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Waste Rubber Recycling Technologies and Reclaimed Rubber Applications

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Abstract:

Waste rubber has emerged as a critical global concern, with its annual production skyrocketing. These discarded rubber products, resistant to decomposition, not only consume vast land resources but also release harmful substances, polluting soil and groundwater. Moreover, they pose a high - risk fire hazard and emit foul odors, severely degrading the surrounding environment. Simultaneously, as rubber resources are scarce, over 70% of natural rubber in China relies on imports. This review delves into the evolution of reclaimed rubber production technologies, from the 1846 lime chloride boiling method—plagued by pollution and low yields—to contemporary physical (microwave, ultrasound, twin - screw extrusion), chemical, biological, and thermochemical methods. New - age green technologies like supercritical devulcanization are enhancing eco - friendliness and production efficiency. Applications in building materials (such as asphalt modification and rubber concrete) and as fillers in rubber products are also explored. These technologies not only enhance resource utilization by converting waste into value - added materials but also adhere to circular economy principles, supporting environmental protection and contributing to carbon neutrality and the UN Sustainable Development Goals.

Keywords: Waste rubber; Recycling technology; Physical recycling; Chemical recycling; Recycled rubber application.

1. Introduction

The widespread use of rubber products has intensified the global waste rubber crisis, with annual volumes exceeding 10 million tons. Improper disposal triggers "black pollution", land occupation, and risks of fire and biological contamination, posing persistent threats to ecosystems and public health. Meanwhile, global rubber resources remain heavily reliant on specific natural rubber producing area and fossil-based synthetic rubber, exacerbating scarcity.

Efficiently recycling waste rubber into valuable "urban mines" is key to easing resource strain and reducing environmental impact. This aligns with

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global circular economy goals, directly supporting carbon neutrality and UN Sustainable Development Goals (SDG 9, 11, 12). Advancing eco-friendly recycling technologies thus becomes a shared international duty to safeguard resource security and foster sustainability.

Waste rubber's major challenge lies in its structure: a vulcanized cross-linked polymer matrix with carbon black, additives, and often fibers/metal. This complex 3D network resists natural degradation ("black pollution") and hinders recycling.

2. Production of Reclaimed Rubber

The idea of reclaimed rubber started in 1846, with early production using boiling calcium chloride solution. This method caused heavy pollution and had low yields. As technology improved, better processes like acid, alkali and neutral methods emerged, enabling industrial-scale production. Since the 20th century, key technologies such as superheated steam, internal mixer, water-oil, extrusion and rapid devulcanization methods developed quickly. Among these, water-oil, extrusion and rapid devulcanization methods became widely used due to their maturity. Modern devulcanization methods fall into physical, chemical and biological regeneration. New green technologies like ultrasonic and supercritical devulcanization have recently appeared, making reclaimed rubber production more eco-friendly and efficient.

2.1 Physical Regeneration Methods

Physical recycling uses energy like microwaves, ultrasound, high shear or heat to break rubber's sulfur-based cross-linked networks, which make it hard and brittle. Twin-screw extrusion devulcanization is particularly promising. It mixes waste rubber powder with devulcanizing agents, then heats (240-300℃) and stirs strongly. High temperature, mechanical shear and chemicals work together to break unwanted C-S and S-S bonds, "freeing" the rubber. Compared to old autoclave devulcanization (hazardous and polluting), twin-screw technology allows continuous production, better control and little secondary pollution. Results depend on operation: temperature must be controlled, and faster machine speeds generate more shear and heat, improving devulcanization. This technology is popular for its simplicity, high output and low pollution.

The thermomechanical method, using twin-screw extruders, is most common in rubber recycling. It enables continuous, efficient production. Product quality is controlled by adjusting barrel temperature and screw speed. The modular screw design lets its length and shape be customized to adjust shear force for different rubbers.

Barbosa et al. found that in natural rubber (NR) thermomechanical devulcanization, materials with higher cross-link density devulcanize more, as dense sulfur bonds are easier to break with shear and temperature[1]. Simon et al. noted that at low temperatures (< critical value), cross-link bonds break selectively, with screw speed having little effect. At high temperatures, fast speeds damage the polymer main chain, so parameters need optimization[2]. Yazdani et al. showed temperature is key for truck tire devulcanization: 220℃ gives 88% sol content (higher than 85% at 280℃) due to increased viscosity and shear stress. High temperatures at low speeds improve devulcanization, and proper temperature-speed combinations work without cracking agents[3].

2.2 Microwave Devulcanization

Microwave devulcanization uses the dielectric difference between fillers and rubber. Microwaves heat wave-absorbing fillers like carbon black in rubber powder, breaking sulfur cross-links (C-S/S-S bonds) to break down the network[4]. Karabork et al. found this increases sol content but may damage rubber's main chain C-C bonds, harming mechanical properties[5].

Aoudia et al. found microwave treatment slightly degrades tire rubber's main chain (C=C, C=O bonds) but mainly breaks cross-links (C-S, S-S bonds), with some C-C and C-O bonds also broken[6]. Simon et al. showed temperature-controlled microwaves treat water-jet GTR better, producing more uniform products. Microwave-devulcanized GTR added to SBR-based rubber improves elongation at break, tensile strength and tear strength[7].

2.3 Ultrasonic Devulcanization

Radiation desulfurization uses high-energy radiation (e.g., electron beams) to create vibration waves, breaking C-S/S-S bonds via electron energy[8]. Ultrasonic desulfurization uses high-frequency waves to make cavitation bubbles; their collapse breaks target bonds. Both methods are fast, controllable and chemical-free.

Compared to other physical methods, ultrasonic desulfurization (Desbrieres et al.) increases molecular movement through cavitation, making high-weight sol [9]. But it uses much energy and is hard to scale up.

2.4 Chemical Regeneration Methods

Chemical devulcanization uses reagents like organic disulfides, mercaptans or inorganic compounds to break rubber's cross-linked structure, keeping most elastomer properties so reclaimed rubber can be reused.

Mechanochemical regeneration breaks vulcanized rubber's cross-links with high mechanical shear. Equipment like screw extruders and solid-phase shear mills generate shear and heat, breaking C-S and S-S bonds while keeping the C-C main chain. Small amounts of regenerants (e.g., mercaptans) help reduce bond-breaking energy[10]. Under mechanical force and heat, rubber powder devulcanizes and reorganizes into partially plastic reclaimed rubber. Compared to chemical methods, this process is continuous, pollution-free, low-energy, and makes reclaimed rubber with good properties: lower Mooney viscosity for easier processing, with over 80% of original tensile strength and elasticity. Twin-screw dynamic devulcanization is now used industrially.

Activators are key in this process, but little research exists on their effect. Yao Jing et al. studied activator 420 : it starts regeneration by breaking sulfur cross-links. At the right dosage, reclaimed rubber performs best—better tensile strength, elongation, cross-linked structure and processability[11].

2.5 Thermochemical Treatment Methods

Heating waste tires at high temperatures breaks them into three products: pyrolysis oil (like fuel, usable directly or as a rubber softener); combustible gas (mostly hydrogen and methane, for fuel or process energy); and carbon powder (replaces carbon black or makes adsorbents for heavy metals like mercury).

Microwave pyrolysis is better than traditional pyrolysis—saves energy, is eco-friendly, efficient and controllable. J.A.V.Mursu et al. found microwave radiation under inert gas breaks rubber molecules into recoverable pyrolysis gas, oil and carbon black[12]. Su Xin et al . used HFSS software to optimize microwave pyrolysis cavity design. With adjacent feed ports 150mm apart and orthogonal, wave interference is minimized, improving energy use and stability[13].

3. Application Fields of Reclaimed Rubber

3.1 Building Materials

Reclaimed rubber for building materials needs only simple physical processing. Rubber powder from waste tires improves asphalt for roads. It recycles rubber and makes asphalt perform better—asphalt often softens in heat and cracks in cold, and rubber powder changes these properties[14].Cheng Xiufang et al. made RPMA asphalt. Rubber powder boosts its high-temperature performance; softening point and cold ductility rise quickly then level off with more rubber[15]. Wang Zhiyuan et al. found 1% rubber powder best stops asphalt cracking in cold, as carbon fiber tubes in the material strengthen it by distributing tensile strength.

Rubber concrete mixes rubber particles into cement. Rubber fills gaps (without reacting with cement), keeping concrete durable while making it lighter, tougher, more impact-resistant, less heat-conductive and better at reducing noise—good for road noise layers and building walls[16]. Rubber amount, particle size and concrete age affect strength. Wu Bizhen et al. found more rubber reduces strength (smaller particles more so), but strength improves over time, partly making up for the loss[17].

3.2 Reclaimed Rubber as Filler

Tires contain rubber (e.g., styrene-butadiene, natural rubber), carbon black/silica, vulcanization agents and additives. “Bound rubber”—rubber stuck to carbon black during production—strengthens tires but makes recycling hard, as it holds rubber and carbon black together. Mechanical shear or chemicals are needed to separate them.

Zhang et al. developed a green method: heating rubber at 200℃ for 20 minutes (no reagents) recovers 66.53% sol[18]. This breaks bonds, freeing carbon black. Adding 10-40% of this reclaimed rubber to natural rubber keeps it strong and more resistant to aging.Lin Ziyang et al. improved pyrolytic carbon black (CBP) for better rubber reinforcement. Acid washing reduces impurities, making it work almost as well as commercial N660[19]. Heat treatment and mixing with other materials also help optimize rubber’s cross-linked structure.

4. Conclusion

The waste rubber recycling has made notable progress in technology and application. The reclaimed rubber finds practical use in building materials, such as rubber-modified asphalt and rubber concrete, and as fillers, contributing to enhanced performance and resource recycling. Future research should focus on developing greener, more efficient devulcanization technologies, expanding high-value applications, and improving the life-cycle assessment to promote the sustainable development of the waste rubber recycling industry.

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