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Waste tyre processing methods and their significance for industry and the environment: An integrated framework for end-of-life tyre management

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ABSTRACT

This review article addresses the issue of the management of end-of-life tyres as one of the most significant problems of the modern economy due to its scale and environmental, legal, and technological aspects. The aim of this study is to present selected currently applied tyre processing methods, discuss the existing regulations, and indicate their importance for industrial development and environmental protection. Based on the analysis, an integrated framework is proposed to illustrate the interrelationships between the legal, technological, environmental, and material recovery aspects of end-of-life tyre management. The study contributes to the systematisation of knowledge regarding the tyre recycling methods and their practical applications, which may provide support for enterprises and institutions involved in waste management.

Keywords: end-of-life tyres, tyre recycling, tyre pyrolysis, material recycling, energy recovery.

INTRODUCTION

End-of-life tyres (ELTs) represent a significant environmental challenge resulting from their extremely large-scale generation and specific material structure. Along with the increasing number of vehicles worldwide, the amount of rubber waste is also growing, with approximately one billion end-of-life tyres being generated annually (Jakóbiec et al., 2011). In the context of the circular economy and continuously increasing regulatory pressure, their proper management has become one of the most important challenges for modern waste management systems.

Tyres are composite materials manufactured from a mixture of rubber, steel components, and textile fibres. Their complex structure significantly complicates the recycling process, which requires the separation of materials with different physical and chemical properties into individual fractions. They are characterised by a low biodegradation rate and high resistance to external factors, including water, chemicals, and high temperatures. As a result of the durability of this type of waste, tyres in the natural environment do not undergo complete biological decomposition; instead, over time, they break down into increasingly smaller particles that may contaminate soil, water, and air. Therefore, their disposal poses a significant environmental threat (Duda et al., 2020).

The storage of tyres over large areas, often in the form of stockpiles, generates serious environmental hazards. These include, among others, the risk of fires caused by spontaneous combustion, intentional ignition, or atmospheric phenomena, as well as the emission of toxic substances during combustion (Duda et al. 2020). This problem is global in nature and affects both developed and developing countries. It creates a need to propose effective processing and material recovery methods, as well as waste management systems that ensure an appropriate level of recycling (Jakóbiec et al., 2011). In response to these challenges, tyre manufacturers, recycling companies, and regulatory bodies are seeking increasingly effective technological and organisational solutions. Tyre recycling is a process that requires continuously developing advanced infrastructure capable of ensuring proper and sufficient material recovery, as well as appropriate legal regulations enabling the effective operation of recovery systems.

The aim of this review is to provide a comprehensive analysis of end-of-life tyre recycling, covering four key areas: environmental aspects, legal regulations, recycling methods, and practical applications of tyre-derived materials. The study integrates these elements into a coherent evaluation framework, demonstrating the relationships between them and emphasising the importance of tyre recycling in the context of the circular economy.

END-OF-LIFE TYRE RECOVERY METHODS

Tyres consist of multiple materials that may have significant value in terms of their potential reuse. In simplified terms, their structure consists of rubber, steel, and textile fibres (Figure 1).

When the service life of tyres comes to an end and they can no longer be retreaded, they are collected and subsequently subjected to recycling processes (Braithwaite, 2021). Tyre recycling is not limited to a single process; several methods are commercially used, each producing different output materials and requiring different types of equipment. The selection of a method and the appropriate approach depend, among other factors, on the type of tyres being processed, the processing volume, and the end market for the recovered material (Donelly, 2026).

The literature identifies several basic methods, including tyre retreading, material recycling, pyrolysis, and energy recovery (Smejda-Krzewicka et al., 2015). The retreading process involves restoring the tread layer of an end-of-life tyre. This enables the reuse of up to approximately 80% of the original tyre structure while maintaining the basic functional properties of the material. Before applying a new tread layer, the tyre undergoes preliminary processing involving the removal of the remaining parts of the worn tread (Smejda-Krzewicka et al., 2015). Two main retreading methods can be distinguished. The first is the "hot" retreading method, in which the process is carried out at an elevated temperature reaching up to 180 °C. This process can usually be performed only once because it affects the structural integrity of the tyre (Rogachuk and Okolie, 2023). The tyre casing is coated with an adhesive layer, followed by the application of an unvulcanised rubber compound. The element is then placed in a mould and subjected to vulcanisation under pressure at a temperature of 423–453 K. The process usually lasts approximately 90 minutes. The advantages of this method include the possibility of regenerating not only the tread but also the sidewalls and shoulders of the tyre; however, its limitation is the necessity of using dedicated moulds for different tyre sizes and tread patterns, which increases investment costs (Smejda-Krzewicka et al., 2015). The second method is "cold" retreading. It involves applying a thin layer of adhesive and an elastic rubber compound to the prepared tyre casing. Subsequently, a tread strip is applied to the tyre surface and bonded to the casing through pressure using special rubber envelopes. This process is carried out at a temperature of 370 K and requires considerably more time, ranging from 4 to 5 hours. This method is more commonly used due to its simpler technology, greater safety, and lower production costs (Smejda-Krzewicka et al., 2015).

Retreaded tyres are environmentally beneficial because they reduce carbon dioxide emissions and, importantly, decrease the extraction of natural resources. Moreover, this process can extend the service life of tyres by up to 4 years (Rogachuk and Okolie, 2023). However, not all tyres are suitable for retreading. Before the process, a thorough technical assessment must be performed to classify the tyre for this type of regeneration. Specialised equipment is used for this purpose. This method is primarily applied to heavy-duty vehicle tyres, while passenger car tyres are used to a lesser extent due to their relatively low tread thickness (Smejda-Krzewicka et al., 2015).

Material recycling is a waste management method based on granulating materials from the same material group and reusing them, often in less demanding applications. Stationary or mobile processing installations are used for this purpose; however, repeated processing may deteriorate material properties. Therefore, a cascading system is applied, in which the requirements for

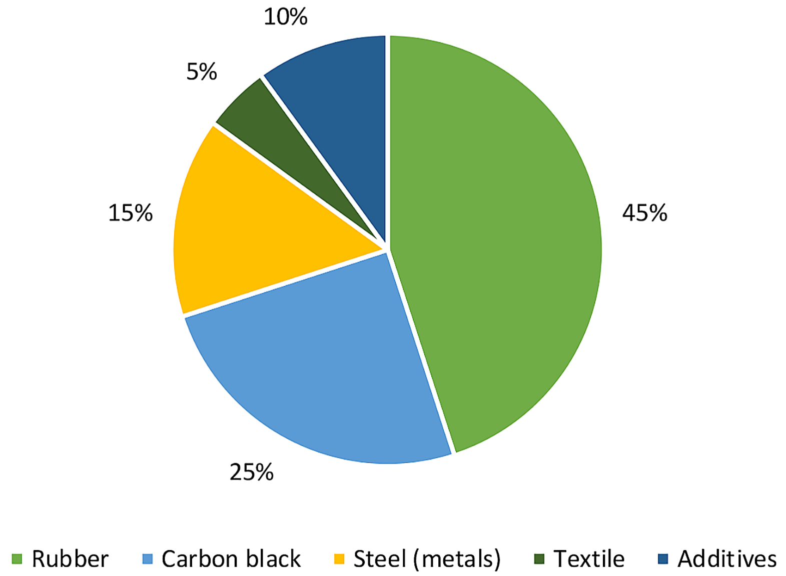

Figure 1. Car tyre composition. Source: own elaboration based on Marín-Genescà et al. (2020)

products become progressively lower with each subsequent processing cycle (Mrozik, 2012).

In the case of tyres, considering their structure and composition, material recycling is generally more difficult compared to materials such as glass or metals. In addition to rubber, a tyre contains steel and textile cords, which must be separated during the recycling process (Trzaska, 2010).

Material recycling of end-of-life tyres is mainly based on size reduction processes. This leads to the production of a mixture of steel, rubber, and fibres, which is subsequently subjected to separation and fractionation (Trzaska, 2010). Typical size reduction methods include cutting and grinding processes. These operations are most commonly performed either at ambient temperature or using cryogenic technology (Trzaska, 2010).

The first method involves mechanical grinding of previously cut tyre fragments. Due to the high elasticity of rubber, this process is challenging; therefore, specialised equipment such as knives and grinding discs is required. The result is a granulate that is subsequently subjected to separation in order to remove textile fibres and steel components (Trzaska, 2010). Cryogenic size reduction involves cooling pre-cut tyres using liquid nitrogen to a temperature at which the material becomes brittle. The tyres are then subjected to mechanical size reduction. This process allows the production of granulate with a more uniform structure and a lower level of impurities compared to the ambient-temperature method (Trzaska, 2010).

Pyrolysis is a thermal decomposition process carried out in the absence of oxygen. It involves heating the material to temperatures exceeding 400 °C. During the process, the chemical structure of the raw material is decomposed, resulting in the formation of various products, mainly hydrocarbons. The efficiency of this process and the composition of the obtained products depend on various parameters, such as temperature, heating rate, and the properties of the processed material (Czajczyńska and Krzyżyńska, 2016).

The literature distinguishes various types of pyrolysis depending on the process conditions, particularly slow pyrolysis and fast pyrolysis. The main differences between these methods include the heating rate of the feedstock, the residence time of the material in the reactor, and the type of final product obtained (Czajczyńska and Krzyżyńska, 2016).

Slow pyrolysis is carried out at a relatively low heating rate and a temperature of approximately 400 °C. It is characterised by a long residence time of the material in the reaction chamber (from several minutes to several hours), which promotes further secondary transformations. As a result, a higher proportion of pyrolytic char is obtained, and maximising its production is the primary objective of this process (Czajczyńska and Krzyżyńska, 2016). Fast pyrolysis, in contrast, is characterised by very rapid heating of the feedstock and a short residence time in the reactor (less than 2 seconds). Such conditions promote the formation of a larger amount of liquid fraction, particularly pyrolysis oil. However, this process requires appropriate feedstock preparation and efficient removal of volatile products. The resulting product is a liquid fuel with favourable properties (Czajczyńska and Krzyżyńska, 2016). The energy recovery process involves the combustion of tyres, from which heat can be recovered and subsequently used in various technological processes. The calorific value of tyres is 7.5 kcal/g, which is higher than that of coal (6.3 kcal/g) or paper (4.2 kcal/g). For this reason, tyres represent an excellent alternative fuel (Smejda-Krzewicka et al., 2015), although their utilisation requires appropriate combustion conditions compliant with emission standards (Industrial Emissions Directive, 2010).

Table 1 presents a comparison of the basic end-of-life tyre management methods.

The compilation can be used by recycling companies, tyre manufacturers, and institutions responsible for waste management. It enables the assessment of material and energy recovery possibilities, as well as the identification of advantages and limitations of individual technologies.

Legal regulations regarding waste management

The management of end-of-life tyres is regulated by European Union and national legislation. The Waste Framework Directive (2025) is of particular importance in this field. Above all, it introduces a waste management hierarchy and promotes the reuse of waste materials. The established order of priorities aimed at preventing waste generation includes:

- waste prevention;
- preparation for reuse;
- recycling;
- other recovery operations;
- disposal.

The Directive also addresses the issue of extended producer responsibility. This means that producers are required, among other obligations, to organise the collection of waste generated from their products and to design products in a way that reduces their environmental impact. Furthermore, it indicates that landfilling is the least preferred waste management method, which is of particular importance in the context of end-of-life tyre recycling (Waste Framework Directive, 2025).

In Poland, this issue is specified in the Waste Act (Dz.U.2013.21). It defines the principles of waste registration, processing, and compliance with requirements concerning recovery levels. The Act also presents a hierarchy of actions related to waste management, where the first priority is minimising waste generation, followed by recovery, and finally disposal (Merkisz-Guranowska, 2007).

MASS AND MATERIAL BALANCE OF TYRES AS A WASTE

End-of-life tyres constitute a valuable source of materials and energy that can be reused in numerous sectors of the economy. Proper management of this waste stream not only reduces its adverse environmental impact but also enables the recovery of resources with significant practical value.

Table 1. Comparison of selected end-of-life tyre management methods (Smejda-Krzewicka et al, 2015; Trzaska, 2010; Donelly, 2026; Czajczyńska and Krzyżyńska, 2016)

Method	Characteristics	Main products and effects	Advantages	Limitations
Retreading	Restoration of the worn tread layer and reuse of the tyre	Tyre suitable for further use	Reduction of waste volume, lower costs, saving of raw materials	Applicable only to tyres in appropriate technical condition
Material recycling	Mechanical size reduction of tyres and separation of textile fibres, steel, and rubber	Rubber granulate, steel, textile fibres	Possibility of material reuse, wide range of applications for granulate	High infrastructure costs, difficulties associated with material separation
Pyrolysis	Thermal decomposition of tyres at high temperature without oxygen access	Pyrolysis oil, gas, pyrolytic char	Possibility of recovering raw materials and energy, reduction of waste volume	High installation and operating costs
Energy recovery	Combustion of end-of-life tyres to generate energy	Thermal energy and electrical energy	High calorific value of tyres, reduction of landfilled waste	Emission of pollutants and lack of recovery of materials for reuse

Depending on the processing technology applied, materials recovered from end-of-life tyres can be used in construction, road infrastructure, sports infrastructure, the energy sector, and the manufacture of various products. The main categories of materials obtained from end-of-life tyres at different stages of processing include tyre shreds, chips, granulates, tyre pieces, steel, and textile fibres (Braithawaite, 2021). Rubber accounts for approximately 6.77% of a vehicle's total mass, with tyres representing a significant proportion of this amount, accounting for approximately 65.5% (Bekisz and Kruszyński, 2022). The global rubber products industry generates hundreds of millions of end-of-life tyres every year. Their total mass increases proportionally with the number of motor vehicles in operation. In 2017, approximately 3.4 million tonnes of end-of-life tyres were generated in the European Union, including 275 thousand tonnes of passenger car tyres and 200 thousand tonnes of truck tyres in Poland (Duda et al. 2020). Similar data regarding passenger car tyre production in Poland have been reported by the European Tyre and Rubber Manufacturers' Association (ETRMA). According to these data, 79% of tyres generated in Poland are subject to recycling and recovery: 42% undergo material recycling (granulation and retreading), while 29% are directed to energy recovery (combustion in cement kilns) and thermochemical recycling through pyrolysis. The remaining part of end-of-life tyres are not recovered (Duda et al., 2020), representing considerable potential for their utilisation in other sectors of the economy, such as construction.

Smaller fractions of shredded tyres, such as rubber powder and rubber granulate, are widely used in road construction to modify asphalt mixtures. This application is common in several European countries as well as in the United States. In California, approximately 10 million end-of-life tyres have been used for this purpose, while in Poland an example is the Kraków ring road, where materials recovered from approximately 25,000 tyres were incorporated into the construction project (Eko-Unia, 2020). In addition, rubber is used in the manufacture of clothing, automotive floor mats, livestock mats, doormats, and playground surfacing for children (Duda et al., 2020).

Another example of the utilisation of tyre-derived materials is railway sleepers. The construction of one kilometre of railway track requires approximately 35 tonnes of recycled materials, half of which consist of materials recovered from tyres, while the other half comprises plastics. As a result, railway tracks with high durability, long service life, and excellent sound insulation properties can be obtained (Eko-Unia, 2020).

Steel recovered from end-of-life tyres also represents a valuable secondary raw material that can be reused, among other applications, in the steel industry for the production of structural steel, thereby reducing the demand for iron ore and lowering the environmental impacts associated with its extraction.

The use of textile fibres recovered from tyres represents an interesting approach to extending the life cycle of this material. Numerous studies confirm that tyre-derived textiles can be effectively reused in a technologically justified manner. Research indicates that waste tyre textile fibres (WTTF) can be successfully utilised in the production of thermal insulation mats, where this fraction constitutes up to 80% of the raw material. The obtained materials are characterised by low thermal conductivity (0.0412–0.0338 W/mK), good tensile strength, and low water absorption (1.5–4.3%), confirming that tyre-derived textiles represent a valuable raw material for insulation applications (Balčiūnas et al., 2025). These materials can also be used as sound-absorbing composites in acoustic barriers, achieving a sound absorption coefficient ranging from 0.04 to 0.99, particularly within the 800–2000 Hz frequency range (Ružickij et al., 2024).

Other studies demonstrate that textiles recovered from tyres, mainly Nylon 6.6 fibres with an average diameter of approximately 22–25 μm, can replace cellulose fibres in asphalt mixtures, significantly improving their mechanical properties. It has been shown that the addition of ELT fibres increases the stiffness modulus of asphalt by more than 15% and extends its fatigue resistance, confirming the technical and environmental validity of their reuse (Landi et al., 2018). Table 2 summarises the applications of materials recovered from end-of-life tyres.

The data presented in Table 3 illustrate how selected countries managed end-of-life tyres in 2021. The comparison includes both, countries with well-developed recycling systems and those that still need to improve and further develop their waste management practices. Consequently, differences in recycling efficiency, recovery structure, and approaches to the circular economy can be identified.

Table 2. Applications of materials recovered from end-of-life tyres (Braithawaite, 2021; Bekisz and Kruszyński, 2022; Duda et al. 2020; Eko-Unia 2020)

Tyre-derived material	Example application
Reusable tyre casing	Extending the service life of tyres by replacing the worn tread
Whole or shredded tyres and rubber fractions	Conversion through pyrolysis into products such as oil, gas, and recovered carbon-rich material
Whole or shredded end-of-life tyres	Use as an alternative fuel, particularly in cement kilns
Rubber powder and rubber granulate	Modification of asphalt mixtures used in road surfaces
Recycled rubber obtained from tyres, combined with plastics	Manufacture of durable railway sleepers with sound-insulating properties
Rubber granulate and rubber powder	Production of playground surfacing and sports surfaces
Recovered rubber and rubber granulate	Production of automotive floor mats, livestock mats, and doormats
Recovered rubber-based materials	Production of selected clothing and accessory components
Tyre shreds, chips, pieces, and rubber granulate	Use as construction, filling, drainage, insulation, or auxiliary materials
Steel recovered from tyre reinforcement	Reuse as secondary raw material in the metallurgical industry
Textile fibres separated from tyres	Use in composite materials, insulation products, or energy recovery, depending on their quality

In 2021, among the analysed countries, the largest quantities of end-of-life tyres were generated in major automotive markets such as Germany and Spain. Poland, as one of the largest countries in the European Union, also belongs to this group, although the amount of end-of-life tyres generated was lower than in Western European countries. Lower values were reported for smaller countries such as Finland and the Czech Republic. Germany is the clear leader in material recycling, processing as much as 260 thousand tonnes of end-of-life tyres. This is undoubtedly the result of substantial investments in appropriate recycling technologies. The Czech Republic and Spain also demonstrate high levels of material recycling, which may indicate the effective implementation of extended producer responsibility systems. Poland performs less favourably in this regard. Although material recycling is practised, its scale remains limited, and a significant proportion of end-of-life tyres is directed to energy recovery. Consequently, there is considerable potential for further development of the material recycling sector. The aforementioned energy recovery constitutes an important component of the waste management system; however, it is not the dominant treatment method. Rather, it complements material recycling. This is illustrated by the Czech Republic and Finland, where tyre combustion represents only one component of the overall end-of-life tyre management system (see Table 3).

In 2021, the European Union as a whole achieved an impressive 97% recovery and management rate, confirming the effectiveness of the implemented European regulatory framework. Several countries, including some not considered in this analysis, exceeded a 100% management rate. This indicates that more end-of-life tyres were processed than were generated domestically, primarily as a result of imports of tyres associated with new vehicles from other countries. With an end-of-life tyre management rate of only 75%, Poland remains below the European average, and this result is among the lowest in the European Union. This constitutes a clear warning signal, indicating that the existing collection and processing system is not operating as efficiently as it should. The system therefore requires further development, both in terms of infrastructure and economic incentives for recycling companies.

The data presented in Table 3 demonstrate that the European end-of-life tyre management system operates effectively; however, its performance varies considerably between countries. The most important conclusion of the analysis is that a high level of end-of-life tyre management is not achieved through a single solution but rather through the combination of an efficient waste collection system, well-developed material recycling, an effective regulatory framework, and close cooperation between industry and the public sector.

For Poland, this implies the need to further strengthen the waste collection system, invest in advanced recycling technologies, and expand market demand for products derived from recycled tyre materials. Such measures would enable the country to achieve performance levels comparable to those of the European leaders.

Table 3. End-of-life tyre management in 2021 – comparison of selected countries. (Tyres Europe, 2021)

Country	ELT generation [t]	Civil engineering, public works [t]	Recycling [t]	Total material recovery [%]	Energy recovery [%]	Management level
EU	3 123 353	107 114	1 601 827	55%	42%	97%
Czechia	81 818	-	51 121	62%	33%	96%
Finland	64 952	50 281	5 893	86%	3%	90%
Spain	255 613	60	145 698	57%	44%	101%
Germany	386 000	-	261 500	68%	34%	102%
Poland	252 600	-	112 500	45%	30%	75%
Turkey	256 297	-	176 318	69%	22%	91%

The latest industry reports indicate that the European tyre market continues to evolve dynamically, directly influencing the future volume of end-of-life tyres (ELTs). According to the ETRMA Quarterly Update (Q1, 2025), sales of passenger car and light commercial vehicle tyres increased by 3% compared with the first quarter of 2024, while imports of these tyres rose by as much as 12% during the first two months of 2025 (ETRMA, 2025). This indicates that an increasing number of tyres are entering the market, which will consequently lead to a higher volume of ELT waste in the coming years. At the same time, the truck tyre segment recorded a 4% decline in sales, reflecting the economic uncertainty affecting the heavy transport sector. These trends demonstrate that end-of-life tyre management systems must remain flexible, as fluctuations in tyre sales and imports directly influence both the composition and the volume of the waste stream requiring recycling and recovery.

TYRE LIFE CYCLE

The life cycle of a tyre comprises several stages (Rogachuk and Okolie, 2023), each associated with distinct environmental impacts, risks, and regulatory requirements. Analysing the tyre life cycle makes it possible to view a tyre not merely as a consumer product but as part of a complex system that begins with natural rubber plantations and ends with waste management processes. This approach enables the identification of the stages at which environmental impacts are greatest and where effective improvements can be implemented.

The first stage is manufacturing, which generates substantial environmental burdens from the outset. The production of natural and synthetic rubber is associated with emissions of substances such as nitrogen oxides and benzene, while the manufacturing processes themselves consume considerable amounts of energy and water. This stage is also responsible for the generation of most production waste and greenhouse gas emissions. Consequently, the tyre industry is subject to regulations such as REACH (REACH Regulation, 2006) and the Industrial Emissions Directive (IED) (Industrial Emission Directive, 2010), which restrict the use of hazardous substances and establish emission standards. In practice, compliance with these regulations requires the adaptation of production lines, implementation of heat recovery systems, and increased use of secondary raw materials. The next stage is transportation, which also generates significant environmental impacts. Tyre logistics are associated with emissions of particulate matter and exhaust gases, as well as fuel consumption, all of which contribute directly to the product's carbon footprint. European Union transport regulations (Ertico, 2026) and tyre storage requirements (Dz.U.2020.296) are intended to mitigate these impacts. However, organisational measures such as route optimisation, intermodal transport, and the use of energy-efficient storage facilities are of particular importance. The use phase represents the most environmentally critical stage of the tyre life cycle. During operation, tyre wear generates microplastics and particulate matter (PM10 and PM2.5), which are released into the air, soil, and water (Muller et al., 2026). Furthermore, incorrect tyre pressure increases fuel consumption, resulting in higher CO_2 emissions (Brzeziński, 2021). Existing legislation regulates, among other aspects, the minimum tread depth and tyre labelling requirements, which provide information on rolling resistance, external noise, and wet grip performance (Michelin, 2023). The simplest and most effective measures include regular tyre pressure checks, the selection of appropriate tyres, and driver education.

The final stage is the end-of-life phase, during which the tyre becomes waste. End-of-life tyres remain highly durable and are not biodegradable; consequently, they may pose a serious environmental threat, particularly when disposed of at illegal dumping sites. In such cases, the risk of fires and the release of toxic substances is particularly high. For this reason, the European Union has introduced a ban on the landfilling of tyres together with an extended producer responsibility system (Waste Framework Directive, 2025).

The analysis demonstrates that the environmental impact of a tyre does not end when its service life expires. Each stage—from manufacturing to end-of-life management—requires dedicated measures and regulatory frameworks. Only by integrating these actions is it possible to effectively reduce environmental impacts and establish a more sustainable operating model for the tyre industry. The presented tyre life cycle assessment serves as an analytical framework that can support decision-making across various sectors of the economy. It may be used by manufacturers to identify the stages associated with the greatest environmental impacts and to implement measures aimed at reducing resource consumption and pollutant emissions. It is also highly relevant for transport companies and vehicle users, as it facilitates a better understanding of the environmental impacts of tyre use while supporting actions intended to reduce both operating costs and emissions.

The framework presented in Table 4 is also valuable for organisations involved in waste management and recycling, as it can support the planning of more efficient collection and processing systems for end-of-life tyres. Furthermore, it provides useful information for public authorities and regulatory bodies by supporting the development and implementation of environmental regulations. The Table 4 presents an analysis of the tyre life cycle, with particular emphasis on the solutions that could be implemented.

The proposed measures are presented as recommendations, as they identify potential directions for improving different stages of the tyre life cycle that have not yet been widely implemented in industrial practice or still require further technological and organisational development. Their primary objective is to reduce the environmental impacts associated with each stage of the tyre life cycle while improving the efficiency of resource management.

Integrated framework for end-of-life tyre management

Figure 2 illustrates the relationships between the environmental challenges associated with end-of-life tyres, the applicable legal regulations, the processing technologies employed, and the opportunities for reusing materials recovered through recycling. The analysis begins by summarising the principal issues arising from the high durability of tyres, the emission of harmful substances, and the global scale of this waste stream. These factors necessitate the implementation of appropriate legal regulations defining the principles of end-of-life tyre management and the responsibilities of the various stakeholders involved in this process.

The relationships presented in Figure 2 demonstrate that the end-of-life tyre management system functions as a network of interdependencies, in which each element influences the others and determines the direction of the entire process. Phenomena related to the environmental impact of tyres constitute the starting point, as they initiate the need to establish new principles and requirements for the management of this type of waste. At the same time, these environmental challenges stimulate the development of modern processing methods aimed at reducing the negative effects of tyre waste on the environment. Legal regulations, created in response to these problems, not only define the obligations of entities involved in tyre management but also establish the framework within which tyre processing technologies can develop and determine the areas in which recovered materials can subsequently be utilised. In turn, technological development leads to the creation of specific products and materials that can be applied in various sectors of the economy, while their use contributes to reducing waste volumes and decreasing environmental pressure. Moreover, the demand for specific applications determines which technological solutions are developed and implemented, as the market requires these methods to be economically viable and practical. In this way, a closed system of interdependencies is created, in which environmental, regulatory, technological, and application-related factors mutually reinforce each other, forming a coherent end-of-life tyre management system.

Table 4. Tyre life cycle analysis (Rogachuk and Okolie, 2023; REACH Regulation, 2006; Industrial Emission Directive, 2010; Ertico, 2026; Dz.U.2020.296; Michelin, 2023; Muller et al., 2026; Waste Framework Directive, 2025; Oponeo, 2025)

Tyre life cycle stages	Hazards	Environmental aspects	Legal aspects	Applied solutions and recommendations
Production[1]	- natural rubber manufacturing processes (nitrogen oxides, benzene) - high consumption of water and electricity, depletion of natural resources	- High energy intensity of processes; - greenhouse gas emissions; - production waste; - water and chemical footprint;	- REACH – restrictions on chemical substances; - IED – industrial emission standards; - environmental regulations for production facilities	- minimisation of energy consumption; - heat recovery; - increasing the share of secondary raw materials in tyre production; - development of technologies reducing energy consumption and the use of primary materials
Transport[2]	- particulate matter emissions; - fuel consumption; - CO_2 emissions from logistics	- Carbon footprint of transportation; - exhaust emissions into the atmosphere;	- EU transport standards; - tyre storage regulations;	- route optimisation; - development of intermodal transport (e.g., rail–road) for tyres and tyre-related raw materials; - locating warehouses and distribution centres closer to end users; - further optimisation of logistics to reduce CO_2 emissions
Use phase[3]	- road noise; - emissions;	- The highest environmental impact stage throughout the entire life cycle; - emission of PM10/ PM2.5 particles	- Minimum tread depth (1.6 mm according to European Directive 89/459/EEC); - safety standards	- regular tyre pressure checks; - driver education increasing users' environmental awareness; - promotion of low rolling resistance tyres
End-of-life[4]	- risk of fires at disposal sites; - toxic emissions from illegal burning; - persistence of waste	- Lack of biodegradability; - long-term soil and water contamination; - availability of landfill space	- ban on tyre landfilling in the EU; - producer responsibilities; - Waste Framework Directive	- development of ELT collection systems; - landfill monitoring; - elimination of illegal practices; - strengthening the control and enforcement of environmental regulations

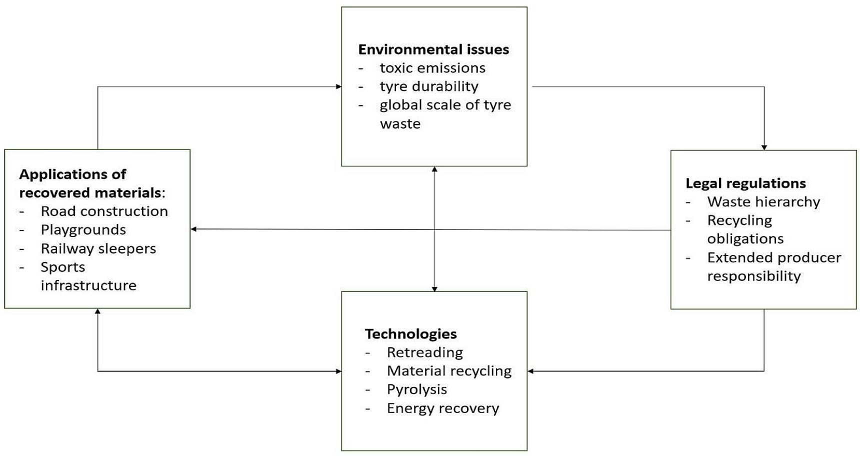

Figure 2. Integrated framework showing the interrelationships between key aspects of end-of-life tyre management

In response to these challenges, several end-of-life tyre management technologies have been developed, including retreading, material recycling, pyrolysis, and energy recovery. Their primary objective is to reduce the volume of waste while increasing the recovery of both materials and energy. An important element of this approach is the potential for reusing materials recovered through recycling, particularly in road construction, sports infrastructure, and playground construction.

CONCLUSIONS

The tyre recycling methods shows that there is no single universal solution that can fully address the problem of ELT management. Each technology performs a different function within the system, responds to specific needs, and can be applied in particular circumstances. Retreading enables a significant extension of tyre service life and represents a resource-efficient method. Material recycling allows the recovery of rubber, steel, and textile fibres; however, it requires advanced infrastructure and generates costs associated with material separation. Pyrolysis, in turn, provides the possibility of recovering high-value raw materials, but it is an energy-intensive process requiring substantial financial investment. Energy recovery serves as a complementary element of the system, enabling the utilisation of fractions that are unsuitable for material recycling.

The most effective tyre management systems are those that combine various methods while ensuring efficient collection systems, developed recycling infrastructure, and a stable market for products derived from processing. The examples of Germany and Spain demonstrate that a high level of end-of-life tyre management can be achieved through consistent investments in appropriate recycling technologies.

An important component of the entire system is also the legal framework, which determines the direction of future actions.

The appropriate integration of technologies, regulations, and organisational measures can substantially reduce the environmental impact of tyres while providing valuable secondary raw materials and energy resources.

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