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Editorial corner – a personal view

Sustainability in the rubber industry: State of the art

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The transition toward sustainable materials and circular economy principles has become a central driver of innovation in polymer science and engineering. The rubber industry, as one of the major consumers of both fossil-based and natural resources, is under increasing pressure (social and regulatory) to reduce its environmental footprint while maintaining performance, safety, and economic competitiveness. This multifactor challenge is accelerating the development and implementation of alternative raw materials, resource-efficient technologies, and system-level design strategies. This trend is evident in the rubber industry as well. Major tire manufacturers, such as Continental, Michelin, and Bridgestone, are increasingly seeking sustainable materials, replacing carbon black, plasticizers, and synthetic rubbers, which are most often derived from petroleum or natural gas, thereby reducing environmental impact and manufacturing costs (https://doi.org/10.1108/PRT-08-2024-0082).

At the same time, sustainability must be addressed from a life cycle perspective. We must consider the impact of the product or service across its entire life cycle, as defined by life cycle assessment (LCA, ISO 14040:2006). These stages are, for example, for a rubber product include raw material acquisition, transportation, manufacturing, use phase, and end-of-life stage (*e.g.*, UL 10006). Importantly, a substantial proportion of these impacts is determined during the design phase.

An important emerging aspect of sustainability in the rubber industry is the growing concern over microplastic emissions originating from tyre wear, which represent a substantial share of total microplastic pollution (https://doi.org/10.1016/j.scitotenv.2025.179114). Recent regulatory developments, including the introduction of Euro 7 standards and UNECE abrasion limits, extend environmental considerations beyond production to explicitly address use-phase emissions (https://unece.org/sustainable-development/press/unece-reduce-microplastic-emissions-thanks-adoption-abrasion-limits). These trends highlight a paradigm shift in which abrasion resistance, material durability, and compound design become critical parameters for both environmental compliance and sustainable product development.

Therefore, collaborative action is needed to minimize the environmental impact of a product, including its performance at the use stage, the chosen raw materials and feedstocks, reusability, manufacturability, and recyclability (https://doi.org/10.3139/9781569908624). Also, new economic models are emerging, such as tire-as-a-service (https://www.goodyear.eu/en_gb/truck/tyre-management/tires-as-a-service.html).

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From the materials point of view, the rubber industry relies on a range of elastomers, including natural rubber (NR), styrene–butadiene rubber (SBR), butadiene rubber (BR), ethylene propylene diene monomer (EPDM), and acrylonitrile-butadiene rubber (NBR). Sustainability strategies differ markedly across these systems. For synthetic rubbers, current research focuses on bio-based monomers and alternative feedstocks (*e.g.*, recycled or CO_2-derived sources) to reduce reliance on fossil resources (https://doi.org/10.1201/9781315152967-6). In contrast, for natural rubber (NR), efforts focus on improving agricultural efficiency, reducing land-use and supply chain impacts, and diversifying sources beyond *Hevea brasiliensis* through alternative plants such as *Taraxacum kok-saghyz*, *Parthenium argentatum*, and *Lactuca sativa* (https://doi.org/10.1039/d5su00177c).

The following sections translate these general sustainability considerations into specific material classes and technological solutions, focusing on plasticizers, fillers and reinforcements, devulcanizates, and processing technologies.

Among the additives used in the rubber industry, plasticizers play a particularly important role in controlling the processability of the compounds and the mechanical properties of the finished product. Conventional plasticizers are primarily aromatic petroleum derivatives, which are associated with several environmental and health concerns and are derived from fossil resources; therefore, the development and use of sustainable alternatives are important (https://doi.org/10.1002/pen.25443).

One of the largest groups consists of bio-based plasticizers, such as vegetable oils (soybean oil, palm oil, castor oil, etc.), fatty acid esters, natural resins, or even molecules produced by fermentation. Their advantage is that they are derived from renewable sources, and with appropriate chemical modification (*e.g.*, epoxidation, hydrogenation), their structures can be adjusted for compatibility and stability with the elastomer matrix. Their use is not only aimed at replacing aromatic oils but can also serve to improve the biocompatibility, recyclability, and market value of the final product (https://doi.org/10.1002/ejlt.200900091).

Another important area is the utilization of industrial byproducts and waste streams as plasticizers in the rubber industry. These may include, for example, biomass-based pyrolysis oils, compounds derived from sewage sludge or wood industry waste, and oil fractions obtained from the pyrolysis of various recycled plastics or tires. Pyrolysis oil is a complex mixture of various aromatic, aliphatic, naphthenic, and oxygen-containing compounds, and after appropriate purification (*e.g.*, desulfurization, solvent extraction, distillation), it can potentially be used in rubber compounds as a plasticizer. Several studies have shown that, with proper preparation, the properties of regenerated and pyrolysis oils (viscosity, saturation, volatility, etc.) can be adjusted to the desired level, making them suitable for use in rubber compounds (https://doi.org/10.1016/j.wasman.2013.05.003).

Rubber compounds contain a significant amount of fillers (up to 30–40 wt%), so partially or even completely replacing them can reduce the environmental impact of the compounds. Nothing proves this better than the fact that the rubber industry uses more than 20 million tons of fillers globally each year, the majority of which consists of carbon black and silica.

Alternative fillers can be broadly divided into two main categories: bio-based and recycled-material-based. Bio-based fillers are typically derived from agricultural by-products or biomass, such as natural fibers, cellulose derivatives, lignin, and polysaccharides. Among these, rice husk-derived silica is particularly notable for its high silica content, large specific surface area, and reinforcing capability comparable to that of conventional silica. Its main advantage lies in utilizing agricultural waste while significantly reducing CO_2 emissions associated with traditional filler production (https://doi.org/10.1016/j.heliyon.2025.e42491). Another important candidate is biochar, produced via pyrolysis of biomass. Biochar exhibits high carbon content, tunable porosity, and good thermal stability. While it generally cannot fully match the reinforcing performance of conventional carbon black, partial substitution can maintain mechanical properties, making it a viable sustainable alternative (https://doi.org/10.1007/s42773-025-00429-3).

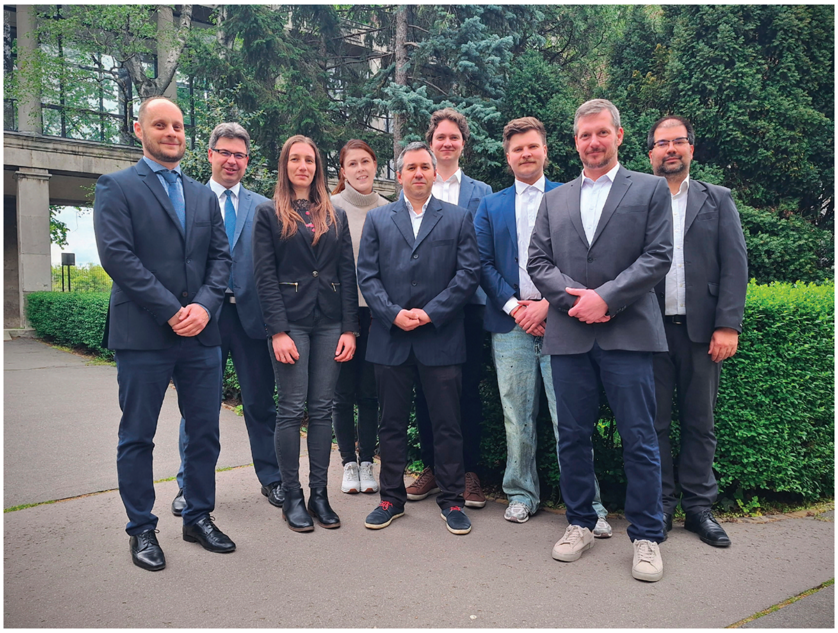
Recycled fillers also play a key role, including pyrolytic carbon black, recovered from waste tires through pyrolysis. This material enables the reintegration of end-of-life rubber products into new compounds, supporting circular material flows. Although its properties differ from conventional carbon black – mainly due to higher ash content and structural heterogeneity – it can still be used as a partial replacement (https://doi.org/10.3390/polym15071604). Another promising filler is ground printed circuit board (PCB) waste. PCB-derived fillers typically contain a mixture of glass fibers, resins, and inorganic components, offering stiffness and potential reinforcing effects, although compatibility and dispersion challenges must be addressed (https://doi.org/10.3144/expresspolymlett.2025.41).

Sustainability in the rubber industry cannot be discussed without proper management of vulcanized waste (https://doi.org/10.3144/expresspolymlett.2025.20). This material – owing to its crosslinked nature – can not be recycled with conventional melt-based recycling technologies. One straightforward and economically attractive approach is the direct incorporation of ground tire rubber (GTR) into new rubber compounds. This practice is already established at low concentrations and is the subject of extensive ongoing development to increase the achievable GTR content through improved dispersion and interfacial interactions. However, the crosslinked nature of GTR inherently limits its processability and compatibility, leading to a deterioration in mechanical properties at higher loadings. Another approach is devulcanization – the selective scission of crosslinks while preserving backbone integrity – offers a rational pathway toward true material circularity. Among the investigated routes, thermomechanical devulcanization via twin-screw extrusion has emerged as the most industrially mature, offering continuous processing and scalable throughput with reasonable selectivity. However, it is often paired with additional chemicals (devulcanization aids such as disulfide-based compounds, thiosalicylic acid, or bifunctional silanes) to further improve the processability of the devulcanized rubbers. Supercritical CO_2-assisted ($scCO_2$) thermomechanical processing, as pioneered industrially by Tyromer Inc., represents a particularly promising variant, that combines the plasticizing effect of $scCO_2$ with mechanical shear to achieve efficient, solvent-free devulcanization (US 7,182,762). On the chemical side, deep eutectic solvents (DES) – particularly choline chloride-urea systems – have attracted growing scientific interest as low-temperature, low-toxicity devulcanization (https://doi.org/10.3144/expresspolymlett.2025.60).

A critical and often underestimated challenge lies in the compounding stage: integrating devulcanized rubber into existing rubber formulations requires careful rebalancing of the vulcanization system, as residual accelerator fragments and partially reformed cross-links alter the cure kinetics of the host compound (https://doi.org/10.3390/polym16040455). Achieving consistent mechanical performance demands compound-specific optimization of sulfur and accelerator dosage, filler loading, and mixing protocol – a non-trivial task given the variability of waste-derived feedstocks.

During rubber processing, highly complex rheological, thermodynamic, and chemical processes occur, making it extremely difficult to determine optimal product and tool designs, as well as optimal process parameters. Furthermore, the properties of rubbers designed for different applications can vary widely, which further increases the complexity of finding the optimal solution. To facilitate this task, computer simulation methods for rubber technologies have been under development for several decades and are now capable of determining a wide range of parameters. Today, it has become possible, among other things, to predict permanent deformation of molded products within a single software by taking the processing history into account (https://doi.org/10.3390/polym17020149), and even to predict the mechanical properties of injection molded products (https://doi.org/10.3390/polym16142033). At the same time, numerous challenges remain in the field of simulation routines. Advances in simulation algorithms and the development of more accurate models can contribute to a better understanding of the behavior of rubber raw materials in the future. By optimizing cycle times and energy consumption and reducing scrap rates, these advancements can help create a more sustainable rubber industry.

The transition toward sustainability in the rubber industry requires coordinated advances in materials, processing, and system-level design. While bio-based feedstocks and recycled fillers and plasticizers offer promising pathways, challenges related to performance consistency, scalability, and economic viability remain. Future progress will rely on integrating circular material flows with design-for-recyclability and improved devulcanization strategies. In parallel, digital tools and life cycle assessment will support more informed material and process decisions. Ultimately, achieving a sustainable rubber industry depends on bridging laboratory innovations with industrial implementation, supported by collaboration across academia and industry, and guided by robust standards and regulatory frameworks. In our view, the rubber industry has a clear and viable pathway toward sustainability, and with continued innovation and industrial commitment, it will remain a key materials platform in a circular economy. This paper was supported by the National Research, Development and Innovation Office, Hungary (2019-1.1.1-PIACI-KFI-2019-00172, 2024-1.1.1-KKV_FÓKUSZ-2024-00080).



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