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End-of-life options of tyres. A review

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ABSTRACT

The increasing motorisation rate worldwide is responsible for the demand of huge quantities of tyres that, after their useful service life, become waste and should be properly managed. Due to the relative low cost of tyres and the complexity related to recycling, worldwide around 41% of the total amount of end-of-life tyres is discarded into landfills or stockpiles without any recovery of the material or of the energy. Moreover, the chemical composition of tyres makes them extremely resistant to degradation phenomena with a potential long-term permanence in the environment. The high energy amount required for the production of tyres and the related environmental impact should encourage the recycling of tyres and also promote the adoption of maintenance activities, such as retreading, that allow a considerable increase in the useful service life of tyres with consequent reduction in GHG emissions. In this article the relevant literature describing the current status of end-of-life options worldwide, the European legislation regarding tyre waste, their possible uses and the related environmental aspects are presented.

1. Introduction

In the last decades the worldwide growth in the use of passenger cars, motorbikes, busses, trucks and off-the-road vehicles required the production of a huge amount of tyres that, at the end of their useful life, became a huge amount of wastes to be disposed [1]. The sales of new tyres in Europe during the year 2020 accounted for 324 million units, 89.5% (70 wt%) for passenger cars and light duty vehicles, 4.9% (20 wt%) for heavy duty vehicles (trucks and busses), 3.6% (1 wt%) for motorbikes and scooters and 1.9% (9 wt%) for agricultural and off-the-road vehicles [2]. The increasing importance of recycling and the simultaneous growth of the performance requirements of new tyres in terms of rolling resistance, abrasion resistance and traction that requires the use of raw materials with constant properties, make it hard to define recycling paths for end-of-life tyres since they are not uniform in their composition. Scrap tyres are constituted by materials that are not degradable in nature in ambient conditions, causing therefore a waste problem; on the other hand they are valuable materials representing a resource opportunity [1,3]. At the beginning of the 20th century, due to the high cost of rubber (similar to the cost of silver), its recycling rate was higher than 50%. Starting from 1960, the import of oil at low prices and the diffused use of synthetic rubbers caused a drop of the recycling rate down to 20%. Moreover, the advent in the market of steel-belted radial tyres caused a further drop due to the increased difficulties in grinding old tires with a recycling rate in 1995 as low as 2% [4,5]. In 1990 around 89% of the scrap tyres produced in the USA went to stockpiles [6], in Europe in 1995 that value was around 80% [7]. Despite nowadays the recovery rate of scrap tyres is around 90% in Europe and USA [8], it is estimated that around 4 billion end-of-life tyres (ELTs) are currently in landfills and stockpiles worldwide and that this amount will increase up to 5 billion by 2030 [9,10]. Stockpiles of waste tyres represent a serious problem due to the potential fire hazard they represent, due to the proliferation of mosquitos and insects caused by water stagnation and due to the loss of valuable resources [4,11–14].

The aim of the present review is to bring together the information related to the end-of-life of tyres in order to give an overview of the situation worldwide and provide details regarding the available technologies and the related environmental impacts. The review: (1) describes the characteristic of tyres; (2) describes the factors affecting the lifespan of tyres with particular attention at the rolling resistance and influence on fuel consumption of vehicles;

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Table 1
Average composition of fuel-efficient passenger car and truck tyres [25].

Material	Passenger car tyre [wt%]	Truck tyre [wt%]
Natural rubber	21.2	37.1
Synthetic rubber	24.5	10.0
Process oil	4.4	0.8
Steel wire	10.8	21.1
Textile fibres	3.7	0.2
Carbon black	18.9	22.3
Silica	7.7	1.3
Antioxidants, antiozonants, curing system	8.7	7.2

(3) summarises the EU legislation that controls the end-of-life of tyres; (4) presents statistics on the end-of-life of tyres worldwide, with particular attention at the improvements of the last decade and at the differences between different regions/countries; (5) describes the available end-of-life technologies and (6) discusses the environmental aspects related to the different technologies.

2. Tyre composition

Tyre is a product with a complex structure and composition, whose function is the transfer of motion from the engine to the road. As it is possible to observe from the composition of passenger car and truck tyres listed in Table 1, tyres are not made only of rubber, which represents around 45 wt% of their mass, but also of steels belts, textile overlays, reinforcing fillers and additives. The rubber fraction of tyres consists of natural rubber and synthetic rubber: natural rubber is used to increase the fatigue and tear resistance, while synthetic rubber (mainly butadiene rubber and styrene-butadiene rubber) determines the tyre performances (rolling resistance, wear and traction) [15–17]. It is also possible to observe that the composition of passenger car and truck tyres differs mainly for the higher natural rubber content present in truck tyres: due to the higher loads and long distances driven, truck tyres need to present higher fatigue and tear resistance [18].

In order to reduce the dependence on natural rubber, added by the EU in the list of critical raw materials in 2020, the Fraunhofer Institute developed a specific rubber compound based on natural rubber extracted from the Russian dandelion (*Taraxacum koksaghyz*). This rubber compound was then used by Continental AG for the industrial production of a bicycle tyre called Taraxagum® [19]. The main limit of extracting natural rubber from dandelion is the very low content of natural rubber that makes, at the moment, unrealistic its use on the large scale. Nonetheless, the Fraunhofer Institute, miming the chemical structure of natural rubber obtained from the Russian dandelion, developed a specific rubber compound for truck tyres made only of synthetic rubber: biomimetic synthetic rubber with optimized abrasion behaviour (BISYKA). Tyres produced using the BISYKA rubber compound achieved 30 to 50% less abrasion than commercial tyres containing natural rubber [20,21]. The French company Michelin is also trying to reduce its dependence on raw materials, in particular through the production of butadiene from biomass wastes, of styrene from yogurt pots and plastic packaging, fibres from polyethylene terephthalate (PET) wastes and carbon black from ELTs [22].

Differently from passenger car tyres, the composition of truck tyres is specifically engineered depending on the axis (front, drive, trailer axes) and on the specific application (long haul, regional/urban operation, highway, construction site, quarry, shifting surfaces) [23]. As shown in Table 1, the compound used for the production of tyres is also composed by reinforcing fillers that improve tear and tensile strength (carbon black), abrasion resistance (carbon black), rolling resistance (silica) and cut-chip resistance (silica) [18]. Antioxidants prevent the occurrence of oxidative phenomena in case of exposure to high temperature and oxygen. Antiozonants increase the resistance to ozone degradation of the external side of tyres. The curing system is constituted by sulphur, zinc oxide and accelerators, necessary to promote the vulcanization of the rubber compound. Steel wires are used in bead to anchor the tyre and under the tread to stiffen the tire casing and to improve the wear resistance. Textile fibres are mainly used in passenger car tyres as reinforcing material to provide dimensional stability and sustain load; they consist of polyester, rayon, nylon and aramid cord fabrics used to make the carcass [15,24].

In Fig. 1 the exploded view of a commercial passenger car tyre allows the understanding of the different elements that compose a

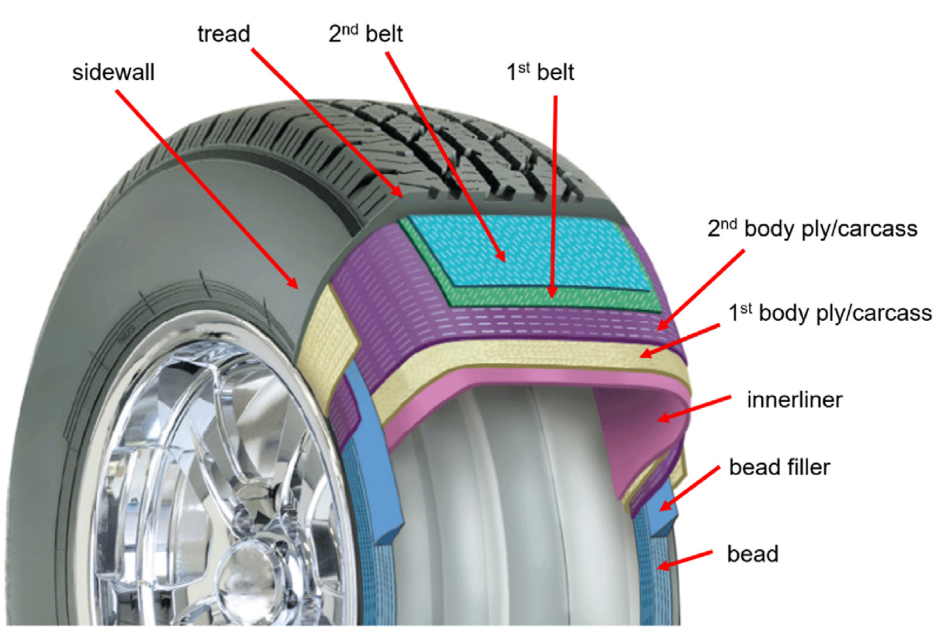

Fig. 1. Exploded view of a commercial passenger car tyre. Adapted from [15].

tyre. The external layer that provides traction due to the contact with the pavement is called tread; it is characterised by a rubber compound and particular pattern that should provide grip minimizing wear. The tread can be divided into three areas: cap (part in contact with the road), base (below the cap, reduces rolling resistance), shoulder (at the outer edges of the tread, is a transition area from the tread to the sidewall). The tread is stabilized by the presence of typically two belts, made of steel cords braided at opposing angles. The structure of the tyre is called carcass or body ply, constituted by one or two levels of polyester, rayon, or nylon cords within a rubber layer. The internal side of the tyre is covered with a thin layer of a synthetic rubber compound (typically halogenated polyisobutylene rubber) that makes it impermeable in order to retain pressure. The contact between the tire and the wheel is assured by the bead, strands of wire within a rubber matrix (bead filler) [15,24,26].

3. Useful life of tyres

Data recorded from Michelin in the UK between 2006 and 2011 on passenger car tyres (205/55 R16) showed that the average lifespan is around 36,554 ± 5851 km for tyres mounted on the front axis and around 63,690 ± 8274 km for tyres mounted on the rear axis [27]. In case of trucks the lifespan is highly affected by the type of use: in case of slow-speed runs and long distances on motorways, it can achieve up to 600,000 km; in case of short-haul and delivery trucks that do a lot of low-speed manoeuvring, frequent turns, frequent braking and accelerating the lifespan can achieve values down to 70,000 km [28].

The lifespan of tyres (and also the fuel consumption of vehicles), is mainly affected by 9 factors:

- Tyre type: the softer the tyre, the higher the grip on the pavement. This results in higher fuel consumption and in more rapid wear due to the higher friction [28,29]. Moreover, to minimize wear, a tyre should be able to compensate the slip occurring during cornering through a deformation instead of sliding on the pavement [30,31].
- Temperature: it is estimated that between 10 °C and 40 °C a variation of 1 °C corresponds to a 0.6% variation in rolling resistance [29].
- Inflation pressure: Goodyear estimated that every 0.7 bar underinflation results in 1% higher fuel consumption due to the higher friction with the pavement [32].
- Driving style: smooth accelerations and decelerations reduce wear and increase tyres' life [29].
- Road type: driving on mountains or cities in comparison to motorways causes more wear and significantly decreases the life expectancy [29].
- Road conditions: gravel and off-road roads cause higher wear on tyres than a smooth pavement [29].
- Tyre position: tyres positioned on the drivetrain will experience more wear than non-driven tyres [29,32].
- Wheel alignment: a wrong alignment of wheels results in higher wear and higher fuel consumption (up to +4.5% in case of obliquely aligned wheels and +18.5% in case of non-parallel wheels) [32].
- Tread depth: the thinner the tread depth, the lower the friction resistance and wear. In order to increase the tyre durability some manufacturers increase the tread depth with a consequent increase in the rolling resistance, wear and fuel consumption [33].

In order to promote fuel efficiency and to extend the lifespan of tyres (reducing, therefore, the amount of waste), the European Commission introduced, starting from 2012, labelling rules for tyres. Tyre labels (see Fig. 2), provide a clear and common classification of tyres performance in terms of rolling resistance, braking on wet surfaces and external noise for passenger cars, light-duty vehicles (LDVs) and heavy-duty vehicles (HDVs).[1] Regarding rolling resistance (RRC), A-labelled tyres should have RRC values ≤6.5 N/kN for passenger car tyres, ≤5.5 N/kN for LDVs tyres and ≤4.0 N/kN for HDVs tyres. The E-label corresponds to RRC values ≥10.6 N/kN for passenger car tyres, ≥9.1 N/kN for LDVs tyres and ≥7.1 N/kN for HDVs tyres [35–37].

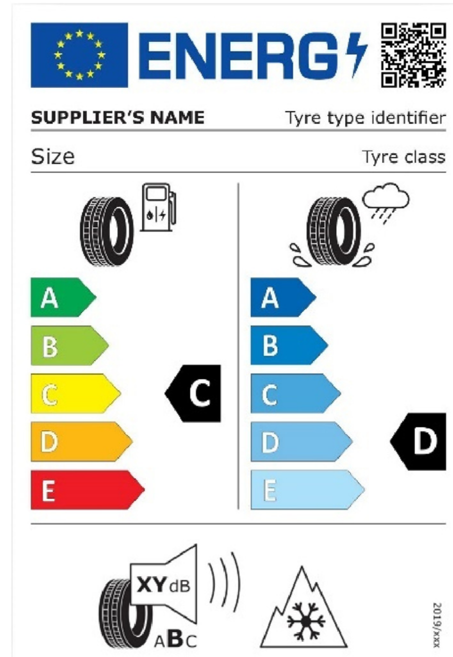

Fig. 2. New EU tyre labelling in accordance with Regulation (EU) 2020/740 [35].

It is estimated that, in the face of a higher price of A-tyres in comparison to E-tyres (price increase of around 70 € per set of 4 passenger car summer tyres), the vehicle fuel consumption (in l/km) is reduced of around 7%, with a fuel saving of around 340 €, a payback period of 10 months[2] and a reduction of 12.7 g/km of CO_2eq emissions [25,38,39].

Comparing the market share of tyres with different labels presented in Fig. 3, it is possible to observe that class E was the most common for all the vehicles categories both in 2012 and 2020, while the contribution of classes A, B and G was almost negligible. The main difference between 2012 and 2020 is the lower contribution of class F with a higher contribution of class C. In general heavy-duty vehicles show better labels in comparison to passenger cars and light-duty vehicles tyres [36,40].

[1] The EU Commission defines passenger cars as vehicles for the transport of passengers with a total mass ≤3.5 t, light-duty vehicles (vans) as vehicles for the transport of goods with a total mass ≤3.5 t, heavy-duty vehicles as vehicles for the transport of passengers (busses and coaches) or goods (trucks) with a total mass >3.5 t [34].

[2] A set of 4 summer tyres with dimensions of 205/55 R16 91 V, useful life of 40,000 km within 4 years and a fuel price of 1.814 €/l were assumed for the calculations. Prices of A- and E-class tyres taken from Ref. [38]. Diesel prices taken from Ref. [39], corresponding to average prices in Italy in the first semester of 2022. Vehicle fuel consumption data and fuel consumption reduction taken from Ref. [25].

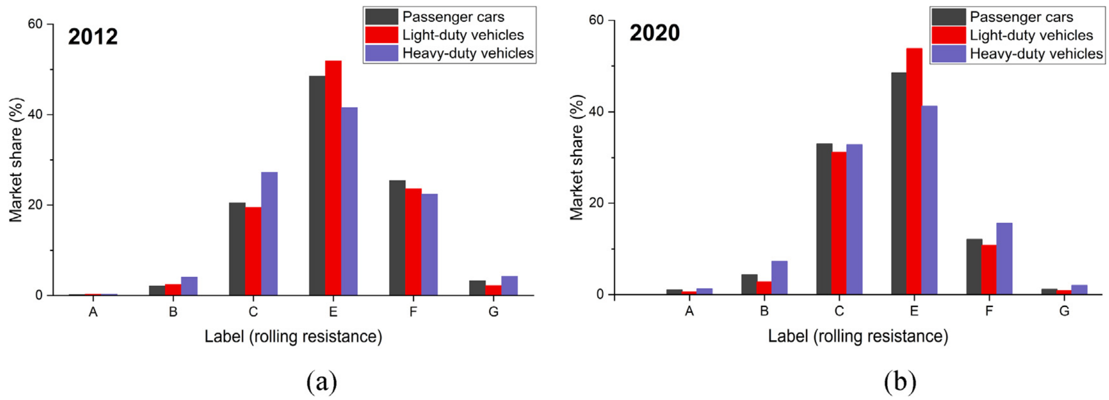

Fig. 3. Market share for passenger car, light-duty vehicle and heavy-duty vehicle tyres in accordance with the EU labelling rules. Comparison between (a) 2012 and (b) 2020 [36].

4. Legislation in the EU

In the European Framework Directive 2008/98/EC, the EU commission impose to handle waste minimizing the negative effects on the environment and on human health and, in order to promote circular economy, has defined a "hierarchy of waste", an order of priority in the waste legislation and policy that starts with the prevention of waste formation, followed by the preparation for reuse and, if it is not possible, by recycling, recovery and disposal. Moreover, the directive introduces the concept of "end of waste", by which a waste stream, after a recycling or recovery operation, if it complies with specific end of waste criteria, can cease to be considered as waste [41]. Regarding the management of used tires and used rubber products, the European strategy is based on the landfill directive 1999/31/EC that establishes the ban from landfills of whole tyres by July 16, 2003 and of shredded tyres by July 16, 2006. Exemptions regard the use of whole tyres for engineering purposes, bicycle tyres and tyres above 1400 mm diameter [42]. In accordance with the European waste list 2000/532/EC, rubber waste is classified as non-hazardous waste [43]. The directive 2000/76/EC on incineration of waste fixes emissions limits for all new cement kilns from the end of year 2002 [44]. In order to prevent vehicles waste and to promote reuse and recycling of vehicles components, the Directive 2000/53/EC of end-of-life vehicles identifies 4 treatment operations: removal of catalysts, removal of metal components containing copper, aluminium and magnesium, removal of tyres and large plastic components, removal of glass [45]. In November 2021, in order to promote circular economy, the European Commission presented the proposal for a new regulation limiting the export of wastes from the EU, promoting the import for reuse and recycling and tackling the illegal waste shipments [46].

In general, three models have been developed worldwide to manage end-of-life tyres:

- *Tyre industry responsibility.* The management of used tyres (recovery, recycling or disposal) is a responsibility of tyre manufacturers that finance these activities through an eco-fee charged on the original sale. The system is usually administered by a non-profit organisation. This model is used in many European countries, Brazil, South Africa, South Korea, Russia and Ukraine [47].
- *Tax system.* Producers pay to the government a disposal duty added to the cost of new tyres. The management of the used tyres is a responsibility of recovery organisations directly financed by the government. Canada, Croatia, Denmark, Latvia and the Slovak Republic have tax-funded systems [7,47].
- *Free market system.* This model assumes the profitability from the recovery and recycling of tyres: specialised enterprises operate independently in accordance with qualitative objectives and specific legislations on the transport, use, disposal and storage of ELTs. Austria, Germany, Ireland, New Zealand, Switzerland, Argentina, China, India, Indonesia, Japan, Malaysia, Mexico, New Zealand, Saudi Arabia, Thailand, the United Kingdom and the USA operate on free market system [7,47].

5. EOL statistics

In 2019, the total amount of end-of-life tyres has been of around 30.9 million tons worldwide, with a total amount of vehicles in use in 2015 of around 1.28×10^9 units [48]. As it possible to observe from Fig. 4, only 59% of end-of-life tyres are correctly disposed while 41% are landfilled, stockpiled or lost [49].

As it is possible to observe from Fig. 5, in the last 25 years the recovery rates for ELT strongly increased, especially in Europe, moving from 20% of recovered tyres in 1994 to 95% of 2019. It is interesting to notice that Japan, having started the regulation of tyres recycling earlier, had recovery rates around 90% already in 1994. Worldwide Canada has the highest recovery rate (>100%), followed by India (98%) and South Korea (95%). In India the recovery rate is very high due to the intensive use of ELT as secondary material in artisanal products [49].

Looking at the ELT data shown in Fig. 6, it is possible to observe that, in 2019, China alone contributed for half of the total amount of

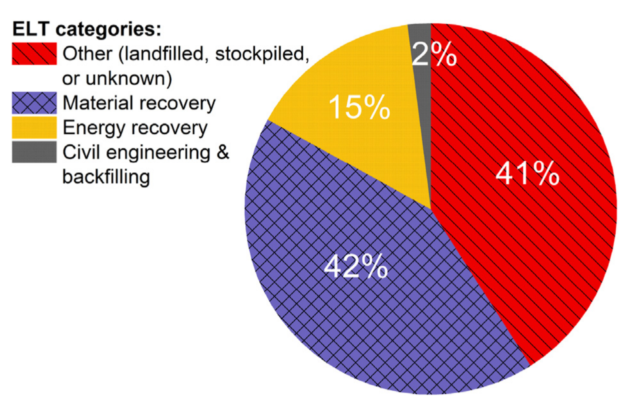

Fig. 4. EOL options for discarded tyres worldwide in 2019 [49].

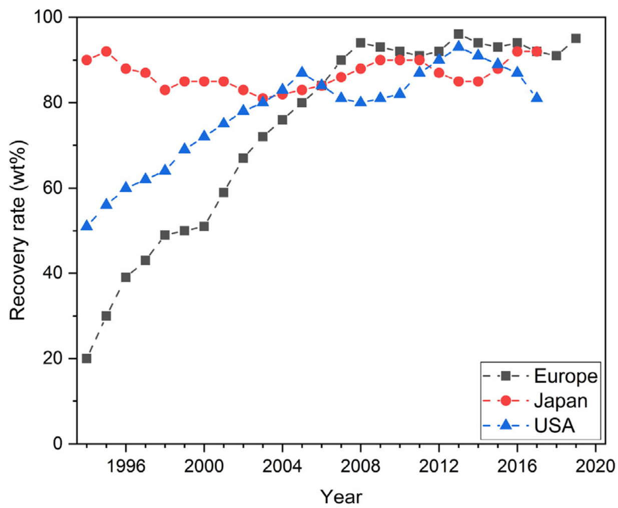

Fig. 5. Recovery rate of ELT from 1994 for Europe, Japan and USA [8,9,50].

discarded tyres (14.5 Mton), USA and Europe for another 23%, India for around 12% and the rest of the world for the remaining 20%. Moreover, the highest amount of non-recovered tyres (9 Mton on a total of 12.7 Mton) derives from China, while USA and EU contributed with 1 Mton of non-recovered tyres [9,49,51]. It is very important to contextualize the reported data considering the motorisation rate (vehicles per 1000 inhabitants) of the selected countries. From Fig. 7 it is possible to observe that China, although its highest contribution to the total amount of ELT, has one of the lowest motorisation rates worldwide. Considering that India and the majority of the so called "developing countries" have a motorisation rate below 50, while developed countries like EU and USA have a rate higher than 600, it is necessary to give thought to the future of ELT management when the motorisation rate of such countries will increase.

Looking at Fig. 8 it is possible to observe that in several countries the amount of non-recovered tyres is very high, with the highest values recorded in Nigeria (95%), Argentina (94%), Russia (80%), Mexico (79.7%), South Africa (75.1%) and China (61%). The lowest values are in Brazil (0.5%), India (2%) and Europe (8%). Looking at the possible operations performed on recovered ELT (material recovery, energy recovery or civil engineering applications & backfilling) it is possible to observe that the last one is mainly performed in the USA (9%) and in Europe (3%). Material recovery is generally preferred to the energy recovery with the highest use in India (76%), Brazil (64.5%) and Indonesia (55%). Energy recovery is preferred in Japan (73%), South Korea (50%) and USA (39%). In Europe, in accordance with the "hierarchy of waste", the material recovery is preferred to the energy recovery (54% vs. 35%) [49].

6. Used tyre management

An important aspect to be considered before treating the different possible options for the management of used tyre, is that a non-negligible fraction of its initial mass is lost in the environment during the use stage without any recovery possibility. This phenomenon is called wear and it is defined as the loss of material occurring during rolling and sliding contact of tyres with the road pavement which results primarily due to fatigue phenomena on smooth roads and abrasive or cutting wear in case of significant road harshness [52]. It is estimated that, along its life, a tyre lose from 15 wt% (passenger car) to 18 wt% (truck) of its initial mass due to the abrasion of the tread with the road [25]. Considering an initial mass of 8.2 kg for a passenger car tyre and of 70 kg for a truck tyres, this means that around 1.2 kg (passenger car) and 12.6 kg (truck) of rubber are lost in the environment during the lifespan of the tyre [25]. Moreover, taking as a reference a service life of 40,000 km for passenger car tyres and 220,000 km for truck tyres, it results that the specific wear (mg/km) is around 30 mg/km in the first case and around 57 mg/km in the second one. These values seem comparable to those measured by Grigoratos et al. that range from 55 to 214 mg/km depending on the tyre under investigation [53]. In the literature it is often found the term "tyre and road wear particles" (TRWP) since wear particles collected at the road site consists of an indivisible mixture of rubber particles,

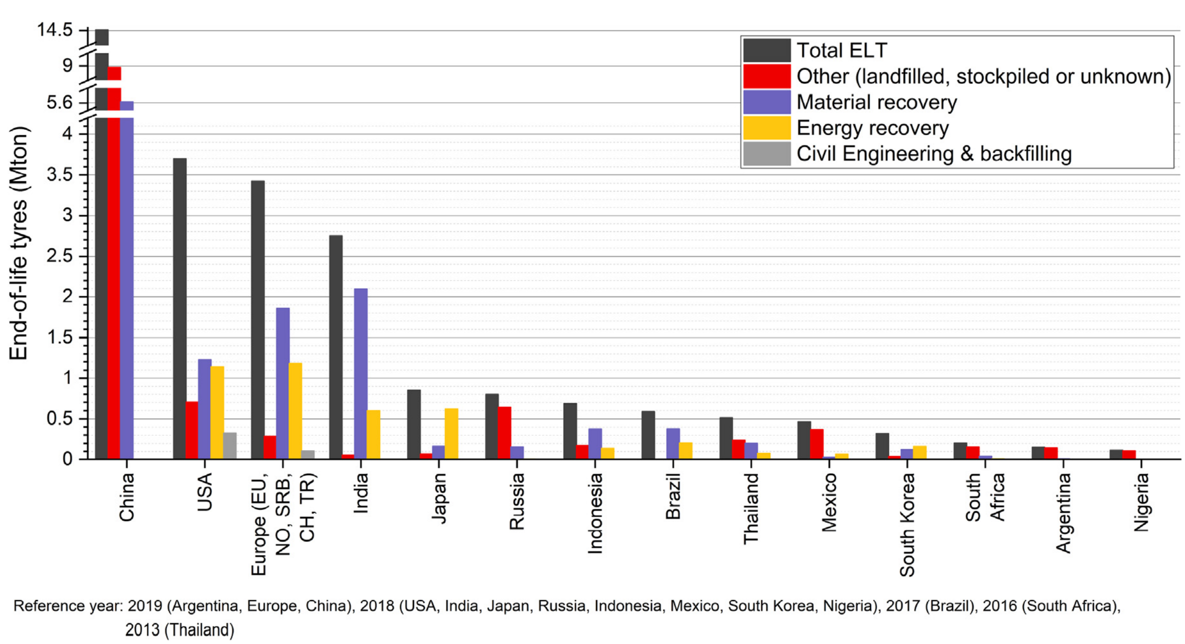

Fig. 6. EOL options for discarded tyres for several countries (in Mton) [49].

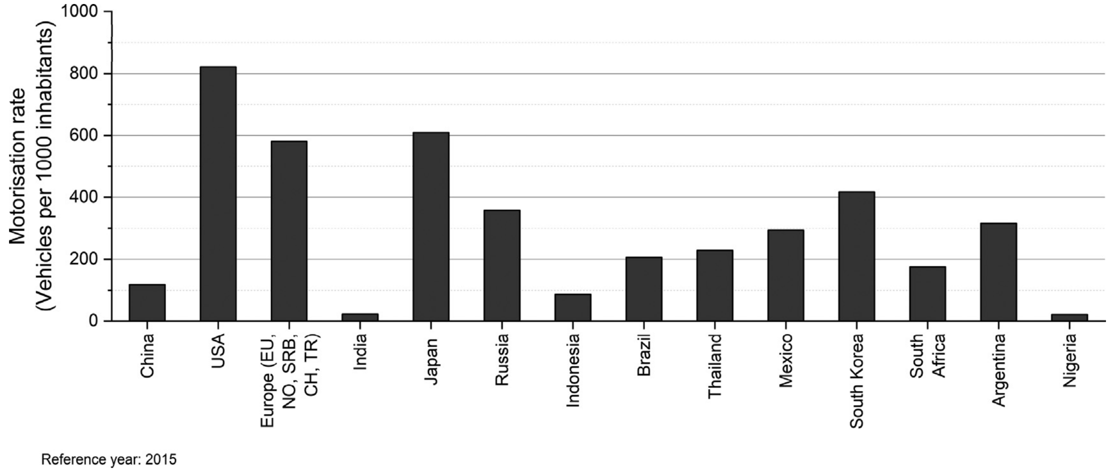

Fig. 7. Motorisation rate for several countries in 2015 [48].

mineral particles from road abrasion and fine dust deriving from other wear particles such as brake wear [54–56]. It is estimated that the world total amount of TRWP is around 5.9 Mton per year and 1.3 Mton are emitted in EU [57]. Tyre and road wear particles can be mainly found in road runoff, roadside soils and river sediments; only a minor fraction is emitted in the atmosphere but it can reach a very high concentration in tunnel dust. It is estimated that around 90% of the material emitted consists of particles with dimension >10 μm and its contribution to ambient PM_{10} and $PM_{2.5}$ ranges from 0.25 to 7 wt% [55,58,59]. Only few information can be found on the terrestrial toxicity of TRWP and on the entry paths of TRWP in the aquatic environment. The major risk for human health is represented by the inhalation of wear particles present in the atmosphere [60].

6.1. Tyres stockpiles

Stockpiles are the less preferable option for the management of end-of-life tyres and consist in the illegal or semi-legal accumulation of enormous quantities of tyres in the environment. In the USA this phenomenon started in the 1960s as a consequence of diverting tyres from landfills and reached the proportion of around 2–3 billions of scrap tyres [4]. It is estimated that around 800 million tyres were discarded in stockpiles in South Africa in 2008 and around 1–2 billions in Mexico [9]. Despite stockpiles are sometimes considered an asset by the owners, they tend to remain in place until the intervention of the government with specific abatement programs. In the USA since 1990 around 94% of tyre stockpiles have been eliminated with a constant reduction in the amount of tyres stock in piles, from 800 million of 1994 down to 188 million in 2005 and 60 million of 2017 [61]. In Europe, Nordic countries in which the producer responsibility has been implemented more than 25 years ago, the recovery rates are around 100% and stockpiles have been eliminated [9]. Other countries like India and Brazil have very high recovery rates due to subsidies to shredding companies (Brazil) and to the various uses of ELT (India): moulded products, protections on fishing boats, weights on roofs, swings [47]. Three main problems can be addressed to practice of tyres stockpiles:

1. the loss of valuable resources that are unused;
2. the risk related to the flammability of tyres: in case of fire the extinction is almost impossible with possible serious consequences on human health and environment due to the release of

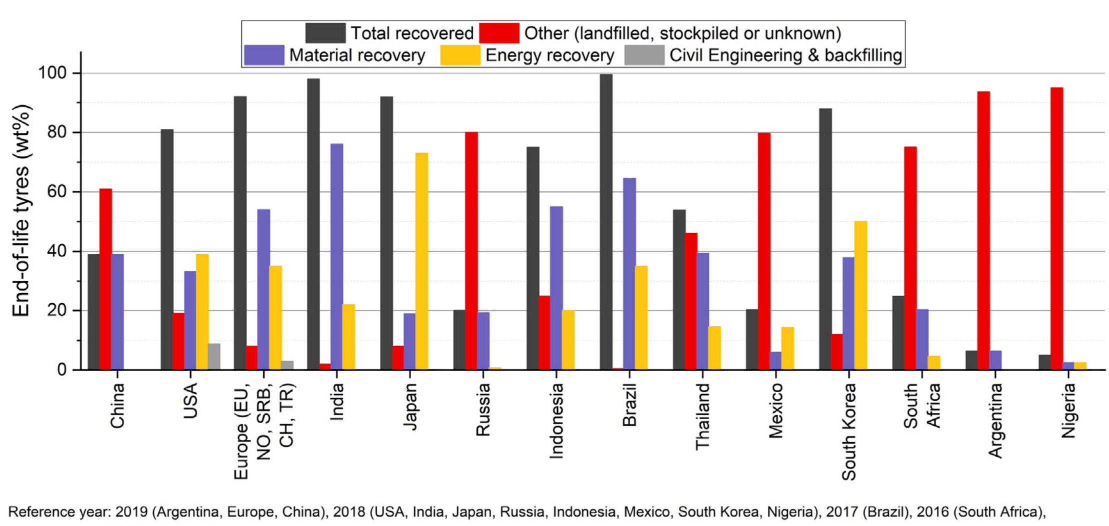

Fig. 8. EOL options for discarded tyres for several countries (in %) [49].

toxic gases, smoke and pyrolytic oil. In California 20 million $ were spent for the clean-up operations of the Westley fire that burned for 30 days in a stockpile containing around 7 million tyres [4,62];
3. especially in hot climates, water stagnation within tyres is the ideal condition for the development of mosquitoes that can transmit fatal diseases such as Nile fever, dengue fever and malaria [4,9].

6.2. Landfill

Despite landfill of tyres is forbidden in the EU from 2003 (2006 for shredded tyres), in many countries it is still a practiced EOL option [47,49]. Usually tyres are shredded to allow compaction and deposit in a dedicated licensed location, that is covered once its capacity has been achieved. With respect to stockpiles the only advantages are the reduced risk of fire and of environmental pollution (if the landfill has been properly designed) and the absence of water stagnation with consequent mosquito breeding [4].

6.3. Civil engineering applications

The use of whole tyres for civil engineering applications consists in the realization of retention walls that can be partially or entirely covered by soil or inert material in order to avoid water stagnation [63]. Shredded tyres can be used for the realization of drainage basins [4]. Rubber ash (size 0.15 mm) can be used for the preparation of mortars partially substituting fine natural sand, while rubber particles (size 4.75 mm) can partially replace natural fine and coarse aggregate in concrete mixtures [10,64–66]. At concentration higher than 20 vol% the mechanical properties of concrete tend to decrease, preventing the use for structural applications [67]. The benefits in comparison to common solutions are mainly related to the reduction of vibration transmission in concrete and to the reduced demand for gravel, stones, concrete and reinforcing steel [63,68]. On the other hand concerns arise from the effective recovery of tyres at the end of their useful life in civil engineering applications to avoid that they become a sort of landfilling process. In any case, it should be noticed that the use of ELT for these applications is subject to public authorization due to the potential hazardous effects [49].

6.4. Energy recovery

Energy recovery is the second less preferable end-of-life option for tyres and, although much preferable in comparison to uncontrolled fires, should be performed only when recycling is not a viable option [4]. Tyre derived fuels (TDF), consisting of whole or shredded tyres, are mainly used in cement kilns (51%), for pyrolysis (China, Indonesia, Mexico and Thailand) and in the steel industry (1%) allowing major cost-savings since they usually are five to ten times cheaper than coal or pet coke [7,49,69]. As it is possible to observe from Table 2, TDF have a high energy content and CO_2 emissions similar or even lower in comparison to those of common fuels; moreover, when used in cement kilns, iron and sulphur are incorporated into the cement [7,70]. Despite the high energy content deriving from the combustion of tyres, it should be considered that a much higher energy amount is required for the production process of a rubber tyre: especially it is estimated that around 90 GJ/ton are required for the preparation of the rubber compound, 115 GJ/ton for the manufacturing process of the tyre and 4 GJ/ton for the grinding process of scrap tyres [4]. Hence, the high energy amount required for the production of tyres should encourage the use of tyre rubber for the original purpose rather than for incineration.

Table 2
Energy content and CO_2 emissions from different fuels [71].

Fuel	Energy [GJ/ton]	Emissions [kg CO_2/ton]	Emissions [kg CO_2/GJ]
Tyres	32.0	2270	85
Coal	27.0	2430	90
Pet coke	32.4	3240	100
Diesel oil	46.0	3220	70
Natural gas	39.0	1989	51
Wood	10.2	1122	110

6.5. Retreading

Retreading is a process for extending the useful life of tyres by removing the old tread and applying a new one [16]. Tyres are firstly inspected for damages (visually and by shearography) in order to filter out casings in bad conditions. The worn tread of selected tyres is then removed using a buffing rasp and the new tread is applied and vulcanized [16,72]. The new tread can be manufactured as a ring, avoiding junctions, or can be a precured strip than has to be cut and can be adapted to casings of different sizes [73]. In case of using the precured strip, to promote the bonding between the new tread and the casing, a thin layer of a special bonding rubber is applied between the casing and the new tread [74]. Tyres of premium level in good conditions with an undamaged casing can be retreaded up to two times with an increased service life of around 220,000 km for each retreading [75]. As a comparison, a low-end imported tyre cannot be retreaded and has a service life of only 120,000 km [75]. Depending on the tyre, the retreading process requires around 30% of the energy and 25% of the raw materials needed to produce new tyre with a consistent reduction in rubber waste and performances equivalent to those of a new tyre [16,74]. Despite these advantages, the remanufacturing rates strongly varies among tyre categories: from a remanufacturing rate of 1% for summer passenger car tyres, to 50% for truck tyres up to 90% for airplane tyres [74]. The reason for the low rate in case of passenger car tyres can be explained considering that the price for a new, middle-range, tyre is around 50 €, the price for retreading around 37 € and the price for an imported tyre from Asia around 35 € [74].

6.6. Recycling or material recovery

Recycling is the most preferable end-of-life option since it is defined as the re-use of a material, after certain processing operations, for its original purpose. Therefore, in case of ELT, recycling should consist in the use of recycled rubber for the manufacturing of new tyres. Recently, the European Commission launched the Blackcycle project, founded by the Horizon 2020, that aims at the production of new tyres from end-of-life-tyres promoting and optimizing a full value chain form ELT to Secondary Raw Materials [76]. In the reality, rubber recycling consists in the recovery of materials, converting rubber waste into an economically useful form that is achieved through the shredding process of scrap tyres into crumb rubber with the simultaneous removal of steel, fibres and other non-rubber components [4,77]. Crumb rubber can be used for the production of rubber-modified-asphalt [4,78,79], playground surfaces [51], artificial turfs [80], lightweight fillers [63], insulating panels [81,82] and in small quantities mixed with virgin rubber for the manufacturing of new tyres [4,83]. Otherwise it can be further treated through other processes such as reclaiming and devulcanization [4,77].

The shredding process of scrap tyres is firstly performed using a cracker mill or a high-impact hammer mill or a rotary shear shredder in order to obtain chips with dimensions of around 2.5 × 2.5 cm^2 [84]. Steel wires and textile fibres are then removed and the rubber chips can be processed at ambient temperature using knife shredders, granulators, raspers, crackermills and micro mills in order to obtain a size of around 40 mesh [68]. The process can be then further carried out in liquid nitrogen (−80 °C) with a hammer mill in order to obtain finer particles (100 mesh) due to the glassy behaviour of rubber below its glass transition temperature [4]. Granulated rubber is mainly used for the production of artificial turfs (37%), moulded objects (22%) and playgrounds (18%); a consistent part (17%) is exported and the remaining is used for asphalt and road paving [85]. At the academic level granulated rubber is widely used for the preparation of thermoplastic elastomers (TPE) based on the use of a thermoplastic matrix blended with GTR: Fazli et al. investigated the use of GTR to produce TPE based on recycled polyethylene [86], Li et al. studied the mechanical properties of high-density polyethylene blended with GTR modified with ethylene-propylene-diene terpolymer, dicumyl peroxide and silicone oil [87], Naskar et al. studied the properties of acrylated high-density polyethylene blended with GTR pre-treated with maleic anhydride and dicumyl peroxide [88]. Many other examples are exhaustively reported in the review paper of Ramarad et al. [89]. Research regards also the incorporation of GTR within thermosetting and elastomeric matrices: a comprehensive overview is reported in the review paper of Karger-Kocsis et al. [90]. A by-product of the shredding and granulating process, that can also be obtained using a high-pressure water jet in a wet grinding process, is the so called “waste tyre dust” (WTR) that has been commonly used as filler to reduce the price of products such as floor mats, microcellular sheets etc. In the last years WTR has been successfully used to increase the mechanical properties of natural rubber after a devulcanization process (Delink process) [91] or through the addition of carbon black [92], to improve the thermal and mechanical properties of polypropylene through the addition of dicumyl peroxide [93].

Rubber modified asphalt (RMA) was firstly used in Arizona by adding thermoplastic elastomers to the hot bitumen in order to improve the resistance to rutting and thermal cracking of road pavements, to increase oxidation and ageing resistance, to decrease noise and increase the service life [4,94]. In the same period, in Sweden, ground rubber from discarded rubber was used to improve the asphalt resistance to studded tyres and snow chains [95]. Nowadays China is the major user of granulated rubber from ELT for the production of RMA [49]. The production process of RMA consists in the incorporation of ground rubber in the bitumen at high temperatures (160–220 °C) in order to allow the absorption of the aromatic oils contained in the bitumen within the polymeric chains of rubber, causing the swelling and softening of rubber particles [96]. Time and temperature of the process should be controlled in order to avoid depolymerisation/devulcanization reactions of rubber particles. After the blending of rubber with bitumen, typical paving procedures are followed [97].

Moulded objects are usually produced by mixing granulated rubber with a polyurethane resin and compression moulded into a metallic mould at around 80 °C [98]. Examples of products are lamps, ramps, vases, playground accessories, rail blocks and hoses [85]. In playgrounds, granulated rubber with dimension of around 1–4 mm can be used, instead of virgin EPDM, to absorbs shocks. Rubber granules are mixed with a polyurethane resin and casted into a mould in order to obtain panels with the desired dimensions. Usually a top layer of EPDM rubber is still maintained due to the more regular dimension of granules in comparison to those made of recycled rubber [80]. Synthetic turfs fields are made of polyethylene or polypropylene fibres attached to a mat of polypropylene covered by a layer of natural rubber and they are immersed in a bottom layer of sand covered by a top layer of rubber granules. The sand is used to hold the plastic mat in place due to its weight while the rubber provides elasticity [80]. Despite the market for playgrounds has experienced an increasing interest in the last years, a drop has been experienced in Europe by the market for artificial turfs due to the negative public perception [49,99]. It estimated that around 3–5 tons of granulated rubber should be refilled each year for each artificial field: the reason is that rubber granules can be lost due to migration in the cloths or shoes of athletes, due to rain or snow and during the maintenance activities [80]. Recently, the European Committee for Risk Assessment (RAC) has presented the proposal for a complete ban of the use of rubber granules in artificial turfs after a transition period of 6 years in order to limit the release of microplastics in the environment [100]. Moreover, the European Chemicals Agency (ECHA) published in 2017 a study regarding the health risks associated to the exposure to rubber granules through skin contact, inhalation or ingestion. The risk, mainly related to the presence of polycyclic aromatic hydrocarbons (PAHs) within rubber granules derived from ELTs, was considered very low based on the concentrations of PAHs measured in different European countries [101]. Although, it was decided that starting from August 2022 the maximum concentration of PAHs in granules and mulches used on artificial turfs or playgrounds is 20 mg/kg, with a reduction of around 80% in comparison to the previous limit [102].

Alternatively, rubber granules can be devulcanized in order to be further used for the production of new tyres [68,103]. Devulcanization is a chemical process that should revert rubber to its virgin state before vulcanization: in the ideal situation it is performed by selectively breaking C–S and S–S bonds in order to separate the rubber macromolecules [104–106]. The process is usually performed through chemical methods, ultrasounds, microwaves and thermo-mechanical techniques [104,105,107–112]. On the contrary, the reclaiming process consists in the breakage of the C–C bonds with a consequent decrease in the molecular weight of the polymer and, consequently, of the properties of the resulting compound [77,90,113]. The higher the selectivity of the vulcanization process, the higher will be the mechanical properties of the revulcanized material [114]. Seghar et al. observed that up to 65 wt% of virgin natural rubber can be replaced by devulcanized rubber [108], while Ghosh et al. observed that up to 30 wt% of virgin SBR rubber can be replaced by devulcanized rubber [115]. Van Hoek et al. and Saiwari et al. developed and improved a method for the devulcanization of GTR allowing the substitution of up to 30 wt% of virgin rubber in the production process of new tyres [116–120]. Commercial products are provided by e.g Rubber Conversion [121], Levgum [122], Tyromer [123], Elastocinca [124], Rubberlink [125].

7. Environmental aspects of different end-of-life scenarios of tyres

Different end-of-life scenarios of tyres have been investigated by life cycle assessment (LCA) in order to have a comparison of the environmental impacts in accordance with different impact categories. It should be noticed that the results reported in the literature are not always comparable due to the different system boundaries, different assumptions and/or different impact categories chosen for the evaluation.

The use of ground rubber from ELT for material recovery leads to a reduction of 3217 kg of CO_2 eq per ton of used tyres in case of artificial turfs, 2703 kg of CO_2 eq in case of moulded objects, 1466 kg of CO_2 eq in case of incorporation in concrete mixtures [126]. For the same applications, the primary energy consumptions is reduced from 74 GJ in case of artificial turfs to 43 GJ of concrete mixtures [126]. The production of 1 ton of carbon black from the pyrolysis of tyres allows the reduction of around 5000 kg of CO_2 eq in comparison to the production process using oil, with a reduction of around 80% of the CO_2 emissions [49]. Ortíz-Rodríguez et al. showed that the use of 1 ton of ELT as alternative fuel in cement kilns allows the reduction of 1110 kg CO_2 eq while its use for the production of rubber modified asphalt has a negative environmental impact due to the emission of 667 kg CO_2 eq [127]. In case of pulverisation of the ELT before using as fuel in cement kilns the benefit is reduced to 500–300 kg CO_2 eq depending on the grinding technique [99,128]. The use of 1 ton of GTR for civil engineering applications leads to a reduction of only 20–80 kg of CO_2 eq in comparison to the common solutions using sand, gravel or rock [129]. The devulcanization process of rubber with the complete recovery of the rubber fraction within tyres may result in a primary energy demand decrease of around 3000 MJ, equivalent to a reduction of around 94% in comparison to the energy required to produce a virgin rubber compound [49,130].

The retreading process of a truck tyre causes the emission of around 60 kg of CO_2 eq,[3] that compared to the emissions related to the production of a new tyre (236 kg of CO_2 eq[4]) represents a reduction of around 74% [25,75]. Considering the consumption of raw materials, in case of a new tyre replaced after 220,000 km, around 210 kg of materials are required to run 660,000 km, while in case of a new tyre retreaded two times, the amount of material is reduced to 96 kg, equivalent to a reduction of around 54%.[5] Similarly, the emissions for the manufacturing of a new tyre replaced two times to run 660,000 km are around $236 \times 3 = 552$ kg of CO_2 eq, while in case of a new tyre retreaded two times they are around 313 kg of CO_2 eq, equivalent to a reduction of around 43%.[6]

8. Conclusions

Nowadays, despite the different possible strategies to manage end-of-life tyres, there are still huge quantities of material that are not recovered and simply dispersed in the environment or accumulated into illegal tyres stockpiles. It was shown that Europe, due to the stringent legislation on the treatment of waste, has a high recovery rate (around 95%) of waste tyres but, despite the Directive on the Landfill of Waste 1999/31/EC that prohibit the landfill of tyres, a significant amount of them (8%) is disposed of into landfills. Excluding landfilling, all the possible end-of-life options for tyres try to use the potential represented by the fact that waste tyres are valuable high-tech materials. The energy recovery from the combustion of tyres is mainly carried out in cement kilns and, despite it allows the reduction in CO_2 emissions in comparison to commercial fuels due to the higher calorific value (32 MJ/kg), it should be considered that only a small part (around 15%) of the energy that is used in the production process of tyres (200 MJ/kg) can be recovered. Recycling is the most preferred option and includes both the material recovery for other purposes (artificial turfs, playground surfaces, rubber modified asphalt, etc.) and the devulcanization in order to obtain rubber to be used for the production of new tyres. Another valuable option that allows the amount of waste to be reduced by increasing the service life of tyres is retreading: in case of truck tyres it reduces the amount of material of around 54% with a decrease of 43% in the emission of greenhouse gases. This review article has provided an updated state-of-the-art regarding the current end-of-life technologies applied to waste tyres, statistics regarding the effective situation worldwide and environmental aspects related to possible scenarios. Considering the necessity to reduce greenhouse gases emissions in order to achieve carbon neutrality, it seems crucial the adoption of sustainable end-of-life options aiming at the circularity of processes and materials. Further regulations and stimuli should come from governments and institutions in order to promote aspects such as recycling, circularity and efficiency.

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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