

Original Article

Sustainability-Driven Material Selection in Rubber Manufacturing: A Comparative Assessment of Vulcanized Rubber and Thermoplastic Elastomers

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ABSTRACT: *The production industry of rubber faces an immense change based on the growth of environmental control, resource limitation, and the need for sustainable material manufacturing. Conventional vulcanized rubber, despite being capable of being more mechanically strong and thermally stable, depends on permanently binding mechanisms, making it harder to recycle and raising the end-of-life environmental load. Conversely, Thermoplastic Elastomers (TPEs) have already appeared as promising alternatives because they can be melted down and have a stronger possibility to recover the materials. In this work, we can discuss a comparative evaluation of vulcanized rubber and thermoplastic elastomers, which are both sustainability-based approaches, and through the material processing pathways, the environmental impact, recyclability, and performance in the life cycle. The approach undertaken combines both a qualitative analysis of the polymerization and processing mechanisms, along with a comparative analysis of the manufacturing efficiency, energy usage, and waste control. A significant release is that vulcanized rubber offers long-term durability and high-performance attributes that can be applied in high-stress applications, but requires more processing energy and fewer reuses. Thermoplastic elastomers also have high processing efficiency, less manufacturing cycle time, and better recyclability, which makes them have a low environmental impact throughout their lifecycle. From a sustainability perspective, TPEs have benefits in closed-loop production and decreased waste of materials, and vulcanized rubber is important to use in cases that demand extreme mechanical performance. The research indicates the essential tradeoffs between performance and sustainability, as well as offers information that can be used as a guide in the selection of materials in the rubber manufacturing systems concerned with environmental concerns.*

KEYWORDS: *Vulcanized rubber, Thermoplastic elastomers, Lifecycle assessment, Sustainable manufacturing, Polymer processing.*

1. INTRODUCTION

The arena of polymer and rubber production has made sustainability a centre of focus on its ability to consume vast energy, heavy use of petrochemical feedstock based and where waste disposal and final disposal are not easy. Traditional rubber products, especially pulsed vulcanized elastomer-based products, are highly prevalent in both automotive, industrial, and consumer applications due to their high mechanical strength, elasticity, and thermal stability. Nevertheless, the crosslinked network that is developed during vulcanization is permanently fixed and makes it hard to recycle the materials, causing landfills and environmental pressure to increase. Due to the globalization of manufacturing and the concept of the circular economy, the sustainability constraints of the conventional rubber systems have become all the more noticeable. This transition is further being fast tracked by regulatory and environmental pressures. Tighter environmental policies concerning emissions, energy efficiency, and waste minimization, and lengthy producer responsibility (EPR) policies are forcing manufacturers to re-evaluate material selection and methods of processing.

The adherence to these frameworks involves a rising need to use such materials that facilitate recyclability, decreased life-cycle emissions, and enhanced efficiency of resources. Industries are therefore looking into other elastomeric materials that will perform and, at the same time, achieve sustainability goals. Here, thermoplastic elastomers (TPEs) have enjoyed a great deal of attraction as a possible replacement for the traditional vulcanized rubber. TPEs, in contrast to thermoset rubbers, can be processed like thermoplastics; coupled with their elastomeric properties, they can be reworked by melting, range through production cycles faster, and extracted more readily in terms of material recovery. The basic variations in types of polymerization and network of vulcanized rubbers versus thermoplastic elastomers, where chemical crosslinking is substituted by physical or reversible interactions, have been demonstrated to have a strong effect on process efficiency and recyclability as observed in comparative analysis by Pydipalli and Tejani [1].

1.2. PROBLEM STATEMENT

Even though the use of thermoplastic elastomers is increasing, there is a complicated process of choosing the material in the production of rubbers because it is associated with certain trade-offs of mechanical performance, processing efficiency, and

environmental impact. [2] Vulcanized rubber still addresses well applications that demand high durability, fatigue, and thermal stability, whereas TPEs have the benefits of being recyclable, offering flexibility of production as well as low energy consumption. The conflicting nature of these attributes can render the selection of a suitable type of material a hard task that a manufacturer can face, as they should meet both the functional and sustainability demands.

In addition, available literature usually considers one aspect of sustainability, either processing or mechanical performance, alone, without considering a comprehensive sustainability approach. The absence of systematic comparative evaluations is where polymerization mechanisms, manufacturing pathways, recyclability, and lifecycle factors are considered as part of the single evaluation paradigm. The limitation of this gap is the inability of decision-makers to make informed, sustainability-driven decisions in the material selection.

1.3. OBJECTIVES AND CONTRIBUTIONS

The main goal of the research is to present a detailed comparison of the vulcanized rubber and the thermoplastic elastomers in a sustainability-oriented approach. The work will be used to compare and contrast their polymerization and processing, manufacturing efficiency, recyclability, and lifecycle environmental impacts. Through integration of material science principles and sustainability metrics, the study aims to explain the performance-sustainability trade-offs of every material class.

The paper outcomes are important as they show:

- A comparative evaluation of vulcanized rubber and TPEs from a sustainability perspective manner;
- A comparison of the impact of polymerization and processing paths on recyclability and lifecycle performance based on the difference described by Pydipalli and Tejani [1]; and
- Pragmatic information and principles to inform industrial decision-making regarding the choice of materials in a manufacturing system of rubber, which is environmentally friendly.

2. RELATED WORK AND LITERATURE REVIEW

2.1. CONVENTIONAL RUBBER VULCANIZATION

Traditional vulcanization of rubber is a proven processing technology, which has been largely applied in the industrial production of rubber for over a hundred years. [3] It is mainly done through the use of sulfur-based crosslinking involving the use of sulfur atoms to establish covalent bonds among polymer chains to establish a structure of a network. Such crosslinked architecture contributes to the enormous improvement of mechanical strength, elasticity, abrasion resistance, and thermal stability of vulcanized rubber, and hence it comes in useful demanding applications, such as tires, seals, gaskets, and components that absorb vibration.

Under a material behavior view, vulcanized rubber displays the properties of a thermoset, that is, once its crosslinked network has been made, the material cannot be melted down or remodeled without degradation, which effectively means it cannot be used in forming a three-dimensional structure. Due to the irreversibility of the crosslinking process, the stability of the dimensions and the durability of the work under mechanical and thermal loading are outstanding. The same feature is, however, very challenging in terms of its sustainability response. [4] This means that because of the inability to reprocess vulcanized rubber by conventional methods of melting, recyclability is limited, and in most cases, energy-intensive grinding or devulcanization processes, which may damage material properties, are required.

Even though improved methods of processing rubber in a chemical and mechanical recycle with the intention of vulcanization have been reported, these methods are complicated, costly, and scarcely adaptable on an industrial level. Consequently, a considerable percentage of vulcanized rubber waste is downcycled or discarded in Landfills, which is one of the reasons behind environmental issues and resource wastage.

2.2. THERMOPLASTIC ELASTOMER PROCESSING

Thermoplastic elastomers are yet another unique type of material where the elastic characteristic of the rubber is merged with the convenience of processing of a thermoplastic material. [5] TPEs, in contrast to vulcanized rubbers, do not depend on covalent bonds but instead on physical crosslinking, e.g., hard-soft segment phase separation, crystalline domain, or hydrogen bonding. It is in such Exchangeable interactions that the material can be softened when heated, and hardened when cooled, without undergoing substantial loss of chemical components.

That TPEs can be melted allows them to be handled using standard thermoplastic processes, such as injection molding, extrusion, and blow molding. The processes provide shorter cycle times, reduced energy, and increased automation potential than the traditional rubber vulcanization. Also, scrap produced during production can be easily recycled back in the production stream, thus tremendously decreasing the material waste.

Sustainably, TPEs have a better ability to recycle and reprocess because they can be melted and remodeled with very little repercussions on performance. The quality is similar to the principles of the circular economy, and it has led to growing use of

TPEs in automotive interiors, consumer products, medical equipment and lightweight industrial parts. There are however, some grades of TPE that can be lower thermal resistant or lack long-term mechanical stability than vulcanized rubber, which restrains their application to high-volume stress products.

2.3. COMPARATIVE STUDIES ON RUBBER PROCESSING

There is an academic trend that examines comparative issues about vulcanized rubber and thermoplastic elastomers, especially when it comes to processing efficiency and measures of sustainability. However, the previous literature has marked the fact that the processing energy requirements are different from vulcanization, as it requires longer curing durations and requires more energy input because of the heat and pressure needs. Conversely, the operating advantages of TPE processing are high melt-flow characteristics and the shortening of the cycle times, which contribute to the enhancement of the manufacturing throughput.

Material reuse and waste reduction have also been compared, and in all cases, thermoplastic elastomers were reported to have higher rates of scrap recovery because of their remeltability. Although mechanically stronger, vulcanized rubber is still disadvantaged in the closed-loop recycling. Pydipalli and Tejani [1] give a comparative study of the differences between rubber polymerization and processing paths with a detailed focus on the comparison between the chemical crosslinking in the vulcanization of rubbers and the reversible physical interactions in the processing of thermoplastics. Their theory has been frequently used to describe manufacturing, energy, and recycling variations in the two material classes.

Altogether, the literature sources point to the idea that neither of the two material systems is completely better; instead, the decision to choose between vulcanized rubber and thermoplastic elastomers should be made considering the performance criteria and objectives in terms of performance, processing, and sustainability. Nevertheless, multi-purpose analyses, which can take into account mechanisms of polymerization, the effects of life cycles, and reachable use in industry, are limited, which is also the rationale behind the comprehensive comparative methodology of the current research.

3. MATERIAL PROCESSING AND MANUFACTURING ROUTES

3.1. VULCANIZED RUBBER MANUFACTURING PROCESS

The vulcanization process of rubber is a multi-step procedure aimed at developing a system of chemically crosslinked elastomeric network that is stable. The former level is compounding, which involves mixing the base rubber polymer with sulfur, accelerating agents, activating agents, fillings, antioxidants, and processing assistance. This is an important step because in formulation, the formulation has a direct impact on the behavior during curing, mechanical performance, and durability. [6] Internal mixers or two-roll mills are usually used to uniformly disperse additives, and these processes demand a high level of mechanical energy.

The material is then subjected to vulcanization, which is a thermally activated chemical reaction where cross-links made of sulfur are formed between polymer chains. The curing time, temperature, pressure, and curative concentration determine the vulcanization kinetics. These parameters need to be finely tuned so as not to under-cure them to mechanical impairment or over-cure them to make them brittle and destroy the property. This is a relatively time-consuming step of the process whose nature is also usually a bottleneck in production.

In terms of production, the vulcanization of rubber is rather a process with a high intake of energy and time. Being subject to prolonged heating cycles, pressurized molds, and post-curing operations makes it addicted to high energy consumption and time-consuming cycles. Though the formed materials are characterized by a high level of mechanical and thermal stability, irreversible crosslinking of the chemical components restricts the possibilities of further processing and the complexity of retrieving the wastes.

3.2 THERMOPLASTIC ELASTOMER MANUFACTURING PROCESS

TABLE 1 Polymerization and processing comparison of vulcanized rubber and TPEs

Parameter	Vulcanized Rubber	Thermoplastic Elastomers (TPEs)
Crosslinking mechanism	Chemical (sulfur-based covalent bonds)	Physical/reversible interactions
Network structure	Irreversible, permanent 3D network	Reversible, phase-separated domains
Material type	Thermoset	Thermoplastic
Processing temperature	High (curing required)	Moderate (melt processing)
Reprocessability	Not reprocessable	Fully reprocessable
Typical manufacturing methods	Compression molding, transfer molding	Injection molding, extrusion

The differences in the polymer network formation are the main difference between the two material systems, as the manner in which they influence the directed behavior of manufacturing, the possibility of recycling, and the sustainability is directly proportional to the fundamental material and processing characteristics of vulcanized rubber and thermoplastic elastomers

(TPEs). Vulcanized rubber depends on the chemical covalent bonds of sulfur, which cannot be broken and bind polymer chains to form an insoluble and strong structure. Conversely, thermoplastic elastomers rely on physical or reversible interactions, described as the phase separation or crystalline domains, that contribute to the elasticity and make the material melt, losing the ability to flow when heated.

Due to such differences in bonding, the vulcanized rubber network structure is an irreversible 3D type of network, thus making it a thermoset material. [7] After curing, it can neither be reshaped nor remelted without diminishing its qualities. Thermoplastic elastomers, on their part, consist of reversible, phase-separated domains, making them thermoplastics and allowing them to be melted and solidified over and over again. Vulcanized rubber is sensitive to high temperatures and a slow rate of curing to facilitate reactions of crosslinking, which consumes more energy and reduces the cycle time. TPEs are processed at moderate temperatures through melting methods, which creates production cycles within a short time and higher manufacturing efficiency.

These processing and structural variations have a direct effect on reprocessability. Vulcanized rubber cannot be reprocessed, and the scraps are not recoverable and can be recycled. However, TPEs can be hermetically recycled, which means that production waste can be recycled and reused in the production process. This is why the common manufacturing processes are different: vulcanized rubber is traditionally processed by compression or transfer molding, and the TPEs can be processed by high-throughput technology, such as injection molding and extrusion. In general, it is possible to notice that the table displays how the principles of polymerization and processing define trade-offs between high performance and sustainability, which gives the technical background to the decision-making process in the area of material choice.

3.3. COMPARATIVE PROCESSING EFFICIENCY

Comparing the two material systems, there exists a significant difference in cycle time, scrap recovery, and automation potential. Vulcanizing rubber processing generally has high-cycle times as it requires curing and takes cold, but TPE processing has high-speed melt-flow characteristics and shorter solidification time. [8] The decrease in the cycle time directly proportionates to the increase in throughput and the decrease in the per-unit energy used in the manufacturing of TPE.

Thermoplastic elastomers have an evident advantage in terms of scrap recovery. Waste in the production process and off-spec parts can be ground up again and returned to the production line, which is conducive to closed-loop manufacturing. By comparison, scrap produced during the vulcanization of rubber is hard to reuse because it is permanently crosslinked and may need downcycling or disposal.

In terms of the potential of automation of the process, TPE production would fit the current, fully automated production lines in the thermoplastic processing. Even the increasingly automated vulcanized rubber processes demand more complicated tooling and curing controls. Such processing efficiency differences and polymerization behavior can be related to the relative framework presented by Pydipalli and Tejani [1], which emphasizes the impact of underlying network formation disparities on manufacturability and sustainability effects throughout elastomer systems.

4. SUSTAINABILITY ASSESSMENT FRAMEWORK

4.1. ENVIRONMENTAL IMPACT METRICS

TABLE 2 Application suitability of vulcanized rubber and thermoplastic elastomers

Application Domain	Vulcanized Rubber	Thermoplastic Elastomers
Automotive tires and seals	Highly suitable	Limited suitability
Automotive interiors	Limited	Highly suitable
Consumer goods	Moderate	Excellent
Industrial vibration control	Excellent	Moderate
Modular and lightweight components	Limited	Excellent
High-temperature applications	Excellent	Limited

The table shows that material suitability depends on the field of application as a result of the variation in mechanical behavior, thermal stability, and processing behavior. Vulcanized rubber is ideal in automotive tires, seals, industrial vibration control, and use in high temperatures, as its chemically [9] crosslinked structure gives it better fatigue resistance, elastic recovery, and enduring thermal stability even under harsh operating environments. This is due to the fact that all these features make the safety-critical and high-stress environments where performance retention and durability are of utmost importance. Nevertheless, its low level of recyclability and flexibility in terms of its processing make it less appealing in those applications where lightweight design and sustainability matter.

Conversely, thermoplastic elastomers (TPEs) are quite effective in automotive interiors, consumer goods, modular or lightweight components, where design flexibility, aesthetic appearance, high-speed production, and recycling are particularly

important. Their ability to melt can allow mass production and closed-loop recycling, which boosts sustainability objectives. Although TPEs exhibit great performance in moderate load situations, they have low thermal resistance and fatigue life, limiting their application in extreme weather. Altogether, the table illustrates that the ability to select the material is based on the optimization of application specificity and the performance requirements with sustainability and manufacturing.

4.2. RECYCLABILITY AND END-OF-LIFE CONSIDERATIONS

A key characteristic of thermoset and thermoplastic elastomers from a sustainability point of view is their degree of recyclability. Thermoset materials, such as vulcanized rubber, have a low ability to be recycled since they are permanently crosslinked chemically. [10] Most probably, end-of-life management involves mechanical grinding to use as fillers, energy recovery based on incineration, or even land filling. Although more complex devulcanization methods are developed, they usually imply large amounts of energy consumption, chemical processing, and degradation of material characteristics to a smaller degree, which restricts their use.

On the contrary, thermoplastic elastomers are more compatible with recycling strategies. Their physical crosslinks are reversible, allowing them to melt and harden without much difficulty in maintaining their structural integrity. This feature supports post-industrial and post-consumer recycling flows, improving the capacity of the material recovery, and providing closed manufacturing systems. The fact that the reuse of TPEs is possible is correlated with the principles of a circular economy and less reliance on virgin resources.

4.3. LIFECYCLE ASSESSMENT (LCA) PERSPECTIVE

Life cycle assessment (LCA) point of view offers an all-round analysis of comparing the sustainability performance of vulcanized rubber and thermoplastic elastomers. [11] The raw material extraction stage takes into account the environmental factor of sourcing of petrochemical feedstocks, fillers, and additives. Complexity in the formulation of material and dependence on specialty chemicals may affect upstream energy demand and emissions. The manufacturing stage represents the effects associated with the processing energy, emissions, and waste production. As it has been explained, vulcanized rubber is usually more affected regarding manufacturing since it needs to be cured, whereas TPEs have the advantage of being processed through simple thermoplastic processing channels.

The two material systems are also differentiated by the use and disposal stages. In high-stress applications, vulcanized rubber can provide longer service life, and this is able to compensate for the increased effects of manufacturing. Nevertheless, there is no significant number of disposal options. Although thermoplastic elastomers have shorter service lives in extreme environments, they have better end-of-life recovery. A balanced sustainability comparison can be achieved by taking a combination of these lifecycle stages, bringing about trade-offs between durability, processing efficiency, and environmental impact, which are important in making successful material selection choices.

4.4. END-OF-LIFE PROCESSING PATHWAYS AND MATERIAL RECOVERY ROUTES FOR WASTE TIRE-DERIVED VULCANIZED RUBBER

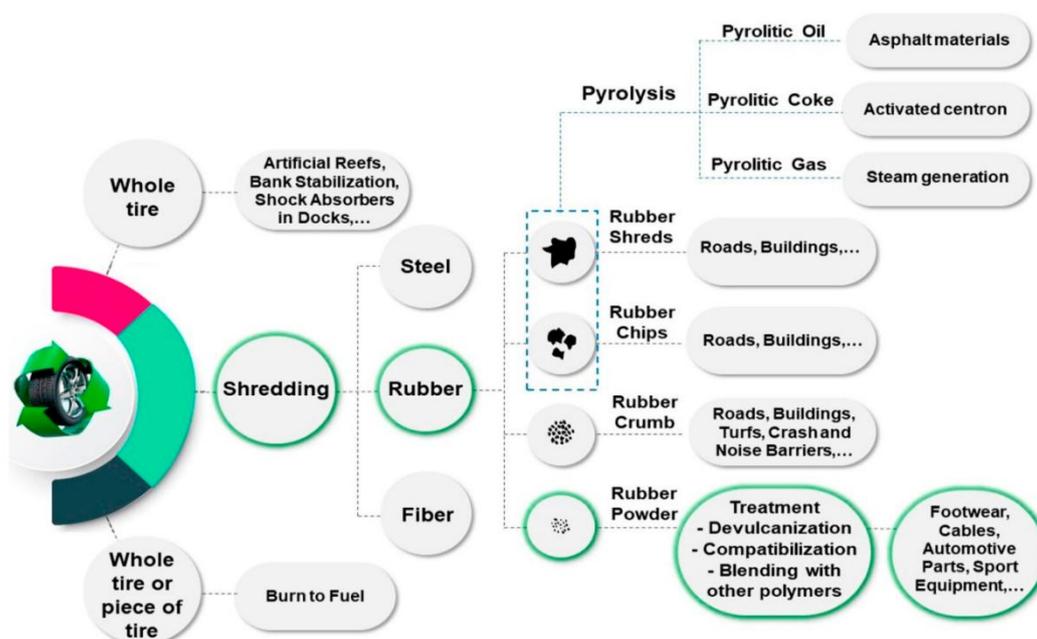


FIGURE 1 End-of-life processing pathways and material recovery routes for waste tire-derived vulcanized rubber

The figure depicts the overall end-of-life management and recycling routes of waste tires made of vulcanized rubber, which are mainly used. [12] It starts with entire tires which can be reused directly in their form, like artificial reefs, dock shock absorbers, or bank stabilization. Tires are more often subjected to mechanical shredding during which the constituents, steel, fiber, and rubber, are separated. The reclaimed rubber fraction can be further divided into shreds and chips, and crumb and powder, which can be used in various secondary applications, such as road construction, building materials, turf systems, and noise or crash barriers.

Concurrently, the illustration introduces the thermochemical recycling through the pyrolysis process, whereby, technologically, rubber is changed into pyrolytic oil, gas, and coke. The products of such are repurposed to make asphalt modifiers, precursors of activated carbon, or to generate steam. The high route treatment methods like devulcanization, compatibilization, and incorporation with other polymer products allow reintegration of rubber powder to more superior products like footwear, automotive parts, cables, and athletic apparatus. On the whole, the photograph highlights the limitations of the material recovery of thermoset vulcanized rubber and new technologies directed at sealing the material cycle.

5. COMPARATIVE PERFORMANCE EVALUATION

5.1. COMPARATIVE SUSTAINABILITY AND PERFORMANCE ASSESSMENT OF VULCANIZED RUBBER AND THERMOPLASTIC ELASTOMERS (TPES)

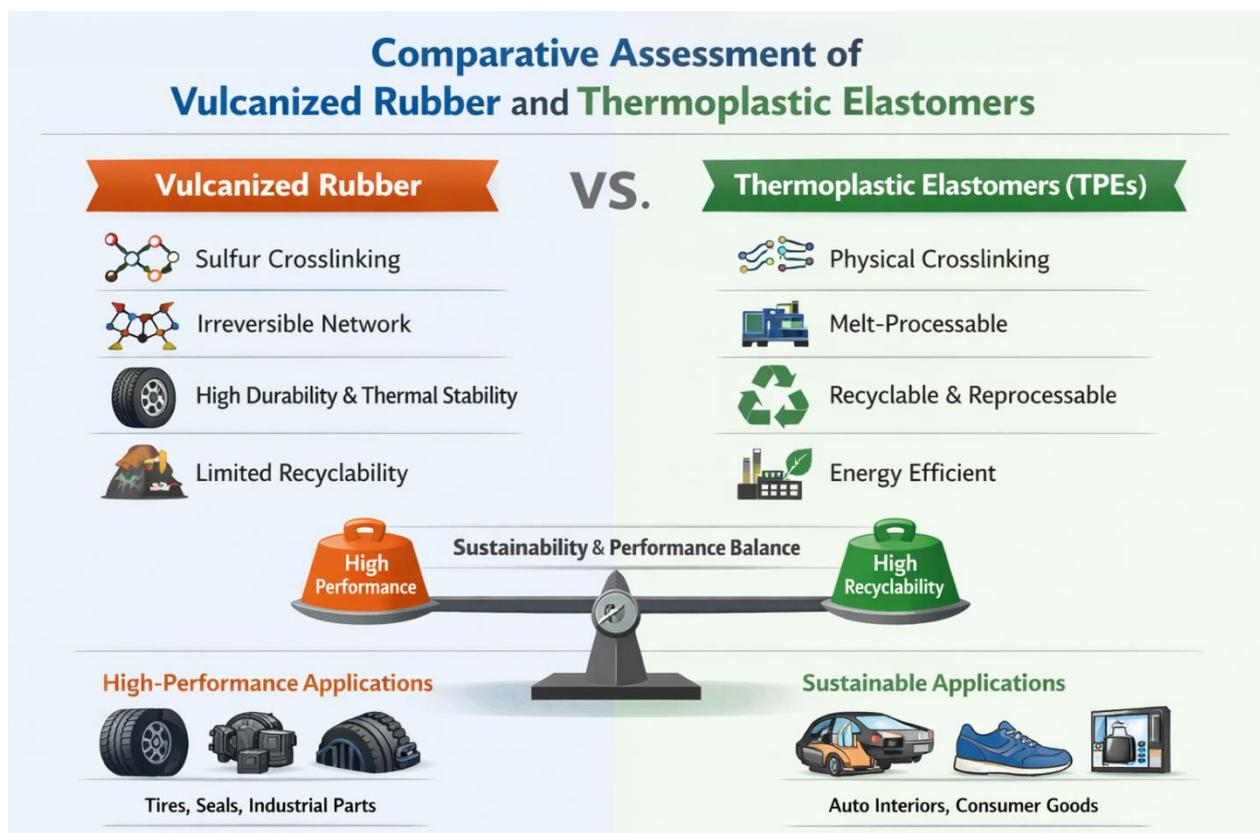


FIGURE 2 Comparative sustainability and performance of vulcanized rubber and TPES

The figure is a comparative infographic presenting side-by-side differences of the basic principles of vulcanized rubber and thermoplastic elastomers (TPES) in terms of performance and sustainability aspects. The sulphur-based chemical crosslinking of vulcanized rubber on the left side results in an irreversible network structure of three dimensions. [13] This type of structure offers high durability, superior elasticity, and superior thermal stability, and hence vulcanized rubber is used where high performance and safety-critical performance is required. Nevertheless, the figure also reveals its poor recyclability, which is indicative of the environmental challenges of thermoset materials and end-of-life disposal.

On the right, thermoplastic elastomers are pictured as depending on physical or reversible crosslinking to allow them to melt down. This enables the recycling and reprocessing of TPES, which helps to achieve better energy and material savings in the production of the products. [14] The icons used to reflect the benefits of TPES in the context of sustainability include recycling and less environmental impact. A balance scale is given at the center of the figure, and visually results in a trade-off between high performance (vulcanized rubber) and high recycling of TPES. This tradeoff brings out the central theme of the research: to settle on a good tradeoff between the mechanical performance and sustainability goals. There are material systems at the

bottom of the figure that connect each material system to its most common areas of use, placing vulcanized rubber in the tires, seals, and industrial parts, and TPEs in car interiors and consumer products.

5.2. MECHANICAL AND THERMAL PROPERTIES

The thermal and mechanical performance of elastomeric materials is a determining factor in the appropriateness of these materials in industries. Both types of elastomers used in vulcanized rubber and in thermoplastic elastomers require a certain degree of elasticity so that they can be structurally deformed and recovered when stressed. Thanks to a chemically crosslinked network and therefore its superior elastic recovery in general, vulcanized rubber has the ability to withstand being loaded repeatedly or over a long period of time. [15] Elastomeric behaviour is also observed in thermoplastic elastomers, but their ability to be elastic is controlled by reversible physical interactions, and can lead to a little greater permanent deformation at extremes. Vulcanized rubber usually performs better than most forms of TPE in tensile strength, especially in high-load and high-strain applications. The crosslinks, which are permanently formed in the vulcanization, offer crack propagation resistance and mechanical failure resistance. Although TPEs can attain moderate to high tensile strength with varying formulations, the ultimate strength of TPEs can be lower than that, particularly at higher temperatures.

The two types of materials also differ in terms of thermal stability. Vulcanized rubber has a wider temperature performance and can be used in applications where there is prolonged exposure to heat. Thermoplastic elastomers are thermoplastic and thereby soften when the temperature is at high levels, which restricts their applications in high temperatures or continuous-load settings. Nevertheless, the development of TPE formulations has enhanced thermal resistance for use in applications.

5.3. DURABILITY AND SERVICE LIFE

Service life and durability are very essential performance indicators that will directly affect the gains in the field of sustainability. Vulcanized rubber is commonly known to have a very high fatigue strength with the ability to resist repeated cyclic loading with minimal degradation. It has found application in rubber product manufacturing and is especially useful in moving as well as dynamic uses like tires, belts, and vibration isolators, where long-term mechanical stability is vital.

Vulcanized rubber is also the preferred choice for many aging behavior under environmental exposure. Crosslinked networks offer the network resistance to creep, stress relaxation, and deformation. Although the two material systems can be stabilized by means of the use of anti-oxidants and additives, vulcanized rubber tends to perform better in terms of resistance to thermal aging and mechanical as well as mechanical fatigue. Gradual changes caused by physical relaxation of crosslinks of thermoplastic elastomers can result in a decrease in properties over time, particularly at long-term exposure to heat or mechanical stress, which may decrease the service life in extreme environments.

5.4. SUSTAINABILITY-PERFORMANCE TRADE-OFF ANALYSIS

The fact that a comparison between vulcanized rubber and the thermoplastic elastomers depicts a basic trade-off between performance retention and environmental advantage. [16] Vulcanized rubber is the material that has high mechanical strength, thermal stability, and long service; the replacement rate and the material use can be minimized. Nonetheless, it requires more energy-consuming processing, which reduces its small recyclability and makes it have a significant environmental impact on the environment. Thermoplastic elastomers, in their turn, offer a considerable degree of sustainability by offering better functioning in the process of processing, recyclability, and waste reduction in manufacturing. TPEs can not necessarily have the same extreme performance nature as vulcanized rubber, but their reduced lifecycle environmental impact provides them with an appeal to applications with moderate mechanical requirements. This trade-off promotes the value of the selection of material, which is application-specific. In safety-criteria, as well as high-performance conditions, the vulcanized rubber longevity could offset its environmental expenses; on the other hand, where the requirements centered on the sustainability, flexibility of design, and recyclability, thermoplastic elastomers are more favorable for usage.

6. INDUSTRIAL IMPLICATIONS AND MATERIAL SELECTION GUIDELINES

6.1. APPLICATION-SPECIFIC SUITABILITY

Use-specific performance tasks are very sensitive in determining the choice between vulcanized rubber and thermoplastic elastomers. Vulcanized rubber remains the choice in the automotive industry in applications where thermal stability, fatigue, and wear and tear of these products are paramount, including tires, engine mounts, hoses, sealing systems, and other car parts. [17] These parts frequently have to work at extreme temperatures, dynamic loads, and a chemical environment, which means the high resilience of vulcanized rubber gives undoubted benefits. Thermoplastic elastomers are, however, finding their use in automobile interiors, cable insulation, and lightweight trim, in which recyclability, shapeability, and lighter weight bring improved sustainability and fuel consumption.

Thermoplastic elastomers are very popular in consumer goods where they are used to apply aesthetic variability, processing, and meet recyclability requirements. Fitness footwear, grips, and domestic appliances, wearables, etc. TPEs have soft-touch properties, which are colorable, and can be used in high-volume, automated production. Vulcanized rubber is also not forgotten in the niche consumer items where high durability is needed, and sustainability is coming to favor TPE-based systems.

In the case of industrial components, the option is based on the conditions of operation. The vulcanized rubber is commonly used in heavy-duty belts, vibration dampers, and closing items that are under great pressure and heavy usage. On the other hand, thermoplastic elastomers are more appropriate in modular industrial components, covers, and other components that necessitate replacement or redesign, and recyclability provides real benefits to the processing speed.

6.2. ECONOMIC AND SUPPLY CHAIN CONSIDERATIONS

Economically, tooling costs are very influential in the choice of materials. Vulcanized rubber generally involves highly specialized molds that can withstand pressure and heat during the curing process, which boosts startup capital expenditure. Conversely, TPE processing utilizes conventional thermoplastic tooling, which tends to be less costly and can be used in the current plastic manufacturing logistics. Industrial adoption is also determined by material availability and the stability of the supply chain. Rubber formulae Vulcanized rubber formulae may also require particular curatives, accelerators, or fillers, which are also vulnerable to supply variations and regulatory inspection. [18] Large-scale manufacturers of polymers typically have more generally standardized supply chains and do not have as variable materials as thermoplastic elastomers. Another aspect that is imperative is scalability. The thermoplastic elastomer production processes are highly scalable because of the reduced cycle times and chances of high automation. Although scalable, vulcanized rubber production implies more complex process control and longer production cycles and, therefore, may restrict flexibility in responding to market demand.

6.3. DECISION FRAMEWORK FOR SUSTAINABLE MATERIAL SELECTION

Matthew's selection needs to be based on a systematic decision model that supports performance, cost, and sustainability balance. Buyers need to consider the environmental and economic costs of vulcanized rubber to the mechanical and thermal performance requirements. Vulcanized rubber is the best option in cases of critical applications where sustainability is a limitation, but high performance and durability are of great importance. On the other hand, moderate levels of performance can be used to substitute thermoplastic elastomers in cases of energy savings, disposal of waste, and the adoption of the circular model. By incorporating the information of the lifecycle assessment with the economic and functional specifications, the decision-makers will be able to determine materials that could deliver an optimal performance-cost-sustainability balance. This strategy facilitates strategic initiatives in replacing materials and harmonizing industrial manufacturing culture in accordance with long-term sustainability goals.

7. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

However, although major progress has been made in the field of elastomer technology, there are still a number of obstacles to finding the right balance between performance and sustainability. To solve these issues, further studies and advances in material design, processing technologies, and sustainability evaluation procedures are needed.

7.1. HYBRID ELASTOMER SYSTEMS

A potential future research is to develop hybrid elastomer systems that have the benefits of both vulcanized rubber and thermoplastic elastomers. [19] Such systems can either be based on the partial crosslinking of thermoplastic matrices or be based upon dynamically reversible crosslinks, which offer improved mechanical behavior at the expense of retained reprocessability. Nevertheless, the development of hybrid systems is associated with problems of the compatibility of phases, the adhesion of the various interfaces, and the control of the process. Future studies should be aimed at the optimization of hybrid network architecture to provide high durability and fatigue behavior without compromising on the recyclability and processing efficiency.

7.2. BIO-BASED ELASTOMERS

The shift to sustainability has increased the interest in bio-based elastomers based on renewable feedstock, including natural rubber, bio-synthesized polyisoprene, and thermoplastic elastomers made of plants. Although bio-based materials reduce fossil resource dependency and decrease carbon footprints, they do not allow high-level implementation because of the fluctuation in material properties, low thermal resistance, and the scalability of supply chains. To solve such drawbacks, future research ought to focus on molecular engineering of materials, better stabilization mechanisms, and lifecycle analysis to support the environmental advantages over traditional petroleum elastomers.

7.3. ADVANCED RECYCLING TECHNOLOGIES

Recycling is still considered to be one of the most important problems of elastomeric materials, especially vulcanized rubber. Recent technological recycling procedures, such as chemical devulcanization, microwave-assisted recycling, and selective bond cleavage, present a prospective recovery of valuable polymer chains and fillers. But these are very energy-consuming methods and have complicated processing procedures. [20] Research should be done to find methods of refining the recycling process, the amount of energy needed, and the quality of material that has been recovered. In the case of thermoplastic elastomers, new sorting technology requiring contamination resistance and multi-cycle reuse should also be introduced to increase material recovery and enable the circular manufacturing paradigm.

7.4. DIGITAL LCA INTEGRATION

Applying digital lifecycle assessment (LCA) tools to material design and production decision-making is a very important direction for the future. Combined with real-time production information and digital twins, digital LCA platforms can be used to drive dynamic sustainability assessments across the product lifecycle. In this way, manufacturers can evaluate the environment at the design stage, optimize the parameters of the processing, and forecast end-of-life results. To be informed by the suggested research, future studies ought to attempt to standardize digital LCA approaches, enhance data exchangeability, and introduce sustainability metrics directly into the industrial material selection and product development processes.

8. CONCLUSION

This work has provided an in-depth, sustainability-related, comparative evaluation of vulcanized rubber and thermoplastic elastomers, the way they were processed, their polymerization mechanisms, performance, and environmental aspects of their lifecycle. The fact that the basic difference between irreversible chemical cross-linking in vulcanized rubber and reversible physical interactions in thermoplastic elastomers determines not only the mechanical properties but also the efficiency and recyclability of manufacturing processes, as well as the final performance of the material. The vulcanized rubber always has better mechanical strength, thermal stability, fatigue, and long-term durability; it cannot be overlooked in mechanical and environmental conditions that require extreme operation.

Thermoplastic elastomers are better suited to specific applications with regard to sustainability. They are melt-processable, thus having shorter production cycles, consuming less energy, and automating processes to a high level. In particular, reprocessing and recycling of TPEs contribute to the closed production systems and considerably minimizes the waste of materials and environmental footprint throughout the materials lifecycle. The features of TPEs are especially indicative that it is a material that can be adapted to automotive interiors, consumer goods, and modular industrial subparts, where the balance between moderate performance requirements and sustainability goals can be maintained.

In spite of these merits, vulcanized rubber is still very much applicable in high-performance spheres where the safety, reliability, and long life of service are of high importance. Under these circumstances, a high manufacturing and end-of-life environmental cost of vulcanized rubber can be offset by its increased ability to retain its performance and last longer in use by mitigating the replacement rate and still being functional in extreme operating lives. Altogether, the results are based on the fact that no universally favorable elastomers can meet all the performance and sustainability requirements. Rather, informed material choices have to be steered by application-specific needs, lifetime aspects, and strategic sustainability objectives. Through a combination of performance indicators and environmental and economic indicators, manufacturers will be able to take balanced decisions that will enable them to sustain not only industrial functionality but also long-term sustainability in rubber manufacturing.

9. FUTURE WORK

Further studies should be aimed at developing material innovation and technologies in processing technology to reduce the performance-sustainability discrepancy in the elastomer system. Specifically, the prospects of hybrid elastomers that combine reversible crosslinking with semi-solid chemical networks can have major opportunities to merge the properties of longevity of vulcanized rubber and the recyclability of thermoplastic elastomers. Further, the enhanced focus on the bio-based and low-carbon elastomers, which are based on renewable feedstock or recycled polymers, can help reduce the reliance on fossil resources and, in turn, decrease the greenhouse effect in the lifecycle. Genuinely experimental support of these materials under actual operating circumstances and long-lasting demands at room temperature, fatigue, and chemical exposure will be necessary to determine the industrial usefulness of such materials.

The second direction of importance is to apply digital manufacturing and sustainability assessment tools to the material selection and product design processes. With the application of the innovative lifecycle assessment (LCA) models, real-time production information, and digital twins, it would be possible to perform a dynamic analysis of the environmental impact of a product over the lifecycle. Recycling and devulcanization technologies, which have a scalable process, should also be tried in the future with the assistance of machine learning to optimize the process and enhance recovery efficacy and quality of materials. Individually, they may contribute to data-driven decision-making and speed up the uptake of sustainable elastomer solutions in the automotive, consumer, and industrial manufacturing sectors.

REFERENCES

- [1] Rajani Pydipalli, and Jayadip GhanshyamBhai Tejani, "A Comparative Study of Rubber Polymerization Methods: Vulcanization vs. Thermoplastic Processing," *Technology & Management Review*, vol. 4, no. 1, pp. 36-48, 2019.
- [2] A. Y. Coran, *Vulcanization, Science and technology of rubber*, Academic Press, pp. 339-385, 1994.
- [3] B. Erman, J. E. Mark, and M. C. Roland, *The Science and Technology of Rubber*. Waltham Ma: Academic Press, 2013.
- [4] G. Holden, *Thermoplastic elastomers*, In *Applied plastics engineering handbook*, William Andrew Publishing, pp. 97-113, 2024.
- [5] M. Akiba, "Vulcanization and crosslinking in elastomers," *Progress in Polymer Science*, vol. 22, no. 3, pp. 475-521, 1997, doi: [https://doi.org/10.1016/s0079-6700\(96\)00015-9](https://doi.org/10.1016/s0079-6700(96)00015-9).

- [6] R. A. Gross, "Biodegradable Polymers for the Environment," *Science*, vol. 297, no. 5582, pp. 803–807, Aug. 2002, doi: <https://doi.org/10.1126/science.297.5582.803>.
- [7] B. Adhikari, "Reclamation and recycling of waste rubber," *Progress in Polymer Science*, vol. 25, no. 7, pp. 909–948, Sep. 2000, doi: [https://doi.org/10.1016/s0079-6700\(00\)00020-4](https://doi.org/10.1016/s0079-6700(00)00020-4).
- [8] J. Hopewell, R. Dvorak, and E. Kosior, "Plastics recycling: Challenges and opportunities," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 364, no. 1526, pp. 2115–2126, Jul. 2009, doi: <https://doi.org/10.1098/rstb.2008.0311>.
- [9] M. Garetti and M. Taisch, "Sustainable manufacturing: trends and research challenges," *Production Planning & Control*, vol. 23, no. 2–3, pp. 83–104, Aug. 2011, doi: <https://doi.org/10.1080/09537287.2011.591619>.
- [10] Material evolution: TPU continues to replace rubber in various applications, Covestro, [Online]. Available: <https://solutions.covestro.com/en/highlights/articles/stories/2025/tpu-more-sustainable-rubber-replacement>
- [11] A. K. Bhowmick and H. L. Stephens, *Handbook of elastomers*. New York: M. Dekker, 2001.
- [12] B. Adak, U. Chatterjee, and M. Joshi, "Rubber-Based Sustainable Textiles and Potential Industrial Applications," *Textiles*, vol. 5, no. 2, p. 17, May 2025, doi: <https://doi.org/10.3390/textiles5020017>
- [13] M. Myhre, S. Saiwari, W. Dierkes, and J. Noordermeer, "RUBBER RECYCLING: CHEMISTRY, PROCESSING, AND APPLICATIONS," *Rubber Chemistry and Technology*, vol. 85, no. 3, pp. 408–449, Sep. 2012, doi: <https://doi.org/10.5254/rct.12.87973>.
- [14] L. Y. Ljungberg, "Materials selection and design for development of sustainable products," *Materials & Design*, vol. 28, no. 2, pp. 466–479, Jan. 2007, doi: <https://doi.org/10.1016/j.matdes.2005.09.006>.
- [15] M. Niaounakis, *Recycling of flexible plastic packaging*. Oxford ; Cambridge William Andrew Cop, 2020.
- [16] P. van den Tempel and F. Picchioni, "Polymer Recycling: A Comprehensive Overview and Future Outlook," *Recycling*, vol. 10, no. 1, p. 1, Dec. 2024, doi: <https://doi.org/10.3390/recycling10010001>.
- [17] A. K. Bhowmick, and D. Mangaraj, *Vulcanization and curing techniques, Rubber products manufacturing technology*, Routledge, pp. 315-396, 2018.
- [18] R. Rajesh Babu and Kinsuk Naskar, "Recent Developments on Thermoplastic Elastomers by Dynamic Vulcanization," pp. 219–247, Jan. 2010, doi: https://doi.org/10.1007/12_2010_97.
- [19] J. Karger-Kocsis, *Thermoplastic rubbers via dynamic vulcanization, Polymer blends and alloys*, Routledge, pp. 125-154, 2019.
- [20] K. A. Iyer, A. Doufas, and D. R. Sunagatullina, "Dynamically vulcanized thermoplastic elastomers based on 4-methyl-1-pentene polymers," *Polymer*, vol. 238, p. 124423, Jan. 2022, doi: <https://doi.org/10.1016/j.polymer.2021.124423>.
- [21] K. C. Jha and M. Tsige, "MOLECULAR MODELING OF THERMAL AND MECHANICAL PROPERTIES OF ELASTOMERS: A REVIEW," *Rubber Chemistry and Technology*, vol. 86, no. 3, pp. 401–422, Sep. 2013, doi: <https://doi.org/10.5254/rct.13.86985>.
- [22] M. M. Farag, *Materials and Process Selection for Engineering Design*. CRC Press, 2020.
- [23] J. S. Loor et al., "Sustainable thermoplastic elastomers: valorization of waste tires, recycled HDPE, and recycled EVA," *Frontiers in Sustainability*, vol. 6, Sep. 2025, doi: <https://doi.org/10.3389/frsus.2025.1638375>.