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A comprehensive review of tire recycling technologies and applications

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Tire waste has emerged as a critical environmental concern due to the massive global production of tires and their resistance to natural degradation. End-of-life tires (ELTs) represent a significant portion of non-biodegradable solid waste, contributing to pollution and posing serious risks to ecosystems and public health. This review paper provides a comprehensive overview of current tire recycling technologies and their applications. Key recycling methods such as mechanical grinding, pyrolysis, and devulcanization processing are discussed in detail. The paper highlights the various value-added applications of recycled tire materials in civil engineering, construction, energy recovery, and manufacturing. Environmental benefits, economic viability, and legislative frameworks are also examined. Finally, challenges associated with tire recycling and potential future directions for sustainable development are outlined. This review aims to guide researchers, industry stakeholders, and policymakers toward more efficient and eco-friendly tire recycling strategies.

1. Introduction

The increasing demand for motor vehicles has led to a corresponding surge in tire production worldwide. According to recent estimates, over 1.5 billion tires reach their end-of-life stage each year, generating a substantial volume of non-degradable waste. Due to their complex composition, mainly natural and synthetic rubber, carbon black, steel, and textile fibers, tires are resistant to decomposition and present significant environmental challenges when disposed of improperly. Traditional disposal methods such as landfilling and open burning are no longer considered sustainable due to their detrimental effects on land use, air quality, and groundwater contamination. In response, global attention has shifted toward tire recycling as a sustainable alternative that not only mitigates environmental risks but also offers economic and industrial opportunities through material recovery and reuse. End-of-life tires (ELTs) have become a pressing environmental issue due to their vast quantity, durability, and slow degradation. Globally, it is estimated that over 1.5 billion tires are discarded each year, amounting to more than 17 million tons of waste. These tires, if not managed properly, can lead to severe environmental and health hazards, including fire risks, water stagnation (leading to mosquito breeding), and leaching of toxic substances into the soil and groundwater.[1] The growth in vehicle ownership, industrialization, and urbanization in both developed and developing countries has led to a continuous increase in tire waste generation. According to the World Business Council for Sustainable Development (WBCSD), the global stockpile of waste tires exceeded 4 billion units by the end of the last decade. Annual growth rates vary by region, with emerging economies contributing significantly due to expanding transportation networks.[2]

The global distribution of end-of-life tire (ELT) generation and recycling efforts varies significantly by region, reflecting differences in infrastructure, policy, and economic development. In the United States, more than 300 million tires are discarded

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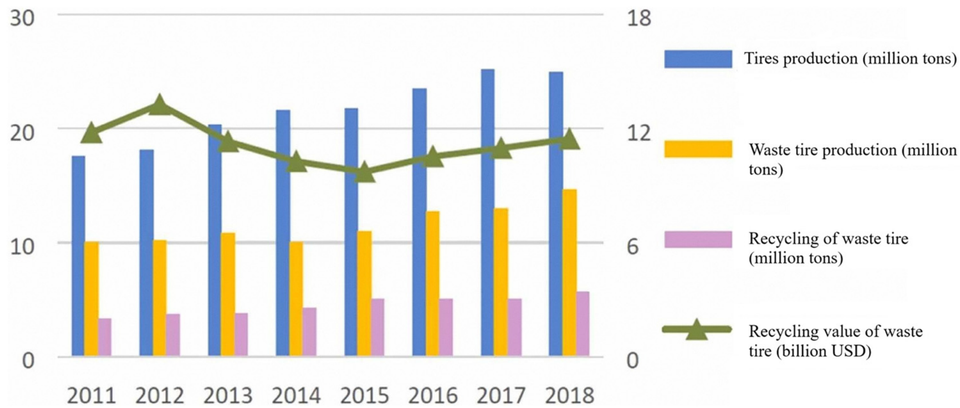

Fig. 1 The estimated production and recycling of tires from 2011 to 2018. Reproduced from ref. 1,3.

annually, and recycling rates are relatively high, hovering around 80%. In the European Union, the adoption of Extended Producer Responsibility (EPR) frameworks has been pivotal. These schemes require manufacturers to take responsibility for the post-consumer stage of their products, resulting in an impressive 95% recovery rate for ELTs, either through material recycling or energy recovery. China is the world's largest vehicle market, generates over 200 million waste tires annually. Although the recycling infrastructure is still developing, the Chinese government has launched various initiatives to boost capacity and encourage industrial-scale tire recycling. In contrast, regions such as the Middle East and North Africa (MENA) face ongoing challenges. While awareness of the environmental impact of tire waste is growing, many countries in this region still depend on landfilling or experience illegal dumping due to limited regulatory frameworks and inadequate recycling facilities. Fig. 1 shows the estimated production and recycling of tires from 2011 to 2018.[1,3]

Improper disposal of end-of-life tires presents several serious environmental challenges. When dumped into landfills, tires occupy a large volume of space and can trap gases, creating instability that complicates waste management. Tire fires are another major concern, they are notoriously difficult to extinguish, can burn for extended periods, and release thick, toxic smoke that poses health and environmental risks. Additionally, as tires break down, they can leach heavy metals and other harmful substances into the surrounding soil and groundwater, potentially contaminating ecosystems. Another issue arises from stagnant rainwater that collects in tire piles, creating ideal breeding grounds for mosquitoes and increasing the spread of vector-borne diseases such as malaria and dengue. In response to these hazards, many countries have taken legislative action to regulate tire disposal and encourage recycling. Within the European Union, the Waste Framework Directive requires member states to minimize landfill use and prioritize recycling. In the United States, individual states have established scrap tire management programs to streamline collection and processing. Countries like Japan and South Korea have adopted sophisticated tire recycling systems grounded in circular economy principles, aiming to reduce waste and maximize resource recovery. Meanwhile, many developing nations are beginning to implement Extended Producer Responsibility (EPR) policies, although enforcement and infrastructure development continue to pose significant challenges.[4,5] This review explores the current state of tire recycling technologies and their wide-ranging applications. It also assesses the environmental and economic implications of recycling processes, identifies barriers to effective implementation, and outlines potential research directions for improving the efficiency and impact of tire recycling efforts.

2. Tire recycling methods: technologies and processes

Recycling of end-of-life tires (ELTs) involves a variety of methods, each designed to recover materials or energy from discarded tires. The choice of method depends on several factors including the condition of the tires, the desired output, and the available infrastructure. Broadly, tire recycling technologies are categorized into mechanical, thermal, chemical, and innovative/alternative methods.

2.1 Mechanical recycling

Mechanical recycling is a widely adopted method for processing end-of-life tires (ELTs), focusing on the physical transformation of rubber into crumb or powdered form without altering its chemical structure. This approach not only diverts tires from landfills but also produces valuable materials for various applications. The process begins with shredding and grinding, where tires are cut into smaller pieces using powerful rotating blades and granulators. This results in crumb rubber of various sizes, tailored to specific applications.[6,7] For finer materials, cryogenic grinding is employed. This technique involves cooling the rubber with liquid nitrogen, making it brittle and easier to pulverize into a fine powder. This method produces clean granulates without surface oxidation, enhancing the quality of the final product. Fig. 2 shows a typical

Fig. 2 Typical products of cryogrinding. 1 – nylon cord, 2 – metal cord, 3 – large size fraction of rubber crumb (1–5 mm), 4 – mean size fraction (1–2 mm), 5 – small size fraction (0.1–1 mm). Reproduced from ref. 7.

product of cryogrinding.[7] After grinding, steel wires and textile fibers embedded in the tire are separated using magnetic separators and air classifiers. This ensures a cleaner final product and allows for the recovery of steel fibers, which can be repurposed in construction materials. The resulting crumb rubber finds a wide range of applications across industries. It is commonly used in rubber-modified asphalt, enhancing the durability and flexibility of pavement surface layers. Other uses include flooring materials, mats, playground surfaces, athletic tracks, and molded rubber products like tiles and protective padding.[8]

In the mechanical recycling process for crumb rubber production, several parameters are optimized to improve quality, efficiency, and cost-effectiveness. These include:

2.1.1 Feedstock preparation. Feedstock preparation is a critical initial step in the mechanical recycling process of end-of-life tires, directly influencing the quality and efficiency of crumb rubber production. Pre-cleaning of tires is essential to remove extraneous materials such as stones, dirt, and metallic debris that may otherwise damage grinding equipment and contaminate the final product. Effective pre-cleaning prolongs the lifespan of machinery and ensures a higher-quality crumb rubber with fewer impurities. Additionally, tire size reduction, typically achieved by cutting whole tires into smaller, manageable pieces like shreds or chips, not only facilitates easier handling but also improves grinding efficiency. Smaller tire fragments allow for more uniform feeding into grinding mills, leading to more consistent particle sizes, reduced energy consumption, and increased overall throughput. Together, these preparatory steps form the foundation for an optimized mechanical recycling process.[9,10]

2.1.2 Ambient and cryogenic grinding. In the mechanical recycling of tires, two primary grinding approaches are employed to optimize crumb rubber quality. Ambient grinding, conducted at or above room temperature, uses rotary or cracker mills where rubber remains pliable, producing irregularly shaped particles with high surface roughness is ideal for bonding in applications like rubberized asphalt, but also generating heat that must be managed to avoid material degradation.[11] In contrast, cryogenic grinding leverages liquid nitrogen to cool rubber chips below their glass transition temperature (typically −80 to −120 °C), making the material brittle and easier to fracture. This results in finer, cleaner crumbs with smoother surfaces and reduced fiber and metal contamination, though the process incurs higher costs due to nitrogen consumption. Particle uniformity in cryogenic grinding is controlled by immersion time and grinding cycles, while ambient grinding offers greater mechanical strength through its textured surfaces.[12]

2.1.3 Grinding parameters. The efficiency and quality of crumb rubber production in mechanical recycling are significantly influenced by key grinding parameters. The choice of mill types and design, such as high-speed rotary mills, cracker mills, or granulators, directly affects the particle size distribution and processing throughput. Each type of mill offers specific advantages depending on the desired crumb size and production scale. Blade sharpness and spacing are also critical factors; sharp and properly spaced blades ensure effective cutting, while dull or misaligned blades can lead to poor grinding performance, inconsistent particle size, and increased wear on equipment. Additionally, controlling the feed rate and load is essential for maintaining optimal grinding conditions. A consistent and well-regulated material flow through the mills prevents overheating, reduces energy consumption, and enhances the uniformity of the final product. These parameters must be carefully optimized to achieve efficient, high-quality crumb rubber suitable for a wide range of recycling applications.[13,14]

2.1.4 Particle size control. Controlling the size of crumb rubber particles is crucial for ensuring suitability and performance in diverse applications. Screen size and configuration play a central role: finer mesh screens (*e.g.*, 10–40 mesh) allow for smaller, more uniform particle sizes favored for high-quality products, although they may reduce processing throughput due to slower flow rates. After initial shredding and sizing *via* screens, often trommel or vibratory types air classification is employed to separate lighter contaminants such as textile fibers and dust from denser rubber particles. This two-stage approach, combining mechanical sizing and pneumatic sorting, enhances the purity and consistency of the final crumb rubber product.[15]

2.1.5 Separation efficiency. Separation efficiency plays a vital role in ensuring the purity and quality of crumb rubber. Efficient steel wire removal is typically achieved through multi-stage magnetic separation systems. After primary shredding, high-strength over band and drum magnets extract the bulk of steel contaminants, while secondary and fine-stage plate magnets further eliminate residual wires, producing nearly metal-free rubber. To remove textile fibers, which are tightly embedded in rubber—a combination of cracker mills for liberation, followed by pneumatic separation using air classifiers or cyclones, is employed. This process enhances purity by allowing denser rubber particles to settle while lighter fibers are carried away.[16]

2.1.6 Moisture content. Moisture content control is a critical step in crumb rubber production, particularly for applications that require precise material properties, such as rubberized asphalt or molding compounds. Following grinding and separation, a drying stage is implemented to reduce residual moisture levels in the rubber particles. Maintaining low moisture content not only improves the adhesion and performance characteristics in end-use applications but also prevents issues like microbial growth and material degradation during storage. Efficient drying can be achieved using rotary dryers, fluidized bed dryers, or infrared drying systems, depending on plant capacity and product requirements.[17,18]

2.1.7 Energy consumption. Energy consumption is a crucial factor in the mechanical recycling of tires, directly impacting operational costs and environmental sustainability. Optimizing grinding speed and torque allows for efficient material size reduction while minimizing power usage. Operating mills at an optimal speed ensures sufficient shear forces for effective grinding without unnecessary energy waste or excessive wear on equipment. Similarly, controlling torque prevents overload conditions that can cause equipment damage and increase downtime. Together, these parameters balance productivity with energy efficiency, contributing to more sustainable crumb rubber production processes.[6,19,20]

2.2 Thermal recycling (pyrolysis)

Pyrolysis is the thermal decomposition of tire materials in the absence of oxygen, producing oil, gas, carbon black, and steel. Pyrolysis is a prominent thermal recycling method for end-of-life tires (ELT) offering an effective way to convert waste into valuable resources. In this process, shredded tires are heated in an oxygen-free environment, typically between 400 °C and 700 °C within a specialized reactor. Under these high temperatures, the rubber undergoes thermal decomposition.[21,22] The volatile components released during heating are condensed into pyrolysis oil, which can be used as a fuel or a chemical feedstock. The non-volatile fractions, such as carbon black and steel wires, are collected as solid byproducts. Additionally, non-condensable gases are generated and are often redirected to fuel the pyrolysis system itself, enhancing the energy efficiency of the operation.

The outputs of this process are commercially valuable:

• Pyrolysis oil, which has applications in energy production and chemical industries.

• Gas, which can sustain the pyrolysis process and reduce external fuel needs.

• Recovered carbon black (rCB), used in rubber products, inks, and coatings.

• Steel wires, which can be recycled for use in construction and metallurgy.

Among the key advantages of pyrolysis are its high energy recovery rate, its ability to significantly reduce landfill waste, and the transformation of tire components into marketable secondary products. However, the method is not without challenges. It requires substantial initial investment, especially for high-quality reactors and emission control systems to manage the release of potentially hazardous gases. Furthermore, the consistency of the end products, especially pyrolysis oil and rCB, can vary depending on the input tire composition and process parameters, posing a hurdle for standardization and commercial adoption. Schematic representation of ELT pyrolysis and ensuing products is shown in Fig. 3.[23,24]

2.3 Devulcanization (chemical recycling)

Devulcanization is a vital process in the recycling of vulcanized rubber, especially for tire materials, as it involves reversing the sulfur cross-links that are created during vulcanization. Vulcanization improves rubber's strength, elasticity, and durability by creating cross-links between the polymer chains through the addition of sulfur. However, these cross-links make the rubber difficult to process and recycle. Devulcanization breaks down these sulfur bonds, restoring the rubber's plasticity and allowing it to be reprocessed for use in new rubber products. Various methods are employed to devulcanize rubber, including the use of chemical agents such as hydrogen peroxide and ozone, heat (often combined with pressure), and ultrasound, which can all help to break the vulcanized rubber network into more workable forms.[25]

One of the primary applications of devulcanized rubber is blending it with virgin rubber to produce new rubber goods. This process significantly reduces the reliance on virgin rubber, which in turn helps conserve natural resources and lowers the environmental impact of rubber production. Devulcanized rubber can be utilized in the manufacturing of various high-value rubber products, including automotive parts, flooring materials, and molded rubber goods. These recycled products are both cost-effective and more environmentally friendly

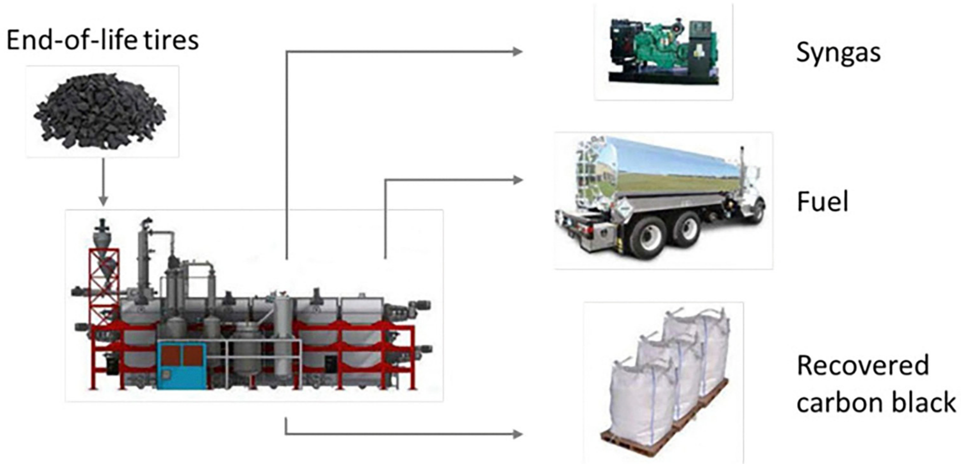

Fig. 3 Schematic representation of ELT pyrolysis and ensuing products. Reproduced from ref. 23.

compared to those made from virgin rubber. However, devulcanization comes with certain challenges. The process requires precise control, as the degree of devulcanization must be carefully managed to ensure that the rubber's properties are restored without degrading its quality. Furthermore, achieving consistent product quality is difficult due to the complex nature of the devulcanization process, which can vary depending on factors such as the type of rubber, the method used, and the specific conditions under which it is processed. Despite these challenges, ongoing research is focused on improving the efficiency and scalability of devulcanization technologies to make them more viable for large-scale commercial use. A schematic representation of degradation and devulcanization processes in a crosslinked rubbery material is shown in Fig. 4.[26–28]

Devulcanization is a critical process in recycling vulcanized rubber, aiming to selectively break sulfur cross-links while preserving the polymer backbone. Traditional devulcanization methods, such as thermal and chemical treatments, often result in non-selective bond scission, leading to degradation of the rubber matrix and diminished material properties. Thermal methods typically require high temperatures (above 200 °C), which can cause uncontrolled main-chain scission and produce low-quality reclaimed rubber with poor mechanical properties. Chemical devulcanization, though more targeted, often involves hazardous reagents and generates toxic by-products, posing environmental and safety concerns.[29]

In contrast, novel techniques such as microwave-assisted and ultrasonic devulcanization offer more selective and energy-efficient alternatives. Microwave devulcanization utilizes dielectric heating, which preferentially targets sulfur bonds due to their higher microwave absorption capacity, thus promoting selective bond cleavage with less polymer degradation.[30] Ultrasonic devulcanization applies high-frequency acoustic waves to generate cavitation and shear forces in rubber slurries, facilitating

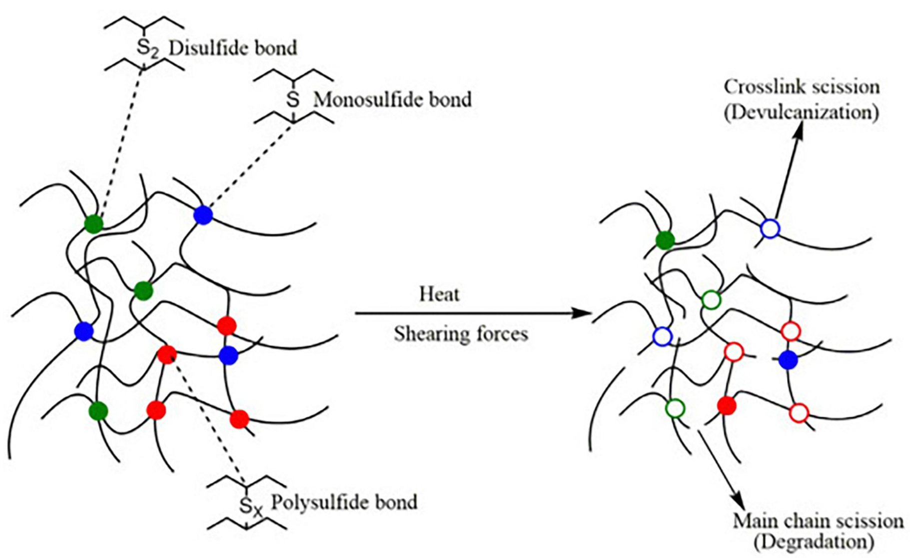

Fig. 4 Schematic representation of degradation and devulcanization processes in a crosslinked rubbery material. Reproduced from ref. 28.

sulfur bond disruption with reduced chemical use.[31] These methods also demonstrate lower energy consumption and shorter processing times. However, challenges remain in scalability and equipment cost, as well as in achieving consistent quality across different rubber compositions.

Hybrid recycling systems that combine mechanical pre-treatment with thermal and chemical processes offer significant advantages in recovering rubber, steel, fibers, and valuable by-products from waste tires. A twin-screw thermo-mechanical treatment of ground tire rubber, enhanced with oil, has demonstrated improved reclaim properties and energy efficiency by applying controlled shear and heat within a single extruder setup.[32] Other studies have explored combined pyrolysis and post-treatment, where pre-shredded tires are thermally decomposed, and resulting pyrolytic oil and carbon black are further refined—yielding higher-value products and better environmental performance than standalone processes.[33] Additionally, mechanical separation methods such as shredding and magnetic de-wiring, when paired with chemical devulcanization or solvolysis, improve process efficiency by reducing material heterogeneity and increasing yield. These hybrid strategies offer a more holistic, efficient, and sustainable pathway for tire recycling.

2.4 Innovative and emerging technologies

To address the environmental and technical challenges associated with traditional tire recycling methods, several innovative and emerging technologies are under investigation and development. One such method is microwave pyrolysis, which utilizes microwave energy to achieve rapid and uniform heating of tire materials. This technique offers improved energy efficiency, better temperature control, and lower emissions compared to conventional thermal pyrolysis methods. Studies have demonstrated that microwave pyrolysis can produce higher yields of pyrolytic oil and gas while minimizing harmful byproducts. Illustration of microwave pyrolysis process is shown in Fig. 5.[34–37] Microwave pyrolysis operates in oxygen-free environments, minimizing emissions of toxic compounds like dioxins and furans, while yielding high-quality pyrolysis products such as oil, syngas, and carbon char with calorific values around 45 MJ kg^{-1} for liquids and 34 MJ kg^{-1} for solids. However, scalability challenges include the need for adequate microwave absorbers, precise control of dielectric properties, and specialized reactor design. In contrast, bio-recycling (microbial or enzymatic devulcanization) offers an environmentally benign alternative using bacteria or fungi to selectively cleave sulfur cross-links in vulcanized rubber. Studies highlight its low-energy requirements and minimal chemical use, making it a clean and potentially sustainable strategy. Despite these benefits, bio-recycling faces practical limitations, including slow reaction rates (surface-limited degradation), dependency on detoxification of additives, and the challenge of industrial scale-up[38,39]

Another promising technology is supercritical fluid extraction, which employs supercritical CO_2 or other fluids to recover valuable oils and chemical components from tires. This method operates under high pressure and temperature, allowing for the selective extraction of compounds without the use of harmful solvents. It has been shown to be effective in extracting plasticizers, antioxidants, and oils from rubber, potentially offering a cleaner and more efficient recycling route.[40–42] Additionally, electrochemical processing is being explored as a method for the selective breakdown of tire components. Through controlled electrochemical reactions, this technique can facilitate the recovery of valuable materials such as metals and carbon black, while reducing the environmental footprint of the recycling process. Although still in the research phase, electrochemical approaches hold potential for more precise and energy-efficient recycling.[43–45] Collectively, these emerging technologies aim to improve the environmental performance, product quality, and economic feasibility of tire recycling. As these innovations continue to evolve, they could

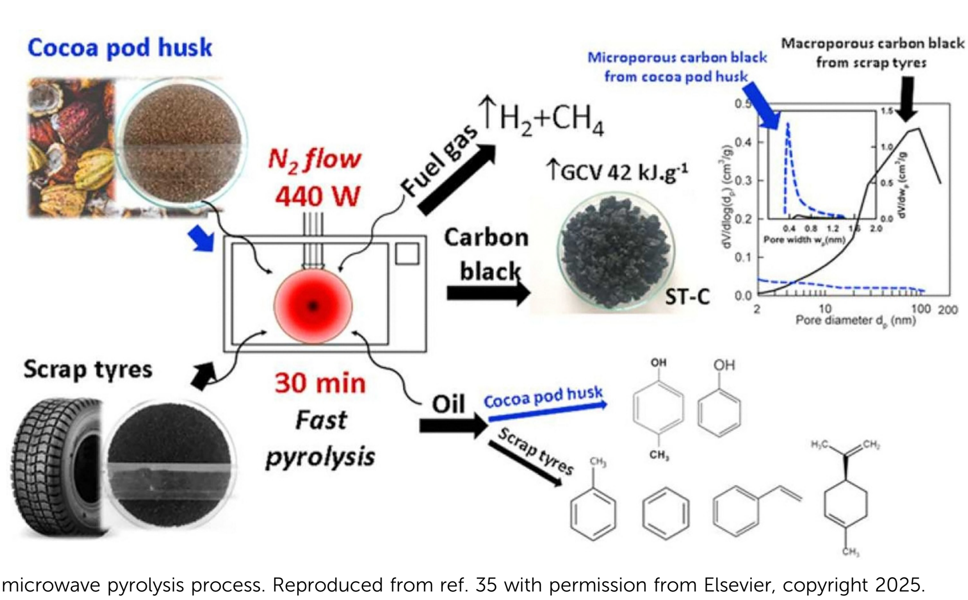

Fig. 5 Illustration of microwave pyrolysis process. Reproduced from ref. 35 with permission from Elsevier, copyright 2025.

Table 1 A comparison between methods of tires recycling

Recycling method	Process description	Energy requirement	Environmental impact	Advantages	Ref.
Mechanical recycling	Shredding, grinding, and separating rubber, steel, and fibers to produce crumb rubber.	Moderate (0.5–1 MJ kg^{-1})	Low emissions; minor dust generation and waste fiber.	Simple, cost-effective, scalable.	30
Ambient grinding	Grinding at or above room temperature.	Moderate	Low emissions; some heat generation.	Does not require cryogenic facilities.	46
Cryogenic grinding	Rubber is embrittled using liquid nitrogen before grinding.	High (energy for cooling)	Safe, clean; energy-intensive due to cryogen.	Produces fine, clean rubber particles.	30 and 47
Pyrolysis	Thermal decomposition in absence of oxygen yielding oil, gas, and char.	High (350–700 °C; ∼1–2 MJ kg^{-1})	VOCs, CO_2, potential toxicants unless cleaned.	Recovers energy and oil; scalable.	47 and 48
Gasification	Partial oxidation to convert tires into syngas.	Very high (>800 °C)	Can be clean if controlled; ash disposal needed.	High-value syngas for energy or synthesis.	46
Chemical devulcanization	Breaks sulfur cross-links using chemical agents.	Moderate	Reagents may be hazardous; controllable if optimized.	Enables reuse of rubber compounds.	29
Microwave devulcanization	Uses microwave radiation to selectively heat and devulcanize rubber.	Medium	Lower emissions; no chemicals; shielding required.	Energy efficient and selective.	30 and 49
Ultrasound devulcanization	Applies high-frequency sound waves to induce devulcanization.	Moderate	Clean method; less mature commercially.	Improved control; minimal chemical use.	48 and 50
Solvolysis	Uses solvents to depolymerize rubber into monomers or oils.	Moderate	Solvent disposal/reuse challenges; less CO_2 emission.	Potential for selective recovery.	51 and 52
Hydrothermal liquefaction	Converts tires into oil using water under supercritical/subcritical conditions.	High (250–450 °C, pressure)	Clean if properly managed; by-product water/chemicals.	Good oil yield; minimal external solvent.	53
Microwave pyrolysis	Selective rubber heating *via* microwaves in inert atmosphere.	Medium to high	Lower emissions than traditional pyrolysis; faster heating.	High oil yield; cleaner process.	30
Bio-recycling (emerging)	Utilizes microbes or enzymes to degrade rubber compounds.	Low to moderate	Eco-friendly, but very slow and under development.	Green solution for long-term future.	54 and 55

complement or even replace traditional methods, contributing to a more sustainable and circular rubber economy. A comparison between methods of tires recycling is summarized in Table 1.

3. Applications of recycled tire materials

Recycled tire materials, particularly crumb rubber, pyrolysis products, and devulcanized rubber, have found numerous applications across various industries. These applications not only divert tire waste from landfills but also contribute to sustainable product development and resource conservation.

3.1 Civil engineering and construction

Recycled tire materials have been increasingly integrated into civil engineering and construction projects, offering sustainable and cost-effective solutions. One prominent application is in rubberized asphalt, where crumb rubber is blended with bitumen to enhance pavement performance. This modification improves durability, flexibility, and resistance to cracking, particularly under varying temperature conditions.[56,57] Studies have shown that rubberized asphalt exhibits improved rutting resistance and cracking resistance, leading to longer-lasting pavements. A study by Fateme Labbafi and his coworkers, compares three types of rubberized asphalt mixtures, dry-process, wet-process with asphalt rubber binder, and wet-process with terminal blend binder against conventional hot mix asphalt (HMA). The evaluation covers performance, cost-effectiveness, and environmental impact across the pavement's lifespan. Using a life cycle assessment (LCA) *via* SimaPro software, the researchers found that while rubberized asphalt mixtures incur higher initial costs and environmental impacts during production, they offer superior long-term performance and extended service life, leading to overall lower lifecycle costs and reduced annual CO_2 emissions. Among the rubberized mixtures, the wet-process with asphalt rubber binder emerged as the most sustainable and cost-effective option.[58] In the construction of road embankments and retaining walls, tire-derived aggregate (TDA), produced from shredded tires, serves as a lightweight fill material. TDA offers excellent drainage and insulation properties, making it suitable for stabilizing slopes and reducing lateral pressures on retaining structures. The U.S. Federal Highway Administration has recognized the use of tire shreds and chips as effective lightweight fill materials for roadway embankments and backfills. For railway track foundations, incorporating granulated rubber into the sub-ballast layer has been found to reduce vibrations and noise, as well as improve load distribution. Research indicates that mixing rubber shreds with granular soil increases damping ratios, demonstrating the potential of such mixes for attenuating vibrations in railway substructures.[16,59] A study by Girts Kolendo and his colleagues highlights the environmental and structural advantages of recycling end-of-life tires (ELTs), emphasizing mechanical recycling and the use of crumb rubber in construction applications. Life cycle assessment (LCA) using OpenLCA software demonstrates that recycling ELTs, rather than incinerating or landfilling significantly reduces CO_2 emissions, with up to 24.06% reduction when crumb rubber replaces river sand in concrete. ELTs contain approximately 70% rubber, 5–30% steel, and up to 15% textile fibers, making them highly recyclable. Incorporating crumb rubber into concrete reduces mass density, enhances ductility by up to 40%, and improves impact resistance, making it ideal for resilient and acoustic applications. Additionally, crumb rubber's elasticity and durability make it suitable for shoreline reinforcement, helping mitigate erosion and improve flood resilience, thereby reinforcing its value in sustainable construction and environmental protection.[60] In the realm of roofing and insulation, ground rubber and fibers from recycled tires are utilized in the production of roofing membranes and insulation panels. These materials contribute to energy efficiency and durability in buildings. For instance, EPDM (ethylene propylene diene monomer) roofing systems, which can incorporate recycled rubber, are known for their long service life and resistance to environmental factors.[61]

3.2 Sports and recreation

Recycled tire materials have found widespread use in the sports and recreation sector, largely due to their superior shock-absorbing properties, durability, and resilience. One of the most common applications is in playground surfaces and athletic tracks, where safety is a top priority. Crumb rubber derived from end-of-life tires is molded into rubber tiles or used as infill in synthetic turf systems, helping to reduce the impact of falls and providing a long-lasting, weather-resistant surface. In equestrian arenas, shredded or mulched rubber is mixed with sand or other base materials to create footing that is softer, reduces dust, and minimizes the risk of injury to horses by offering consistent traction and cushioning. These surfaces also require less maintenance and perform well under various weather conditions. Another significant application is in artificial turf systems for sports fields. Crumb rubber is often used as an infill material between the synthetic grass blades. This not only helps in providing a more natural feel underfoot but also enhances the field's shock absorption, stability, and playability. Additionally, rubber infill contributes to the longevity of artificial turf by preventing matting and maintaining fiber uprightness. Fig. 6 shows the use crumb rubber of as infill martials in artificial turf.[62–64]

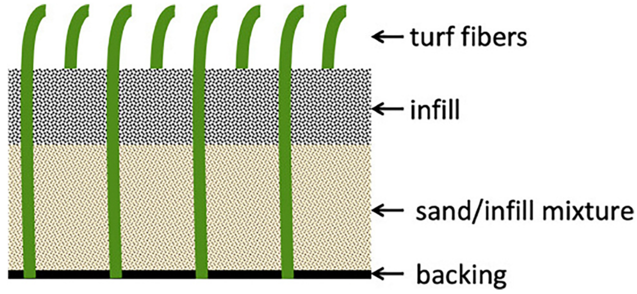

Fig. 6 Illustration of using crumb rubber of as infill martials in artificial turf. Reproduced from ref. 63.

3.3 Automotive and industrial products

Recycled tire rubber plays a significant role in the automotive and industrial sectors, where durability, resilience, and cost-effectiveness are critical. One of the primary applications is in the production of molded rubber goods. Items such as floor mats, dock bumpers, parking curbs, and wheel chocks are commonly manufactured using crumb rubber or processed tire-derived material. These products benefit from the inherent strength and weather resistance of tire rubber, making them ideal for high-wear environments. In more technical applications, devulcanized rubber, rubber in which the sulfur cross-links have been broken down is blended with virgin rubber compounds. This blend is used to manufacture new tires, industrial hoses, belts, and gaskets. The use of devulcanized rubber not only reduces reliance on virgin rubber but also lowers production costs and environmental impacts.[65] Recycled tire rubber is also utilized in noise and vibration control. Its dense, elastic properties make it excellent for sound barriers, especially in urban infrastructure projects near highways or railways. Additionally, it is used in vibration dampening pads placed beneath heavy machinery or equipment to reduce structural vibration and noise transmission. Incorporating recycled rubber into automotive and industrial products presents a sustainable strategy for reducing landfill waste and enhancing product performance across multiple sectors.

A study by Edgaras Strazdas and his colleague investigates nine different rubber granulate plates, varying in fraction size, thickness, and density. An impedance tube analysis was conducted to evaluate each plate's sound absorption coefficient (α) and sound transmission loss (DTL). Based on these tests, two plates exhibiting superior acoustic performance were selected for further investigation. These plates were then integrated as core filler materials within louver structures. The study focused on how the angle of the louvers and the number of rubber-filled plates influenced the system's overall sound-reducing efficiency. Results revealed a maximum sound reduction of 17.3 dB at the 8000 Hz frequency band, along with a maximum equivalent sound level reduction (LAeq) of 7.3 dBA demonstrating significant potential for noise pollution mitigation in urban infrastructure. Fig. 7 shows the results of sound absorption (α) of the rubber granulate.[66]

Another study investigated the effect of grain-size composition of rubber crumb on the sound insulation properties of cement and gypsum composites. The findings demonstrated that such composites could serve dual functions, providing both sound absorption and structural support, thereby paving the way for innovative applications in building construction and infrastructure development. Fig. 8 show rubber

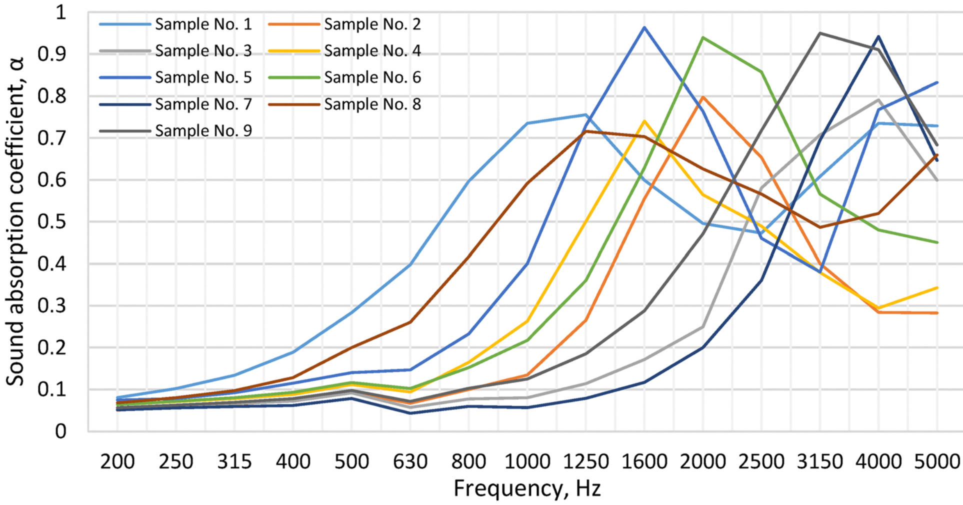

Fig. 7 Sound absorption (α) of the rubber granulate plates. Reproduced from ref. 66.

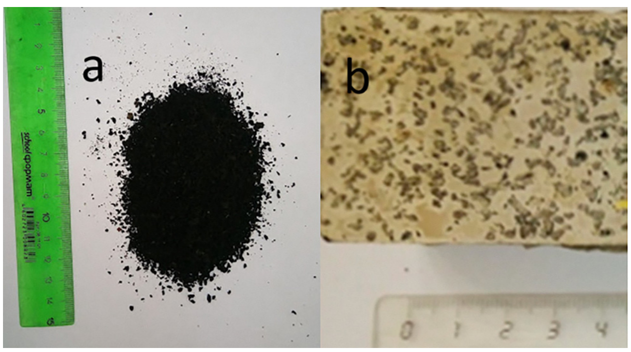

Fig. 8 (a) Rubber crumb of improved grain composition, (b) macrostructure of cement composite with rubber crumb. Reproduced from ref. 67.

crumb of improved grain composition and macrostructure of cement composite with rubber crumb. Fig. 9 shows the results of the samples test for sound absorption (ν-coefficient of variation).[67]

3.4 Energy recovery and fuel

Due to their high calorific value, ranging between 30 and 35 MJ kg^{-1}, waste tires are considered an attractive source for energy recovery, especially in industries seeking alternatives to traditional fossil fuels. One of the most common methods is the use of tire-derived fuel (TDF), which involves shredding tires for combustion in cement kilns, paper mills, and industrial boilers. TDF offers a comparable energy yield to coal and helps reduce reliance on conventional fuels. The pyrolysis oil and gas can be utilized as alternative fuels or refined further for use in the petrochemical industry. While energy recovery through these methods effectively diverts tires from landfills, it ranks lower in the waste management hierarchy than material recycling due to potential environmental and emission concerns.[68–72]

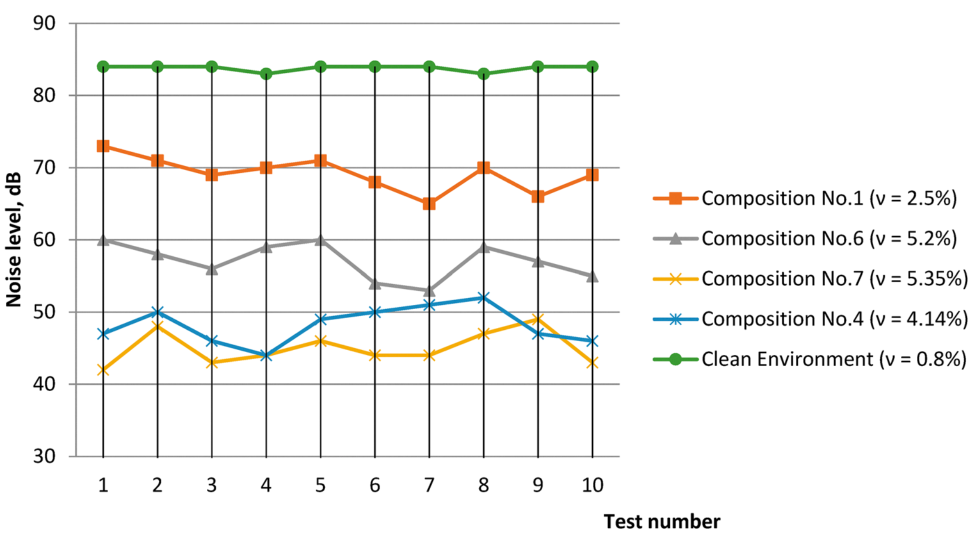

Fig. 9 Results of the samples test for sound absorption (ν-coefficient of variation). Reproduced from ref. 67.

3.5 Environmental and agricultural uses

Recycled tire materials are increasingly being utilized in environmental and agricultural applications due to their resilience, permeability, and eco-friendly nature. One notable use is in soil conditioning and landscaping mulch, where rubber chips serve as a long-lasting alternative to organic mulch. Unlike wood-based mulch, rubber does not decompose quickly, providing long-term coverage and reducing the need for frequent replacement. It also resists mold, pests, and weeds, making it a low-maintenance solution for gardens and green spaces. In agricultural water retention systems, crumb rubber is incorporated into soil to improve its moisture-holding capacity, especially valuable in arid and drought-prone regions. Studies have shown that the addition of rubber granules helps to maintain soil moisture levels, potentially reducing irrigation needs and improving plant survival during dry periods. Recycled tire chips also play an important role in leachate control and landfill engineering. Their high permeability and compressive strength make them ideal for use in drainage layers and leachate collection systems in landfills. By facilitating fluid flow and preventing clogging, tire-derived aggregates help manage waste decomposition byproducts more efficiently. A study by Vahideh Sadeghizadeh and his colleague investigate the potential of using crumb rubber (CR) as a soil amendment has demonstrated significant benefits in improving soil quality. The study found that CR significantly increases soil organic matter and micronutrient availability, particularly zinc (Zn) and iron (Fe) ($p < 0.001$). The incorporation of CR also enhances soil structure by reducing the aggregate fractal dimension, soil penetration resistance, and bulk density. Additionally, CR improves the water holding capacity in sandy soils and increases both plant-available water content and air capacity in clay soils ($p < 0.001$), suggesting its potential use in sustainable agriculture and soil management practices. Soil retention curves of silty clay (A) and loamy sand (B) soils as affected by different CR level is shown in Fig. 10.[73]

3.6 Innovative applications of recycled tire materials

Recycled tire materials are finding new and innovative uses across various high-tech industries. 3D printing filaments have become a notable application, where rubber powder derived from recycled tires is being incorporated into polymer filaments used for additive manufacturing. This not only helps to recycle tire waste but also adds unique properties to the printed objects, such as increased flexibility and durability.[74] In the carbon black recovery process, pyrolysis of tires produces recovered carbon black (rCB), which is increasingly being refined and used in products such as inks, paints, and rubber reinforcement. rCB is a valuable material due to its reinforcing properties, and its use in manufacturing can help reduce reliance on virgin carbon black, which is typically produced from fossil fuels. Additionally, battery and supercapacitor materials derived from pyrolytic carbon from tires are being researched for use in energy storage devices. These materials show potential due to their high conductivity and stability, making them promising candidates for improving the performance of energy storage systems like batteries and supercapacitors. Fig. 11 shows the process of waste tire conversion into energy device.[44] In addition, some properties of recycled tire materials have to be enhanced for more suitability to their corresponding applications as summarized in Table 2.

4. Environmental and economic aspects of tire recycling

Tire recycling not only provides an environmentally sound alternative to landfilling but also contributes to economic growth through material recovery and energy generation. However, like any waste management strategy, it involves trade-offs that must be carefully evaluated in terms of sustainability, cost, and impact.

4.1 Environmental benefits

Waste tires are bulky and non-biodegradable, occupying substantial space in landfills. Their hollow structure can trap gases like methane, leading to buoyancy issues that damage landfill liners and compromise environmental safety. Recycling tires alleviates these problems by diverting them from landfills, thereby conserving space and reducing associated risks. Improper disposal of tires, such as open burning or accumulation in stockpiles, can lead to severe air and water pollution. Tire fires

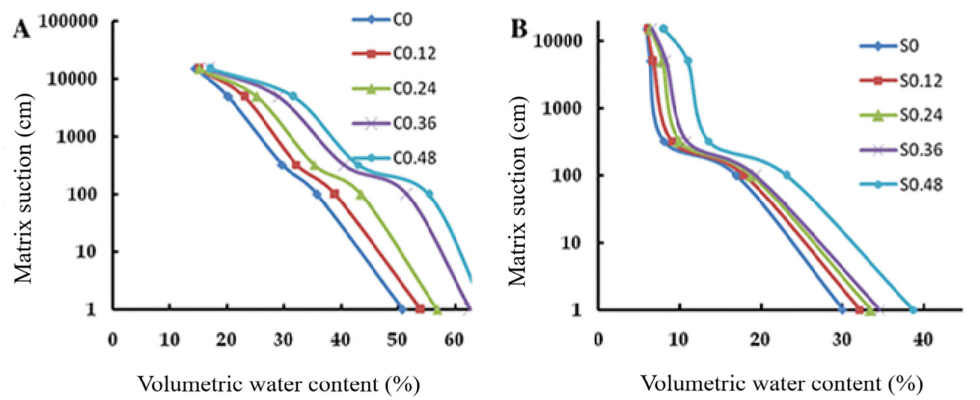

Fig. 10 Soil retention curves of silty clay (A) and loamy sand (B) soils as affected by different CR level. Reproduced from ref. 73.

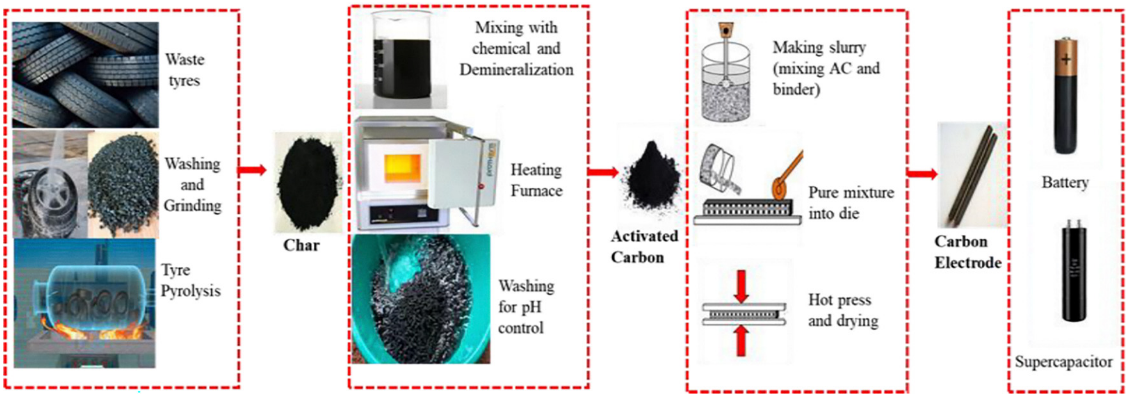

Fig. 11 The process of waste tire conversion into energy device. Reproduced from ref. 44.

Table 2 Key enhanced properties of recycled tire materials and their corresponding applications.[75–84]

Enhanced property	Description	Application
Elasticity	Maintained or improved rebound resilience through controlled particle size and blending	Playground mats, vibration pads
Damping capacity	Excellent vibration and noise absorption due to rubber's viscoelastic behavior	Railway pads, soundproofing layers
Wear resistance	Enhanced through devulcanization or filler reinforcement	Road surfaces, molded mats
Thermal insulation	Low thermal conductivity of rubber-based composites	Construction insulation, HVAC ducts
Impact resistance	Ability to absorb energy makes recycled rubber ideal for safety applications	Athletic tracks, protective flooring
UV/ozone resistance	Additives or blending improve durability outdoors	Roofing membranes, exterior tiles
Adhesion to asphalt	Surface-modified crumb rubber bonds well with bitumen	Rubber-modified asphalt for pavements
Fire retardancy	Improved with specific additives (*e.g.*, alumina trihydrate)	Railway crossings, safety mats
Hydrophobicity	Surface-treated rubber resists water absorption	Drainage layers, hydrophobic coatings

release toxic compounds, including polycyclic aromatic hydrocarbons and heavy metals, which can contaminate air, soil, and water sources.[85–88] Recycling prevents such hazardous scenarios, thereby protecting environmental and public health. Tire manufacturing consumes significant amounts of natural rubber, synthetic polymers, and petroleum-based products. By recycling tires, the demand for these raw materials decreases, leading to conservation of natural resources and reduction in the environmental impact associated with their extraction and processing. The production of new tires is energy-intensive, resulting in substantial greenhouse gas (GHG) emissions. Recycling tires reduces the need for new production, thereby lowering GHG emissions. Additionally, utilizing tire-derived fuel (TDF) as an alternative energy source can result in up to 20% reduction in CO_2 emissions compared to coal.[4,72,89–92] A study in *Journal of Environmental Management* reports that using crumb rubber in asphalt results in a 71.9% reduction in CO_2 emissions relative to landfilling or incineration, while saving USD 16.1 million per year in resource costs across an Australian plant.[72] Chemical recycling also delivers substantial climate benefits. The production of recovered carbon black (rCB) *via* pyrolysis can save 1.43–4.8 t CO_2 eq. per ton compared to virgin carbon black.[60,93]

4.2 Economic advantages

The tire recycling industry plays a significant role in supporting local and national economies through job creation. From tire collection and sorting to advanced processing (*e.g.*, shredding, devulcanization, pyrolysis) and manufacturing of recycled products, a wide range of employment opportunities are created. According to the U.S. Environmental Protection Agency (EPA), recycling industries, including tire recycling, can create ten times more jobs than landfill or incineration alternatives. Recycled tire materials, such as crumb rubber, tire-derived fuel (TDF), pyrolysis oil and gas, molded rubber products, and recovered carbon black (rCB), have substantial market demand. For example, crumb rubber is used in rubberized asphalt, playground surfaces, and sports fields, while pyrolysis oil can be used as an alternative fuel. These products offer profitable revenue streams for recycling businesses. By replacing virgin materials with recycled rubber, industries can significantly reduce raw material costs. For instance, rubberized asphalt costs more upfront but saves money long-term due to longer service life and reduced maintenance. Similarly, in construction and manufacturing, using recycled rubber as fillers, blends, or insulation materials can lead to substantial savings.[94] Many countries provide financial incentives to encourage recycling operations. These may include, tax credits or exemptions, grants for equipment or research, preferential procurement policies for recycled content products, and environmental compliance benefits. For example, the EU Waste Framework Directive and the U.S. Scrap Tire Management programs encourage sustainable recycling practices through regulatory and financial mechanisms. In addition, comparative studies consistently show that recycling tires into crumb rubber or recovered carbon black offers significant environmental and economic benefits compared to using virgin materials. For instance, recycling one ton of ELTs emits approximately 123 kg CO_2 eq. (car tires) *versus* 2767 kg CO_2 eq. for producing a ton of new tires, and reduces emissions by more than 70% compared to incineration.[60]

4.3 Economic challenges

Advanced tire recycling technologies such as pyrolysis, microwave treatment, or devulcanization often require substantial capital outlays for setup, permitting, and specialized equipment. The costs of building and operating such facilities can be a barrier to entry, especially for small and medium-sized enterprises.[68,95] The market for products such as crumb rubber, pyrolysis oil, and recovered carbon black (rCB) is highly sensitive to fluctuations in global oil prices and demand from construction, automotive, and chemical sectors. These shifts affect profitability and investment stability. Recycled materials often face tough competition from virgin rubber and new carbon black, which may be more consistent in quality and less costly during periods of low oil prices. This competition reduces the market share and attractiveness of recycled tire products, especially in industries requiring strict quality specifications.[16,96] Various circular economy models are being actively implemented in the tire industry to enhance resource efficiency and sustainable end-of-life management. A prominent approach is Extended Producer Responsibility (EPR), widely adopted across the EU, including Belgium, Italy, the Netherlands, and Ireland, which mandates manufacturers to finance and physically manage collection and recycling targets, achieving up to 85–100% recovery rates. Companies like Sumitomo and Hankook have developed closed-loop 'tire-to-tire' systems, where digital tracking tools and retreading practices facilitate continuous material recirculation in new tire production. In Japan, integrated resource-cycling policies supported by the Basic Recycling Law and tire-specific regulations have created robust systems targeting high recovery through retreading and material reclamation. These models showcase how policy frameworks, industry innovation, and technological tracking can converge to form circular supply chains, enabling sustainable tire lifecycle management.[97,98]

4.4 Environmental concerns

Although pyrolysis and TDF are more environmentally favorable than open burning or landfilling, these processes can still emit harmful pollutants such as NO_x, SO_x, volatile organic compounds (VOCs), and particulate matter if emissions controls are inadequate. The energy efficiency and environmental performance depend heavily on the design and maintenance of the processing systems.[95] Crumb rubber, commonly used as infill for synthetic turf fields, has been linked to microplastic pollution and potential chemical leaching, including polycyclic aromatic hydrocarbons (PAHs), metals, and additives. These substances may affect soil and aquatic environments when carried by stormwater runoff.[99–101] Research developed by Andres Duque-Villaverde and his colleagues to validate an analytical method using ultrasound-assisted extraction followed by liquid chromatography-tandem mass spectrometry (UAE-LC-MS/MS) to detect 11 environmentally and health-relevant compounds in tire rubber, including antiozonants like 6PPD and DPPD, and vulcanization agents such as CBS, DTG, and HMMM. The method was successfully applied to 40 real-world crumb rubber samples from football fields, playgrounds, pavements, and commercial products, as well as to several alternative infill materials like sand, cork, thermoplastic elastomers, and coconut fibers. Results showed that all target compounds were present in crumb rubber, with 6PPD reaching concentrations of up to 0.2% in new synthetic fields, and 6PPD-quinone is an emerging contaminant linked to salmon mortality that detected up to 40 $\mu g\ g^{-1}$ in football pitch samples. HMMM was also widely found, up to 36 $\mu g\ g^{-1}$. In contrast, alternative infill materials were largely free from these contaminants. This study represents the most extensive investigation of these specific compounds in tire-derived particles and is the first to include the analysis of HMMM, 6PPD-quinone, and DTG in playground environments.[102] In addition, microplastic pollution–primarily generated during grinding and wear of recycled rubber has increasingly been recognized as a source of secondary microplastics in aquatic and terrestrial ecosystems.[85] In the case of pyrolysis, the increasingly used thermal recycling route ashes and solid residues contain up to 12–14% inorganic matter by weight alongside heavy metals like zinc, manganese, and copper, which, if improperly managed, can contaminate soil and groundwater. The char and pyrolytic carbon black products may also harbor elevated sulfur and trace metal levels, including sulfur contents over 2% and ash above commercial-grade limits (∼13%).[103] Products made from recycled tires such as floor mats, sound barriers, and rubber mulch will themselves reach the end of their useful life. Unfortunately, many of these items are not easily recyclable again, creating a secondary waste stream that must be addressed through further innovation in product design or disposal strategies.

4.5 Regulatory support and international standards

Under EPR schemes, tire manufacturers are held responsible for the entire lifecycle of their products, including take-back, recycling, and final disposal. This encourages eco-design, minimizes illegal dumping, and ensures systematic tire recycling infrastructure. Countries such as Canada, Germany, and Japan have implemented comprehensive EPR programs for waste tires.[104] ISO 14001 provides a framework for organizations to set up effective environmental management systems (EMS), including sustainable practices for rubber recycling industries.[105–107] ISO 15270 offers specific guidelines for the recovery and recycling of plastics, including post-consumer rubber and polymer materials, promoting safe and efficient processes. Governments and municipalities across Europe, the U.S., and parts of Asia have adopted GPP policies that encourage or mandate the use of recycled materials in public infrastructure and construction. This drives market demand for products made with recycled tire rubber such as rubberized asphalt, playground surfaces, and noise barriers.[108–110]

5. Challenges and future perspectives

Despite the significant progress in tire recycling technologies and the growing number of applications, several challenges continue to hinder the full realization of its environmental and economic potential. Addressing these barriers requires coordinated efforts across industries, governments, and research communities.

5.1 Technical challenges

Tires are made from a complex mix of materials, including natural and synthetic rubber, steel wires, polyester/nylon fibers, carbon black, and numerous chemical additives (*e.g.*, sulfur, plasticizers, antioxidants). This heterogeneous nature complicates mechanical separation, sorting, and recycling, often requiring multi-step processes to isolate valuable components.[2] The inconsistency in the physical and chemical properties of recycled tire rubber (due to variations in tire formulations and wear history) limits its use in high-performance or load-bearing applications such as premium rubber goods, automotive components, or structural materials.[65,111,112] Vulcanized rubber is highly cross-linked, making devulcanization a technically demanding process. While thermal, chemical, and mechanochemical methods exist, controlled devulcanization without degrading the polymer chains remains a major hurdle, impacting the mechanical integrity and value of the recycled material.[30,113–115] Even after processing, residual metals (*e.g.*, zinc, steel), fibers, and oils from the original tires may remain embedded in the rubber matrix. These contaminants can compromise material safety, mechanical properties, and suitability for sensitive applications, such as food-grade or medical products.

5.2 Economic and market barriers

Despite the growing demand for recycled tire products, their market penetration remains low in some sectors. This is often due to concerns about the performance of recycled rubber compared to virgin materials, and lack of awareness regarding the benefits of tire recycling. Many industries continue to rely on traditional materials like virgin rubber, steel, or carbon black because they are seen as more reliable in terms of quality consistency and performance.[30,111,116]

In many developing countries, the lack of financial incentives or supportive policies hinders the establishment and expansion of tire recycling facilities. While some developed nations offer subsidies, tax breaks, or even extended producer responsibility (EPR) programs to encourage recycling, such measures are often absent in lower-income regions. This lack of financial support can limit the availability of infrastructure and stifle industry growth.[16,117,118] A research study by León Padilla and his colleagues, evaluates the performance of Ecuador's Extended Producer Responsibility (EPR) model for end-of-life tires (ELTs), in effect since 2013, through case studies and comparative analysis with ELT management systems in Colombia and Brazil. The study finds that while Ecuador's program marks progress in national waste management, it faces key challenges. These include the need to strengthen markets for recycled ELT products, encourage related sectors to innovate new and complementary goods, and support small and medium-sized enterprises (SMEs) by improving access to knowledge about ELT by-products. Additional recommendations include raising the consumer fee known as Ecovalor, and enhancing data quality and availability for better monitoring.[119] The price competitiveness of recycled tire products often fluctuates with market prices for oil, virgin rubber, and carbon black. For instance, when oil prices are low, the cost of virgin rubber and carbon black also drops, making it cheaper to produce new tires and related products. This creates a volatile market for recycled tire materials, making it difficult for recycling companies to sustain competitive pricing in the face of cheaper alternatives.[24,46,120] In addition, large-scale implementation of tire recycling is influenced by a complex mix of cost dynamics, industrial compatibility, and government policies. The capital and operational expenditures for recycling technologies vary significantly—with pyrolysis facilities typically costing between \$500 000 and \$2 million to set up, and requiring substantial ongoing expenses for labor, utilities, and regulatory compliance. Operational costs can be partially offset by revenue from by-products: in Saudi Arabia, for instance, processing one ton of tires *via* pyrolysis yields net profits of \$70–\$100, with annual revenues reaching around \$47 million for a medium-scale plant. The viability of recycling operations is further shaped by market demand and pricing, with recycled rubber typically costing \$1–\$1.50 per kg, compared to \$2–\$2.40 per kg for virgin rubber—making recycled materials economically appealing in markets with supportive conditions. Government policies play a critical role in influencing market dynamics. Environmental levies and tipping fees—such as South Africa's tire levy of approximately USD 223 per ton—help improve profitability and justify investment in recycling infrastructure. In parallel, policy incentives—including EPR mandates, tax breaks, and grants—are accelerating the sector's growth, particularly in North America and the EU, by creating steady supply chains and demand for recycled products. A case in point is Taiwan's REDISA model, which collects disposal fees on tyre sales and invests approximately 80% of proceeds into recycling programs and infrastructure development. Additional enablers include cross-industry collaborations such as partnerships between recyclers and energy-intensive industries like cement plants that consume pyrolysis oil reducing feedstock costs and securing off-take agreements. Combined, these factors, investment costs, product market pricing, tariffs, and regulatory frameworks—determine the scale and sustainability of different tire recycling pathways. Without such policy supports and market linkages, even technically viable recycling methods can struggle to achieve large-scale adoption.

5.3 Regulatory and policy issues

One of the major challenges in the tire recycling industry is the global disparity in waste management regulations. Different countries and even regions within a country may have varied laws and guidelines governing tire disposal and recycling, which can result in uneven progress toward recycling adoption. Some regions have strict regulations that mandate tire recycling, while others may lack the necessary policies or incentives to encourage proper disposal. This regulatory fragmentation hinders the development of a global recycling market and creates barriers for businesses that want to expand internationally.[116,121] Even in regions where tire recycling regulations are in place, enforcement gaps can undermine their effectiveness. In many cases, illegal dumping of tires or poor recycling practices may continue due to insufficient oversight or inadequate infrastructure for waste management. This leads to increased environmental pollution, including the risk of tire fires and the release of toxic chemicals into the environment. Governments must enhance their enforcement mechanisms to ensure compliance with regulations and improve the efficiency of the recycling process.[112,122,123] The lack of universal product standards for recycled tire-derived materials complicates both the certification and trade of such materials. Without standardized criteria for material quality and performance, it becomes difficult for industries to adopt recycled tire products on a large scale. This lack of standardization also discourages manufacturers from sourcing recycled materials, as they cannot be assured of consistent quality. Establishing international standards for recycled tire products would help create a more reliable and efficient market and foster the global use of recycled tire materials.[124]

5.4 Environmental and social concerns

Public concerns have emerged regarding the use of crumb rubber in sports fields and playgrounds due to potential health risks. Some studies have raised alarm over the possibility of toxic chemical leaching and the release of microplastics from recycled tire materials, especially when exposed to heat and wear. These concerns have sparked debates over the safety of recycled tire-based products, particularly in high-contact environments like children's play areas and athletic tracks. While research has shown that the levels of harmful chemicals in these materials are generally low, public perception often lags behind scientific evidence, leading to hesitancy in the adoption of such materials.[101,125] While tire recycling helps alleviate the burden of tire waste, end-of-life management for products made from recycled tires is still not well established. Products such as molded rubber goods, rubberized asphalt, and crumb rubber used in artificial turf will eventually reach their own end-of-life, at which point disposal and recycling options are limited. Unlike the original tires, which can be shredded and processed in various ways, the recycled products made from tires may present unique challenges for disposal or further recycling, leading to additional environmental concerns. Research is needed to develop sustainable solutions for managing post-recycling waste.[63,101,126] Occupational health risks associated with the tire recycling industry have raised concerns, particularly in relation to exposure to fine rubber particles, chemicals, and high temperatures during processing. Workers involved in shredding, grinding, or pyrolysis processes may be exposed to potentially harmful substances, including volatile organic compounds (VOCs) and heavy metals. Proper safety protocols, protective equipment, and monitoring are essential to ensure the well-being of employees working in tire recycling facilities. Research into safer processing technologies and improved protective measures is crucial for reducing the risk of occupational diseases.[85,127]

5.5 Future perspectives

The ongoing development of advanced recycling technologies holds the key to improving the efficiency and quality of tire recycling. For example, selective devulcanization is a process that breaks the sulfur cross-links in rubber without degrading the polymer chain has the potential to produce recycled rubber with properties similar to virgin materials. Microwave pyrolysis, an emerging method, uses microwave energy to break down tire components, offering faster and more energy-efficient processes. Additionally, enzymatic treatments are being explored for their potential to selectively degrade rubber while preserving its quality. AI-driven sorting systems are also expected to revolutionize the sorting of tire waste by automating and improving the separation of rubber, steel, and other materials with higher accuracy and speed.[128–133] Circular economy (CE) principles are gaining traction in the tire industry, and integrating tire recycling into these frameworks can help create a sustainable system where tires are designed for recycling from the outset. Tire manufacturers are increasingly adopting design-for-recycling strategies that consider the ease of disassembly and material recovery at the end-of-life stage. The CE model encourages the reuse of tire-derived materials in the production of new products, reducing waste, and promoting resource efficiency. This not only reduces reliance on virgin materials but also aligns with broader environmental goals, such as reducing carbon footprints and preserving natural resources.[134–136] The tire recycling sector can greatly benefit from public-private partnerships (PPPs). These collaborations bring together governments, recyclers, and manufacturers to drive investment in recycling infrastructure, improve efficiency, and expand markets for recycled tire products. Governments can support the development of recycling facilities through subsidies, tax incentives, and supportive legislation, while private companies can contribute technical expertise, resources, and market access. This synergy can lead to the creation of a closed-loop system that maximizes tire recycling and minimizes waste.[137,138] Public and industry awareness are crucial for the widespread adoption of recycled tire products. By educating consumers and businesses about the safety, performance, and environmental benefits of using recycled materials, the market for these products can be expanded. This includes dispelling myths about the toxicity of materials like crumb rubber in playgrounds and sports fields, as well as highlighting the economic benefits of using recycled rubber in various applications, from construction to automotive products. Comprehensive educational campaigns can lead to higher demand and greater acceptance of recycled tire products. The integration of recycled materials into durable, high-performance products is essential for enhancing both the market value and environmental impact of tire recycling. Manufacturers can design products that are optimized for both performance and sustainability, ensuring that they meet industry standards while minimizing their environmental footprint. The development of eco-friendly, safe, and long-lasting products from construction materials to automotive parts, can drive demand for recycled tire-based products. In addition, incorporating recycled materials into products like insulation or rubber flooring can further reduce the consumption of virgin materials and contribute to a more sustainable, circular economy.[60,84,112,139,140]

6. Conclusion

Tire recycling is a critical pillar of sustainable waste management, especially in a world facing mounting environmental and industrial pressures. With over a billion tires reaching end-of-life annually, the need for efficient and environmentally sound recycling solutions is more pressing than ever. The following key conclusions and future directions are drawn from this review:

1. Mechanical, thermal, and chemical recycling methods each offer unique advantages. Emerging techniques such as microwave pyrolysis and selective devulcanization show promise for higher material recovery and better product quality.

2. Recycled tire materials are successfully used in pavement surface layers, sports fields, insulation products, molded goods, and fuel sources, highlighting their versatility and market potential.

3. Many recycling techniques contribute significantly to resource conservation and energy recovery, although lifecycle and cost-benefit analyses are needed to optimize implementation.

4. Persistent Challenges are inconsistent regulations and enforcement across regions, limited standardization of recycled material quality, public concerns over safety and health, especially in playground and sports field applications and occupational health risks in recycling facilities.

5. The integration of AI for sorting, enzymatic treatments, and advanced devulcanization techniques can dramatically improve recycling outcomes and reduce environmental.

6. Embedding recycling into tire design and production stages supports a closed-loop model that enhances sustainability and reduces dependency on virgin materials.

7. Collaboration between government entities and private industry can drive innovation, infrastructure investment, and market expansion.

Future research directions should focus on developing safer and cleaner devulcanization and pyrolysis technologies that minimize environmental emissions and energy consumption. Additionally, comprehensive evaluations of the long-term environmental impacts and by-products of large-scale tire recycling are necessary to ensure sustainable implementation. The design and application of predictive models and digital tools can further optimize circular economy strategies, aiding in the efficient integration of recycled materials into new production cycles. Finally, establishing standardized databases and certification systems for recycled tire-derived materials will enhance quality assurance, support regulatory compliance, and build greater confidence among manufacturers and end-users.

Conflicts of interest

There are no conflicts to declare.

Data availability

This manuscript is a comprehensive review and does not involve the generation or analysis of primary research data, software, or code. All relevant information, data, and references necessary to support the findings and conclusions are fully included and accessible within the main text and cited literature. Therefore, no additional datasets or supplementary materials are required for readers to understand, verify, or replicate the content presented in this work.

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