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Review Article

The role of deep eutectic solvents in advancing rubber science: A mini review

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Abstract
Deep eutectic solvents (DESs) have emerged as promising tools for advancing rubber research because of their unique properties and eco-friendly nature. This mini review highlights the different applications of DESs in rubber research, mentioning their role in the devulcanisation of waste rubber, enhancement of mechanical properties, and the mechanisms by which DESs interact with rubber compounds, basically their ability to disrupt sulfur bonds and cross-linked structures, are discussed in detail. Moreover, DES integrations, including Choline Chloride (ChCl): ethylene glycol and ChCl: oxalic acid, yield high hemicellulose and cellulose compositions, underscoring their efficacy. Furthermore, this review highlights the chemical mechanisms by which DES compounds disrupt sulfur bonds and cross-linked networks, as well as discusses the chemical mechanisms by which DESs react with rubber compounds, disrupting sulfur bonds and cross-linked networks. However, future research should explore optimizing DES formulations and seeking broader applications in rubber science to fully harness their potential for sustainable and innovative advancements in this field.

Keywords: solvents, plant-derived, sustainable solvents, rubber production, eco-friendly

Introduction

Deep eutectic solvents (DESs) are a promising class of green solvents that are more environmentally friendly than ionic liquids (ILs), with properties that make them highly relevant for applications in the rubber industry. These solvents are formed through a eutectic mixture of a hydrogen bond donor (HBD) and a hydrogen bond acceptor (HBA), resulting in low melting points and unique physicochemical characteristics [1]. DESs are known for their low volatility, nonflammability, and high thermal stability, making them safer alternatives to conventional solvents [2]. DESs are broadly classified into five types based on their components as shown in **Figure 1**. Type I comprises metal salts and quaternary ammonium salts, such as $ZnCl_2$ and choline chloride. Type II involves metal salt hydrates paired with quaternary ammonium salts, such as $CrCl_3.6H_2O$ and choline chloride. Type III consists of hydrogen bond donors combined with quaternary ammonium salts, such as urea and choline chloride. Type IV uses metal salts in combination with hydrogen bond donors, such as $ZnCl_2$ and ethylene glycol. Type V includes mixtures of purely molecular compounds that do not involve metal-based salts, such as thymol and menthol [3,4]. DESs have attractive unique properties, involving low melting points, e.g. a mixture of choline chloride and urea (1:2 molar ratio), which has a melting point of approximately 12°C, regardless of whether components are solid at room temperature [5]. DESs have a high viscosity, which can be both a challenge in some applications and beneficial in other applications, particularly in electrochemical processes. DES are nonflammable and have low vapor pressures, creating them safer to handle and minimizing the risk of fire hazards unlike conventional organic solvents [6].

The properties of DESs can be easily tuned by varying the type and ratio of HBD and HBA, as well as the water and temperature composition, allowing the customisation of DESs for specific applications [7]. DESs often demonstrate high ionic conductivity, indicating that they are reasonable for use in electrochemical applications, including fuel cells and batteries [8]. Many DESs are composed of biodegradable and natural, compounds, which are environmentally friendly alternatives to conventional solvents. They also tend to have low toxicity, further increasing their green chemical credentials [9]. The density, phase behavior, surface tension, and polarity of DESs can be overwhelmed by the choice of components, molar ratio, and water content, which are essential factors in determining the suitability of DESs for different applications [10,11]. In a wide range of fields, DES have been applied, highlighting their versatility and effectiveness. DESs can serve as solvents or catalysts in different chemical reactions, increasing reaction efficiency and selectivity in catalysis [12]. In addition, DESs are utilised in extraction and purification methods, providing a green alternative to conventional solvents in separation processes. DESs play an essential role in electropolishing, electroplating, and metal extraction, giving enhanced performance and sustainability in separation processes [13]. Moreover, DESs are used for the devulcanisation of waste rubber and the modification of rubber properties, in rubber research, DESs are used for more efficient recycling and increased material performance [14].

Solvents in the rubber sector

Solvents are indispensable in the rubber industry. They are included in every step of the rubber processing chain, from the initial extraction of rubber to the final stages of product finishing, and solvents facilitate the dissolution of rubber, making it easier to handle and shape into different products [15]. They also assist in the combination of fillers and additives, which increase the properties of the final rubber products. However, the utilisation of solvents in the rubber industry isn't without its environmental consequences. In addition, the disposal of spent solvents presents a challenge because of their hazardous nature [16]. Given these challenges, sustainable alternatives to conventional solvents are pivotal in the rubber industry. Sustainable solvents, designed to reduce toxicity, be highly recyclable, and efficient, can decrease the environmental impact of the rubber industry [17].

Solvents have various roles in rubber processing, especially softening, vulcanising, plasticising, crosslinking density, dispersion, and thermo-oxidative aging. During assembly, solvents can soften rubber layers. Solvents can manage the vulcanisation kinetics of natural rubber, which can enhance the mechanical properties of the vulcanisates. As plasticisers, solvents can be applied in rubber processing, and also, solvents can control the crosslinking density of rubber. In rubber, solvents can increase the dispersion of silica. Additionally, solvents can slow down the thermo-oxidative aging behavior of rubber [18, 19, 20]. Solvent-based adhesives are widely applied in different industries, involving rubber processing, because of their strong bonding capabilities and versatility. This adhesive applies solvents to dissolve polymers and other compounds, making a fluid adhesive that can be used for surfaces and substrates [21, 22]. The most plentiful and the least expensive are aliphatic hydrocarbon solvents which are applied for cyclized rubber, rubber, and hydrocarbon polymers (Buty rubber, Buna-S, and polyisoprene). The aromatic hydrocarbon solvents used for chlorinated rubber, chloroprene polymers (Neoprene), and butadiene acrylonitrile copolymers with low acrylonitrile contents are toluene and benzene [23].

Nitroparaffins, ketones, and chlorinated hydrocarbon solvents or esters are necessary to dissolve butadiene-acrylonitrile copolymers with relatively high acrylonitrile contents (Buna-N). The solvents for rubber-based adhesives are low molecular weight liquid petroleum hydrocarbons, the aromatic hydrocarbons, including toluene and benzene, and molecular-weight lower aliphatic ketones, including methyl ethyl ketone[24]. However, many solvents have poor evaporation rates and limited solvency for certain rubber elastomers applied as primary rubber adhesives and coatings. For natural and synthetic rubber, particularly silicone rubber, mixtures of chlorinated hydrocarbon solvents can be applied as coatings or adhesives [25]. Solid rubber in solvents, such as naphtha, trichloroethane, and toluene, has solid contents ranging from 10-25% [26].

Organic solvents are oxygenated solvents that contain oxygen molecules and are made from olefins through chemical reactions, including esters, alcohols, carboxylic acids, ketones, glycol ethers, and glycols. Before and during vulcanisation, oxygen absorbers can be applied to remove oxygen from rubber [27]. It can increase the tensile strength by enhancing cross-linking density during the curing process, increasing the robustness of the rubber and subsequently improving the elongation at break, which occurs in less brittle and more flexible rubber. Additionally, oxygenated solvents minimize the compression set, minimizing permanent deformation under load and enhancing the durability of rubber products[28] .

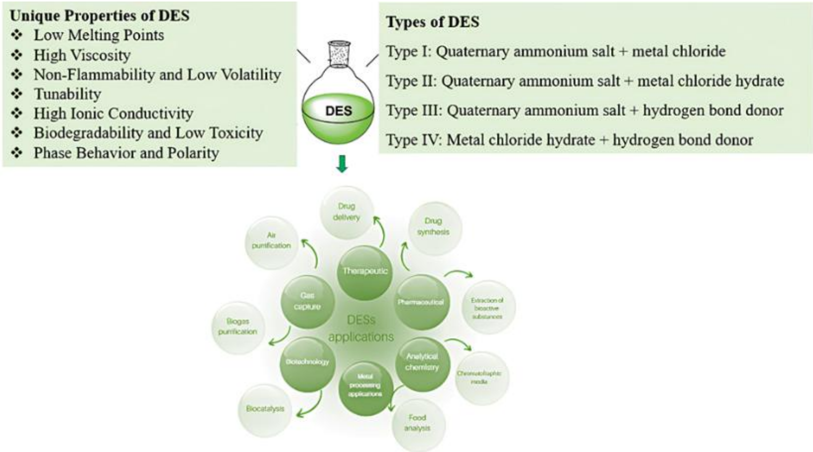

Figure 1. Types of DES and its properties and application

The main application of halogenation solvents in butyl rubber is to increase its stability and resistance to thermal oxidation and aggressive media. Halogenated butyl rubbers, including bromobutyl and chlorobutyl, have been developed to enhance vulcanisation properties, making in better performers in applications like tire inner liners [29] . Moreover, common solvents utilized in rubber compounding involve aliphatic solvents like heptane and hexane, aromatic solvents like xylene and toluene, ketones like methyl ethyl ketone and acetone, chlorinated solvents like methylene chloride, and esters like butyl acetate and ethyl acetate [30].

The use of conventional solvents in industrial processes poses significant environmental challenges, including volume of usage, release into nature, nonrenewable sources, and health hazards [31,32] In chemical synthesis, conventional solvents account for approximately 80% of the total volume of chemicals used. This high volume highlights the scale of potential environmental impact. Nearly 20 million tons of solvents are released into nature each year, leading to pollution of water, air, and soil and affecting biodiversity and ecosystems [33-35]. Many conventional solvents are derived from nonrenewable sources, mainly petroleum. The extraction and refinement of these sources can also have an environmental effect. Additionally, most conventional solvents are volatile organic compounds (VOCs), which can impact health problems, including neurological damage and respiratory issues, when humans are exposed to them [36, 37] . Various types of solvents are commonly used for applications including mold cleaning, adhesive formulation, and surface treatment in the rubber industry. Oxygenated solvents, often found in rubber coatings and printing inks, also contribute to indoor air pollution and can lead to respiratory and neurological health issues [38]. Hydrocarbon solvents, while effective, pose significant environmental challenges due to its high volatility, they release volatile organic compounds (VOCs), contributing to air pollution and presenting serious health risks to workers through prolonged exposure [39]. Halogenated solvents, which are used in degreasing and surface preparation, are particularly hazardous; they persist in the environment and are linked to severe toxicological effects, including carcinogenicity [40]. These impacts underscore the urgent need for greener alternatives and safer handling practices within the rubber sector [41].

Sustainable solvents offer various key benefits that create them an attractive alternative to traditional petroleum-based solvents: recyclability and reusability, catalyst support, biodegradability, low toxicity and versatility. After a reaction or extraction process, many sustainable solvents can be easily reused and recovered, for example, supercritical CO_2 can be recycled by simply decreasing the pressure to separate the solute, permitting the carbon dioxide to be used in subsequent process. This characteristic reduces solvent waste and obviates the need for disposal [42]. Certain sustainable solvents like DESs and ILs solvents can effectively dissolve and help catalysts, enabling efficient catalytic reaction. The properties of these solvents support them to stabilize catalysts and facilitate their interaction with reactants [43] . Bio-based sustainable solvents derived from renewable resources like plants are more attractive than their petroleum-based counterparts, if released into the ecosystem, this decreases their environmental impact [44] . Many sustainable solvents like fatty acid methyl esters and ethyl lactate have lower toxicity than traditional solvents, it makes more safer for workers to manipulate and decrease the risk of exposure. Sustainable solvents can be utilized in a wide range of applications involving coatings, cleaning, extractions and adhesives. In many industries, their unique properties allow them to effectively replace petroleum-based solvents [45, 46, 47] .

ILs can significantly increase the vulcanisation process of rubber by enhancing the dispersity of zinc oxide (ZnO) and elevating the cross-linking density (vc) of rubber [48]. ILs serve as coagents in sulfur vulcanisation process, leading to better dispersion of ZnO particles between the rubber matrices. This results in dispersion in a more uniform distribution of cross-links, which increase the mechanical properties of the rubber, including hardness and tensile strength. Afterwards, it can decrease the vulcanisation time and lower the onset vulcanisation temperature, making the process more efficient [49]. The unique properties of lLs, such as their high thermal stability, low vapor pressure, and excellent ionic conductivity, contribute to this enhancement. Therefore, the utilisation of lLs in rubber vulcanisation gives a promising approach to achieving better performance and sustainability in rubber products [50].

Nevertheless, ILs give significant advantages in rubber production, their high cost and inherent toxicity are notable concerns. Based on Watanabe et al. 2017, the manufacturing of ILs involves complex synthesis processes, heading to higher costs than conventional solvents. Moreover, ILs can show varying degrees of toxicity relying on their chemical structure, with some ILs mentioning harmful effects on aquatic and terrestrial organisms [51, 52, 53]. To handle these challenges, researchers are exploring the development of greener ILs with lower toxicity and enhanced biodegradability. These efforts are intended to balance the advantages of ILs with their environmental and health impacts, creating them more sustainable for industrial application [54].

Application for DES

In addition, tunable viscosity, polarity, and ability of DESs to dissolve a wide range of compounds, including fillers, additives, and curing agents, offer significant advantages in rubber compounding, processing, and recycling [55, 56]. DESs also provide fascinating opportunities in rubber vulcanisation because of their unique properties and range of utilisation (**Table 1**). Compared with HBD and HBA, DESs are applied in gas adsorption, biomolecule interactions, separation, and organic synthesis [57]. Additionally, in rubber vulcanisation, DESs can increase the dispersion of sulfur and vulcanizing agents within the rubber matrix, leading to more efficient cross-linking reactions and enhanced mechanical properties. The interaction of DESs with other additives, such as activators and accelerators, can influence the kinetics of the vulcanisation reaction and the final properties of the rubber, particularly increasing the formation of complexes crucial for activation [58, 59] .

In addition, DES can break down rubber seed shells to extract hemicellulose and cellulose efficiently. Acidic DESs combinations as ChCl:oxalic acid, ChCl:lactic acid, and ChCl:formic acid yielded high cellulose content (24.43%, 20.42%, and 20.31%) and then ChCl:ethylene glycol and ChCl:urea produced high hemicellulose content (46.86% and 41.14%) [69].

In rubber, devulcanisation intends to the process of breaking specific crosslinks, including sulfur-sulfur (S-S) and carbon-sulfur (C-S) bonds, without predominantly impacting the main polymer chains and then allowing the rubber to be reutilized whereas retaining most of its original properties [70-72]. Moreover, reclamation includes breaking both crosslinks and main chain (carbon-carbon) (C-C) bonds, which often results in more significant changes in the properties of the treated rubber. Different devulcanizing agents can be applied as conventional methods. Benzoyl peroxide is considered effective at 80°C for 30 minutes, resulting in a devulcanisation percentage of 45.2% [70]. On the other hand, diphenyl disulfide is utilized at a higher temperature of 180°C for a longer duration of 240 minutes, resulting in a higher devulcanisation percentage of 78.4% [73]. DESs have demonstrated promise in increasing the devulcanisation process and enhancing the properties of recycled rubber.

Overall, as functionalization agents, DESs facilitate green grafting of polar groups and surface modifications, enhancing adhesion and polarity without harsh chemicals. DESs like choline chloride–glycerol increase the deproteinization and cleaning of natural rubber latex with minimal degradation, outperforming conventional techniques in purity and stability in extraction and purification. In vulcanization, its ionic nature elevates crosslinking kinetics and enables tailored curing under milder conditions, particularly in high-filled systems. DESs also enhance filler dispersion, including silica, carbon black, and graphene oxide, through increased interfacial compatibility, yielding rubber nanocomposites with superior mechanical and barrier properties. Under mild conditions, perhaps most innovatively, DESs help selective devulcanization of waste rubber, enabling efficient sulfur bond cleavage and elevating circular economy best practices. Beyond performance, their biodegradability, low toxicity, and scalability make DESs exceptionally attractive for industrial deployment in green rubber processing [60-68].

Table 1. Rubber vulcanisation with DES

Types of DES Used	Key Findings	Research Outcomes	Reference
Type III: Quaternary ammonium salt + hydrogen bond donor (e.g., choline chloride + ethylene glycol)	Investigated the effects of DES on rubber vulcanisation kinetics and mechanical properties.	Found that DES enhance vulcanisation kinetics and improve mechanical properties such as tensile strength and elongation.	[60]
Type III: Quaternary ammonium salt + hydrogen bond donor (e.g., choline chloride + glycerol)	Studied the environmental benefits of using DES in rubber processing.	Demonstrated that DES reduce environmental impact by being biodegradable and less toxic than traditional solvents.	[61]
Type III: Quaternary ammonium salt + hydrogen bond donor (e.g., choline chloride + malonic acid)	Analyzed the performance improvements in rubber compounds using DES.	Reported significant improvements in the performance of rubber compounds, including better cross-linking and durability.	[62]
Type III: Quaternary ammonium salt + hydrogen bond donor (e.g., choline chloride + lactic acid)	Examined the cost-effectiveness and sustainability of DES in rubber vulcanisation.	Concluded that DES are cost-effective and sustainable alternatives, reducing overall production costs and environmental footprint.	[63]
DES tailored for vulcanisation	Investigated the influence of DES on vulcanisation and rheological behaviors of rubber vulcanizates.	Enhanced vulcanisation, improved mechanical properties, and better rheological behavior.	[64]
DES with metal ions	Examined metal ion-based DES for reinforcement and strain softening of silica-filled natural rubber nanocomposites.	Significantly enhanced mechanical reinforcement and reduced strain softening.	[65]
Oligomer DES	Examined the impact of oligomer DESs on the structure and properties of natural rubber vulcanizates and their nanocomposites.	Oligomer DESs were found to accelerate vulcanisation, improve crosslinking density, and enhance mechanical properties.	[66]
Type III: (Polyethylene glycol (PEG600, HBD) and tetrabutylammonium bromide (TBAB, HBA)	This study thoroughly investigates how DES affects the dispersion of zinc oxide, morphology, co-vulcanisation kinetics, and strain-softening behaviors in natural rubber/styrene-butadiene rubber (NR/SBR) blends	DES substantially enhances the dispersion of ZnO within NR/SBR blends, accelerates the vulcanisation process of SBR and the NR/SBR blend and increases their crosslinking densities	[60]
Type III: Stearic acid and tetrabutylammonium chloride	DESs is used to tailor reinforcement and softening behaviors and to replace the silane coupling agents for preparing volatile organic compounds-free nanocomposites	DESs are able to regulate the crosslinking network structure of rubber matrix and accelerate the vulcanisation by reacting with non-rubber components in natural rubber (NR) and by improving the proportion of disulfidic linkage	[67]
Polymerizable deep eutectic solvents	The effect of this variable modulus interfacial layer (polymerizable deep eutectic solvents and graphene oxide) on the interfacial and mechanical properties of aramid fiber/rubber composites was investigated	The modulus interfacial layer with a platform in the aramid fiber and rubber composite facilitated the transfer of stress concentration, inhibited microcrack expansion, and enhanced the interfacial bonding properties between the aramid fibers and the rubber matrix	[68]

Mechanisms of action of DES in rubber

(i) Hydrogen bonding and ionic interactions

DESs are composed of a mixture of HBD and HBA, which are often organic salts and neutral molecules capable of making extensive hydrogen bonds. These hydrogen bonds and ionic interactions are essential in rubber science. The HBD and HBA components interact with the sulfur atoms in the cross-linked network when DESs are introduced to vulcanized rubber. These interactions weaken the sulfur-carbon (S-C) bonds and sulfur-sulfur (S-S) bonds, effectively breaking them down. In the devulcanisation process, this disruption is crucial; the rubber can be recycled by breaking down the cross-linked network, which has durable and elastic properties [74].

(ii) Solubilization and dispersion
DES have capable of solubilization different fillers and additives between the rubber matrix. This is in order to their high solvation capabilities, which come from the unique integration of ionic and hydrogen-bonding interactions. They increase the compatibility and dispersion of these components, when DES are applied, showing in a more homogenous mixture. This enhanced dispersion is essential in rubber processing as it makes those fillers, including silica or black, are evenly distributed throughout the rubber matrix. This uniformity intends to increase mechanical properties, including enhanced elasticity, tensile strength, and resistance to tear and wear [73].

(iii) Plasticization
The plasticizing effect of DESs is another crucial aspect of their interaction with rubber compounds. DES can minimize the viscosity of rubber, making it more pliable and easier to process, and basically beneficial during recycling and manufacturing processes. Owing to the ability of DESs to interact with the polymer chains in rubber, minimizing intermolecular forces and allowing the chains to shift more freely. This facilitates the shaping and molding of rubber products and can enhance durability and flexibility [75].

(iv) Thermal stability and enhancement
The DES also affects the thermal stability of rubber materials. The ionic nature of DESs and their ability to form strong hydrogen bonds with rubber molecules support a stabilizing effect against thermal degradation. This is important in applications where rubber products are exposed to high temperatures. By integrating DESs, the thermal stability of rubber can be significantly enhanced, extending the lifespan and performance of rubber products [65].

At the molecular level, the interaction of DESs with rubber compounds involves various key mechanisms: disruption of cross-links, depolymerization, enhanced solvation, stabilization of degraded products. In vulcanized rubber, the hydrogen bonding interactions between sulfur atoms and DES components disrupt the cross-linked network. The breaking of the S-C and S-S bonds tends toward the depolymerization of rubber, turning it back to a more processable form. DESs have a polar and ionic environments that increase the solvation of rubber additives enhancing their dispersion and effectiveness. During the degradation of rubber, DESs can stabilize the products formed, covering the reformation of cross-links and intending in recycling processes [66].

In terms of increasing vulcanisation kinetics, modifying strain behavior, enhancing reinforcement characteristics, and optimizing mechanical and electrical properties, the combination of deep eutectic solvents with rubber processing has significant advantages [67]. Following the above literature review, DESs could act as effective alternatives to traditional solvents, providing sustainable solutions with enhanced performance characteristics for different rubber applications. Manufacturers can increase the quality and functionality of rubber products while addressing environmental concerns related to conventional solvent application by leveraging the unique properties of deep eutectic solvents [68]. However, as further research, optimizing formulations and understanding the underlying mechanisms should take part to advance the utilisation of DESs in the rubber industry.

Additionally, deep eutectic solvents (DESs) have demonstrated significant promise in the rubber industry due to their multifaceted advantages across processing, performance, and sustainability. These materials notably accelerate vulcanisation, allowing faster curing and improved production efficiency. DESs enhance mechanical properties such as tensile strength, elongation, and abrasion resistance critical factors for durable rubber products. Environmentally, they have a lower ecological impact owing to their biodegradability and reduced emissions. Their cost-effectiveness stems from the use of inexpensive, readily available starting materials, while their tunable nature enables customization for specific rubber formulations. Moreover, DESs improve rheological behavior, supporting better consistency and processability during manufacturing. The synergistic compatibility with these additives contributes to extended product lifespan and enhanced performance. Importantly, they are nontoxic and nonflammable, making them safer for handling and reducing workplace hazards [69-74]. These combined benefits also open new avenues for innovation in rubber materials and sustainable production technologies.

Patents and case studies of solvents in the rubber industry

Solvents have long played a critical role in rubber formulation and processing, as evidenced by various patents that describe chlorinated hydrocarbon blends with controlled evaporation rates and nonflammability for rubber adhesives and coatings [16]. Another patent outlines solvent-modified rubber compositions with enhanced cold, oil, and ozone resistance, which are applicable in automotive and industrial products [69]. However, these solvent systems also pose significant health and environmental risks. Case studies involving rubber industry workers have reported elevated incidences of dermatologic diseases and exposure to chemical carcinogens associated with traditional solvents [70]. Responding to such concerns, the U.S. Environmental Protection Agency (EPA) has promoted safer degreasing agents to reduce workplace hazards and operational costs [71].

In light of this shift, deep eutectic solvents (DESs) are increasingly recognized as viable green alternatives. Recent studies highlight their utility in host–guest supramolecular systems relevant to rubber formulations [72], and their effectiveness in the devulcanisation of waste rubber using urea–choline chloride DESs, achieving high efficiency with reduced energy input [73]. One case achieved a devulcanisation rate of 50% using DES for waste rubber powder, reinforcing their potential for circular solutions in rubber recycling [30].

Regulations of sustainable solvents

The utilisation of sustainable solvents in rubber production is increasingly aligning with global regulatory standards, which are designed to raise environmental sustainability and protect human health. Therefore, some key points on how sustainable solvents can promote rubber manufacturers comply with this regulation: Global Platform for Sustainable Natural Rubber (GPSNR), Harmonization of Standards, Green Chemistry Principle, Life Cycle Assessment [76].

The global platform for sustainable natural rubber supports a policy framework that sets out commitments for sustainable natural rubber sourcing and producing. These involve environmental, economic and social aspects of sustainability. By adhering to these policies, rubber manufacturers can make sure compliance with global standards and play their commitment to sustainability [77]. The GPSNR works to harmonize standards to enhance respect for human rights, prevent land-grabbing and deforestation, protect water resources and biodiversity, increase yields, and enhance supply chain traceability and transparency. Sustainable solvents demonstrate a role in this by controlling the environmental impact of rubber production. The principles of green chemistry, which involve the use of sustainable solvents, are being combined into regulatory frameworks. These principles intend to reduce the utilisation of hazardous substances and increase the use of materials that are safer for human health and the environment [78]. In addition, life cycle assessments (LCA) are becoming a standard tool or handling the environmental impact of products, involving solvents applied in rubber production. Manufacturers using sustainable solvents can benefit from better LCA results, that can facilitate regulatory compliance and market access [79, 80, 81]. It assesses the overall ecological footprint by applying factors such as solvent manufacturing, raw material extraction, usage, transportation and end- of -life recycling or disposal. For example, biomass-derived solvents are gaining attention for their renewable nature and potential to decrease reliance on fossil fuels [82, 83].

Economic incentives, including subsidies or tax benefits, can demonstrate a significant role in encouraging the rubber industry to transition to sustainable solvents but several potential incentives can be introduced: tax credits, subsidies, reduce tariffs, green loans, research and development grants, and public -private partnerships. by sharing tax credits, the government can ensure that it is financially appealing for companies to invest in green technologies, involving eco-friendly solvents. Rubber manufacturers may accept grants or subsidies to help defray the costs of adopting sustainable solvents, converting aspects such as workforce training and results and discussion [80-86]. Lowering import tariffs on sustainable solvents can ensure them more affordable than traditional solvents, are, increasing the likelihood of switching to more sustainable options. Financial institutions can help sustainability projects, especially the use of sustainable solvents in rubber production, through low -interest loans. Research into new sustainable solvents can be bolstered by funding from international bodies and governments, aiding their improvement and industry application. Joint initiatives between private companies and government can foster the development and adoption of sustainable solvent technologies in the industry [84].

The design thinking framework for developing sustainable solvents in rubber production mentions various key steps. Firstly, it demonstrates understanding the environmental and health impacts of conventional rubber solvents and gathering insights from industry stakeholders on the challenges and needs in adopting sustainable best practices. Then, it introduces identifying core problems correlated with current solvent use, including volatility, toxicity, and environmental persistence, and managing criteria for sustainable solvents, involving non-toxicity, biodegradability, and performance efficiency. Additionally, in rubber production, potential sustainable solvents including DESs, bio-based solvents, and ILs are brainstormed, along with their innovation utilisations and integrations in the ideation phase. The prototyping phase should focus on developing small-scale trials and experiments to detect the effectiveness of these sustainable solvents, basically their interactions with rubber materials, vulcanisation processes, and mechanical property enhancements. Afterwards, the testing phase implements field trails to assess the real-world application of sustainable solvents in rubber production, collecting data on environmental impact, performance, and cost-effectiveness to refine and validate the approach [87-90].

The sustainable development goals (SDGs) related to sustainable solvents in rubber production involve increasing health and well-being (Goal 3) through the application of nontoxic and biodegradable solvents that increase worker safety. Clean water and sanitation (Goal 6) are supplied by decreasing harmful solvent application, which prevents water resources. Industry, innovation, and infrastructure (Goal 9) advantages from the development and adoption of sustainable solvents, fostering innovation and sustainable industrial best practices. Responsible consumption and production (Goal 12) are related to the promotion of sustainable solvents to reduce waste and environmental impact. Climate action (Goal 13) is elevated by sustainable solvents that are distributed to control greenhouse gas emissions and mitigate climate change. Protecting life below water (Goal 14) and living on land (Goal 15) is increased by decreasing solvent pollution, which preserves aquatic and terrestrial ecosystems. Therefore, these goals strongly cover the importance of adopting sustainable solvents to make an eco-friendlier rubber production process [91,92].

Challenges

The multi-dimensional challenges of adopting deep eutectic solvents (DESs) in rubber applications, linking each issue to the unique chemistry and industrial demands of this sector. Transitioning to sustainable solvents such as DESs is not merely a substitution—it often requires a fundamental reconfiguration of rubber processing systems. Traditional solvents, such as toluene or hexane, have well-characterized interactions with rubber matrices and are compatible with existing vulcanisation and blending equipment. DESs, in contrast, often exhibit high viscosity, low volatility, and distinct polarity, which influence mixing dynamics, heat transfer, and diffusion into rubber networks. This can necessitate redesigns in processing hardware (e.g., mixers, extruders, vulcanisation ovens) to maintain throughput and product integrity, especially in large-scale applications [93]. Chemical compatibility and reactivity present additional complexity. DESs may interact unpredictably with vulcanizing agents, accelerators, or fillers such as carbon black and silica. Their hydrogen-bond donor–acceptor architecture can interfere with cure kinetics or the crosslinking process, potentially compromising mechanical performance if not properly controlled. This is especially critical for automotive or industrial rubber parts that require high standards of durability and aging resistance [94]. Moreover, process stability is pivotal. Many DESs are moisture-sensitive or degrade at elevated temperatures, which challenges their reliability under industrial thermal profiles. Maintaining the physical and chemical integrity of DESs during cycles of heating, shearing, and storage remains a technical hurdle that must be addressed through careful selection of eutectic components and real-time monitoring [93]. Tools like Analytical Eco Scale, Environmental method index (NEM), and Green analytical procedure index (GAPI) are utilized to assess the greenness of solvents and processes. These tools allow researchers and manufacturers to quantitatively evaluate solvents not only based on biodegradability and toxicity but also lifecycle considerations like carbon footprint and energy input. In the case of DESs, while their components are generally benign (e.g., choline chloride, urea), the production energy, recyclability, and post-processing environmental impact need to be critically assessed and optimized to validate their claimed sustainability [95-97].

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Future research direction

In the rubber industry, future research on DESs should explore multiple promising areas. Advanced characterization methods including Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM) and nuclear magnetic resonance (NMR), can be used to gain deeper insights into the molecular interactions between rubber materials and DESs, leading to the optimization of formulations and processing techniques. Exploring the innovative applications of DESs, especially their use in smart materials and self-healing rubber, can lead to the development of high-performance, cutting-edge rubber products. Additionally, recycling and reuse of DESs might be prioritized to increase a circular economy, with research dedicated to developing efficient recovery and purification techniques to minimize waste. The synergistic effects of integrating DESs with other additives can increase the functional and mechanical properties of rubber composites. To ensure environmental safety and compliance with regulations, making biodegradable and nontoxic DES from natural and renewable sources is pivotal. Understanding environmental impact assessments, especially life cycle analyses, will provide valuable data on the sustainability advantages of DESs over conventional solvents. This approach will shift rubber industry toward greener, more sustainable best practices.

Beyond current advancements, future opportunities lie in integrating computational modelling and machine learning techniques to accelerate the design and discovery of novel DES systems tailored to rubber applications. Predictive simulations can offer insights into solvation dynamics, compatibility with rubber constituents, and long-term stability under varying processing conditions. Moreover, collaboration among academia, industry, and regulatory bodies is essential for establishing standard testing protocols and certifications for DES use in rubber manufacturing. The incorporation of DESs into next-generation biobased rubber formulations, such as those involving natural rubber latex or lignin-derived polymers, could also support the development of fully sustainable and biodegradable elastomeric systems. As global industries move toward carbon-neutral goals, DES-based innovations hold the potential to reshape not only production methods but also end-of-life strategies for rubber materials through greener devulcanisation, regeneration, and reuse pathways.

Conclusion

The rubber industry has conventionally depended on petroleum-based solvents, which can have significant health and environmental impacts, but the growing awareness of sustainability has led to the development of innovative green chemistry solutions that prioritize the utilisation of eco-friendly solvents in rubber production. Sustainable solvents can be utilized in rubber compounding, cleaning, coating, vulcanisation, recycling process and testing, giving a more environmentally responsible alternative to conventional solvents. By embracing green chemistry principles and bombinating sustainable solvents into their operations, rubber producers can contribute to a healthier, cleaner environment while maintain product performance and quality. The rubber industry is well-positioned to lead the way in adopting innovative sustainable solvents solutions as the requirements for sustainable best practices continues to grow. Therefore, Deep eutectic solvents are reshaping the rubber industry by offering sustainable, tunable, and multifunctional alternatives to conventional solvents. In processing, DESs have demonstrated the ability to accelerate vulcanisation kinetics, modify rheological behavior, and enhance dispersion of fillers, contributing to improved manufacturing efficiency and compound uniformity. In terms of material performance, rubber treated with DESs shows increased tensile strength, elongation, and abrasion resistance—key factors for demanding applications like automotive components and industrial seals. Their role in environmental sustainability is equally significant. Derived from benign, biodegradable components like choline chloride and urea, DESs reduce reliance on toxic solvents and minimize volatile organic compound (VOC) emissions, aligning with green chemistry and occupational safety goals. In rubber recycling, DESs have proven effective in devulcanizing waste rubber, enabling circular economy strategies with lower energy demand and higher recovery efficiency. Furthermore, the concept of task-specific DESs allows for customization based on the needs of particular rubber formulations, whether for compatibility with additives, enhanced self-healing, or conductive properties in smart materials. Ongoing research continues to expand their potential, from integrating DESs into bio-based elastomers to exploring their synergistic effects with functional fillers. Collectively, DESs are not only enabling greener processing but also opening new frontiers in functional, durable, and eco-conscious rubber products.

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