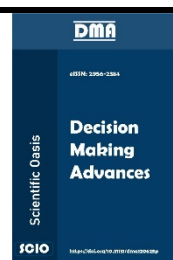




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## Smart and Sustainable Waste Tire Management: Decision-Making Challenges and Future Directions

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### ABSTRACT

The vehicle number has grown significantly in recent decades, resulting in a significant increase in the number of waste tires globally. The environment and public health are seriously endangered by the growing amount of waste tires. As a result, considerable effort is being put into the search for viable alternatives for sustainable management. Even though numerous treatments for waste tires have already been tested and proved successful, their continued industrial implementation remains difficult in both everyday life and research efforts. Finding practical, cost-effective, and ecologically friendly ways to manage waste tires is one of the biggest environmental challenges of the 21st century. By focusing on smart tire waste management, this study examines some of the most important decision-making challenges that support social and environmental sustainability. The main topics of this research are the examination of certain fundamental problems and challenges, as well as some key management strategies for this environmentally unfavorable type of increasing waste. This comprehensive analysis not only identifies significant gaps but also establishes the foundation for addressing some of the most significant decision-making issues in waste tire management by providing recommendations for further research in this important and vulnerable area of academic and practical analysis.

## 1. Introduction

Urbanization, an increase in the volume of e-commerce, and world economic trends are only some of the causes of the increase in the number of vehicles globally. Around 95 million vehicles were produced globally in 2019, and so by 2025, that number is projected to rise to over 100 million [1]. The demand for rubber products on a global scale is closely related to the expansion of the automotive industry. The European Tire and Rubber Manufacturers' Association (ETRMA) estimates that the automobile sector utilizes about 65 % of the rubber goods produced [2, 3]. Waste tires (WTs) are generated as a result of increased vehicle use, and their management is becoming exceedingly challenging. Worldwide, more than 2 billion tires are produced each year, and the same number is

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thrown away as waste [4]. WTs represent considerably more than 2 % of all waste in the world, but they are a severe type because they require more than 100 years to decompose [1, 5]. As a result, it is considered that one of the most important requirements for sustainable WT management is the traceability of the 5R principles (reduce, remanufacture, reuse, recycle, and recover) [2].

Due to a significant increase in the growth of road transportation, WT production has been rising in recent decades. Only about ten percent of the more than 20 million tons of WTs produced each year are recycled and reused [6]. WTs are categorized as "black pollution" due to their low recycling efficiency and the environmental problems they can cause when handled improperly. Although WTs are a large and common type of waste, they also provide challenges due to their high rate of renewability. Annually, around one billion WTs are released into the environment globally, and forecasts indicate that by 2030, this number will rise by more than 20 %. [2]. The management of WTs is a severe global environmental issue that has a growing impact on sustainability's social component. WTs landfilling are environmentally un-friendly and recovering, recycling, or using energy recovery are preferable alternatives. As a result, researchers are focused on more efficient and cost-effective ways to deploy WT based on their industrial treatments [7].

WTs are valuable materials for energy recovery as well as a source of secondary raw materials for the circular economy. Current trends indicate that their application in the production of value-added materials should increase soon. This study examines the current challenges and improvements in WT management. By highlighting the fundamental trends in the management of WTs, one could help eliminate some unanswered questions concerning how to treat them. This paper highlights limitations in WT management and offers suggestions for further research under developing appropriate legislation, which are highlighted in the concluding remarks.

The remainder of this paper is structured as follows. Section 2 presents the major challenges in waste tire management, with a special focus on treatment solutions, practical issues in WT reuse, and regulations. Section 3 overviews the actual trends in waste tire management. Section 4 offers not only conclusion remarks but also future research directions.

## **2. Challenges in Waste Tire Management**

WTs are increasingly being produced all over the world, and their management is a challenging academic and practitioner area [1]. The goals for managing WTs are shown in Figure 1, which makes it clear that the primary action to take is to avoid their occurrence. Since the production of WTs cannot be prevented, it is possible to influence it to increase reuse to end the practice of landfilling. Given the high value of materials acquired through recycling or energy recovery, special emphasis is placed on WT treatment. However, the question remains: where does environmentally acceptable treatment end? Following the 5R principle, the problem is to draw a line between recycling and energy recovery because even recycled WTs can be used later for energy purposes. In this regard, the developed legislation supporting the three established methods of wastewater management indicates the importance of this rapidly growing waste. In this regard, the legislation that has been developed to support the most widely used methods for the management of WTs illustrates the significance of this constantly expanding waste. In this part of the article, certain fundamental issues and challenges will be discussed in order to manage it sustainably, taking into account the general uncertainties regarding the flows of WTs as a significant part of the total world waste.

### **2.1 Treatment Solutions**

There are many challenges, dilemmas, and issues with WT management whose solutions influence the success of upcoming trends in this sensitive area. One of the key issues is related to the

possibility of their reusing. WTs can be retread to return to the vehicle, but they are also widely used as a source of raw materials when they are recycled. Both treatments assume reusing, but the key difference is that WT can be retreaded first, and then recycled.

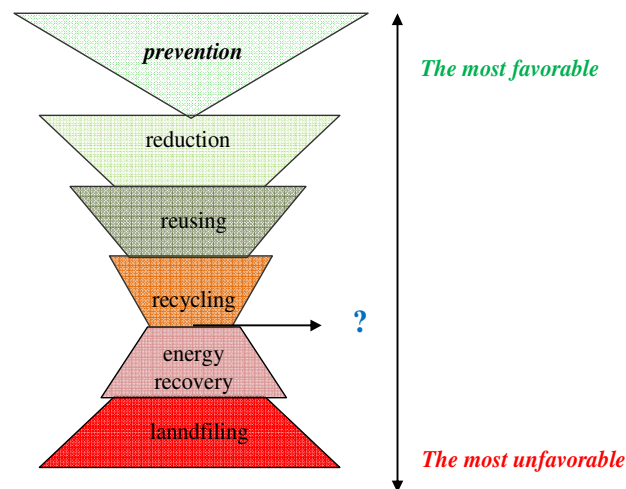


**Fig. 1.** Hierarchy of goals in WT management

Retreading implies replacing the worn tread with a new one (the outer layer of rubber) to prolong the tire's useful life. This industrial treatment is beneficial for the WTs of commercial vehicles due to its four-time reproducibility [6]. Because of its ability to save both resources and energy, it is the most effective method for WTs. The fundamental issue with retreading is that consumers lack sufficient information about its dependability. Retreaded WTs perform on par with brand-new tires and are around 50% less expensive than new tires. It makes them a cost-effective option, especially for businesses with a high volume of commercial vehicles [8]. Even though not all WTs may be directly reused, many sustainable treatment options available do not entail landfilling unless another treatment is also required.

Recycling is considered the option that is most environmentally friendly because a portion of the waste generated during the shredding process is frequently used as an alternative fuel (energy recovery) [3]. Although it is well known that materials made from recycled waste are a useful alternative to raw materials, this fact has not been fully recognized by society. Rubber granulation has proven to be a high-performance material for the production of tread for retreading in addition to being used as a material for new tire production. WTs are used to create reusable packaging that is mostly employed in the food supply chain. Because they are resilient to stress and bending stresses, recycled WTs have also utilized concrete structures, playgrounds for children and sports, and concrete and asphalt mixtures [3].

The implementation of WTs for energy recovery poses a unique group of challenges. Retreated and recycled WTs are put through this thermochemical process, which is thought to have certain adverse effects on the environment [7]. It is periodically likened to pyrolysis, which produces oils and replacement fuels for diesel. However, if harmful environmental effects are prevented by installing and promptly maintaining suitable filters, they can be used as fuel in cement kilns.

## 2.2 Main Practical Issues in Waste Tire Reuse

Following the 5R approach in WT management is essential because it ensures the prolongation of the length and cost-effectiveness of their treatment, thereby guaranteeing ecological and social

sustainability. Retreading is the biggest challenge in WT management [1, 8]. Tires on commercial vehicles are different in size and construction from those on passenger cars, which is crucial for efficient WT management. Commercial vehicle WTs are more challenging to manage due to the possibility of multiple retreads, while passenger car WTs can only be retreaded once. To increase the reduced rate of retreading, it is necessary to create an appropriate set of models, which will be enormously beneficial for transportation companies with a significant number of vehicles. The largest companies in the world have installed lines for retreading their WTs since the cost is around half that of a new one and is supported by EPR legislation [5]. One of them is the biggest tire manufacturer, Michelin, whose retreaded brand "Remix" is already widely recognized as a retreaded WT with comparable features to new tires.

Studies have found that the recycling of passenger car WTs uses less energy because of their reduced weight. WTs for passenger vehicles are, however, similarly suitable for recycling as WTs for commercial vehicles once they have retreated. The performance of raw materials and products produced in this way must be improved to increase the scope of their potential future applications [5]. Despite its various applications, discovering alternative uses for recycled WTs, especially as original material, is a significant field for future academic research and presents significant practical challenges due to numerous applications. Many issues also concern the use of WTs for energy recovery, particularly concerning potential harm to the environment. The environment is protected by appropriate filtration systems specifically created for each stage of this process, and this method of handling WTs offers substantial benefits for many industries [4, 8]. Social sustainability has gained more and more attention recently, which goes beyond the detrimental effects of WTs on human health. In this context, each WT treatment is linked to the development of new jobs, which is a significant step toward sustainable waste management.

### *2.3 Regulations*

WTs have clearly defined legislation. The conception of three distinct types of official documents demonstrates the current and ongoing challenges of managing WTs and finding long-term solutions to the emergence of current issues. The Extended Production Responsibility (EPR), which makes it apparent that the tire manufacturer requires control of WTs after their useful lives are through, is the one that is most frequently employed in the EU countries. The Free Market System (FMS), whereby local regulations regulate the collection and treatment of WTs, and the Tax System (TS), in which collection and treatment are funded by consumer taxes, are also currently in use.

Legal regulations support all methods for the sustainable management of WTs. More than 20 years ago, the Nordic countries of Finland, Sweden, and Norway pioneered EPR management in WT. Since then, numerous nations have followed suit, with Ireland being the most recent in 2017. Many other European nations, including the Netherlands, Belgium, and Italy, use EPR. [9]. Nordic countries, Finland, Sweden, and Norway started the EPR While FMS is used in Austria, Bulgaria, Croatia, the UK, Germany, Ireland, and Switzerland, TS has been adopted in Denmark and Slovakia [10]. According to ETRMA statistics, in 2019, nearly 95 % of WT from the EU, the United Kingdom, Norway, Serbia, Switzerland, and Turkey is alarming, highlighting the urgency of implementing smart technologies for the sustainable management of this type of rapidly expanding waste [2]. Even though laws are being constantly improved, there is still a concern with the accumulation of WT in landfills, and no appropriate, universally applicable industrial solution has been created. This is the result of the sophisticated physicochemical structure of WTs, which varies based on the purpose (increased performance, service life, safety, noise reduction, etc.), and manufacturer [11]. Improvement of legal

regulations should be aimed at promoting the reuse of WTs since they can be used for recycling and energy recovery after re-treading.

### 3. Actual Trends in Waste Tire Management

The turnover for the tire industry in the EU in 2020 was more than 10 % lower than in 2019. This industry is substantially impacted by the COVID-19 crisis, and the present condition in Ukraine seems to have a considerable effect on the projected continuation of the downward trend [11]. This results in an increase in the demand for WT reuse. In Europe, over 4 million tons of WTs are thrown annually, according to the ETRMA report [12]. Due to this, one of the most significant global issues for human health and the environment is the quantity of WTs. Even though market factors suggest concentrating on WT treatments that involve their reuse, statistics reveal that more than 90 % of them are designed for energy production or material recovery [13]. According to the ETRMA data [14], WTs were collected and used for material recycling and energy recovery in 2019 in Europe [3]. Despite insufficient reusing, economic sustainability is supported regarding the cost of new raw material procurement, energy demands, and illegal dumping. The minimization of harmful emissions and the ecological and social sustainability associated with the amount of landfill waste were not ignored regardless of the high prevalence of WTs for energy recovery purposes.

Due to the current pandemic and the Ukrainian crisis, the EU is increasingly moving from the global to the local market. This is shown in Figure 2, which shows the decreasing trend in the import of tires for commercial vehicles. It is noted that 2016 was the turning point in the import of tires, which is explained by the increase in the volume of their production at the local level. However, the number of retreaded WTs is in a continuous downward trend [11]. Energy recovery, which involves using waste or entire materials as fuel in power plants, paper mills, and cement kilns, is a popular technique for managing WTs [15]. Although it is a reasonably secure method, smart solutions are needed to enhance all facets of sustainable WT management due to negative environmental impacts (possibly harmful emissions), financial considerations (expensive furnaces), and efficiency considerations (increasing the number of WTs). Contemporary trends attempt to prevent both the generation of WTs and their land-filling [5]. Retreading as a treatment that extends the useful life of the tires can enable them to some extent to achieve this [16].

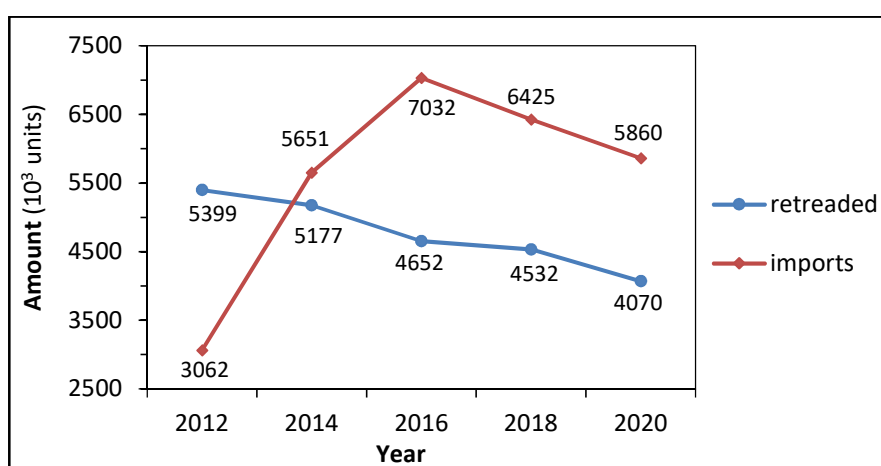


**Fig. 2.** Imported tires and protected waste tires for commercial vehicles in the EU [17].

The importance of WT management is proven by the increasing trend in academic research on its sustainable management [18, 19]. It was observed that there are increasingly numerous publications

issued each year that successfully explain the significance of WT reuse for sustainable global waste management [20]. Figure 3 indicates the annual distribution of research articles in the field of WT management. This proportion has significantly increased since 2017 [5]. In the past decade, the number of publications including the term "waste tire" has increased by about 80 % [2]. This clearly illustrates the growing importance of sustainable WT management. Academic research presently focuses on these treatments since legislation aims to increase the reuse of WTs by focusing on retreading and recycling. The energy crisis was one of the worst that the globe has faced in the last ten years, but energy recovery from WTs was not academically dismissed either.

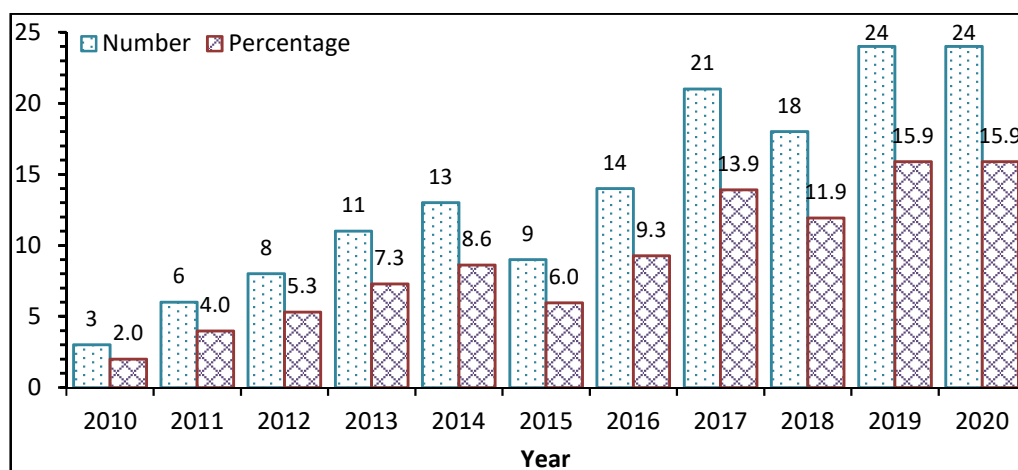


Fig. 3. The distribution of papers per year across the period 2010–2020 [5]

#### 4. Conclusion Remarks and Future Research Directions

The increasing volume of waste tires is one of the most serious environmental issues on a global level. Improper management of WTs poses a serious threat to the environment and human health. Therefore, the sustainable improvement of alternatives that support their reuse is receiving increasing attention. The contemporary initiatives to improve WT recycling are supported environmentally and economically by eliminating fees for waste disposal, decreasing production costs by using recycled materials, and the reduction of exploitation of natural resources in favor of recycled rubber.

Given that WTs are considered to have higher calorific values than coal, they have a considerable potential to provide energy to both industrialized nations like the United States and developing nations like China and India. As a result, one of the research's future approaches will focus on promoting innovative methods for efficiently recycling and using many WTs, which is a huge challenge, especially in developing countries. Additionally, WT treatment can provide materials that have a wide range of applications from everyday life to commercial and industrial applications. Retreading of WTs is considered an understudied aspect of their management. As the main limitations are related to reliability while in use, future studies need to provide information on the validity of retreading for both commercial and passenger cars. The numerous uses of recycled WTs make this type of waste even more challenging for academic research when it comes to the widespread application of the raw materials acquired using this method. Therefore, it is of significant relevance to investigate new WT industrial applications and marketplaces, which would be a continuous and essential topic of further studies.

#### Conflicts of Interest

The authors declare no conflicts of interest.

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