 illustrates various methods used for improving the density of composite plastic by incorporating waste polyethylene:

Table 3 Methods Used for Improving Composite Density Using Waste Polyethylene.

Method	Description	References
Incorporation as Filler	Waste polyethylene is added as a filler material to the composite plastic matrix during the manufacturing process.	[28,29]
Optimization of Processing Parameters	Researchers optimize processing parameters such as mixing time, temperature, and pressure to ensure uniform filler dispersion.	[30,50,51]
Varying filler loading levels	The concentration of waste polyethylene filler is varied to identify the optimal loading level for achieving the desired density.	[32,33,52]
Surface modification of polyethylene	Surface treatments or modifications of waste polyethylene particles are applied to enhance compatibility with the matrix.	[34,35,48]
Hybridization with other fillers	Waste polyethylene is combined with other fillers or reinforcements to create hybrid composites with improved density.	[49,53,54]

Shaker and Rodrigue [43] conducted an experiment in which they combined several weight percentages (0, 20, 35, and 50 wt.%) of GTR with two types of particles—non-renewable particles (NRR) and renewable particles (RR)— alongside LDPE. The objective was to determine the density of the raw materials and the resulting sample formation arising from using both dry and molten mixture preparation techniques. The thickness of GTR, with an NRR of 1.169 g/cm³ and RR of 1.246 g/cm³, surpasses that of clean LDPE, which has a density of 0.910 g/cm³. GTR exhibits a greater density than other studied composites, making it a better material. Nevertheless, the density of GTR/LDPE composites experiences an initial drop due to the creation of bubbles, holes, and gaps that emerge between the two phases. During this interval, the value rises proportionally with the rising GTR concentration for both dry and dissolved mixtures of chemicals. Nevertheless, the regeneration process had no impact on the density of the composite materials since the results for both LDPE/NRR and LDPE/RR composites are similar, falling within the range of experimental uncertainty. Both mixing techniques exhibited a comparable pattern. Zadeh and Rodrigue [55] contributed information about mechanical and physical factors. The study investigated the characteristics of composite materials comprising polyester recycled tire fibers (RTFs) blended with ground tire rubber (GTR) and maleic anhydride, as well as linear low-density polyethylene (LLDPE). The research investigated the effect of varying RTF content levels (10, 25, and 50 wt.%) on a manufacturing process that utilizes extrusion and injection techniques. The composite materials exhibited increased density due to the elevated density of RTF (1.27 g/cm3) compared to LLDPE (0.938 g/cm3). Generally, the density of the compounds increased by approximately 2%, 6%, and 12% at concentrations of 10%, 25%, and 50%, respectively. The researchers' investigation [43] and [55] revealed that the density of polyethylene increased when it was strengthened using used tire rubber, even if holes and cavities were present in the composite after its production. The rise was caused by the disparity in density between the base material (PE) and the additional material (GRT), with the latter having a higher density than the former.

4.3.Thermal Conductivity

Table 4 illustrates the diverse options for enhancing the thermal conductivity of polyethylene-based materials, offering opportunities to tailor thermal properties to meet specific application requirements across various industries, including electronics, automotive, aerospace, and packaging.

Table 4 Methods of Improving the Thermal Conductivity of Polyethylene.

Material	Description	Percentage of loading	Refs.
Carbon Nanotubes (CNTs)	- Carbon nanotubes are cylindrical carbon structures with extraordinary thermal conductivity properties.	20%	[56]
Polymer Blends	- Polymer blends incorporating thermally conductive polymers or copolymers with polyethylene can improve thermal conductivity while maintaining flexibility and processability.	40%-60%	[57]
Phase Change Materials (PCMs)	- Phase change materials embedded within polyethylene matrices can enhance thermal conductivity by absorbing and releasing heat during phase transitions, contributing to improved thermal management properties.	Up to 19.3%	[58]
Hybrid Composites	- Hybrid composites combining multiple fillers or materials, such as carbon nanotubes with metal or ceramic fillers, can synergistically improve the thermal conductivity of polyethylene while addressing other mechanical or functional requirements.		[59]

GTR particles from waste tires were mixed in proportions (0-70 wt.%) with LDPE and HDPE in a study by Gensca et al. [44]. The presence of GTR in the samples leads to significant variations in thermal conductivity. Surprisingly, the compounds containing 50% GTR exhibit higher conductivity than those with 70% GTR. This finding contradicts the expectation that carbon black in particles GTR would enhance conductivity. Interfacial polarization enhances thermal conductivity, resulting in HDPE and LDPE compounds containing 50% GTR, exhibiting the highest conductivity. Conversely, compounds without any additives in their matrix have the lowest conductivity.

4.4.Tensile Strengths

A study was conducted by Kakroodi and Rodrigue [42] to investigate the impact of adding ground tire rubber (GTR) to high-density polyethylene (HDPE) with varying weights (ranging from 50 to 90 wt.%) on the material's properties. The samples demonstrated that HDPE with GTR percentages ranging from 50% to 70% exhibited excellent tensile elongation at break and satisfactory tensile strength. However, the attributes of models with higher GTR levels deteriorated. A possible cause for this phenomenon is that adding more GTR powder to HDPE reduces homogeneity. Kazemi et al. [38] investigated the effect of adding clean fiber (CF) and ground recycled (GR) to recycled low-density polyethylene (rLDPE) at various weights (ranging from 0% to 30%) on its mechanical properties, specifically tensile strength and tensile modulus. The test findings demonstrated a significant improvement in the mechanical properties of the material when carbon fiber (CF) was incorporated into recycled low-density polyethylene (rLDPE) through a combination of extrusion and injection molding. More precisely, when a 30% increase was applied, there was a notable enhancement of 15% in the tensile strength and a substantial improvement of 192% in the tensile modulus. Conversely, adding GR to rLDPE led to a decrease of 15% in both tensile strength and tensile modulus. Shaker and Rodrigue [43] conducted an experiment where they combined GTR (0, 20, 35, and 50 wt.%) with low-density polyethylene (LDPE), using both non-renewable particles (NRR) and renewable particles (RR). The tensile modulus of both the melt-mixed and the melt-mixed samples was determined. As anticipated, the values decline as the GTR content increases due to the lower GTR modulus (approximately 2 MPa) compared to LDPE (72 MPa). Additionally, there is an increase in the amount of space inside the material, which causes a loss in its ability to resist the forces applied to it. The tensile modulus of LDPE/RR samples is lower than that of LDPE/NRR components produced during dry blending, with a maximum of 35% GTR. Nevertheless, the tensile modulus increases proportionally with the concentration of GTR. The tensile modulus of LDPE /RR composites surpasses that of LDPE/NRR composites due to incorporating more significant amounts of GTR during melt blending, which decreases the size of RR particles. The tensile strength of LDPE/RR composites, which were created by the blending process, exhibited a greater magnitude than that of LDPE/NRR. The adhesion/interaction interface plays a critical role in controlling this parameter. Ultimately, the strain at which the material breaks diminishes as the amount of GTR increases due to a growing quantity of imperfections. Nevertheless, most of the composites, namely LDPE NRR samples with a weight percentage of up to 20% in dry blend and up to 35% in melt blend, as well as LDPE/RR samples with a weight percentage of up to 20% in melt blend, may be classified as excellent thermoplastic elastomers (TPEs) due to their elongations at break exceeding 100%. In this instance, the regeneration procedure did not enhance the quality of the breed. The mechanical properties of linear low-density polyethylene were examined in a study by researchers Moghadamzadeh and Rodrigue [60]. The polyethylene was reinforced with recycled polyester fibers (RTFs) and mixed with ground tire rubber (GTR) and maleic anhydride in varying proportions (10%, 25%, and 50% by weight). The study revealed a decrease in the tensile strength values as the content of the reinforcing material was progressively increased by 2%, 10%, 14%, and 11%. This reduction may be attributed to two distinct phenomena: insufficient bonding between RTF and LLDPE, facilitated by the compatibilizer, and the restricted mobility of the GTR molecules caused by their cross-linked structure. Nevertheless, the flexible composition of the compatibilizer led to a notable increase in the maximum stretching capacity before fracture. Kiss et al. [45] conducted a study on the possibility of value-added recycling of ultra-fine ground tires. Rubber (uGTR) is manufactured by waterjet milling, which involves comparing the attributes of mixes, including distinct uGTR tires, with those of ordinary small ground tires. The rubber contents, also known as fGTR, and their weight percentages (10%, 20%, and 30%) were created by mixing with low-density polyethylene (LDPE). An observed decline in tensile strength was noted in samples that included both fine-grained tire rubber (fGTR) and ultrafine-grained tire rubber (uGTR) as the GTR content increased. A greater mean particle size reduces specific surface area and less interfacial adhesion. When the concentration of GTR was 10 wt.%, samples with uGTR exhibited a tensile strength of roughly 30% greater than those with fGTR. The disparity diminished as the GTR content augmented. The impact of size only marginally counteracts the power-diminishing influence of the GTR. Additionally, it was noted that the elongation at break of materials, including uGTR, increased modestly at a filler concentration of 10 wt.%; however, it decreased when the GTR percentage was increased. For fGTR samples, the elongation at break fell significantly, suggesting inadequate adhesion between LDPE and GTR. However, the higher specific surface area of uGTR somewhat offsets this issue, resulting in improved outcomes. An investigation was conducted to analyze the impact of six different fractions of rubber powder, with diameters ranging from 120 to 500 μm, on the mechanical characteristics of TPE samples. These samples were created by blending waste tire rubber (GTR) with low-density polyethylene (PE-LD) using a laboratory mixer known as the Brabender Plastograph. According to a study conducted by Hrdlik et al. [60], the tensile strength of samples with smaller grain sizes was more than 10% greater than that of models with larger grain sizes, as determined by tensile strength testing. The samples containing a mixture of ethylene propylene diene rubber (EPDM) exhibited a significant increase in tensile strength, reaching up to 33% enhancement at the lowest particle size. The increased efficacy of smaller GTR particles with higher surface quality in binding to the thermoplastic matrix may be attributed to the activity of EPDM. The study conducted by Mastalygina et al. [47] examined low-density polyethylene (PE) blended with varying amounts of natural rubber (NR) (10-30 wt.%). The results showed that the tensile strength and Young's modulus of the PE/NR composites were about half of the values seen in pure PE. Incorporating NR into PE helps decrease the relative elongation at break. Upon adding 10 wt.% of NR to PE, the relative elongation at break fell to a magnitude four times less than that of pure PE. As the concentration of NR rose, no further alterations were seen. Khan et al. [61] made LDPE/GTR composites. GTR was included in the mixture at different proportions, namely 1 part percent (phr), 2 phr, 3 phr, 4 phr, and 5 phr. The data indicate a negative relationship between GTR content and tensile strength. Specifically, when the GTR content of pure LDPE rises to 5phr, the tensile strength decreases from 111 to 79.21 N/mm2. The decrease in performance can be attributed to decreased affinity between the blends and degradation of the recycled GTR due to exposure to the environment or during processing and milling. It was noted that as the rubber content increases, the elongation percentage also increases, because the presence of the elastic phase leads to a minor increase in plastic deformation, indicating greater flexibility in the samples. Rezaei-Abadshi et al. [62] have conducted numerous experiments using ground tire rubber (GTR) powder as a partial substitute for natural rubber (NR) in thermoplastic elastomers. These elastomers are mainly composed of linear low-density polyethylene (LLDPE) and NR, with LLDPE accounting for 60% of the weight and NR accounting for 40%. The relationship between GTR content and tensile strength and elongation at break is shown. The mechanical characteristics of the LLDPE/NR mix are diminished when 5-10 wt% of the NR phase is substituted with GTR due to the inadequate bonding between unaltered GTR and the polymer matrix. Insufficient adhesion between surfaces results in the formation and expansion of voids within the interfaces. Voids result in the development of fractures and a reduction in the tensile strength of the mixes. This results in the formation of imperfections within the molecular structures of the rubber. However, when the GTR level reaches 20-40 wt.%, the tensile strength of the mixes increases. The inclusion of carbon black in the GTR serves as an active filler, enhancing the material's tensile strength. Table 5 illustrates various methods and additives used to enhance the tensile strength of polyethylene.

Table 5 Materials Used for Improving the Tensile Strength of Polyethylene.

Material	Description	Weight ratio percentage	Ref.
Glass Fibers	To enhance tensile strength, glass fibers are commonly used as reinforcements in polyethylene composites. These fibers offer an excellent strength-to-weight ratio and can be tailored to meet specific applications.	90/10	[63]
Carbon Fibers	Carbon fibers offer high tensile strength and stiffness, making them effective reinforcements for polyethylene matrices. Composite materials incorporating carbon fibers exhibit improved mechanical properties, including enhanced tensile strength, modulus, and impact resistance.	70/30	[64]
Natural Fibers (e.g., Hemp, Flax)	Natural fibers derived from plants, such as hemp and flax, can be used as eco-friendly reinforcements in polyethylene composites. While they may have lower tensile strength compared to synthetic fibers, they offer advantages such as sustainability, biodegradability, and reduced environmental impact.	10%-30%	[65,66]
Nanofillers (e.g., Nanoclay)	Nanofillers, such as nano clay particles, can enhance the tensile strength of polyethylene composites by improving the interfacial adhesion between polymer chains and the reinforcing phases. These nanofillers effectively distribute stress and inhibit crack propagation, thereby improving mechanical properties.	5%-20%	[67]
Hybrid Composites	Hybrid composites, which combine different types of fibers or reinforcements, such as glass fibers with carbon or aramid fibers, can synergistically enhance the tensile strength of polyethylene matrices. By optimizing the combination of materials, hybrid composites can achieve tailored mechanical properties to meet specific application requirements.	70/30, 50/50 and 30/70	[68]
Polymer Blends	Blending polyethylene with other polymers or copolymers, such as polypropylene or ethylene-vinyl acetate, can improve tensile strength by enhancing molecular alignment and intermolecular interactions within the polymer matrix. Polymer blends offer versatility in tailoring mechanical properties while maintaining processability and cost-effectiveness.	50/50	[69]

These materials provide a range of options for enhancing the tensile strength of polyethylene-based materials, enabling the development of high-performance composites suitable for diverse industrial applications. Researchers have demonstrated a loss in tensile strength through experiments looking at the effect of reinforcing polyethylene with rubber, particularly waste tires (GTR). This decrease may be due to the weak bond strength between the base material and the additional material. A significant increase in tensile strength of up to 30% is observed when a smaller particle size is used, rather than a larger particle size. The researcher confirmed this result [42]. The discrepancy may be due to increased polyethylene bonding surface area. However, research has conclusively shown that using recycled rubber for reinforcement leads to superior results compared to using natural rubber (NR) in the situation described in the study [47], especially when GTR is present in high proportions. Despite its declining qualities, it still deserves praise in comparison to its positive economic and environmental benefits.

4.5.Hardness

Kakroodi and Rodrigue [42] assessed the hardness of HDPE with different proportions (ranging from 50 to 90 wt.%) of ground tire rubber (GRT) using a Shore scale. The experiment had favorable outcomes within the 50-70% range and used materials with a shore hardness ranging from 95 to 88. Nevertheless, the hardness values exhibited a substantial drop with increasing proportions of GRT. In their study on the effect of adding clean fiber (CF) and ground recycling (GR) to recycled low-density polyethylene (rLDPE), Kazemi et al. [38] found that increasing the GR ratio resulted in a 6% decrease in hardness values. Conversely, increasing the CF ratio to 30% led to a 7% increase in hardness values. The research examined the effects of varying weights (ranging from 0% to 30%) on the material's mechanical properties. In their experiment, researchers Shaker and Rodrigue [43] mixed two types of GTR particles—non-renewable particles (NRR) and renewable particles (RR)—in several weight ratios (0, 20, 35, and 50 wt.%) with low-density polyethylene. The hardness results indicate that for molded parts, which were measured using the Shore A and Shore D scales, there was a steady decrease in hardness with increasing GTR content in both the dry mix and melt mix procedures. This phenomenon can be attributed to the inherent elasticity of the rubber particles. Moghadamzadeh and Rodrigue [55] obtained the following findings in their investigation of the mechanical and physical components. This research investigates the effect of varying amounts of recycled polyester fibers (RTFs) in conjunction with ground tire rubber (GTR) and maleic anhydride derived from linear low-density polyethylene (LLDPE) on the manufacturing process, specifically extrusion and density enhancement. The weight percentage of the RTF material ranges from 10% to 50%. The elevated quantity of RTF results in reduced hardness values due to the heightened concentration of GTR molecules and compatibilizers, which are inherently softer components inside the composites. No substantial disparity was detected between the incompatible and compatible samples. The hardness of the material reduces by about 4%, 7%, and 9% when the RTF content rises from 10% to 25% and 50%, respectively, compared to the hardness of the base material (measured at 63.1 shore D). Kiss et al. [45] have repurposed ultra-fine ground tires to add extra value through recycling. Rubber (uGTR) production involves using waterjet milling to compare the characteristics of various combinations of uGTR tires and traditional small ground tires. The rubber contents, also known as fGTR, and their corresponding weight percentages (10%, 20%, and 30%) were generated by blending with low-density polyethylene (LDPE). Both the delicate and ultrafine GTR significantly decreased the composites' hardness (Shore D) compared to LDPE, resulting in a synthetic rubber-like characteristic. The ultrafine GTR exhibited increased stiffness, likely due to its larger contact area and enhanced adhesion between components. A study conducted by Bodude et al. [46] resulted in the production of low-density polyethylene (LD-PE) using rubber particles in powdered form, measuring 150 µm in size. The rubber granules used vary between 5% and 25%. The hardness test revealed that the initial hardness value of the base material, measured at 11.48 BHN, increased modestly to 12.98 BHN after incorporating 5% ground rubber filler. Conversely, the hardness reduced to 10.47 BHN when the filler content was increased to 10%. Nevertheless, the hardness level peaked at 14.06 BHN after including 20% padding. Abadji et al. [62] studied the effect of replacing NR with GTR on the hardness property and found that it is less than pure (LLDPE), but its values increase with increasing GTR content. The reason for this is attributed to the presence of carbon black in waste tires. Table 6 presents a list of studies that utilized various types of waste tires to reinforce polyethylene.

Table 6 Different Types of Waste Tires that Can be Used for Reinforcing Polyethylene Composites:

Type of Waste Tires	Description	Refs.	Property improved
1. Whole Tires	- Whole tires, including passenger car tires, truck tires, and industrial tires, can be used as a source of reinforcement in polyethylene composites. These tires are typically shredded or ground into smaller particles before incorporation into the composite matrix.	[70]	Shear and compressibility
2. Tire Crumb Rubber	- Tire crumb rubber refers to finely ground rubber particles obtained from waste tires through grinding or shredding processes. These rubber particles can vary in size and are commonly used as a filler or reinforcement material in polyethylene composites to improve mechanical properties.	[71]	Stress releaser
3. Tire Fiber	- Tire fiber is derived from the reinforcement layers of waste tires, such as steel-belted radial tires. These fibers are extracted through mechanical processes and can be incorporated into polyethylene composites to enhance tensile strength, stiffness, and impact resistance.	[72]	Interfacial adhesion
4. Tire Powder	- Tire powder is a fine powder obtained from waste tires through grinding or milling processes. This powder is a mixture of rubber, carbon black, and other materials. It can be used as a filler material in polyethylene composites to enhance properties such as thermal conductivity and mechanical strength.	[73]	Tensile strength, elongation at break, and impact strength
5. Tire Chips	- Tire chips are larger pieces of rubber obtained from waste tires through shredding or chipping processes. These chips can vary in size and are typically used as a filler or reinforcement material in polyethylene composites for applications requiring impact resistance and vibration damping.	[74]	Thermoplastic properties

These different types of waste tires provide versatile options for reinforcing polyethylene composites, offering opportunities to tailor material properties and meet specific performance requirements in various applications. These studies demonstrate the use of waste tires as a reinforcement material in polyethylene composites, aiming to enhance mechanical properties and sustainability while addressing the challenge of managing tire waste. The researchers reached a consensus that the hardness diminishes as the proportion of recycled rubber increases, and they ascribed this decline to the rubber's ductility characteristic. Nevertheless, the researcher [62] has a dissenting view from their perspective. In his investigation, a variation in hardness values was observed, ranging from high to low, although a significant increase of up to 20% was noted at elevated levels of recycled rubber. The divergence in the researchers' findings prompts us to explore the underlying causes, which may be attributed to the manufacturing techniques used and the dimensions of the particles used in the reinforcing process.

4.6.Impact Strength

When mixed with various weight ratios (0, 20, 35, 50 wt.%) of ground tire rubber (GTR) with low-density polyethylene (LDPE) in two situations - one involving non-renewable particles (NRR) and the other involving renewable particles (RR) - researchers Shaker and Rodrigue [43] observed a decrease in impact strength across all composite materials as the GTR content increased, this decrease can be attributed to weak adhesion at the interface between GTR and LDPE and reduced pressure inside the mold, resulting in the formation of voids within the parts. Furthermore, the LDPE/NRR samples exhibit a more significant impact strength than the LDPE/RR samples, which may be attributed to the presence of a cross-linked structure in the GTR, which enhances the deformability of the particles. As a result, the LDPE/NRR samples can absorb more energy before the onset of cracking. Consequently, the production procedure decreased the impact strength due to reduced cross-link density inside the RR particles. The impact strength of molten mixed samples surpasses that of dry composite samples owing to enhanced adhesion at the interface of GTR and LDPE, resulting in fewer model flaws. The impact intensity of incompatible mixes is relatively consistent over the range of concentrations examined. MoghadamZadeh [55] showed the impact of different levels of recycled polyester fibers (RTFs) combined with ground tire rubber (GTR) and maleic anhydride from linear low-density polyethylene (LLDPE). The RTF content levels tested were 10%, 25%, and 50%. Calculate the weight percentage. However, including the compatibilizer significantly enhanced the Charpy impact strength, with improvements of 18%, 29%, and 50% seen at 10%, 25%, and 50% RTF, respectively. This characteristic is primarily attributed to increased GTR, which enhances stress transmission between the two surfaces, making the composites more pliable. Consequently, there is improved energy absorption via the elastic deformation of the GTR rubber. Bodude et al. [46] prepared low-density polyethylene (LD-PE) with crushed rubber particles measuring 150 µm. The quantities of rubber granules used ranged between (5%-25%) + 5% for each percentage. The results indicated a marginal improvement in the impact strength of the composites with a higher amount of rubber particles. The filler concentration initially reached (20.94J) at a filler content of 15% but then decreased as the filler concentration increased. Composites of ground tire rubber and low-density polyethylene (LDPE/GTR) have been developed by researchers Khan et al. [61]. They added GTR in proportions (1 phr, 2 phr, 3 phr, 4 phr, and 5 phr) and examined the effect of the additive on the impact strength. They observed that the rubber content in the LDPE/GTR formulation increased, leading to an increase in impact strength. The decrease in the sample occurs gradually due to the rubber's ability to absorb energy. Ultimately, this material is flexible and cross-linked, allowing it to maintain its flexibility because its temperature is above its glass transition temperature (Tg) at ambient temperature. The study findings showed that the impact strength of polyethylene significantly improved when reinforced with GTR ground tire rubber in appropriate proportions. However, this improvement reaches a maximum point with increased content and then experiences a minor decline. The reason for this rise is the material's inherent elasticity and interconnectivity, which enable it to retain its flexibility. Ultimately, the temperature of the substance exceeds the Tg under normal conditions. Nevertheless, it came to our attention that one of the researchers [43] had a divergent viewpoint. The researcher observed a reduction in the impact strength values, attributing this to poor adhesion at the interface between GTR and LDPE, as well as a drop in pressure inside the mold, resulting in the creation of voids within the pieces. Based on this, it may be inferred that the impact strength of polyethylene is enhanced by reinforcing it with GTR.

4.7.Flexural Strength & Flexural Modulus

Adding carbon fiber (CF) enhanced the bending modulus, but incorporating ground recycled (GR) reduced it. 30CF-INJ had a flexural modulus that was 142% more than rLDPE-INJ. However, adding 30 wt.% GR resulted in a 15% decrease in the flexural modulus. Furthermore, the latter has a significantly greater flexural modulus when compared to the compression molding technique. This phenomenon can be attributed to the enhanced scattering and alignment of the filler in samples produced by Kazemi et al. [38]. In their study, they compared the incorporation of clean fiber (CF) and ground waste (GR) at different proportions (ranging from 0% to 30%) with recycled low-density polyethylene (RLDPE). Shaker and Rodrigue [43] combined different weight percentages (0, 20, 35, and 50 wt.%) of GTR with low-density polyethylene (LDPE) in two scenarios: one using non-renewable particles (NRR) and the other using renewable particles (RR). The flexural modulus values decrease as the amount of Ground Tire Rubber (GTR) increases, primarily due to the elastic nature of GTR and the presence of voids and inadequate interfacial adhesion. The LDPE/NRR values were more significant than the LDPE/RR values up to a GTR content of 20% for both blending strategies. Nevertheless, by augmenting the GTR content, the regeneration procedure can alter this pattern and elevate the flexural modulus of LDPE/RR to surpass that of LDPE/NRR. The flexural strength of linear low-density polyethylene was investigated by Moghadamzadeh [55]. The polyethylene was enhanced with recycled polyester fibers (RTFs) and combined with ground tire rubber (GTR) and maleic anhydride in different ratios (10%, 25%, and 50% by weight). An increase in the additive content resulted in a drop in the flexural strength values. The corresponding decline percentages were 2%, 10%, 14%, and 11%. This phenomenon may be attributed to the inadequate interfacial adhesion between binary mixes of polar and nonpolar components. Bodude et al. [46] created low-density polyethylene (LD-PE) using 150-µm-sized powdered rubber particles. The rubber granules used ranged between 5% and 25%. The specimen with 5% filler showed a maximum flexural strength of 44.06 MPa, while the model with 20% filler had a slightly lower flexural strength of 40.07 MPa. However, both values were lower than the flexural strength of LD-PE, which was 57.58 MPa. The fluctuating decrease can be attributed to increased reinforcement and a decrease in the total surface area accessible for matrix-filler interaction. Khan et al. [61] created composites using ground tire rubber and low-density polyethylene (LDPE/GTR). GTR was included in the mixture at various ratios, namely 1 part per hundred (phr), 2 phr, 3 phr, 4 phr, and 5 phr. The experiment revealed a negative correlation between the rubber content in the LDPE/GTR formulation and the flexural strength of the specimen. The reason for this might be the relatively reduced rigidity of LDPE compared to other thermoplastics and perhaps the presence of a void or flaw within the mixture. Rubber exhibits resistance when subjected to a load. Using rubber will significantly impact the hardness and diminish the material's flexural strength. The flexural strength at break cannot be determined since the specimen did not undergo fracture under the imposed stress. Hence, the flexural strength was decided at a distortion of 25%. Blended materials exhibit excellent flexibility by mitigating the rigidity of the overall composition. The elastic modulus of the DPE/GTR mix decreases as the rubber component increases, primarily due to the inadequate compatibility between GTR and LDPE. The rubber molecules were unable to intertwine with LDPE molecules adequately and could not entangle with LDPE as effectively as plastic materials [61]. While producing PE/GTR composites and conducting flexural strength tests, a slight decline in strength was observed as the GTR ratio increased. The presence of this phenomenon may be attributed to inadequate interfacial adhesion between the binary mixtures, including polar and nonpolar constituents, as well as the level of flexibility exhibited by the rubber. The research findings analyzed in this review are shown in Table 7.

Table 7 Studies on Recycled Rubber-Filled PE Composites.

Matrix	Reinforcements	Finding the impact on properties	Refs.
HDPE matrix HD6605 +MAPE	90, 80, 70, 60, and 50 wt.% GTR	Tensile strength and hardness values decrease with increasing ratio (GR)	[42]
rLDPE	GR or Clean fiber CF (10, 20, and 30 wt.%)	(Tensile, Hardness, Flexural Strength) It decreases as the percentage increases (GR) and increases as the percentage increases (CF)	[38]
LDPE	(0, 20, 35, and 50 wt.%) GTR	(Density) increases with increasing percentage of (GR) (Hardness, tensile, flexural modulus, and Impact) decrease with increasing ratio (GR)	[43]
LDPE/ HDPE	0, 5, 10, 20, 40, 50, and 70% GTR	Increase in thermal conductivity	[44]
LDPE	10, 20, and 30 wt.% fGTR and uGTR	(Hardness, Tensile) Decreases with increasing percentage (GR)	[45]
LDPE	with 150 µm rubber waste (5%, 10%, 15%, 20%, and 25%)	(Hardness, bending, Impact) Fluctuating between increases and decreases, the best results are when 20%	[46]
PE, grade 15803-020	10, 20, and 30 wt.% of natural rubber (NR)	Tensile decreases with increasing percentage (NR), water absorption increases with increasing percentage (NR)	[47]
LLDPE(LL8460)	(10, 25, and 50 wt.%) (recycled tire fibers (RTFs)	(Tensile, Impact, Hardness, and flexural) Decreases with increasing percentage (RTFs) density increases with increasing percentage (RTFs)	[55]

PE-LD-Riblene 24	25% and 50% of GTR+ 25% (EPDM or SEBS) (650, 550, 492, 426, 381, and 120) (μm)	(Tensile strength) There is a slight decrease with decreasing particle size and a significant increase with the smallest particle size, 120 (μm)	[60]
LDPE	1 phr, 2 phr, 3 phr, 4 phr, and 5 ph GTR	(Tensile Testing, Flexural Strength) Decreases with increasing percentage GTR Izod Impact density increases with an increasing percentage	[61]
LLDPE	Replacement NR (40, 35, 30, 20, and 0) By GTR (0, 5, 10, 20, and 40)	(Tensile strength) It decreases with increasing percentage of GTR and increases slightly at 40%. Hardness decreases for pure (LLDPE); however, it increases with increasing GTR content.	[62]

5.CONCLUSIONS

- The utilization of waste polyethylene offers a promising solution to the environmental and economic challenges posed by plastic pollution. By embracing recycling and developing innovative technologies and policies, society can harness the potential of waste polyethylene to create a more sustainable future.
- GRT is evenly distributed throughout the polyethylene (PE) base material; however, the bond strength is insufficient, as evident from the SEM images. The wipers contained contaminants derived from old rubber, specifically discarded tires. These images include gaps.
- The density values of recycled rubber-reinforced polyethylene increase due to the increased density of the rubber compared to the base material.
- The thermal conductivity test conducted with the inclusion of reinforced materials shows that it is contingent upon the specific kind of additive used. The combination of GTR waste rubber and polyethylene yields elevated conductivity levels. Owing to the elevated carbon black content in rubber.
- In summary, the utilization of waste polyethylene plastic offers multiple environmental benefits by reducing landfill waste, preventing marine pollution, minimizing greenhouse gas emissions, conserving natural resources, mitigating microplastic pollution, and promoting circular economy principles. By prioritizing recycling and sustainable waste management practices, society can significantly mitigate the environmental impacts of plastic pollution.
- An increase in the content of these reinforcing materials leads to a decrease in the values of properties such as tensile strength, flexural strength, and hardness. However, higher impact strength values were observed when reinforced with ground tire rubber (GRT) at low concentrations. Additionally, the present results suggest that the particle size has a significant influence on the features. Specifically, smaller particle sizes provide superior results.

ABBREVIATIONS AND ACRONYMS

LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
PVC	Polyvinyl chloride
PS	Polystyrene
PP	Polypropylene
SBS	Styrene-butadiene-styrene block copolymer
SBR	Styrene-butadiene rubber
GTR	Ground tire rubber
HDPE	High-density polyethylene
PET	Polyethylene Terephthalate
PUR	Polyurethane
EPS	Expanded Polystyrene
CF	Carbon Fiber

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