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Sustainable mobility: The route of tires through the circular economy model

Javier Araujo-Morera, Raquel Verdejo *, Miguel Angel López-Manchado, Marianella Hernández Santana *

Institute of Polymer Science and Technology ICTP-CSIC, Juan de la Cierva 3, Madrid 28006, Spain

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A B S T R A C T

Until nowadays, the concept of the 3Rs (Reduce, Reuse, Recycle) has tried to develop responsible consumption habits. Nonetheless, the rise of ecological thinking has generated the appearance of four new Rs in addition to these basic 3Rs; the currently 7Rs (Reduce, Reuse, Recycle, Redesign, Renew, Repair and Recover) which refer to the actions necessary to achieve the change towards a circular economy (CE) model. This model aims at extending the lifetime of the resources through their rational and efficient use to generate value repeatedly, reducing costs and waste. In this review, we examine the route followed by tires from the CE perspective, analyzing end-of-life strategies that aim to improve the circular flow of tire rubber materials. We discuss the most relevant studies on the "7Rs" concepts applied to tires, comparing different scientific approaches, as well as their industrial and commercial implementation. We also illustrate the drawbacks and feasibility of each of the R-hierarchy strategies. From the early stages of production to the post-consumption step, the path that tires trail within this CE model evidences the commitment and efforts towards the development of effective management schemes for achieving a real sustainable mobility.

Contents

* Corresponding author.
E-mail addresses: r.verdejo@csic.es (R. Verdejo), marherna@ictp.csic.es (M. Hernández Santana).

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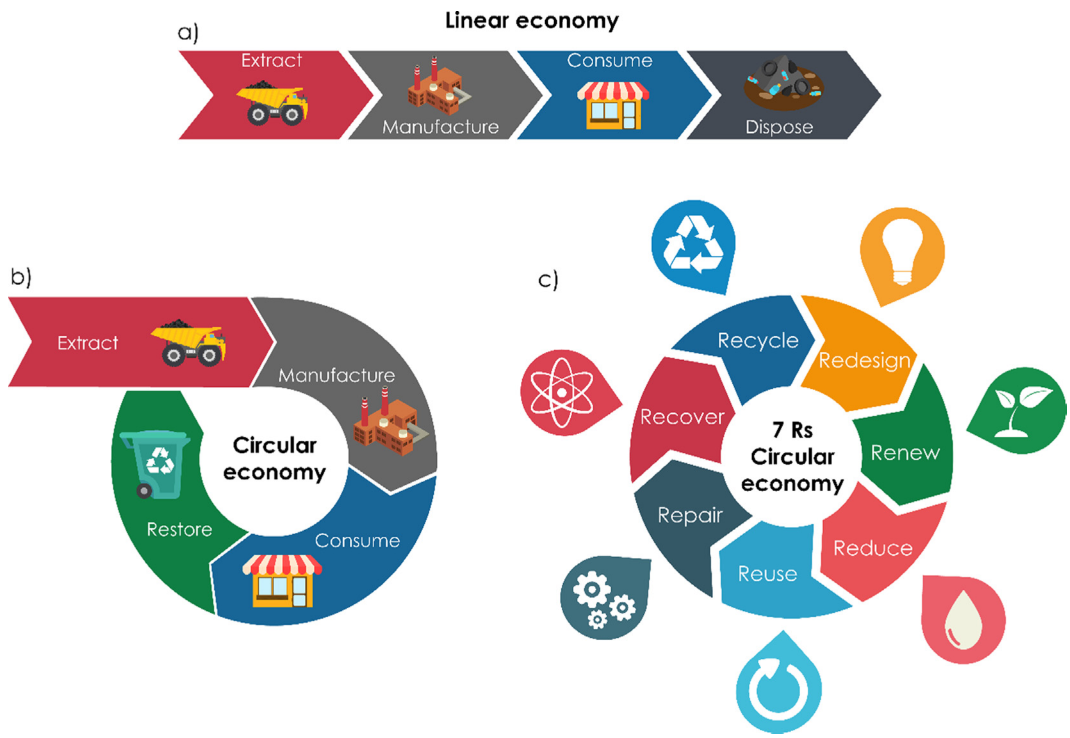

Fig. 1. a) Linear and b) circular economy models. c) 7Rs of the circular economy model.

1. Introduction

The linear economy model of "extract-manufacture-consume-dispose" was globally adopted since the industrial revolution (Fig. 1a). This model resulted in a worldwide urban solid waste of approximately 1.300 million ton/year in 2010, which is expected to increase to 2.200 million ton/year by 2025, being plastics an important contributor (Segui et al., 2018). This situation put forward a new model, i.e. the circular economy (CE) model, that replaces the notion of "disposability" with "restoration". In the CE model the entire system is ready to reuse, repair, restore and recycle resources so that they generate value over and over again, causing their rational and efficient use (Fig. 1b) (Ellen MacArthur Foundation, 2020). Initial axioms of the CE model were termed the "3Rs", "R"educing waste, "R"eusing and "R"ecycling resources and products, and have become familiar in many national waste regulations around the world (Gaustad et al., 2018; Vermeulen et al., 2018). These basic axioms have now been derived further to broaden the CE approach to the "7Rs" (Redesign, Renew, Reduce, Reuse, Repair, Recover and Recycle) (Fig. 1c) (Reike et al., 2018).

While tires have long provided a circular solution in terms of the 3Rs, the novelty of the CE (and the 7Rs axioms) applied to tires is now determined by product and material circularity, and resource productivity. The product circularity focuses on: i) new and innovative tires with the aim of avoiding safety problems and saving fuel (Redesign); ii) new technologies to extend their useful lifetime (Repair and Reuse); and iii) devulcanization technologies with the aim of obtaining rubber with the same performance as in the fresh/virgin rubber (Recycle). In the case of the material circularity, it focuses on obtaining beneficial by-products (Recover). Meanwhile, the resource productivity focuses on the substitution of petroleum-derived products by other natural or bio-based raw materials (Renew); as well as new technologies for reducing the weight of tires and the benefits they involve (Reduce).

The aim of the present review is to analyze tire management considering the 7Rs approach. The review starts with a brief analysis of tires and their industry, giving updated consumption and disposal data. Then, it gathers the most relevant studies on the application of the 7Rs to tires, comparing different scientific approaches, as well as their industrial and commercial implementation. It ends with an outlook and some general perceptions. The peer-reviewed literature discussed in this review was identified through different professional search engines and databases (Web of Science, Scopus, Google Scholar, etc.), combining several keywords (e.g., tire, elastomer, rubber, green, biobased, redesign, recycle, ground tire rubber, self-healing, reclaim, devulcanization, reuse, pyrolysis, incineration, retread, waste, among others). Collected literature for each R-hierarchy strategy was critically reviewed and assessed, illustrating the drawbacks and feasibility of each "R" approach within the tire industry.

2. The tire industry

Tires are essential for mobility, and fundamental for the safety of vehicles. They perform numerous functions: bear the weight of the vehicle, transferring the load to the surface; provide grip between the vehicle and the road for braking and acceleration; and act as vibration absorbers, enhancing road comfort and safety and improving the overall performance of the vehicle (The International Market Analysis Research and Consulting Group - IMARC Group, 2020).

A tire is manufactured from a variety of materials, including several rubber components, each of which provides a specific and unique purpose. Natural rubber (NR) is used in tire casings requiring high durability, while synthetic rubbers are used in tread materials to provide tire grip. Chemicals (expressed in parts per hundred rubber – phr) serve as antioxidants, curatives, and processing aids; carbon black (CB) and silica are added as reinforcing agents; and cords composed of textile, fiberglass and steel wire (brass, bronze or zinc plated) provide stability and stiffness. About

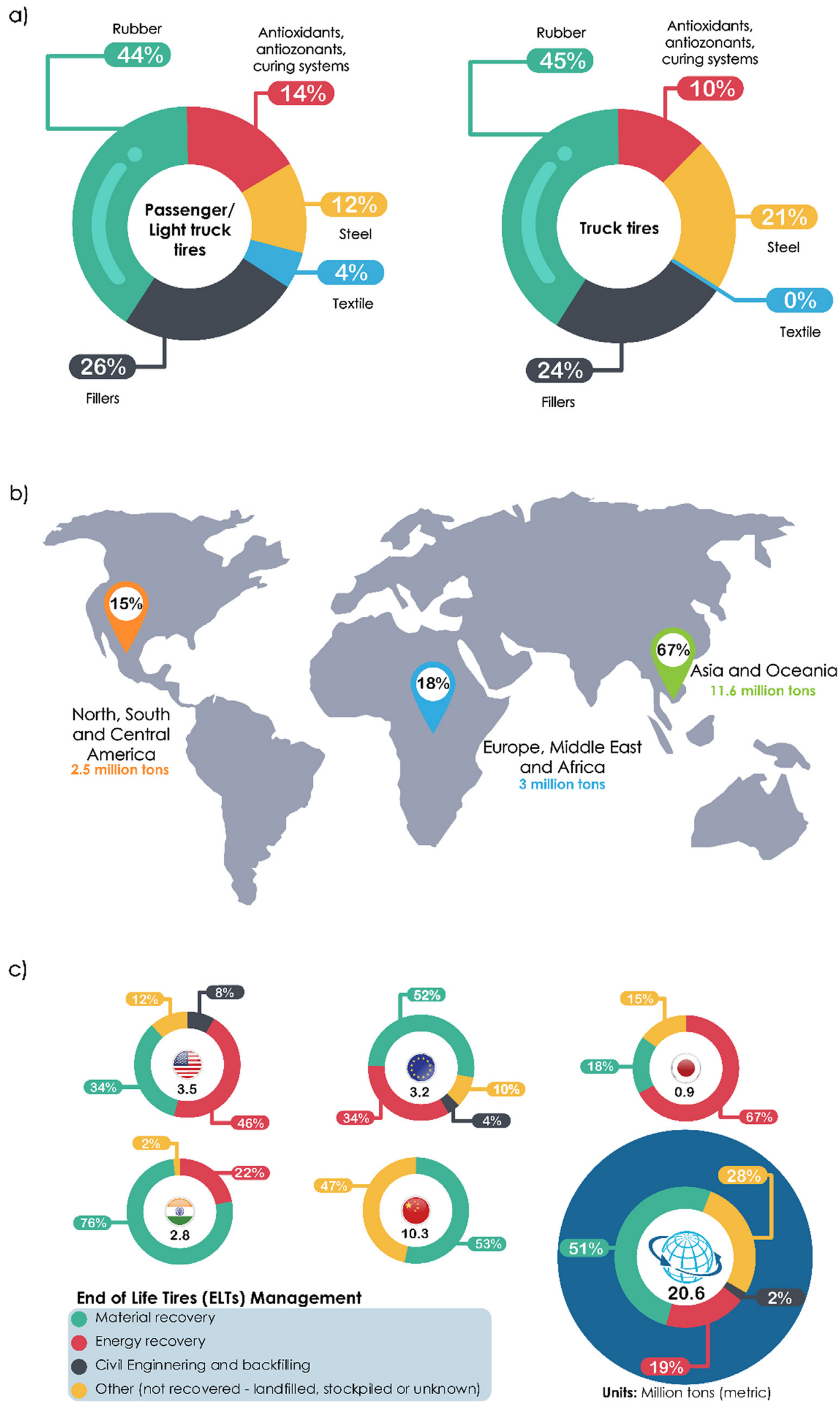

Fig. 2. a) Composition of vehicle tires in weight percentages (%). b) Tire production worldwide. c) ELT management by country/regions (World Business Council For Sustainable Development - WBCSD, 2018).

three quarters of the tire correspond to the rubbery compound, which includes the polymer, fillers and chemicals. The composition in weight percentage of raw materials varies depending on the tire type (Fig. 2a). These materials are selected based on their mechanical and physical characteristics and on their interactions with other constituent materials, providing a broad range of properties

(Anderbilt et al., 2010). Such composition makes waste management of used tires extremely difficult. Due to their chemical and biological resistance to degradation, tires result in negative environmental impacts. Moreover, in illegal landfilling, tires have the capacity to retain water, which provides a breeding ground for different disease vectors such as mosquitoes and rats, among others. Additionally, in case of burning, tires produce significant air pollution, contamination of the soil and surface and ground water problems (Beach and Schroeder, 2000).

World population evolution, rapid urbanization, and increasing consumer spending power have contributed to the growing demand for bicycles, motorcycles, buses, trucks, and airplane and passenger vehicles. According to the International Rubber Study Group (IRSG), the world tire production in 2018 was estimated in 17.1 million ton (Fig. 2b). In addition, rising income levels in developing countries will make vehicles more accessible, further increasing tire sales in those markets in the upcoming years (The Freedonia Group, 2018). Such global market creates a significant annual demand for tire replacement and, thus, generates a great number of end-of-life tires (ELT). ELT are considered as tires that can no longer serve their original purpose and mostly come from automobiles and trucks. ELT recovery systems can be classified into three groups: material recovery, energy recovery, civil engineering, and backfilling, all of which contribute to the industry efforts to build a circular economy. Fig. 2c shows ELT generated by country/region: China, Europe (countries covered by the European Tire & Rubber Manufacturers Association – ETRMA), India, Japan, and USA. The total amount of ELT generated is estimated to be more than 20 million ton, while the amount of ELT recovered rounds up more than 14 million ton/year. Overall, 70% of the ELT recovered (in ton) by the countries/regions are concentrated in two recovery route sub-categories: production of tire-derived material (TDM), with 52%, and tire-derived fuel (TDF), with 19% (World Business Council For Sustainable Development - WBCSD, 2018). Detailed information will be given in the following sections.

ELT management is a core activity of the tire industry, like all the other phases of the design and production process and has three main models worldwide. According to the Extended Produced Responsibility (EPR) model, tire industries are responsible for the management of used tires. This model is very common in the European countries, also used in Brazil, South Africa and South Korea and, recently, Russia and Ukraine (European Tyre & Rubber Manufacturers Association - ETRMA, 2019) The participants of the system create a non-profit organization that manages the collection and ensures that the mandatory levels of recovery and recycling of waste tires are accomplished. The additional cost is generally passed on to consumers, with an environmental fee (ecological fee) added to the price of the tire. In the Tax model, the responsibility lies on the State and collection and recovery are financed by a tax on production, passed on to the consumer. Producers or sellers impose a disposal liability, added to the cost of a new tire, and paid to the national budget. The management of waste tires is carried out by recovery/recycling organizations and financed by the State. Only a few countries, Denmark, Slovakia, and Croatia, run such a system. While the Free-Market model considers the profitability of recovery and recycling of tires. It assumes that used tires are a source of valuable raw materials and that the involved companies profit from their management. In this system, the State establishes legislations to have an ELT management plan; however, the responsibility (tax) is not imposed on particular participants. The countries with this system are Argentina, China, India, Indonesia, Japan, Malaysia, Mexico, New Zealand, Saudi Arabia, Thailand, Austria, Switzerland, Germany, the UK, and the United States (Sienkiewicz et al., 2017; World Business Council For Sustainable Development - WBCSD, 2018).

3. Circular economy applied to tires

The CE model is growing in the tire industry, whether it is for the convenience of opening new opportunities in the sustainable market, for pure survival in an increasingly demanding environmental legal context, or for the true conviction of companies that are more aware of the need to minimize their environmental impact. Applying the CE model and the 7Rs to tires involve studying and comparing tire management from different perspectives (the scientific, industrial, and commercial), while innovating in search of the right combination of design, materials, and advanced engineering. The following sections detail the different studies and approaches developed by these actors according to each of the "Rs" of the CE model.

3.1. Redesign

The starting point of the CE is based on the redesign of the products and services themselves, considering the environmental consequences. The main objective of these designs has so far focused on reducing fuel consumption and, consequently, pollutant emissions, while maintaining road safety (Fig. 3). The next challenge is to bring down tire design to individual components or elements to facilitate tire repair or disassemble and reuse in the manufacture of new ones.

These new designs have materialized into innovative products, some of which are already in the market. Airless or non-pneumatic tires that do not deflate under any circumstance use 3-dimensional structures to bear the weight of the vehicle. Goodyear trades airless tires for zero-turn radius mowers, while Michelin offers a line of airless radial tires for construction, recreation, and small-scale utility vehicles. Cooper has been active in the development and evaluation of non-pneumatic tire technology for military use. Moreover, Hankook, Bridgestone, Michelin and Goodyear have introduced concept tires that would bring airless tires to the passenger vehicle market. One example is Michelińs Tweel tire, an airless integrated tire and wheel assembly, in which the rubber tread is fused to the wheel core with polyurethane rods. The Tweel tire targets performance levels beyond what is possible with conventional pneumatic know-how due to its shear band design, additional suspension, and decreased rolling resistance (Bras and Cobert, 2011). Michelin also introduced Vision, a biodegradable 3D printed smart concept tire, manufactured using sustainable materials. It is airless and equipped with sensors that offer real time updates on the condition of the tire (The International Market Analysis Research and Consulting Group - IMARC Group, 2019).

Another line of innovation and redesign considers self-sealing tires. This technology involves the use of a sealant material placed as an inner layer below the tread. When a puncture occurs, the sealant prevents the loss of air pressure by filling the hole. In addition, run-flat tires can travel safely for up to 80 km at 80 km/h even after a tire loses its pressure due to a puncture, according to the manufacturers' specifications. This feature allows drivers to navigate to a safe and convenient place to repair or replace the affected tire. Run-Flat tires also eliminate the need for occasionally used spare tires and rims, preserving materials and freeing up boot space (Amick, 2018).

Tires can lose about 3–6% of pressure per month without the driver's knowledge. Deflated tires can cause up to 4% increase in fuel consumption while reducing tire lifespan by 45%. Many manufacturers are also developing sophisticated and inherent detection systems (chips, tags or sensors) that, integrated into a tire, can wirelessly transmit real-time information, such as pressure,

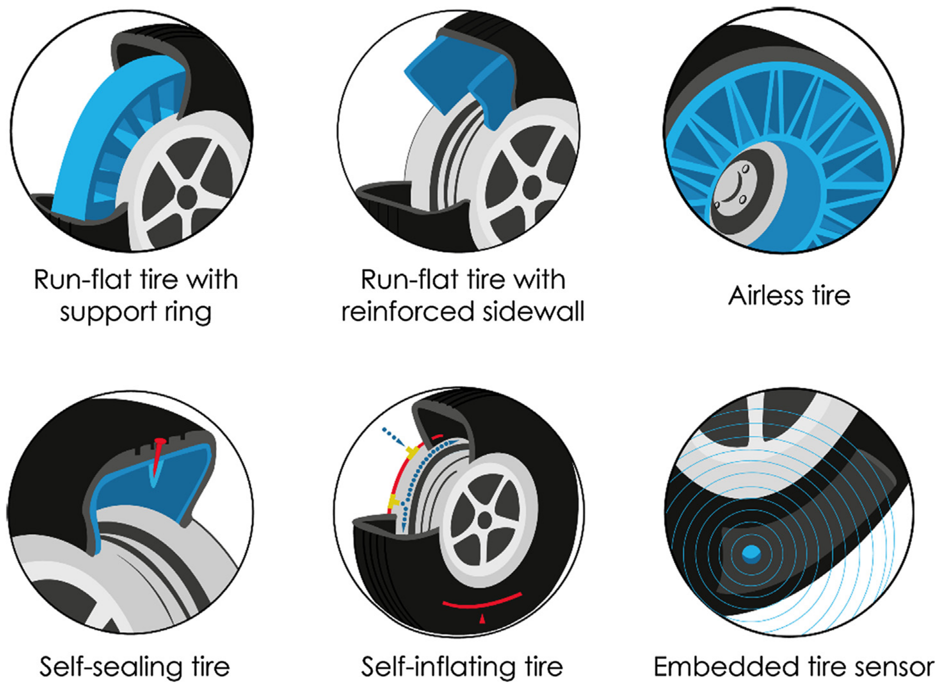

Fig. 3. Innovative tire concepts and designs (Amick, 2018).

tire temperature and tread wear, warning of malfunctions (Kuncoro et al., 2019). Goodyear has implemented the so-called self-inflating tires, i.e. a sensor/pump combination embedded within the tire structure, which could ultimately eliminate the need for drivers to manually control tire pressure. Another example is the Tire Pressure Monitoring Sensor (TPMS), an electronic device that alerts drivers in case of a tire puncture or under inflation below a threshold (Simonot-Lion and Trinquet, 2017). This feature improves safety, by improving traction, vehicle handling, decreases fuel consumption, increases braking efficiency, reduces tire wear and extends tire lifespan (Kuncoro et al., 2019). Potential applications as sensors by the combination of rigid conductive fillers and flexible and insulating matrices can also be derived from the development of electrically conducting elastomeric compounds (Aguilar-Bolados et al., 2020). Different studies already published have addressed sensing strain, compression and damage.

Summarizing, it is the opinion of the authors that the incorporation in the tire of sophisticated and inherent detection systems, as well as innovative concepts and designs would remain a challenging issue. In an ideal context, the products must be designed, not only based on performance and aesthetics, but also based on other key aspects derived from their subsequent management. They should be designed to be easily repaired, be able to adapt to the new needs of the client, and when they can no longer be useful, they must be simple to be reused in other production processes. When the design of the products considers these concepts, the following links in the chain of the CE will be developed more easily.

Table 1
A comparison of NR, RDNR and GNR features.

	NR	RDNR	GNR
Molecular weight	High	High	High
Branching	Yes	Yes	No
Gel	Yes	Yes	No
Protein	High	High	Low
Allergenic protein	Yes	Yes	No
Fatty acid	Low	Low	High
Tensile Strength	High	High	High
Modulus	High	High	Low
Elongation	Medium	Medium	High
Agricultural regions	Tropical	Temperate	Arid
Growing	Slow	Fast	Slow
Rubber location	Tree bark	Roots	Roots

3.2. Renew

The manufacture of tires from renewable resources is a clear objective to achieve sustainability and reduce the dependency on fossil fuels (Barrera and Cornish, 2015). NR has unique reinforcing properties, tear, impact and abrasion resistance, among others. However, the supply of NR from Pará rubber tree (*Hevea brasiliensis)* cannot meet the growing world demand and, thus, new sustainable alternatives are being sought. The two main sources of alternative rubber crops are Russian dandelion (*Taraxacum kok-saghyz*) (Cherian et al., 2019; Niephaus et al., 2019; Ramirez-Cadavid et al., 2019; van Beilen and Poirier, 2007) and guayule (*Parthenium argentatum*) (Cheng et al., 2020; Rasutis et al., 2015; Sproul et al., 2020; van Beilen and Poirier, 2007). Russian dandelion is a fast-growing resource and produces large amounts of biomass, emerging as a powerful alternative to Pará rubber tree since it synthesizes large amounts of high-quality poly(*cis*-1,4-isoprene) in its roots (Niephaus et al., 2019). Russian dandelion natural rubber (RDNR) shows excellent chemical and physical properties and tires made from RDNR can be as resilient as those made from *Hevea brasiliensis* (van Beilen and Poirier, 2007). However, RDNR has a potential disadvantage since it contains more associated proteins that can lead to allergic reactions, limiting its use to non-medical applications. On the other hand, guayule natural rubber (GNR) has a structural backbone with 99.9% poly(*cis*-1,4-isoprene) units and analogous molecular weight and physico-mechanical properties to NR (Rasutis et al., 2015). GNR also undergoes the same degree of strain-induced crystallization of NR; however, its tensile strength is slightly lower (Mahata et al., 2020). Table 1 shows a comparison of some properties of the different rubber crops

(Cornish, 2017). Apart from the physico-mechanical properties, time to harvest and cultivation area are distinctive aspects to be considered when analyzing the potential of the alternative crops. Both NR and GNR are slow-growing crops that take seven and two years to reach maturity, respectively, whereas RDNR is a fast-growing crop, taking only six months. As for location, NR grows in countries near the equator and in Southeast Asia, with 93% of the world's supply. Meanwhile, GNR is a tree native to arid and semi-arid regions and RDNR grows in harsher climate conditions than NR. These differences allow crops to be moved closer to production facilities.

Comparing all these features, GNR and RDNR can be thought as strong raw material alternatives to traditional NR. Unfortunately, it is still too expensive to extract or process the rubber from both RDNR and GNR. Nevertheless, most of the internationally renowned tire companies have now experimental farms in various parts of the world and have conducted significant research on their commercial potential. In our opinion, the development of alternative sources of NR is essential to ensure raw material availability and to reduce the dependence on petroleum-derived products. In this framework, it is mandatory to establish new production processes, improve logistics and promote other initiatives to raise the economic competitiveness of GNR and RDNR as rubber sources.

Another approach to achieve sustainability is to provide substitutes to the other components of the tire, such as the fillers. It is well known that CB is the main reinforcing filler in the tire industry. The traditional methods of production of CB can be classified into two categories: incomplete combustion and thermal decomposition of hydrocarbons, depending upon the presence or absence of oxygen. However, alternative approaches are now being considered to produce renewable CB from biomass products, such as oils and vegetable fats (Peterson et al., 2016; Toth et al., 2018). Peterson et al. (2016) demonstrated the potential to use renewable CB from birchwood biochar in partially replacing CB without any loss of compounds properties. They made a biochar through slow pyrolysis, which contained 89% carbon and < 2% ash. The resulted composites made from SBR filled with 30% of 50/50 (biochar/CB) showed equal or higher values compared to CB compounds in terms of tensile strength, toughness and elongation properties. Toth et al. (2018) produced renewable-based CB from the pyrolysis of pine and wood oil in a continuous, high-temperature spray process. In this study, products with similar structures to commercial CB were identified depending on the process temperature. The results showed that at 1300 and 1500 °C, the produced green CB was structurally like medium-disperse CB grades. An additional and intense research line is focused on replacing traditional CB by cheap, abundant, and renewable non-petroleum-based fillers (Ali et al., 2020; Bahl et al., 2014; Barana et al., 2018; Chuayjuljit et al., 2001; Dominic et al., 2020; Egbujuo et al., 2020; Fathurrohman et al., 2020; Gabriel et al., 2019; Mgbemena and Mgbemena, 2020; Mohamad Aini et al., 2020; Pajtášová et al., 2019; Rahmaniar and Susanto, 2019; Ren et al., 2019; Snowdon et al., 2014) Their use would enhance the long-term sustainability and carbon footprint of tire compounds. Unfortunately, not many bio-based renewable fillers have the potential to produce a reinforcement level comparable to that of CB while concomitantly generating more sustainable materials and minimizing pollution. Thus, they can only be used as partial substitutes of CB and/or in combination with other fillers. Some examples of valorized agricultural and industrial residues with comparable reinforcing effects are eggshells (Ren et al., 2019), rice husk (Chuayjuljit et al., 2001; Dominic et al., 2020; Rahmaniar and Susanto, 2019), chitin (Egbujuo et al., 2020), coffee (Pajtášová et al., 2019), cellulose (Ali et al., 2020), montmorillonite (Fathurrohman et al., 2020), kaolin (Gabriel et al., 2019; Mgbemena and Mgbemena, 2020), and lignin (Bahl et al., 2014; Barana et al., 2018; Mohamad Aini et al., 2020; Snowdon et al., 2014).

Researchers have also focused on the substitution/modification of silica in tire tread compounds. Silica is another reinforcing filler used in the tire industry in combination with CB; it is known for the reduction of hysteresis or energy loss, which leads to a production of energy-saving tires with low rolling resistance and, thus, low fuel consumption. Chuayjuljit et al. (2001) prepared silica from rice husk ash (RHA silica) with higher specific surface area and lower moisture content than commercial silica. They concluded that NR compounds reinforced with RHA silica were suitable for applications where mechanical properties are desirable, but hardness is not the major concern. Other researchers (Gabriel et al., 2019) evaluated replacing silica by metakaolin (MK) in the tread rubber compounds. They found a significant reduction of rolling resistance with 75% and 100% MK without affecting wet traction. Fathurrohman et al. (2020) investigated the use of silica-organomodified montmorillonite (MMT) dual filler in the reinforcement of NR truck tire tread compounds. They found that the introduction of MMT (5 phr) enhanced the elastic response of the material (i.e., wet grip and rolling resistance) while maintaining the abrasion resistance. Finally, Mgbemena and Mgbemena (2020) studied the performance of NR/organomodified kaolin compounds for tire sidewalls. The organomodified fillers were prepared from derivatives of rubber seed oil (RSO) and tea seed oil (TSO). Their results showed an increase in tensile strength, fatigue failure and tear strength. NR/TSO compounds filled with 10 phr of modified kaolin were the best material for tire sidewalls considering optimum cure times, maximum torque, and tear strength.

The main tire industries are aware of all these developments and are implementing bio-based components in their production. Bridgestone and Goodyear include soybean oil as a natural ingredient in tire tread compounds, replacing traditional petroleum oil. Firestone commercializes agriculture tires with 10% soybean oil, which increases the tread life by 10% and reduces the use of petroleum-based oil by up to 8.5 million gallon/year. Pirelli and Goodyear report the use of silica derived from rice husks, to produce tires with improved rolling resistance. Yokohama uses orange oil, derived from orange peels, instead of petroleum in tires, increasing fuel economy, reducing rolling resistance, while maintaining good traction (Amick, 2018).

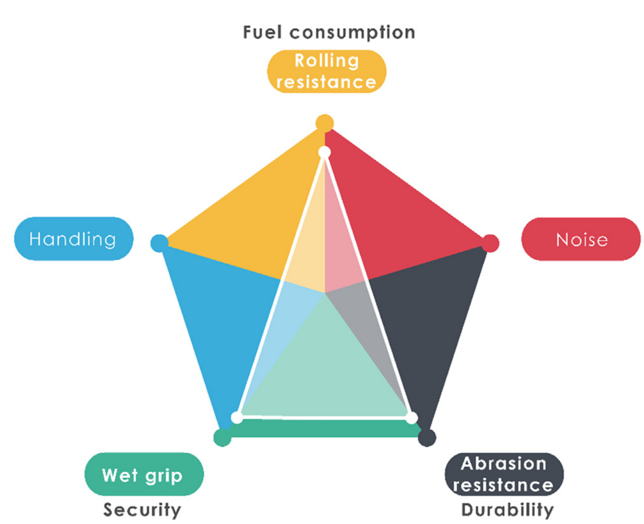

Fig. 4. Illustration of the "magic triangle" of tires.

3.3. Reduce

Reducing consists in the optimal use of materials. Tire industry targets the weight of the tires to reduce their contribution to the total weight of the vehicle (Rodgers et al., 2016). Such weight reduction also achieves another clear objective, fuel saving. Approximately a quarter of the materials of a tire corresponds to fillers, like CB. Thus, one straightforward approach is the substitution of CB by other reinforcing fillers in lower proportions and/or densities. Previous studies in the field of rubber nanocomposites have shown that organoclays (Arroyo et al., 2003) and other forms of carbon, including graphite, graphene, graphene oxide and carbon nanotubes (CNT) can be considered as effective substitutes of CB (Bokobza, 2019; García et al., 2019; Hernández et al., 2012; Rathanasamy, 2019; Valentini et al., 2018) These carbon additives with various morphologies have attracted significant attention due to their outstanding properties, such as exceptional modulus and remarkably high electrical and thermal conductivities. Particularizing this approach to tires, Poikelispää et al. (2013) reported the effect of the partial replacement of CB by MWCNT in tread compounds. They found that by replacing a small amount of CB, the mechanical properties of the tread compound were significantly enhanced. They also observed an increase of the reinforcing effect with MWCNT content, but high loading fractions resulted in poor dispersion of the nanotubes. Shao et al. (2018) reported a 1.5% improvement on dry conditions and 6.5% on wet conditions when substituting 50 phr of CB (N234) by 20 phr of CNT, which was ascribed to the increased hysteresis loss and decreased storage modulus at high frequency domain. Meanwhile, the high specific surface area and strong filler–filler interactions led to a decrease in rolling resistance. They concluded that CNT-filled rubber compounds reduced the tire weight and showed superior handling and traction performances suitable for racing and sport car tires.

One of the most challenging topics in the tire industry is the design of rubber tread compounds with an improved rolling resistance, and without compromising performance in terms of abrasion resistance and wet grip. Tires must operate efficiently under dissimilar conditions, dry, wet, or snow-covered surfaces, while simultaneously fulfil the driver's expectations in terms of acceptable wear resistance, low noise, and good ride quality. Among all the properties considered in the development of tires, these three main properties form the "magic triangle", well known in the tire industry (Fig. 4).

Two recent reviews on tire design have focused on low rolling-resistance tires (Aldhufairi and Olatunbosun, 2018; Andersen et al., 2015). Reducing rolling resistance is an effective method of reducing fuel consumption and CO_2 emissions. When a tire rolls on the road, mechanical energy is dissipated as heat due to friction, which is known as rolling resistance. Rolling resistance, therefore, plays a major role in increasing vehicle fuel consumption (Akutagawa, 2017). It depends on the type of tire, the nature of the rolling surface, and the operating conditions, i.e. inflation pressure, load and speed. The environmental benefit of low rolling resistance tires is propelling the demand for such products worldwide, with great focus on understanding and modeling such property.

Several tire manufacturers have developed green technologies that can reduce CO_2 emissions. Bridgestone has developed Ecopia tires, which reduce carbon footprint of cars by offering exceptionally low rolling resistance, excellent fuel economy, and reducing the frequency of replacement. Continental tires, branded as EcoPlus + technology, and Firestone's Fuel Fighter technology are focused on reducing rolling resistance while enhancing grip on wet surfaces and improving tread life (Roy et al., 2019). Also, the Beijing Tiancheng Linglong Tire company is working on the development of graphene rubber compounds for fuel efficient tires. The graphene-enhanced tire is stated to be produced with only a few minor process adjustments to ensure an industrial viable product. This tire is claimed to be safe and antistatic, and with low fuel consumption. In addition, its abrasion resistance and thermal conductivity is said to be extremely high (Linglong Tire, 2019). On the other hand, Gratomic is developing graphene-enhanced tires to increase their resistance and reduce friction. The graphene enhanced Gratomic tires are reported to present more than 30% increase in wear resistance over the "premium tires" from other known trademarks. Tests based on industry standard dynamic mechanical analysis (DMA) showed a significant progress in rolling resistance, indicating more than 30% improvement in fuel economy. Wet and ice braking distances were also improved by 40% (Gratomic, 2020).

3.4. Reuse

Reuse is about giving products an extended useful life before reaching the limiting time to dispose them (Forrest, 2014). The most critical component of the tire is the tread because it determines the final performance. Also, it is the thickest component of the tire that suffers the most due to abrasive loss. The tread ensures the gripping action between the road surface and the whole tire; thus, after several uses, its thickness is reduced, and a slippery action takes place on the road surface. At this point consumers have to decide whether to replace the deteriorated tire with a new one (normally expensive) or to retread it, which is a less expensive alternative (Sharma, 2013).

Retreading is a safe re-manufacturing process, which consists of replacing the tread on worn tires, using heat and pressure, preserving the structure, and maintaining its performance (EY, 2016). A tire can be retreaded several times depending on the type and conditions; car tires can be retreaded 2–3 times; light truck tires 4–5 times; heavy truck tires 8–9 times; and aircraft tires up to 14 times (Imbernon and Norvez, 2016a; Sharma, 2013). Retreading is also a way of reusing that generates energy, material and natural resources savings. It is a safe, low-cost, and environmentally friendly solution. Retreading helps to reduce deforestation, decreases land use for the NR industry, reduces particulate air pollution as well as CO_2 emissions, and contributes to reduce waste generation. Fig. 5a summarizes the main benefits of retreading.

Most of the retreading market of the commercial vehicle segment is expected to grow ̴5% (compound annual growth – CAGR) during the 2021–2026 period. In terms of demand, the Asia-Pacific region is expected to account for the highest sales worldwide. Europe is estimated to be the next big market to hold a leading share in the global retreading market followed by North America during the 2018–2028 period (Fact MR, 2021). Moreover, many leading tire manufacturers are joining the retreading business as they foresee a huge market potential. They are applying innovative manufacturing strategies and processes to remove operational problems to provide high-quality retreaded tires that can closely match the quality of their original ones. From the authors' point of view, retreading is a popular, environmentally friendly, and cost-effective yet high-quality process that should remain in time and should be considered as an alternative to traditional tires. It involves economic and environmental benefits to the society and tire industry and guarantees that tires are not discarded imprudently, contributing to their circular economy.

Certain small-scale projects have also succeeded as alternatives for the productive reuse of scrap tires, using them in their original form without any physical or chemical treatment; and requiring no infrastructure, planning, or regulation (Connor et al., 2013; Ostoji et al., 2017). Applications as insulation for the foundations of buildings, art projects, protective barriers along roads and highways, playground equipment, to protect sloping waterfront banks and roadsides, shock absorbers on large vehicles or fenders for boats,

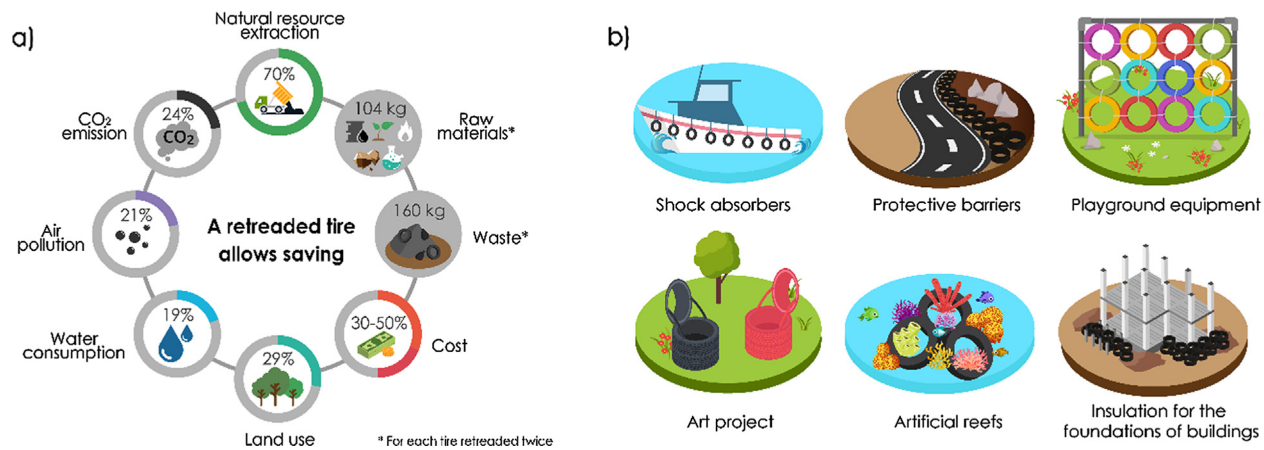

Fig. 5. a) Main saving benefits of a retreaded tire. b) Other applications for scrap tires.

artificial reefs (offering protection to marine organisms) are simple and economical uses for scrap tires (Fig. 5b) (Sienkiewicz et al., 2012).

3.5. Repair

Repair forms part of the CE principles whose aim is to extend the lifetime of products. It enables raw materials and energy savings and helps to reduce waste. In this framework, an upfront technology that deserves attention is the development of self-healing materials. This class of smart materials offer the possibility of increasing their useful lifetime and, therefore, helps to decrease the ecological and economic costs of future materials (Geitner et al., 2018).

Self-healing materials have the capability of recovering their initial properties after suffering damage. White et al. (2001) pioneering work demonstrated the basic self-healing phenomena in polymers. Since then, research focused on self-healing materials and, especially, self-healing rubbers has rapidly expanded with new concepts and strategies being developed in academic and industrial laboratories around the world. Self-healing materials are generally grouped according to the healing mechanism into two main categories: extrinsic and intrinsic. In extrinsic self-healing materials, a so-called healing agent is contained in discrete particles (capsules or fibers) embedded into a polymeric matrix and released upon damage. The discrete healing agent is consumed in the healing reaction and, hence, healing is limited to a single event. On the other hand, intrinsic self-healing polymers make use of moieties becoming an inherent part of the material itself. In this case, multiple healing reactions can take place at a given damage site (Hernández Santana et al., 2018a; 2018b).

One of the successful routes for achieving intrinsic self-healing is by promoting physical interactions and/or the formation of dynamic chemical bonds between the interfaces of a damaged zone (i.e. crack) (Sattar and Patnaik, 2020). Nonetheless, attaining such healing in rubbers is especially challenging, since cross-links restrict polymer chains to form new bonds across former (pre-) damaged areas. Different dynamic reversible groups, such as hydrogen bonding (Nie et al., 2019; Utrera-Barrios et al., 2020a; 2020b), disulfides (Hernández et al., 2016; Imbernon et al., 2016), Diels-Alder chemistry (Polgar et al., 2015; Tanasi et al., 2019), and ionic interactions (Das et al., 2018, 2015), have attracted growing attention in the self-healing rubber field. Moreover, the combination of different self-healing mechanisms (mostly intrinsic) is currently emerging as a strategy to provide an optimal compromise between mechanical performance and reparability (Utrera-Barrios et al., 2020a; 2020b).

Self-healing is an incipient technology when dealing with tires. However, there are several studies already published using the different rubbers contained in a tire, which can pave the way for industrially attractive developments. Vulcanized NR with healing properties was developed by Hernández et al. (2016). In this work, the authors took advantage of the dynamic character of the disulfides bonds (S-S) naturally present in sulfur-vulcanized rubbers. The disulfide group can introduce a healing functionality at low temperatures, while keeping a reasonable level of bond strength. These bonds can reversibly be cleaved and formed, leading to the renewal of cross-links across damaged surfaces (Canadell et al., 2011; Lafont et al., 2012; Pepels et al., 2013). Based on the disulfide exchange reactions, the rubber would accordingly acquire self-healing ability. Reversible ionic cross-links have also been studied as self-healing moieties in NR compounds (Thajudin et al., 2019). The self-healing NR with zinc thiolate recovered 60% of its initial mechanical properties in 1 min and almost 100% in 10 min without the aid of any external resources. More recently, Utrera-Barrios et al., 2020a; 2020b designed a mechanically robust composite based on ENR filled with thermally reduced graphene oxide (TRGO) with 85% of healing efficiency at room temperature, which was promoted by hydrogen bonding interactions with the rubber matrix.

In another study, Hernández Santana et al. (2018a, 2018b) designed a self-healing compound using SBR as the matrix and ground tire rubber (GTR) as sustainable filler. Semi-efficient sulfur-based compounds recovered 50% of their mechanical strength, being this recovery ascribed to disulfide exchange reactions. Moreover, the addition of a coupling agent improved (up to 80%) the mechanical strength of the SBR-GTR compounds without negatively affecting the healing efficiency. Araujo-Morera et al. (2019) continued this line of research and reported an in-depth study of the healing behavior of the material at a molecular scale by means of dielectric spectroscopy and dynamic-mechanical analysis. The compounds fully recovered their relaxation times and stiffness; meanwhile, the structure of the healed rubber network became more heterogeneous, suggesting chain inter-diffusion and reversible disulfide bonds as healing mechanism. Furthermore, the incorporation of GTR improved the rolling resistance while preserving wet grip and healing ability.

In another investigation, Das et al. (2015) modified the bromide functionalities of bromobutyl rubber (BIIR) into ionic imidazolium bromide groups, resulting in the formation of reversible ionic associates. The reversibility of these ionic clusters facilitated the healing process due to rearrangements induced by temperature or stress-induced, allowing to preserve the original properties of the network.

Although this field of research is growing and getting attention worldwide, self-healing rubbers are still far from acceptable to be used in the tire industry, due to their low mechanical strength. Adding reinforcing fillers and/or combining different healing strategies (Utrera-Barrios et al., 2020a; 2020b) is seen as the path to follow for improving the overall mechanical performance of self-healing rubbers without compromising their repair capability (Imbernon and Norvez, 2016b; Sattar et al., 2019).

3.6. Recover

Energy and material recovery provide a complementary alternative to address tire waste issues and achieve the goals of sustainable development following CE principles. Pyrolysis, gasification and incineration are thermo-chemical conversion technologies that transform scrap tires into valuable chemical products, fuels, and power (Myhre et al., 2012; Ślusarczyk et al., 2016). These techniques are particularly useful for ELT, and do not depend on the quality or type of tire (Li et al., 2010; Martínez et al., 2013). These recovery process offers an environmentally attractive route to reduce the accumulation of waste tires, and represents a valid alternative for a reusable product by converting scrap tires (Sienkiewicz et al., 2012). Volume reduction of waste by more than 90% and net energy recovery with possible material recovery are the main advantages of these methods. However, generation of toxic gases, disposal of ashes, and so forth are some problems associated with these thermal treatments (Manoharan and Naskar, 2019).

3.6.1. Pyrolysis

Pyrolysis consists in the thermo-chemical decomposition (400–1200 °C) of organic compounds into low molecular weight products at reduced or normal pressure and under an inert atmosphere, preventing oxidation and changes of phase or chemical composition (Bockstal et al., 2019; Forrest, 2014; Imbernon and Norvez, 2016a; Mavukwana and Sempuga, 2020).

Pyrolysis of waste tires produces a series of valuable chemical compounds in solid, liquid and gaseous phases, which can become value-added products as additives and starting materials for other products that can be used in the petrochemical, energy or steel industries (Bockstal et al., 2019; Forrest, 2014). Solid products include low grade CB, fly ash, coal, and other inorganic materials as residues of zinc, silicates, iron oxide, sulfides, carbonates, and other impurities (Imbernon and Norvez, 2016a). The carbon fraction can be processed to produce activated carbon, recovered CB, and recovered inorganic compounds that can be used as fillers (Shulman, 2019; Torretta et al., 2015). The liquid fraction contains tar, water, aromatic hydrocarbons and organic substances (oils) with a high calorific value, similar to heavy fuel oil, which are generally mixed with diesel oils and other petrochemical products, after removing sulfur-polluting compounds (Isayev, 2013; Torretta et al., 2015). Meanwhile, the gas phase is rich in organic compounds (hydrogen (H_2), methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), carbon monoxide (CO) and carbon dioxide (CO_2), hydrogen sulfide (H_2S)) (Imbernon and Norvez, 2016a). Once purified, this fraction can be used as an energy source to help carry out the pyrolysis operation (Forrest, 2014).

Although the rising costs of petrochemical raw materials and energy raises the potential of this method, it is less frequently used worldwide than incineration for obtaining energy. Some technological issues must be solved in order to make pyrolysis a more environmentally and economical viable option (Connor et al., 2013; Li et al., 2010). Its feasibility is strongly affected by non-competitive prices and the low quality of the obtained products, mainly CB and oil, which prevent their direct use for other manufacturing processes (Myhre et al., 2012). Furthermore, the high operation and maintenance costs and the absence of a wide market for consumption of the obtained products are the main drawbacks against the implementation of a successful pyrolysis process (Isayev, 2013).

Beston, Mingjie, and Klean Industries are some of the various companies that market their pyrolysis plants and machinery, adjusted to meet the different customers' requirements (Beston, 2021; Klean Industries, 2021; Mingjie, 2021). They customize designs (models), configurations (batch, semi-continuous, and fully continuous), reactor size, capacity, operating pressure, heating materials (charcoal, wood, fuel oil, natural gas, liquefied petroleum gas (LPG)) and patterns (horizontal and rotatory). Moreover, Metso Outotec has developed a patented process for processing scrap tires to recover oil, non-condensable fuel gas, steel, and commercial grade CB. The process involves an indirectly fired rotary kiln, char handling, steel recovery, grinding and pelletizing circuit, oil condensing system, and gas cleaning system. The capability to generate a CB product appropriate for rubber use enhances the economic feasibility of this process (Metso:Outotec, 2021). In our opinion, scientific research and industrial investments should focus on pyrolysis technologies that meet simultaneously the requirements of reliability, automation, security, and durability. The resulting products should widely be used in factories to produce other goods, achieving a real tire circular economy model.

3.6.2. Gasification

Gasification is a partial oxidation process that uses pressure, heat, and a reactive agent (air, oxygen, hydrogen, or steam) to convert tire waste into a gas mixture primarily composed of CO and H_2, with a low calorific value (5–6 MJ Nm^{-3}) (Ramos et al., 2010), along with CO_2 and light hydrocarbons (CH_4), also known as synthesis gas or syngas. Syngas is dependent on the operating conditions and the concentration of the oxidizing agent. It is used as fuel in fuel cells or gas turbines to obtain a wide range of other fuels and chemicals (Manoharan and Naskar, 2019; Ślusarczyk et al., 2016). Some of the advantages of this treatment are its high conversion performance and energy efficiency of around 34% (higher than that of incineration). Moreover, syngas contaminants (H_2S, NH_3) can be removed using selected known technologies. Nonetheless, gasification tends to have a slightly higher temperature range than pyrolysis (1200–1500 °C).

3.6.3. Incineration

Incineration is the oxidation of combustible material to give inert waste. It is a highly exothermic and spontaneous process that starts at controlled high temperatures (1000 °C) and, once initiated, it becomes self-supporting (Forrest, 2014; Myhre et al., 2012). This process produces H_2O, O_2, CO_2 and several toxic gases; although the use of high enough temperatures can avoid the formation some of these toxic components, such as dioxin. Incineration is often carried out by the tire industry to dispose of production waste and rejects, and to produce their own energy. Tire manufacturers and retreading companies use this process to produce the steam required in the vulcanization (Torretta et al., 2015). It is also a common process for providing the energy to power cement kilns for manufacturing Portland cement (Beach and Schroeder, 2000; Isayev, 2013; Ślusarczyk et al., 2016), but also in thermal power plants, pulp and paper mills, steel mills, industrial boilers, sewage treatment installations, or farms (Myhre et al., 2012). In the particular case of the cement industry, the use of very high temperatures (~2.000 °C) ensures the complete combustion of all the tire components, converting the steel to iron oxide and sulfur recovered from rubber to sulfates. These generated salts and metal oxides are useful ingredients in the final cement product (Forrest, 2014).

Energy from incineration is used in many countries with established tire waste management systems (Connor et al., 2013) and varies in different regions of the world, often due to local considerations such as landfill regulations and the amount of space available. About 45% and 38% of postconsumer tires and industrial wastes in the United States and in the EU, respectively, are used as a supplementary non-fossil fuel in some form of energy recovery process (Forrest, 2014).

3.7. Recycle

Recycling, as defined by the Parliament and Council of the EU (European Parliament, 2008) is any recovery operation whereby waste materials are reprocessed into substances, materials or products, either for the original or other purposes. The first step in any tire recycling route must consider the production of crumb from scrap tires. This crumb can be produced from whole tires or the remains of tire treads from the retreading process (tread buffings). Using the whole tire as starting material has disadvantages over tread buffings, due to the presence of either fabric or metal particles, which not only contaminate the product but can also act as stress concentration points resulting in premature tears, breaks and cracks (Forrest, 2014). Therefore, removing fabric and metal, in the most efficient way possible during the recycling process, is very important to ensure the quality of the final product.

The utilization of worn tires involves a sub-dividing process that yields a fine granular material denominated ground tire rubber (GTR). There are different techniques by which tire waste can be reduced in size, all of which have practical and technical advantages and disadvantages (Hoyer et al., 2020; Zefeng et al., 2018). These processes are generally carried out by cutting, shearing, or impact (or a combination of these), and may vary in the environmental conditions in which they occur (ambient, wet or cryogenic) (Ramarad et al., 2015; Rodgers et al., 2016; Wang et al., 2017). The selection of the process depends on different factors, such as the starting form of the waste product, the desired final rubber particles characteristics, the tolerance of residual contamination and the target price. GTR is the starting point for most of the reclaiming and devulcanization processes, as will be discussed next.

3.7.1. Uses of GTR

In the framework of direct recycling options, a wide variety of successful applications has been proposed for GTR (Isayev, 2013; Rodgers and D'cruz, 2015). It can be used in the manufacture of ground covers in playgrounds, lower layers of floor coverings, walkway tiles, mulch for agricultural purposes, landscape applications and sports surfaces such as running or jogging tracks. Moreover, compounds containing GTR can make up a variety of rubber products, such as conveyor belts, tubes, molded and extruded profiles, shoe soles and heels, car mats, mattresses, sealing plates, battery boxes and other hard rubber goods (Mishra et al., 2019; Rodgers and D'cruz, 2015).

GTR can contain CB, clay, calcium carbonate and silica in its composition and, hence, can act as filler in plastic composites. Blends of GTR with various thermoplastics, mainly polyethylene (PE), polystyrene (PS), polypropylene (PP) and polyvinyl chloride (PVC) (de Sousa et al., 2015a, 2015b; Liang et al., 2019; Mujal-Rosas et al., 2015; Orrit-Prat et al., 2011), can be shaped and remelted into a wide range of extruded and molded products. Their mechanical properties will depend on the thermoplastic matrix, GTR content (Hernández et al., 2017; Lima et al., 2015; Zhang et al., 2009), particle size (Sonnier et al., 2007), dispersion degree and GTR-polymer interaction at the interface (Formela et al., 2014; Naskar et al., 2002; Song et al., 2017).

GTR can also be incorporated into virgin rubber as semi-active filler. However, the compatibility with the matrix is a major issue. In addition, the type of curing system, the cross-link density of the rubber, and the presence of other ingredients, such as fillers, accelerators (Formela et al., 2016), and plasticizers, need to be considered (Ramarad et al., 2015). Usually, the direct incorporation of GTR in rubber composites significantly deteriorates their physical and viscoelastic properties, especially the tensile strength, compared to the virgin composites. This behavior is ascribed to the weak matrix-filler adhesion, between the crumb rubber and the rubber matrix, and the lack of reactive sites on the GTR surface (Yehia, Ismail, et al., 2004). The curing behavior is also affected by the presence of GTR, through the migration of sulfur or accelerators between the vulcanized GTR and the virgin matrix. Nevertheless, several studies have showed that it is possible to include around 10–30% of GTR to NR and SBR matrices, without sacrificing the essential characteristics of the rubber vulcanizates. Moreover, tangent delta, a direct measure of internal energy dissipation, have been shown to increase with GTR content (Araujo-Morera et al., 2019; Han and Han, 2002; Ramarad et al., 2015).

As stated above, GTR particles have limited adhesion to most polymers and form a weak interface, which leads to poor mechanical properties and limited applications. To address this issue, GTR surface have been modified by several methods (Ramarad et al., 2015). Small polar groups on the GTR surface can be attained using plasma(Cheng et al., 2015; Xinxing et al., 2009) or ozone(Cao et al., 2014; Cataldo et al., 2010), high-energy gamma(Herrera-Sosa et al., 2014) or ultraviolet irradiation (Shanmugharaj et al., 2005). More recently, Araujo-Morera et al. (2021) reports a successful combination of a cryo-grinding process with a chemical treatment, for modifying the surface of GTR and improving the interfacial adhesion with a SBR matrix.

Moreover, chemical methods can be used to introduce polar groups and simultaneously produce partial devulcanization. Acids (Hernández et al., 2017; Hernández Gámez et al., 2018; Yehia, Mull, et al., 2004) coupling agents (Aggour, 2012; Naskar et al., 2002), and chlorination (Rungrodnimitchai and Kotatha, 2015) treatments have also been studied.

The use of GTR in the cement and concrete industry is another area of research that has been developed considerably in the last decades (Forrest, 2014; Rodgers and D'cruz, 2015; Thomas and Gupta, 2015; Youssf et al., 2016). The elasticity given by GTR improves fracture resistance, lowers density, favors heat and sound insulating and energy absorption properties, and reduces cracking and vibration transmission. The asphalt industry also uses GTR as filler for road surface treatment. Blending GTR with asphalt has advantages in the performance of roads and their longevity as it reduces the noise of the vehicles traveling on it, improves crack and skid resistance, and provides a more comfortable ride (Hallmark-Haack et al., 2019; Shu and Huang, 2014; Wu et al., 2016). Finally, in sludge treatment plants, a bed of GTR is effective at absorbing mercury (II) and other heavy metals (the presence of thiol and other sulfur residues can immobilize the metal ions) and organic solvents from waste water runoffs, such as toluene, benzene, ethylbenzene, o-xylene.

3.7.2. Reclaim/Devulcanization

Any process to obtain a low modulus polymer material by breaking the starting permanent tridimensional network is called reclaiming. Reclaim of rubber refers to the recovery of original elastomers in a way that they can be used to replace a fresh polymer (Rodgers and D'cruz, 2015). Reclaiming from rubber waste products has the greatest potential in terms of recycling, as vulcanized rubber waste can be mixed, processed, and vulcanized again (Isayev, 2013; Markl et al., 2020). Reclaiming deals with the cleavage of carbon–carbon (C-C) bonds on the rubber backbone with the aim of reducing the molecular weight to achieve plasticity.

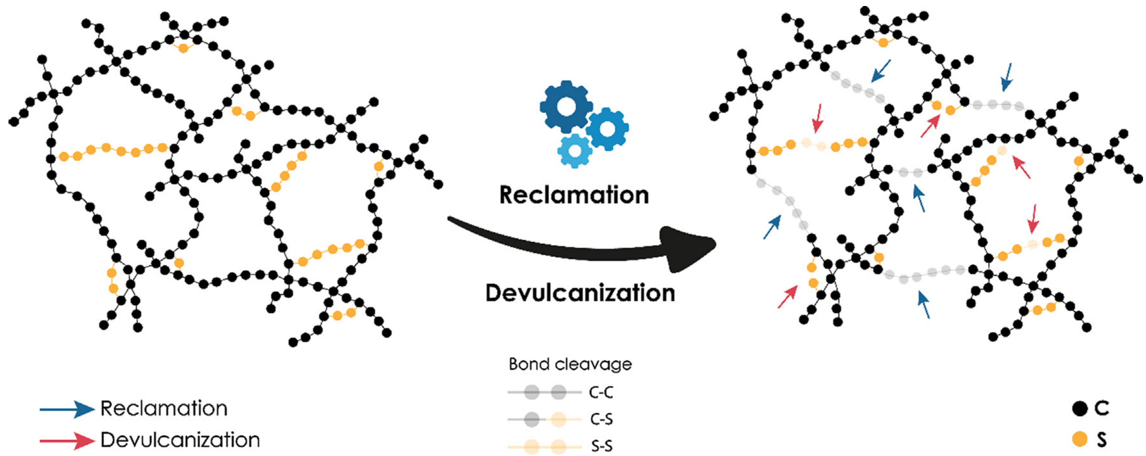

Fig. 6. Schematic representation of reclamation and devulcanization processes in a cross-linked rubber network.

On the other hand, devulcanization causes the selective breakup of the chemical network. It consists of the cleavage of the intermolecular bonds of the network, such as carbon–sulfur (C-S) and/or sulfur-sulfur (S-S) bonds, that breaks down the macromolecular chains without damaging the backbone network and avoiding material degradation (Fig. 6). Devulcanization can be carried out by different means, such as chemical (Sabzekar et al., 2015), mechano-chemical (Ghorai et al., 2016; Padella et al., 2001), ultrasonic (Feng and Isayev, 2006; Isayev et al., 2014; Yun et al., 2003, 2001), microwave (Aoudia et al., 2017; Colom et al., 2018; de Sousa et al., 2017; Seghar et al., 2015), biological (Ghavipanjeh et al., 2018; Kaewpetch et al., 2019; Li et al., 2012; 2011), thermo-mechanical (Formela et al., 2013; Si et al., 2013; Tao et al., 2013; Ujianto et al., 2017), and supercritical CO_2 (Asaro et al., 2020; Jiang et al., 2013).

The most promising techniques are microwave and ultrasonic devulcanization, due to the good properties of devulcanized material, the possibility of high productivity and ease of implementation. Furthermore, these devulcanization techniques are free of chemical agents during the process that makes them an eco-friendly technology. Microwave devulcanization involve microwave irradiations causing the cross-links breakage in the material network due to the molecular motion and raising the rubber temperature. Whereas ultrasonic devulcanization involves the application of ultrasonic waves to the vulcanized rubber. However, the process conditions must be carefully selected to achieve a selective breaking of chemical links and avoid degradation of the material (Asaro et al., 2018).

Both reclaiming and devulcanization aim to obtain a rubber compound that can be reprocessed and revulcanized like virgin rubber. However, the difficulty to precisely focus on one type of bond rupture and the simultaneous occurrence of both processes hinders the full recovery of the original properties (Sienkiewicz et al., 2017). Thus, reclaimed/devulcanized rubber can only provide a low-cost material to compounds for less demanding products (Isayev, 2013).

4. Conclusions

In this review, we have exhaustively and critically detailed the management of tires following the different strategies stablished in the CE model, comparing scientific perspectives, as well as their industrial and commercial implementation. In the early stage of production, the optimization of innovative and avant-garde designs will improve tire performance and reduce their environmental impact with the use of alternative renewable raw materials. At the consumption stage, retreading and repairing processes extend the lifetime of tires along with the environmental benefits that these techniques bring. Meanwhile, in the post-consumption stage, the most relevant currently, the main management routes focus on energy and material recovery applications.

To attain the goal of sustainable mobility, it is necessary both to develop a comprehensive used tire management system, and to change the paradigm where ELT are considered as waste to be considered as a resource. In this review, we have highlighted the different ELT management systems to reduce landfills and find innovative and environmentally friendly uses, becoming a stronger source of economic and greener growth for industries.

Research and development of both established and emerging tire technologies are of vital importance too. With the optimization of the reclaiming/devulcanization processes, industries would be able to recycle the tire in new tailored made products without having to use any virgin rubber. Likewise, emerging technologies such as the development of self-healing elastomers, whose objective is to extend the useful life of rubber products by reducing waste and saving raw materials and energy, can be seen as an innovative pathway to produce new advanced tires that will lead to the development of sustainable mobility.

5. Outlook and perspectives

This review clearly states the actual commitment and efforts towards the development of effective tire management schemes. Nonetheless, implementing a real sustainable mobility and circular economy model requires a long-term vision based on three main pillars: sustainable use of resources, technological innovation, and economic growth. In this sense, the main tire industries should expand the use of renewable material resources, develop innovative solutions, and invest in groundbreaking technologies to integrate more recycled and renewable materials in its tires, as well as to prolong their useful lifetime. Examples in such direction are already at the core of strategic plans of main tire companies. The Bridgestone Group has set the goal of using 100% sustainable materials in its products by 2050 and beyond; while Michelin is investing in high technology recycling so that by 2048 tires are 100% recycled. Likewise, all these actions should generate new business models and lead to sustainable economic growth. The challenge is to ensure that any process that achieves its technical objectives is also economically viable and, therefore, has good commercial potential.

However, industries should not work on their own. It is the authors' opinion that joint actions and cooperation with scientists and government regulatory institutions are needed. Scientific assets will, with no doubt, help in the establishment of research and development programs that will lead to the tire circularity and alleviate the current public concern on the impact of tires on the environment.

CRediT authorship contribution statement

Javier Araujo-Morera: Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Raquel Verdejo:** Conceptualization, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Miguel Angel López-Manchado:** Conceptualization, Writing - review & editing, Visualization. **Marianella Hernández Santana:** Conceptualization, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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