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Original Article

Sustainable Design and Application-Driven Selection of Thermoplastic Elastomers in Modern Rubber Manufacturing

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ABSTRACT: *The present paper offers a holistic, practice-based model in the choice of thermoplastic elastomers (TPEs) in modern rubber production with a focus on the sustainable design approach. The thermoplastic elastomers consisting of a combination of the elasticity characteristic of traditional vulcanized rubber with the ease with which thermoplastics are processed have become key to decarbonization, recycling, and lightweighting in the automotive, consumer, medical and industrial industries. But to be truly sustainable, it is not only a solution that involves the replacement of materials but a systemic overall approach that involves the sourcing of raw-materials (biobased feedstuff, reclaimed/rubber grinding), compounding and additives (compatibilizers, sustainable fillers), processing (energy and solvent reduction), and end-of-life (reuse, mechanical and chemical recycling, biodegradation when suitable). The paper integrates the latest innovations in TPE chemistry and processing, such as polyolefin TPEs (TPO/TPE-O), thermoplastic vulcanizates (TPV), thermoplastic polyurethanes (TPU), styrenic block copolymers (SBC/TPS), and thermoplastic polyester elastomers (TPEE), and projects them in envelopes in application performance indicators needed by the contemporary rubber products such as dynamic abrasion resistance, compression set, fuel/oil resistance, low-temperature flexibility, and long- The approach is pairing property-process matrices, lifecycle assessment (LCA) heuristics, and selection flowcharts to rank options of material selection by the criticality of use, manufacturing feasibility, environmental indicators (embodied carbon, recyclability, toxicity), and cost. The paper records the representative case studies, e.g., automotive door seals (high weathering, moderate abrasion), soft-touch consumer grips (aesthetics and tactile performance), and reclaimed tire-based TPE composites (circular economy approach) and illustrates how formulation options, e.g. grade of TPU vs TPV, presence of plasticizer, content of nanofiller, compatibility of compatibilizer, etc., compromise performance and sustainability. Quantitative data are given: the range of predicted embodied carbon (kg CO 2 -eq/kg) of major TPE families, approximate thresholds of recycled content with current technology, meeting standard mechanical property requirements, and comparative energy consumptions between extrusion and injection moulding pathways. The paper also reviews additive technologies which reduce environmental impact, bio-based plasticizers, silica and lignin fillers, low-ZnO curing aids, and non-toxic crosslinking strategies and how they impacted processability and long-term performance. Lastly, we also suggest an implementable selection algorithm (flowchart and decision tables) to industry practitioners combining regulatory requirements (e.g., RoHS, REACH), recyclability goals and end-use performance, thereby permitting a traceable, auditory path between the product requirement and material/formulation selection. The framework specifically references and develops literature in the field of rubber additives and sustainability (such as the article Emerging Trends in Rubber Additives for Enhanced Performance and Sustainability by the user), a way to pragmatically implement in manufacturing lines, yet provides insight of research gaps, including standardized eco-metrics of TPE blends, scalable devulcanization routes to reclaimed tire rubber (GGR) integration and long-term field testing of bio-based TPEs. The goal of this contribution is to have both a technical reference to materials engineers and a decision support tool to product designers who may want to re-engineer rubber products that have a lower carbon footprint, and still maintain good performance.*

KEYWORDS: *Thermoplastic Elastomers (Tpes), Sustainable Rubber Manufacturing, Application-Driven Material Selection, Life Cycle Assessment (Lca), Thermoplastic Vulcanizates (Tpv), Thermoplastic Polyurethanes (Tpu), Styrenic Block Copolymers (Sbc/Tps), Thermoplastic Polyester Elastomers (Tpee), Polyolefin Elastomers (Tpo/Tpe-O), Circular Economy in Elastomers.*

1. INTRODUCTION

Thermoplastic elastomers (TPEs) hold a special and rapidly growing niche in today's polymer engineering due to their ability to combine the keeping ability and tenderness of traditional rubbers with the meltability of thermoplastics. [1] This amalgamation of behaviour allows effective production via injection, extrusion, and blow moulding, giving reduced cycle durations, higher design latitude and enhanced dimensional restraint than thermoset rubbers. This has seen TPEs being widely used in various industries, such as automotive interior and exterior parts, soft-touch consumer grips, medical tubing, sealing systems, and vibration-damping applications. In addition to the efficiency of manufacturing, their thermoplastic enables easier reprocessing and recycling and, therefore, TPEs are naturally one of the options of inclusive strategies in the circular economy.

Simultaneously, the rubber and elastomer sectors have been under regulatory and market-based pressure to decrease greenhouse gas emissions, use more recycled and bio-based materials, and exclude dangerous components like phthalate plasticizers and heavy-metallic additives. These drivers transform the priorities in materials selection, with the focus no longer on performance but on the more holistic competence of functionality, sustainability, and compliance. The recent developments in the bio-based monomer, recyclable block copolymer structures and recycling-friendly crosslinking architectures and dynamic bonding chemistry have greatly enlarged the design space of TPEs. Nevertheless, with this growth, things become complicated as designers will have to maneuver with a wide range of material solutions, formulations and processing pathways. As a result, the application of environmental indicators like life cycle assessment to conventional performance parameters and production limitations has become essential in the rational and justifiable material choice in contemporary rubber and elastomer design.

1.2. IMPORTANCE OF APPLICATION-DRIVEN SELECTION OF THERMOPLASTIC ELASTOMERS

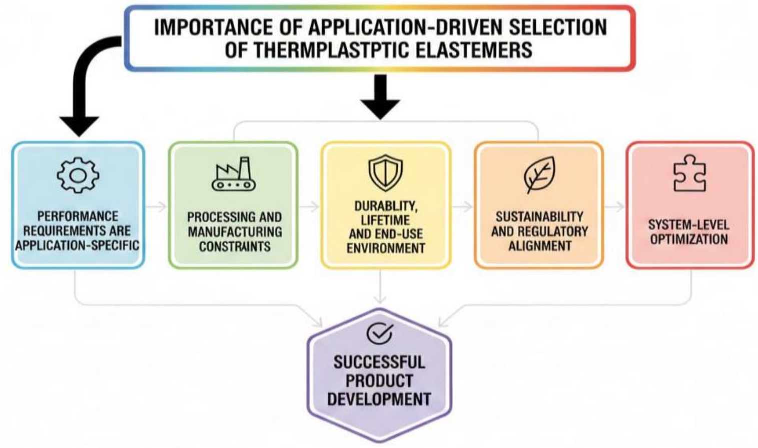

FIGURE 1 Conceptual flowchart of ML-enhanced molecular docking pipeline

1.2.1. PERFORMANCE REQUIREMENTS ARE APPLICATION-SPECIFIC

Thermoplastic elastomers represent a highly diverse family of materials whose mechanical, thermal and chemical properties can be very different, so selection becomes crucial depending on application necessities. Softness, resistant to abrasion, compression set, chemical resistance, [2] low-temperature elasticity requirements vary between such applications as automotive seals, consumer grips, medical tubing and industrial components. A material that has been optimized in one application can be ineffective in a different application, which hampers the importance of defining the targets of performance in direct relation to the conditions of service as opposed to applying common classes of materials.

1.2.2. PROCESSING AND MANUFACTURING CONSTRAINTS

Selection based on application should also take into consideration processing paths and manufacturing facts. The various TPE families have various melt viscosities, thermal stability ranges, shear or moisture sensiveness, and are also suitable for injection molding, extrusion, overmolding or co-extrusion. Choosing a TPE that is not compatible with the processing method may cause efficiency dilemmas, defects, or too many energy demands to the manufacturing process, despite the fact that intrinsic material characteristics may seem promising.

1.2.3. DURABILITY, LIFETIME, AND END-USE ENVIRONMENT

End-use environment is a very important niche in defining long-term performance. UV radiation or ozone, oils and fuels, repetitions of mechanical loading or temperature cycling may cause significant changes in material durability. The selection process to be used is application-based to ensure that involved resistance against aging, weathering, and chemical attack is given priority, where it is needed. This allows timely failure to be prevented and unnecessary replacement to be minimised an essential consideration in cost and environmental footprint.

1.2.4. SUSTAINABILITY AND REGULATORY ALIGNMENT

Application-driven selection becomes more and more based on the combination of sustainability goals and technical specifications. Recycled or bio-based content targets, embodied carbon and chemical regulations compliance are dependent on the sector and product category. By providing a fit between material selection and application-relevant sustainability and regulatory requirements, it becomes possible to have a more realistic life cycle assessment and to design responsible products.

1.2.5. SYSTEM-LEVEL OPTIMIZATION

Finally, application-driven selection allows optimization at the system level as opposed to optimization at a material level. With a solid foundation of simultaneous performance, processing, durability, cost and environmental impact in a particular application, designers are able to make informed trade-offs and choose TPE systems that provide balanced, robust and sustainable solutions.

1.3. THERMOPLASTIC ELASTOMERS IN MODERN RUBBER MANUFACTURING

Modern elastic manufacturing now relies on thermoplastic elastomers as they have radically changed the way elastomeric products are designed, processed and incorporated. [3] Compared to traditional thermoset rubbers, which need time- and energy-intensive vulcanization processes, the TPEs can be made through normal thermoplastic processing methods like injection molding, extrusion, and blow molding. It can be used to shorten the cycle times, increase production-throughput, and enhance dimensional consistency, and TPEs are especially appealing in high volume manufacturing industries (e.g. automotive, consumer goods, and medical devices). Multi-material processing with overmolding and co-extrusion of TPEs is also possible, and enables soft elastomeric elements to be fabricated onto hard substrates of thermoplasts without the need for secondary bonding processes. From a manufacturing point of view, TPEs aid lighter production processes by lowering the scrap rate as well as allowing in-process recycling of offcuts and runners. The fact that they are compatible with both automated manufacturing and Industry 4.0 practices further enhances their presence in the contemporary rubber processing settings. Besides this, the growing range of TPE chemistries, including styrenic block copolymers and thermoplastic polyurethanes, to polyester elastomers and thermoplastic vulcanizates, enables the manufacturers to customise performance across the spectrum of hardness, elasticity, chemical resistance, and durability. Notably, TPEs respond to increased sustainability demands in the rubber production as well. Their thermoplastic character enables mechanical recycling and the use of recycled material, and the immediately developing bio-based monomers and active concepts of interconnections enhance the potential of circularity. Though TPEs fail to completely supersede thermoset rubbers, especially in extreme high-temperature applications and load-bearing applications, they are becoming a viable replacement used where processing flexibility, design flexibility and environmental factors are essential. Subsequently, TPEs have become a base technology in the transformation of rubber production to more efficient, flexible, and sustainable production procedures.

2. LITERATURE SURVEY

2.1. EVOLUTION OF TPE CHEMISTRY AND MANUFACTURING

Thermoplastic elastomer (TPE) chemistry has experienced significant development over the last ten years, in accordance with the need for materials possessing the rubber-like elasticity and the thermoplastic processability, as well as enhanced sustainability. [4] Recent progress in the synthesis of block copolymers allows designers to optimally control phase-separated morphologies by designing the domains of soft and hard segments to optimize elasticity, toughness, and thermal stability. Controlled living polymerization methods and control over segment chemistry have been applied in the case of styrenic TPEs and polyurethanes to enhance creep and abrasion resistance and fatigue, as well as softness. In the case of TPEs made of polyester, one-pot and melt polycondensation approaches have made the production process easier and provided high-molecular-weight polymers with high tensile strength and resilience. Meanwhile, manufacturing innovation, including reactive extrusion and in-line compounding, has provided dynamic vulcanization at the industrial level and thus a uniform production of thermoplastic vulcanizates (TPVs) with a miniature dispersion of the phase of rubber. [5] Recent review articles also focus more on application-specific material design, such as the TPU grades designed to be biocompatible and sterilization-resistant in medical devices, or TPE-S developed to be tactile soft in consumer products. A significant shift in the literature to sustainable feedstocks is also mirrored by reports of bio-based TPEs and partially bio-derived TPEs, such as TPU analogs of renewable polyols, bio-based diacids and diols into TPEs, and petroleum-based TPEs to bio-based TPEs reflecting performance equality to other high-performance materials.

2.2. SUSTAINABLE ADDITIVES AND FILLERS

Sustainable additives and fillers have become instrumental facilitators of establishing the balance between performance enhancement and reduction of environmental impact in TPE systems. [1]The orthodox petroleum-based plasticizers, fillers and processing aids are under increasing search as a result of toxicity, volatility and regulatory scrutiny, and bio-based and low-impact alternatives are under intensive search. Investigations of epoxidized vegetable oils, bio-oils and ester-based plasticizers reveal that these materials can enhance the flexibility, processability and low temperature performance besides lowering the emissions of volatile organic compounds (VOCs)s. Natural fillers include lignin and cellulose nanofibers, and bio-silica have been considered as reinforcing fillers as well as functional additives to provide UV-stability and barrier properties. Studies on hybrid filler have demonstrated that nano-scaled bio-fillers have the capability of replacing conventional carbon black or precipitated silica at least at a partial level without causing serious mechanical strength losses when the dispersion as well as interfacial compatibility are well controlled. [6] The work cited by the user on emerging rubber additives is in line with the overall literature by classifying next-generation additives, including nano-silicas, bio-derived oils, and devulcanization catalysts, which can be used to facilitate the use of reclaimed rubber and lower environmental impact. Also, ground tyre rubber (GTR) has been of common interest to be used as a filler in TPE matrices, where compatibilization approaches involving maleated polyolefins, epoxidized natural rubber or reactive coupling agents have shown to significantly increase interfacial adhesion, giving rise to high tensile strength and impact strength.

2.3. RECYCLING, DEVULCANIZATION, AND CIRCULARITY

Recycling and circularity have been the primary issues and opportunities in the evolution of sustainable TPE materials. Whereas mechanical recycling of single polymer TPE systems is comparatively easy because they are thermoplastics, complicated mixtures, TPVs and multi-phase systems are prone to property loss on re-processing. In response to this drawback, much research has been carried out into the utilization of reclaimed rubber as a raw material due to the end-of-life tyres and industrial waste streams in the creation of TPEs. [7] Devulcanization methods: Cryogenic grinding, thermo-mechanical shear processes, and chemical devulcanization methods are devulcanization technologies that are designed to selectively break the sulfur crosslinks without degrading the polymer backbone. Recent investigations emphasize disulfide exchange reactions and other selective chemical ways as the new avenues to print reclaimed rubber and improve compatibility and reactivity. When made in TPE matrices, these devulcanized rubbers have the potential of partially recovering elastomeric performance and have the added advantage of lowering dependence on virgin raw materials. [8] Also, recent advances in vitrimer-like dynamic crosslinked networks provide this groundbreaking solution, which integrates elastomeric functionality with reuse via reversible covalent bonding. Such systems provide a blend of thermoplastics and thermosets to allow repeated reshaping and recycling without losing their mechanical integrity, and thus support the concept of TPE technology and circular economy.

2.4. ENVIRONMENTAL AND REGULATORY CONSIDERATIONS

In the context of research focus and industrial implementation of TPE technologies, environmental evaluation and regulation compliance are more likely to influence it. Research into life cycle assessment (LCA) has emphasized that bio-based or recycled material is not a sufficient precondition to having an environmental benefit because upstream agricultural inputs, energy use and end-of-life scenarios are very likely to be significant factors in the overall effect. Recent literature, therefore, recommends holistic cradle-to-grave studies in order to authenticate sustainability statements. [9] The regulatory requirements like REACH, RoHS, end-of-life vehicles and electronics regulations have a powerful impact on the selection of additives, especially by limiting the toxic substances like heavy-metal-based accelerators, some of the flame retardants, and phthalate plasticizers. These limitations have led to the faster production of safer substitutes, such as the use of non-toxic curing agents and bio-derived plasticizers. Not only that, several reviews indicate that there are no standardized testing procedures that determine recyclability, durability, and long-term aging of TPE blends, which complicates objective comparison between studies. Developing consistency in mechanical performance retention processes following recycling, chemical resistance, and environmental aging is more quickly considered an important factor to achieve transparent material choice and provide a way to the regulatory acquiescence of future sustainable TPE systems.

3. METHODOLOGY

3.1. OVERVIEW OF SELECTION FRAMEWORK

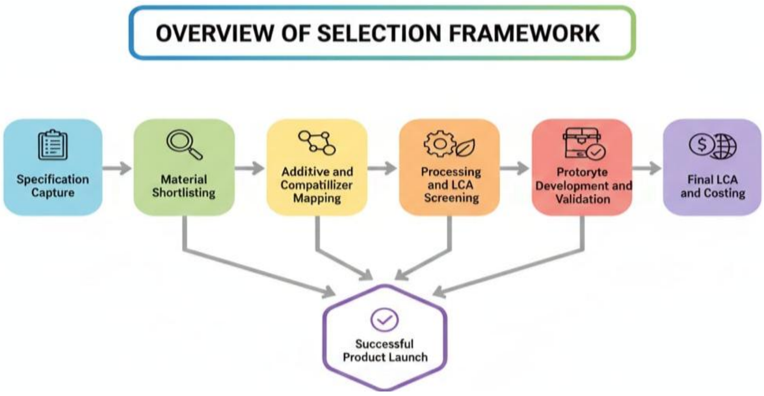

FIGURE 2 Overview of selection framework

3.1.1. SPECIFICATION CAPTURE

A detailed definition of application-specific needs (mechanical performance: tensile strength, elongation, fatigue and resistance, thermal, chemical and aesthetics: colorability and surface feel) is used as input to the selection framework. [10] Standards related to regulatory MSS requirements are chemical compliance, safety and end-use sector standards. Simultaneously, the targets of sustainability are set like minimum content of recycled or bio-based materials, permissible carbon footprint, and maximum content of harmful additives. This measure will be used to make sure that the downstream material decisions are reflected in the technical and environmental goals.

3.1.2. MATERIAL SHORTLISTING

Candidate TPE families are filtered based on the established requirements, and the list includes styrenic TPEs, thermoplastic polyurethanes, polyester TPEs, and TPVs. A comparative property matrix is developed based on literature data, supplier datasheets, and includes such important parameters as tensile strength, elongation at break, abrasion resistance, compression set, glass transition temperature, density, and range of processing temperatures. This is a systematic comparison that allows one to quickly do away with unhelpful materials. Materials with baseline performance and processing limits are only passed to the next stage.

3.1.3. ADDITIVE AND COMPATIBILIZER MAPPING

There is an evaluation of potential shortlisted TPEs for each compounding strategy to refine performance and sustainability results. It involves the choice of fillers, plasticizers, stabilizers and compatibilizers in order to improve the mechanical properties, processability or compatibility of re-used content. [11] Whenever possible, bio-based or low-toxicity additives are sought, and compatibilization strategies are found in blends with reclaimed rubber or recycled polymers. It is a step between material selection and formulation design, and it is necessary so that performance targets are feasible.

3.1.4. PROCESSING AND LCA SCREENING

Initial processing paths, including extrusion, injection molding or reactive extrusion, are evaluated in terms of energy use and production strategies. Embodied energy, greenhouse gas emissions, and resource intensity are estimated using proxy life cycle assessment (LCA) information found in published databases and the literature. This screening allows one to find out about disproportionately high environmental burdens in formulations early, although it is approximate. The applications of materials and processes with poor preliminary LCA are prioritized and prototyped, and the expensive processes are avoided.

3.1.5. PROTOTYPE DEVELOPMENT AND VALIDATION

The formulation is scaled by selecting formulations into laboratory or pilot level, and subjected to realistic manufacturing conditions. AMuteximational, thermal and ageing are analysed based on applicable standards that apply within the ASTM or ISO to confirm the anticipated performance. [12] The results of the tests are assessed by comparison with the original specification, and formulations are improved by modifying compositions or processing. It is a technical experimental feedback process that makes sure that it is technically feasible before the final choice.

3.1.6. FINAL LCA AND COSTING

To calculate significant environmental impacts at all life cycle stages, a refined formulation is carried out by making use of primary processes data and confirmed databases, assessing environmental impacts. Simultaneously, a detailed cost analysis is conducted, which includes the cost of raw material, cost of processing energy, additives, and expected scale-up effects. The latter step will make it possible to have an even assessment of performance, sustainability, and economic viability. The justification for the implementation or further development of the chosen system of materials is provided.

3.2. PROPERTY–PROCESS MATRIX

One of the key analytical tools of the proposed methodology is the propertyprocess matrix that allows making a systematic comparison between material performance and processing limit and various thermoplastic elastomer (TPE) families and formulation strategies. [13] The rows in this matrix are the major performance measurements: tensile strength, elongation at break, tear and abrasion resistance, compression set, thermal stability, chemical resistance, density, and hardness, whereas the columns represent potential families of additive or blend variants (e.g., TPE-S, TPU, TPE-E, TPV). The expectations of property ranges each cell obtains based on literature, supplier data and previous experimental outcomes, as well as the qualitative commentaries reflecting sensitivity to processing. Other properties that these notes may contain are sensitivity to shear history, moisture uptake, thermal degradation, or additive migration, which are critical to manufacturability and long-term performance. Processing-related parameters (e.g., melt temperature window, viscosity behavior, extrusion or injection molding compatibility, etc.) are also incorporated within the matrix and its tolerance to recycled/reclaimed content. Through comparisons between intrinsic material behavior [1] and formulation-dependent accommodations, the matrix shows trade-offs between performance improvement and the complexity of the processing-complexity-performance-complexity-price-performance-complexity-experiments-complexity relationships can be shown, such as resulting performance improvement via added filler at the cost of increased melt viscosity or reduced processing windows. Notably, the property process matrix not only acts as a screening tool, but also as a framework of decision-support, thus allowing the designers to see how alterations of formulation or processing conditions affect a number of performance dimensions at the same time. Such systematic notation allows the clear comparison of the options of materials, minimizes the importance of trial and error experimentation, and enables efficient decision-making at the early design stage. Last, but not least, the matrix can be used as a binding factor between material science concerns and manufacturing realities, to make sure that the chosen TPE systems are technically and practically feasible.

3.3. LCA HEURISTICS AND EMBODIED CARBON ESTIMATES

Under this framework, life cycle assessment (LCA) heuristics are used as a heuristic, used in the initial screening of materials to perform early material selection, prior to proceeding with resource-intensive, full-scale LCAs. Proxies. At this point, the literature-reported embodied carbon ranges serve to compare candidate thermoplastic elastomer (TPE) families on a per-kilogram basis, although the underlying uncertainty and variability of the range, arising from the feedstock origin, process efficiency, [14] and system limits, is recognized. TPE based on polyolefins, such as thermoplastic olefins (TPOs), thermoplastic vulcanizates (TPVs), tend to have lower degrees of embodied carbon (normally within the range of around 1.5 to 4 kg CO 2 equivalent per kilogram) because of comparatively straightforward polymerization procedures and energy-saving high-volume manufacturing facilities. Conversely, thermoplastic polyurethanes (TPUs) tend to exhibit larger values of embodied carbon, typically with the range of 2.5-6 kg CO 2 -equivalent per kilogram, due to the energy-intensive production of isocyanates, polyols, and chain extenders, and to the effect of fossil- versus bio-based monomer feedstock. Such per-kilogram comparisons can, however, also be confusing when taken on their own, as less dense or more efficient material may allow part mass to be reduced or service life increased and thus balance out higher material-level emissions. The use of reclaimed materials, especially ground tyre rubber (GTR) or devulcanized rubber, adds further complexity but also potential, in that substituting virgin polymer content with reclaimed rubber can lead to the effective embodied carbon of the combination to near zero or singularly negative at specific allocated ratios; however, reclaimed rubber may be applied to designate specifically embodied carbon of the blend. This advantage, however, [15] will depend on the accounting of devulcanization energy, distances of transportation, and losses of the processing. Therefore, these heuristics are useful at giving directional hints when it comes to screening and prioritization, but cannot be used in lieu of detailed LCAs. Detailed process-based energy information, realistic transport conditions and clear end-of-life assumptions are needed to make a solid and justifiable sustainability analysis.

3.4. COMPOUNDING AND ADDITIVE SELECTION RULES

The compounding and additive selection factors have a determining role in balancing between performance, sustainability and regulatory goals of the thermoplastic elastomer (TPE) systems. In the context of maximizing recycled or reclaimed content, literature is always keen on the uniqueness of good compatibilization in order to eliminate interfacial incompatibilities of dissimilar polymer phases. [16] The maleated polyolefins and other epoxidized oils are popular compatibilizers because they assist in improving the interfacial adhesion, which is either through reactive or polar interactions at relatively low levels of environmental and toxicological risks. Such materials facilitate increased content of recycled polymers or reclaimed rubber without causing dramatic degradations in mechanical strength, which fosters circular material strategies. In applications with increased abrasion and tear resistance needs, like in automotive parts, shoes or hoses used in the industry, TPU and TPEE matrices are a common choice because of their inherent toughness and mechanical wear resistance. The addition of fillers like nano-silica, carbon black, and developing nanomaterials like graphene nanoplatelets has been demonstrated to considerably enhance abrasion resistance, tear durability and fatigue life. But their utilization exhibits trade-offs connected to augmented melt viscosity, dispersion difficulty, and feasible embrittlement at full filler contents. Consequently, filler type, surface chemistry and loading degree have to be well balanced with processability and impact toughness, especially in situations of injection molding or extrusion where there are very tight processing tolerance bands. [17] Simultaneously, an increasing regulatory pressure and a health concern have increased the pace of substituting traditional phthalate-based plasticizers with less toxic ones. Epoxidized soybean oil and other epoxidized vegetable oils are, however, being used as bio-based plasticizers having lower toxicity, lower volatility and better compatibility with polar TPEs. In addition to plasticization, these additives may have thermal stability and aging resistance properties. Taken together, these compounding guidelines lead us to the fact that a holistic formulation approach must be taken into consideration, where mechanical performance, processability, environmental impact, and regulatory compliance are no longer optimized independently.

3.5. TESTING PROTOCOLS

Effective screening and testing of thermoplastic elastomer (TPE) formulations requires a standardized and application-relevant testing protocol to be effective in screening and comparing materials. The tensile testing is performed first to determine mechanical performance as prescribed by the ASTM D412, and the tensile strength, tensile elongation, and tensile modulus are determined to enable evaluation of elasticity, as well as load-bearing capacity. ASTM D624 is used to measure tear resistance, especially important in dynamic or edge-loaded applications, to distinguish between materials with similar tensile characteristics and on which the crack propagation resistance varies. The abrasion resistance, which is a very important requirement when it comes to evaluating footwear, automobile, and industrial parts, is tested by the use of ASTM D5963, which simulates the loss of a material in predetermined abrasive situations. ASTM D395 assesses the long-term behavior of deforming under compression set testing to provide an understanding of how an elastic material recovers after long-term compressive deformation and thermal deformation. Screening of low-temperature performance is done according to ASTM D2137, which tests the brittle point or flexibility [18] at temperatures below the ambient temperature, a critical attribute of outdoor or cold-environment applications. The environmental durability is also evaluated by using accelerated weathering tests, such as ISO 4892 or ASTM 154, which are tests that mimic ultraviolet sunlight, moisture content, and thermal cycling to foretell against aging, discoloration, and property deterioration. The chemical resistance is determined by use of ASTM D471, whereby samples are subjected to oils, fuels or liquids that can be encountered in their application to measure swelling, mass change, and mechanical retention. Accelerated aging tests with high temperature, UV exposure and contact with chemicals are done to estimate service life with retention of property recorded over time. Together, the provided set of tests allows for a rapid but high-quality screening of candidate materials so that only the formulations that can satisfy the initial performance and life cycle characteristics can continue to the intensive qualification and life cycle testing phase.

4. RESULTS AND DISCUSSION

4.1. CASE STUDY A: AUTOMOTIVE DOOR SEAL

The case study demonstrates how the selection framework proposed was applied to an automotive door seal, which had to have long-term weather resistance, elastic recovery and be able to produce at a cost lower than that of competing vehicles. [19] The functional specifications were in low air and moisture permeability, resistance to ozone and ultraviolet exposures, and less than 25% compression set after 70 hours at 100 o C to enhance sealing performance during long service life. According to these demands, thermoplastic vulcanizates (TPVs) utilizing EPDM/PP and thermoplastic polyester elastomers (TPEEs) were short-listed because they are known to be used in exterior automobiles. Although TPEEs provided a good mechanical strength and thermal stability, TPVs were preferred because of better compression set behaviour, reduced density, as well as well-known recyclability routes in polyolefin feeds. The chosen compound included an EPDM/PP TPV compounded with about 20 wt%. silica filler to topple abrasion and dimensional integrity without generating a major increase in hardness. Anti-ozonant additives in polymer form that are non-volatile and provide a long-term resistance to ozone cracking and UV degradation were used, meeting the durability needs of exterior degradation. Maleated polypropylene (MAPP) was employed as a compatibilizer to enhance the transfer of stress and minimize the interfacial failure in order to improve interfacial adhesion and enhance overmolding or bonding to the polypropylene substrates. [1] It was verified that the TPV formulation was achievable with regard to compressing the set and had a good weathering performance in conjunction with being usable through extrusion. According to the sustainability view, initial embodied carbon screening showed a figure between 1.8 and 2.8 kg CO 2 equivalent per kilogram, which is comparable to polyolefin-based elastomer systems. Despite the limitation of recyclability in the phase of Croslinked rubber, the moderate recoverability at the end of life through mechanical recycling and density/solvent separation can be effective, which makes the TPV solution a middle balancing option in terms of performance-cost and environmental consideration.

4.2. CASE STUDY B: CONSUMER SOFT-TOUCH GRIP

The case study transposes the material selection framework on a consumer soft-touch grip in which the key performance of the consumer is the perception of the product, aesthetics, and comfort, and the overall mechanical experience of the material is moderate durability. The specification stressed a soft skin feel, controlled surface friction, no surface tackiness, moderate abrasion resistance and long stability of color under handling and under light UV exposure. According to these qualifications, [20] the shortlist was limited to styrenic block copolymer-based TPEs (SEBS-type TPE-S) structural materials and the ether-based thermoplastic polyurethanes (TPUs), because of their prevalence in consumer electronics, hand tool and personal care products. Materials of SEBS were chosen due to the low hardness level inherent to their usage, good tactile feedback and easy colouring, as well as compatibility with overmolding on polyolefin materials. The chosen SEBS formulation added a fine mineral filler to gain a matte surface finish and lowered surface gloss in an effort to raise perceived quality and minimize fingerprints visibility. Softness and damping behavior were found by using a bio-based plasticizer without being tacky, with less dependence on petroleum-based additives. This formulation provided the required soft-touch appearance along with good color stability and good processing properties, such as low melting temperature and broad processing range. Simultaneously, TPU formulations based on ether were tested because they have a strong resistance to abrasiveness, tear strength, and are long-lasting in repeated handling. Although TPUs were found to offer better wear resistance and anti-surface polishing with time, they were found to be costly in terms of material, more dense, and embodied carbon when compared to the SEBS-based alternatives. In the end, the SEBS variant was chosen as the solution of choice to be used in the applications that focus more on aesthetics, tactile comfort and sustainability, it has fewer embodied carbon and cost benefits. Nevertheless, when the product experiences high levels of abrasion or has high levels of service life, TPU should be chosen despite its increased environmental and economic cost, which demonstrates that application-specific trade-offs should be considered when choosing materials.

4.3. CASE STUDY C: GTR–TPE RECLAIMED COMPOSITE

The case study illustrates how the proposed framework was implemented in a recycled-material system aimed at the optimization of the use of ground tyre rubber (GTR) in a thermoplastic elastomer-based floor mat in an automotive or consumer product. The main requirement was to add 30-50 wt% GGR and, at the same time, be flexible enough, abrasion resistant and dimensionally stable to be used as a non-structural material. One polypropylene based thermoplastic vulcanizate (TPV) was identified as a shortlisted material because it has the ability to take in recycled polyolefin streams, good cost base, and is well processed. In order to resolve the consistent incompatibility of vulcanized rubber particles and thermoplastic matrix, a reactive compatibilization plan was followed. The desired formulation was made up of TPV base combined with about 40 wt% GGR, 5 wt% maleated polypropylene (MAPP), in order to allow interfacial attachment with the PP phase and 3 wt% epoxidized natural rubber (ENR) as a secondary binding compound in order to allow titration with the rubber phase. The reactive extrusion with varied dynamic vulcanization parameters was also processed, which allowed regulating the GTR particle size and dispersion, and this was essential in obtaining reasonable mechanical performance. This composite produced tensile strength, elongation, and abrasion resistance that would provide use on floor mats and other similar applications not involving a load, and properties were below virgin TPV formulations. In sustainability terms, the initial life cycle assessment showed significant embodied carbon savings in comparison with virgin TPE parts, in part when the feedstock polymer was replaced. Nevertheless, practical difficulties were also pointed out, such as the oscillation change in the composition of GTR and the particle size, and the odor control of reclaimed rubber. Nevertheless, these constraints do not rule out the prospects of

GTR -TPE composites as practical circular-material solutions with performance demands that are moderate and sustainability benefits as a priority.

4.4. COMPARATIVE TRADEOFF ANALYSIS

TABLE 1 Comparative tradeoff analysis

Metric	TPE-S (%)	TPU (%)	TPV (%)	TPEE (%)
Cost Advantage	70	40	85	45
Abrasion Resistance	60	95	65	90
Weathering Resistance	65	85	90	85
Recyclability	80	85	55	70
Bio-based Availability	65	75	40	70

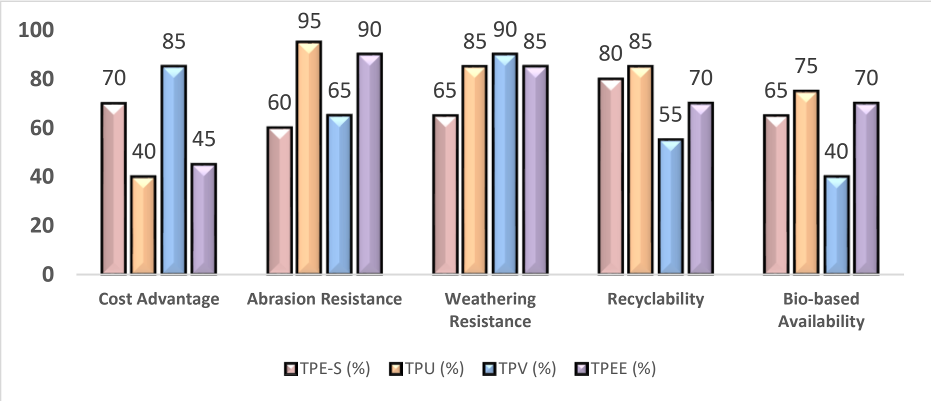

FIGURE 3 Comparative tradeoff analysis

4.4.1. COST ADVANTAGE
On a cost front, TPVs have the greatest relative advantages, which is considered due to the abundance of polyolefin feedstock and established, high-throughput manufacturing processes. Cost positioning of TPE-S materials also proves to be favorable because styrenic block copolymer can be produced easily, and it is also easy to process the same. On the other hand, TPU and TPEE systems will be more expensive, as the chemistries are more complicated, the cost of raw materials is higher, and more processing control is strategic.

4.4.2. ABRASION RESISTANCE
The most resistant materials are TPU and TPEE, which have the advantage of hard-segment crystallinity and good intermolecular contact, resulting in high wear resistance at repeated contacts. TPE S and TPV materials have moderate resistance to abrasion that is normally adequate when used in consumer and automotive interior use, but might be restrictive in very abrasive service conditions. This gap can be reduced partially with the use of additive reinforcement.

4.4.3. WEATHERING RESISTANCE
EPDM-based TPVs are exhibiting the best weathering performance with resistance to ozone, UV radiation, and thermal ageing, and therefore, they are ideal for exterior use in automobiles. [21] TPU and TPEE also do not suffer in weathering conditions, particularly when these plastics are stabilized with suitable UV absorbers and antioxidants. TPE-S materials have middling resistance and usually need further stabilization to be used in the long run outdoors.

4.4.4. RECYCLABILITY
TPE-S and TPU have a relatively high degree of recyclability, especially when applied in mono-material structures that can be recycled through the mechanical method with relatively low property loss. TPEE materials will be moderately recyclable, although they are subject to phase separation and hydrolytic impairments, making reprocessing difficult. TPVs are more difficult to recycle, since they have a dynamically vulcanized rubber phase that is not melt reproducible.

4.4.5. BIO-BASED AVAILABILITY
TPU and TPEE systems are the most advanced in bio-based versions, with renewable polyols, diacids/diols becoming more popular at a commercial level. There are some bio-based materials in TPE-S, which are offered mainly in the form of renewable oils, and to a smaller degree using bio-derived blocks. TPVs are currently indicating limited bio-based availability, considering that EPDM and polypropylene is mostly of fossil-based nature, limiting levels of renewable content.

4.5. DISCUSSION

The similar comparison and the case studies highlight a primary performance sustainability tradeoff in the selection of thermoplastic elastomers. Greater-performance materials like TPU and TPEE tend to be better in abrasion resistance, mechanical strength and durability, although these performance advantages are often accompanied by increased embodied carbon, as the synthesis pathways and chemistries tend to be more energy-consumptive. These materials can, however, give overall net environmental advantages in the entire service life of a component: they can be made generally thinner, possess longer lives and require replacement less frequently, supporting the fact that life cycle assessment should be used instead of using carbon metrics on a material basis. The findings also emphasize the judgmental role of additives in achieving the performance and sustainability goals. The built-in compatibility with compatibilizers, bio-based plasticisers, and low-toxicity stabilisers allows increased inclusion of reclaimed or recycled material without compromising on acceptable mechanical performance and regulatory compliance, conforming well to what the user has previously focused on in new additive technologies. Lastly, conditions of processing form a subject of critical but underestimated concern in sustainable material selection. The strategy of reactive extrusion and dynamic vulcanization parameters has a strong effect on phase morphology, dispersion quality and interfacial adhesion, which consequently determine the mechanical performance and durability. Simultaneously, processing decisions have a direct impact on the energy use and emissions, meaning that the processing efficiency should be addressed as a part of the broad selection platform used in conjunction with the material formulation.

5. CONCLUSION

Transition to sustainable manufacturing in the rubber industry demands a paradigm change from a traditional material selection approach to performance-based and sustainability-focused decision support. This work has shown that TPEs represent an attractive alternative to vulcanized rubbers in view of their recycle capacity, lower energy consumption during processing, freedom of design and ameliorated environmental impact. By blending the solutions to these two challenges through sustainable design principles, combined with application-based material selection criteria, manufacturers can gain functional performance and enhanced environmental benefit.

Comparative evaluation clearly shows the excellence of TPEs in reprocessability, shorter cycle time, and fit to the circular economy. Their remelting and reforming capabilities help to minimize material waste, supporting closed-loop manufacturing processes. Moreover, the development of bio- and recyclable TPE compounds has improved their sustainability without significantly affecting mechanical strength, service life or thermal characteristics across a range of industrial uses.

However, the study also demonstrates that material choice is still application dependent. Although TPEs work well in relatively light consumer and automotive applications in which flexibility and processability are the key requirements, traditional thermoset rubbers may be preferred in extreme thermal or load environments. Hence, selection based on sustainability cannot be solely based on environmental measures, but must be based on mechanical performance, lifecycle assessment results, cost effectiveness and possibly the regulations compliance.

Ultimately, implementing an application-based, structured approach to selection also allows manufacturers to maximize material performance while improving environmental stewardship. The combination of lifecycle thinking, energy-efficient processing technologies, and recyclable elastomer systems means TPEs are perfectly placed as an important facilitator for sustainable innovation in rubber production. Forthcoming research directions should explore advanced high-temperature resistance, bio-based feedstock extension, and unified regular protocols for sustainability assessment to further robust TPEs in next-generation industrial applications. Shifting from traditional material selection-based practices to performance-based and sustainability-related decision frameworks is part of the transformation process towards sustainable manufacturing in the rubber industry. This research work has proved that TPEs are an attractive substitute to conventional vulcanized rubbers because of their recyclability, reduced energy consumption during processing, flexibility in design and potential for low environmental impact. Through the adoption of holistic sustainable design principles while combining with application-specific choice of materials, manufacturers are able to deliver on functionality and enhanced environmental benefits.

The comparative evaluation shows that TPEs offer many benefits for reprocessable, short production cycle materials and are compatible with the circular economy. Their remelting and molding capabilities not only prevent waste but also facilitate closed-loop manufacturing. Furthermore, the development of biodegradable or recyclable TPE formulations also contributes toward their sustainability profile while maintaining relatively good mechanical, durability and thermal performance for a wide range of industrial applications.

Yet, the analysis also reveals that material choice must be balanced against application requirements. Although TPEs exhibit excellent performance in lightweight, consumer and automotive products with flexible and easy processability requirements, under the most extreme conditions of high-temperature or high-load environments, conventional thermoset rubbers may still be more suitable. Thus, sustainability-based selection should not exclusively depend on environmental criteria; it should take mechanical performance, lifecycle assessment results, cost-effectiveness and regulation compliance into consideration as well.

Finally, by utilizing a systematic application-based selection process, manufacturers are able to maximize material performance and promote environmental stewardship. The infusion of lifecycle principles, energy-saving processing technologies and scrap-tolerant elastomer systems proves TPEs critical to unlocking the potential of sustainable innovation in today's rubber industry. In future, it is suggested to develop a bio-based feedstock strategy and enhance the temperature resistance under high temperature conditions while also promoting standardization of the sustainable assessment system in order to facilitate TPEs for more potential industrial applications.

REFERENCES

[1] G. Holden, Thermoplastic elastomers, In Applied plastics engineering handbook, William Andrew Publishing, pp. 97-113, 2024.

[2] J. E. Mark, B. Erman, and M. Roland, The science and technology of rubber. Amsterdam: Elsevier Academic Press, 2013.

[3] R. P. Babu, K. O'Connor, and R. Seeram, "Current progress on bio-based polymers and their future trends," Progress in Biomaterials, vol. 2, no. 1, p. 8, 2013, doi: https://doi.org/10.1186/2194-0517-2-8.

[4] P. Parcheta, E. Głowińska, and J. Datta, "Effect of bio-based components on the chemical structure, thermal stability and mechanical properties of green thermoplastic polyurethane elastomers," European Polymer Journal, vol. 123, p. 109422, Jan. 2020, doi: https://doi.org/10.1016/j.eurpolymj.2019.109422.

[5] H. Nakajima, P. Dijkstra, and K. Loos, "The Recent Developments in Biobased Polymers toward General and Engineering Applications: Polymers that are Upgraded from Biodegradable Polymers, Analogous to Petroleum-Derived Polymers, and Newly Developed," Polymers, vol. 9, no. 12, p. 523, Oct. 2017, doi: https://doi.org/10.3390/polym9100523.

[6] P. Gallezot, "Conversion of biomass to selected chemical products," Chem. Soc. Rev., vol. 41, no. 4, pp. 1538–1558, 2012, doi: https://doi.org/10.1039/c1cs15147a.

[7] L. Asaro, M. Gratton, S. Seghar, and N. Aït Hocine, "Recycling of rubber wastes by devulcanization," Resources, Conservation and Recycling, vol. 133, pp. 250–262, Jun. 2018, doi: https://doi.org/10.1016/j.resconrec.2018.02.016.

[8] M. Capelot, M. M. Unterlass, F. Tournilhac, and L. Leibler, "Catalytic Control of the Vitrimer Glass Transition," ACS Macro Letters, vol. 1, no. 7, pp. 789–792, Jun. 2012, doi: https://doi.org/10.1021/mz300239f.

[9] J. George, M. S. Sreekala, and S. Thomas, "A review on interface modification and characterization of natural fiber reinforced plastic composites," Polymer Engineering & Science, vol. 41, no. 9, pp. 1471–1485, Sep. 2001, doi: https://doi.org/10.1002/pen.10846.

[10] P. Jia, H. Xia, K. Tang, and Y. Zhou, "Plasticizers Derived from Biomass Resources: A Short Review," Polymers, vol. 10, no. 12, p. 1303, Nov. 2018, doi: https://doi.org/10.3390/polym10121303.

[11] Arunima Reghunadhan et al., "Thermoplastic elastomers (TPEs) from rubber-plastic blends," Advances in Thermoplastic Elastomers, pp. 291–314, Jan. 2024, doi: https://doi.org/10.1016/b978-0-323-91758-2.00008-8.

[12] Y. Lin et al., "Application-Driven High-Thermal-Conductivity Polymer Nanocomposites," ACS Nano, vol. 18, no. 5, pp. 3851–3870, Jan. 2024, doi: https://doi.org/10.1021/acsnano.3c08467.

[13] Jayadip GhanshyamBhai Tejani, "Thermoplastic Elastomers: Emerging Trends and Applications in Rubber Manufacturing," Global disclosure of economics and business, vol. 6, no. 2, pp. 133–144, Dec. 2017, doi: https://doi.org/10.18034/gdeb.v6i2.737.

[14] N. R. Legge, "Thermoplastic elastomers, Rubber Chemistry and Technology, vol. 60, no. 3, pp. 83-117, 1987, doi: https://doi.org/10.5254/1.3536141

[15] E. Maréchal, "Creation and Development of Thermoplastic Elastomers, and Their Position among Organic Materials," Handbook of Condensation Thermoplastic Elastomers, pp. 1–31, May 2005, doi: https://doi.org/10.1002/3527606610.ch1.

[16] N. T. Dintcheva, G. Infurna, M. Baiamonte, and F. D'Anna, "Natural Compounds as Sustainable Additives for Biopolymers," Polymers, vol. 12, no. 4, p. 732, Mar. 2020, doi: https://doi.org/10.3390/polym12040732.

[17] L. F. Dumée, "Circular Materials and Circular Design—Review on Challenges Towards Sustainable Manufacturing and Recycling," Circular Economy and Sustainability, vol. 2, Jun. 2021, doi: https://doi.org/10.1007/s43615-021-00085-2.

[18] P. Sahu, J. S. Oh, and A. I. Isayev, "Chapter 21 Recycling and circular economy of thermoplastic elastomers," Advances in Thermoplastic Elastomers, pp. 529–561, Jan. 2024, doi: https://doi.org/10.1016/b978-0-323-91758-2.00009-x.

[19] Y. Zhang, J. Wang, Y. Xue, and J. Yang, "Impact of environmental regulations on green technological innovative behavior: An empirical study in China," Journal of Cleaner Production, vol. 188, pp. 763–773, Jul. 2018, doi: https://doi.org/10.1016/j.jclepro.2018.04.013.

[20] Wole Soboyejo, "Mechanical Properties of Engineered Materials," CRC Press eBooks, Nov. 2002, doi: https://doi.org/10.1201/9780203910399.

[21] A. Pouzada, Selection of thermoplastics, Design and Manufacturing of Plastics Products, UK: William Andrew Publishing, pp. 87-140, 2021.