End-of-Life tyres applications

Technologies and environmental impacts

Joao Patricio
Yvonne Andersson-Sköld
Mats Gustafsson

Foto: Fotograf Satu AB, VTI

VTI rapport 1100A
Published 2021
vti.se/publications

VTI rapport 1100A

End-of-life tyres applications

Technologies and environmental impacts

Joao Patricio

Yvonne Andersson-Sköld

Mats Gustafsson

Author: Joao Patricio (VTI), Yvonne Andersson-Sköld (VTI), Mats Gustafsson (VTI)
Reg. No., VTI: 2021/0306-7.2
Publication: VTI rapport 1100A
Published by VTI, 2021

Publikationsuppgifter – Publication Information

Titel/Title

Däckåtervinning – tekniker och miljöpåverkan/ End-of-life tyres applications – technologies and environmental impacts

Författare/Author

João Patricio (VTI, http://orcid.org//0000-0002-4994-7735)

Yvonne Andersson-Sköld (VTI, https://orcid.org/0000-0003-3075-0809)

Mats Gustafsson (VTI, https://orcid.org/0000-0001-6600-3122)

Utgivare/Publisher

VTI, Statens väg- och transportforskningsinstitut/
Swedish National Road and Transport Research Institute (VTI)
www.vti.se/

Serie och nr/Publication No.

VTI rapport 1100A

Utgivningsår/Published

2021

VTI:s diarienr/Reg. No., VTI

2021/0306-7.2

ISSN (gäller endast VTI rapporter//only applies to VTI rapporter)

0347–6030

Projektnamn/Project

Sammanställning och analys av en resurseffektiv hantering av uttjänta däck/ Compilation and analysis of resource-efficient handling of end-of-life tyres

Uppdragsgivare/Commissioned by

Naturvårdsverket/ The Swedish Environmental Protection Agency

Språk/Language

Engelska/ English

Antal sidor inkl. bilagor/No. of pages incl. appendices

63

Kort sammanfattning

Förbrukningen av däck ökar i hela världen, och 2019 uppskattades den globala produktionen till cirka 2,2 miljarder ton. Däck innehåller olika kemikalier och måste därför vid återvinning hanteras på lämpligt sätt. Uttjänta däck har dock många unika egenskaper som gör dem lämpliga för flera olika applikationer. Denna rapport fokuserar på analys av hantering av uttjänta däck i Europa och speciellt i Sverige. I studien ingår att undersöka återvinningstekniker som finns på marknaden för att hantera uttjänta däck och deras förväntade miljöpåverkan. Studien baseras på en litteraturgenomgång som kompletterats med information från intervjuer med ett urval relevanta aktörer. I Sverige utgör uttjänta däck ett stort avfallsflöde på cirka 85 000 ton per år. Sextiofem procent av däcken i Sverige används som energikälla för energiproduktion eller inom cementindustrin, 9 procent används som sprängmattor, 25 procent för materialåtervinning och 1 procent exporteras.

Flera möjligheter för användning av uttjänta däck (eller gummimaterialet) presenteras i rapporten, som till exempel användning av däckstrimlor som lättviktsmaterial och användning av granulerat gummi som tillsats i asfalt- eller betong. Många av de presenterade applikationerna bedöms ha en stor potential. Det finns dock ett behov av bättre marknadsföring av applikationer och bättre länkning mellan olika aktörer. Från miljöanalysen framgår att användningen av uttjänta däck minskar behovet av flera jungfruliga råvaror. Analysen av de miljö- och hälsoeffekter som beskrivs i litteraturen ger dock motstridiga resultat och dessutom finns mycket lite information och kunskap om lakbarhet, biotillgänglighet, toxicitet och relaterade risker för människor och miljö för de olika användningsområdena. Vissa studier har visat att användning av uttjänta däckmaterial inte är miljöfarligt, medan andra har visat på ett möjligt läckage av metaller och PAH. Vetenskapligt välunderbyggda riskbaserade gränsvärden för miljö- och hälsofarliga ämnen i granulerat gummi, kan bidra till större acceptans och användning, särskilt inom användningsområden där de däckbaserade produkterna kan komma i kontakt med känsliga grupper i befolkningen, till exempel barn. Standardisering av däckbaserade material med specifika fysikaliska och kemiska egenskaper kan vara ett steg framåt för att öka produktionen av högkvalitativa material.

Nyckelord

Däckåtervinning, miljöpåverkan, cirkulär ekonomi, lättviktsmaterial, gummigranulat, energiåtervinning

Abstract

The worldwide consumption of tyres is growing, with an estimated global tyre production of approximately 2.2 billion tons in 2019. Tyres may contain a large variety of chemical compounds and therefore must be managed properly. On the other hand, end-of-life tyres contain several unique characteristics that make them suitable for multiple applications. This report focuses on analyzing end-of-life tyre management in Europe in general and Sweden in particular. The study also investigates the recycling technologies available in the market to manage end-of-life tyres. Furthermore, the expected environmental impacts for end-of-life tyres, in general, are investigated. The study is done based on a literature review, which is complemented with information obtained from interviews with relevant actors. In Sweden, end-of-life tyres are a substantial waste flow, accounting for approximately 85,000 tons per year. Sixty-five percent of tyres in Sweden are used as an energy source for energy production or in the cement industry, 34% are reused or recycled and 1% are exported. The report presents several opportunities for the use of end-of-life tyres (or materials) highlighting the material versatility. Examples include the use of tyre shreds as lightweight material or the use of granulated rubber in applications such as asphalt or concrete production. Many of the presented applications have a high potential contribution to a more circular economy. However, there is a need to better brand the applications as well link different stakeholders. Regarding the environmental analysis, the use of these end-of-life tyres may reduce the need of several virgin materials and reduces energy use. The literature analysis of potential leaching and human and environmental risks are inconclusive and there is still a lack of knowledge regarding leaching, bioavailability, toxicity and the related human and environmental risks in different applications. While some studies have shown that the use of end-of-life tyres materials is safe for the environment, others have shown a potential release risk of metals and PAHs. Therefore, the implementation of scientifically and risk-based regulations that define substances limits for tyre-derived products would potentially help the acceptance and use of these materials by users and contractors. Particularly for applications in which the tyre-derived products might be in contact with sensitive groups in the population, e.g. children. The standardization of tyre-derived materials with specific physical and chemical characteristics could be a step forward to increase the production of high-quality materials.

Keywords

Tire recycling, environmental impact, circular economy, shreds, rubber granules, energy recycling energy recovery

Sammanfattning

Förbrukningen av däck ökar avsevärt över hela världen, och år 2019 uppgick den globala produktionen till 2,2 miljarder ton. Även i Sverige ökar förbrukningen av däck, och år 2016 såldes 2,3 miljoner sommardäck och 2,8 miljoner vinterdäck till personbilar i Sverige. Däck består huvudsakligen av naturligt och syntetiskt gummi, men de innehåller också stål, kimrök och kemikalier, som till exempel vulkaniseringsmedel. Däckens funktion är främst beroende av däckets konstruktion och den kemiska sammansättningen av det specifika receptet som används av tillverkningsföretaget. Hanteringen av uttjänta däck, "end-of-life" hanteringen, behöver ske med försiktighet för att inte utgöra någon form av risk för miljön eller människors hälsa.

Uttjänta däck kännetecknas av att ha unika egenskaper som gör dem möjliga att använda i flera applikationer. Elasticitet, vattenabsorption och hög draghållfasthet är bara några exempel på mångsidigheten av däckegenskaper som kan vara till nytta i applikationer av uttjänta däck. Medan vissa applikationer är väletablerade på marknaden, måste andra utforskas ytterligare och marknadsföras bättre för att komma till nytta. Dessutom rekommenderar Europeiska unionen starkt utveckling av strategier och processer som främjar en cirkulär ekonomi. Det är välkänt att när den cirkulära ekonomin genomförs väl kan den leda till flera miljövinster, till exempel en minskning av antalet och mängden resurser som utvinns ur naturen eller för att minska energiförbrukning vid produktion. Därför kan uttjänta däck bidra avsevärt till en mer cirkulär ekonomi.

Denna rapport fokuserar på att analysera däckhantering av uttjänta däck i Europa i allmänhet och Sverige i synnerhet. I fokus är återvinningstekniker som finns på marknaden för att hantera uttjänta däck. Dessutom undersöks de förväntade miljöeffekterna för varje teknikalternativ. Rapporten baseras på en litteraturgenomgång som kompletterats med information som erhållits genom intervjuer med ett urval av relevanta aktörer.

Totalt genererades mer än 3,1 miljoner ton uttjänta däck inom Europeiska unionen (EU-28). Cirka 1,5 miljoner ton återvanns genom att granuleras för att användas som råvara. Av detta uppskattades hälften användas som konstgräsfyllning och 30 % för att producera gummiplattor. Energiåtervinning är också ett vanligt avfallshanteringsalternativ för uttjänta däck i Europa, och cirka 1,2 miljoner ton används för detta i cementugnar och i värmekraftverk. Slutligen användes en liten del för tekniska ändamål som exempelvis ljudbarriärer vid motorvägar och ytstrukturer. Uttjänta däck i Sverige utgör ett avfallsflöde motsvarande ca 85 000 ton per år. I Sverige används 65 procent av däcken som energikälla för energiproduktion eller inom cementindustrin, 9 procent används som sprängmattor, 25 procent går till materialåtervinning och 1 procent exporteras.

Uttjänta däck har flera unika egenskaper som gör dem lämpliga att användas inom flera olika användningsområden. I litteraturstudien framgår att det finns mer än 20 tekniker och produkter som är möjliga att använda för att ta tillvara dess egenskaper. Teknikerna kan indelas i två grupper, varav den ena innefattar återvinning av de uttjänta däcken genom att till exempel använda däckstrimlor för olika ändamål såsom lättviktsmaterial eller för dess strukturpåverkande egenskaper i olika konstruktioner. Ett annat användningsområde är som dräneringsmaterial. De uttjänta däcken kan användas hela, skäras i bitar (i strimlor eller som aggregat). De kan också sorteras i sina ingående separata komponenter såsom gummigranulat eller stål. Gummigranulat kan användas för produktion av betongprodukter, i asfalt, som underlag för konstgräsplaner, för avloppsrening, som sko-material, bäddunderlag för spårtrafik, i bullerbarriärer, utomhusplattor, med flera användningsområden. Den andra gruppen innefattar energiåtervinningstekniker, såsom att däcken används direkt som energikälla i industrier vid energi- eller cementproduktion. Dessutom inkluderar denna grupp pyrolys- eller förgasningsprocesser, där däcken används för att extrahera ut energibärare såsom syngas eller oljor som kan användas för att producera energi eller användas för att producera andra produkter.

Från miljöanalysen framgår att återanvändning av uttjänta däck är önskvärd för att minska behovet av användning av flera jungfruliga material. Ur ett livscykelperspektiv kan dessutom en minskad

energianvändning energiminskning uppnås som även medför minskade utsläpp av växthusgaser. Detta är en generell förväntan, men det är inte säkerställt att detta gäller för varje enskild teknik eller användningsområde. Ytterligare studier behövs för att bedöma dessas energi- och klimatpåverkan. Det finns mycket lite information och kunskap om lakbarhet, biotillgänglighet, toxicitet och relaterade risker för människor och miljö för de olika användningsområdena. Den information vi fann i litteraturanalysen är dessutom motstridig. Vissa studier visar på att användning av uttjänta däckmaterial inte är miljöfarligt, medan andra visar på ett möjligt läckage av till exempel metaller och PAH. För de flesta ingående komponenter saknas dock studier. Dessutom har, i vissa applikationer, indikerats en potentiell risk för barn som kommer i kontakt med produkter där däckkomponenter ingår. Om till exempel granulerat gummi används på lekplatser eller i konstgräsplaner är det viktigt att det inte finns någon förekomst av kemikalier eller metaller som utsätter användarna för risker. Detsamma gäller om däcken är direkt i kontakt med miljön. Det krävs därför mer kunskap och riskbedömningar för de olika användningsområdena. Dessutom bör det göras helhetsbedömningar där positiva och negativa aspekter kan vägas samman med hänsyn till ett livscykelperspektiv. En sådan studie kan också användas för att belysa om användningsområdet kan vara mer lämpligt efter att en riskreducerande åtgärd vidtagits respektive vilket användningsområde som är bättre ur risksynpunkt. För att minska hälso- och miljörisker kan också förordningar införas, till exempel för att definiera gränsvärde för specifika ämnen i granulerat gummi.

Europeiska kommissionen utreder för närvarande ett förbud mot användning av granulerat gummi i konstgräs för att minska eventuell miljöpåverkan. Det finns dock lösningar för att minska spridningen av dessa mikroplaster såsom installation av fysiska barriärer runt planen, installation av avborstnings-anläggningar för spelarna eller installation av filter i avloppen för att undvika att gummit kommer ut i ytvattendräneringssystemet. Det finns också ett förslag om att införa anmälningsskyldigheter för anläggningar för alla fyllnadsmaterial som används i konstgräs. Detta skulle göra det möjligt att använda gummigranulat förutsatt att det inte medför några risker för användarna.

Ur ett cirkulär-ekonomiperspektiv bör nya däck utformas och tillverkas på ett sådant sätt så att återvinningsprocessen kan underlättas när däcken börja bli uttjänta. Detta hänger också samman med att förbättra förutsättningarna att skapa bättre kopplingar mellan olika intressenter för att främja en cirkulär ekonomi. Intressenter inkluderar däcktillverkare, potentiella användare av uttjänta däck, liksom entreprenörer eller andra slutanvändare.

Även om det finns många potentiella applikationer för uttjänta däck eller produkter som är baserade på uttjänta däck, finns det många gånger hinder för deras användning. För det första behövs bättre marknadsvillkor och bättre marknadsföring av potentiella applikationer. För det andra krävs det att de potentiella användarna är öppna för att prova nytt och anpassa sig till ny teknik om det behövs. För det tredje behöver även konsumenterna eller slutanvändarna också bli mer öppna med avseende på att våga konsumera den nya produkten. Om det skulle finnas fler standarder för däckbaserade produkter skulle det finnas en möjlighet till ett högre förtroende både för potentiella användare och konsumenter. Standardiseringen av däckbaserade material med specifika fysiska och kemiska egenskaper kan vara ett steg framåt för att öka produktionen av högkvalitativa material eller produkter och därmed även skapa det nödvändiga ökade förtroendet.

Summary

Worldwide, there is a significant increase in tyres consumption, with a global production of tyres achieving 2.2 billion tons in 2019. The situation in Sweden is not different, with the number of tyres for passenger cars sold in 2016 accounting for 2.3 and 2.8 million for summer and winter tyres, respectively. Tyres are mostly composed of natural and synthetic rubber, but also contain steel, carbon black and chemical substances such as vulcanization agents. Tyres' chemical composition is mostly dependent on their function as well as the recipe used by the manufacturing company. At the end of life, tyres needed to be managed accordingly so they do not expose any kind of risk to the environment or human health.

End-of-life tyres are characterized for having unique characteristics, making them a great resource to be employed in multiple applications. Elastic modulus, water absorption, or tensile strength are just some examples of end-of-life tyres characteristics, that make them versatile. Additionally, the European Union highly recommends the development of strategies and processes that promote a Circular Economy. It is well known that when well implemented, Circular Economy practices can lead to several environmental benefits, for instance, the reduction of the number of resources extracted from nature or the reduction of the energy used in the production phase. Therefore, end-of-life tyres can contribute significantly to a more circular economy. This report focuses on analysing end-of-life tyre management in Europe in general and Sweden in particular. It investigates the recycling technologies to manage end-of-life tyres currently available on the market. Furthermore, the expected environmental impacts for EOL tyres, in general, are evaluated. The report is based on a literature review, which is complemented with information obtained through interviews with relevant actors.

In total, more than 3,1 million tons of waste tyres were generated in the European Union (EU28). Approximately 55% were recycled, by being granulated to be used as a raw material. From that, half was estimated to be used as infill artificial turf and 30% to produce rubber tiles. Energy recovery was also a common waste management alternative for 37% of EOL, both in cement kilns, urban heating and power plants. Finally, a small part (3%) was used for engineering purposes, including highway sound barriers and surface structures. The remaining 5 % was unknown. In Sweden, end-of-life tyres were a substantial waste flow, accounting for approximately 85,000 tons per year. In 2020, 65% of EOL tyres in Sweden were used as an energy source for energy production or in the cement industry, 34% were reused or recycled, and 1% was exported.

EOL tyres have multiple unique characteristics that make them versatile and suitable to be used as raw material in several different applications. In the literature we found more than 20 technologies for end-of-life tyres and products application, which were divided into two groups. The first group includes end-of-life tyres recycling. End-of-life tyres can be used whole, cut into pieces (shreds or tyre-derived aggregates), or separated into end-of-life tyre-derived products such as rubber granulates or steel. The applications are multiple. Tyre shreds can be recycled for civil engineering applications, including used as lightweight material, for structural purposes, or as drainage material. The granulated rubber can be used to produce concrete products, in asphalt, as turf in artificial fields, as footwear material, beds for train lines, in noise barriers, outdoor tiles, among other applications. The second group considered energy recovery technologies. In this case, end-of-life tyres are utilized directly as an energy source in industries such as energy or cement production. Additionally, this group also includes the pyrolysis or gasification process, which uses tyres to extract energy products, such as syngas or oils. The energy products can be used to produce energy or as a resource to produce other products.

From the literature review, one can observe that end-of-life tyres components use may reduce the need for the use of several virgin materials. Additionally, energy reduction can also be achieved. Therefore, and when compared to the use of virgin materials, the use of EOL tyre products may contribute to a significant reduction of greenhouse gas emissions, if we consider the whole life cycle. However, the literature analysis on other environmental and health effects is inconclusive. The tyres may contain

hazardous substances and their leaching, bioavailability and toxicity in the different applications has not yet been studied in deep. In literature, some studies have shown results indicating that the use of end-of-life tyres materials do not expose risks for the environment, while others indicate a potential release of metals and PAHs. One of our suggestions is therefore to perform detailed risk assessment studies, for each EOL tyres application, as well as a sustainability assessment showing and evaluating the positive and negative health and environmental impacts. These risk assessments should be performed using a holistic and systemic approach. For example, granulated rubber used in turfs may replace the usage of virgin materials, and with that reduce greenhouse gas emissions from a life cycle perspective. However, playgrounds or turfs are meant to be used by children, so it is necessary to assure that there is no presence of chemicals or metals in levels that expose risks to the users. The same applies if the tyres are directly in contact with the environment. Another solution could be the implementation of scientifically- and risk-based regulations that define limit values for specified chemical substances for some EOL products, such as granulated rubber.

The European Commission is analysing a potential ban on the use of granulated rubber in artificial turfs. However, there are solutions to reduce the dispersion of these microplastics, including the installation of physical barriers around the pitch, installing player "brush down" areas, or installing or retrofit filters to the drains to avoid that the rubber enters the surface water drainage system. A suggestion is the introduction of notification obligations for facilities using artificial grass, to comply with the suggested practices for all the infill materials. These obligations would allow the use of granulated rubber in the artificial field if they do not expose any risks to the users.

From a circular economy perspective, new tyres should be designed and manufactured in a way that facilitates reuse or recycling processes at their end of life. A suggestion, to promote a circular economy, is a better link between the stakeholders. Stakeholders include tyres producers, end-of-life tyres potential users, as well as contractors or other final users.

Even though there are many potentials applications for end-of-life tyres or derived products, many times there are barriers that seem to hinder their use. Firstly, a better branding of potential applications is necessary for the future. Secondly, that the potential users are open to try new resources and adapt to new technologies if necessary. Thirdly, that the consumers or end-users are also opened to use the new product. If more standards for tyre-derived products would be available, there could be a possibility of a higher acceptance both from the potential users and from consumers. The standardization of tyre-derived materials with specific physical and chemical characteristics could be a step forward to increase the production of high-quality materials or products. However, there is also a need for more comprehensive risk assessment for each EOL tyres application, that evaluates both the positive and negative aspects.

Foreword

This report presents the results of a project funded by the Swedish Environmental Protection Agency regarding possible techniques for tyre recycling and the environmental impact of these technologies. The report includes an assessment of opportunities for increased recycling of end-of-life tyres, both mechanical and chemical recycling and its environmental effects. The project included:

- description and a review of recycling methods for end-of-life tyres
- identification of the effects on the environment of the different recycling methods in accordance with the Regulation (1994:1236) on producer responsibility for tyres in an environmentally acceptable way
- identification of the recycling of end-of-life tyres by other EU countries.

The work has been carried out partly through literature studies and partly through interviews with the industry and other relevant actors. A big thank you to everyone who has participated in interviews. We would also like to thank you for the comments made by the examiners and also for the other valuable comments we have received on the report in connection with the investigation procedure.

Gothenburg, November 2021

Yvonne Andersson-Sköld
Project leader

Granskare/Examiner

Dr. Tommy Edeskär, Luleå Universitet och GeoSkills AB, Prof. Ann-Margret Strömvall, Chalmers tekniska högskola

Glossary

PAHs - Polycyclic aromatic hydrocarbons

PM - Particulate matter

NO_x - Oxides of nitrogen

SO_x - Oxides of sulfur

HC - Hydrocarbon

CO_2 - Carbon dioxide

CO - Carbon monoxide

EOL - End-of-life

EU - European Union

EPR - Extended Producer Responsibility

REACH - Registration, Evaluation, Authorisation and Restriction of Chemicals

Innehållsförteckning

1. Introduction

In 2019 the global tyre production was estimated to be 2.2 billion tons with an expected volume to reach 2.7 billion tons in 2025 (Research and markets, 2020). These tyres were mostly used in passenger vehicles, but can also be found in trucks, buses, heavy machinery, among others. Considering the Swedish market, sales of number of tyres for passenger cars in Sweden in 2016 accounted for 2.3 million summer tyres and 2.8 million winter tyres (Däckbranschen, 2021). Depending on the type and frequency of use, tyres have different lifespans and at the end of the lifespan, they will be eventually disposed of as waste. In Europe, passenger vehicle tyre is designed to last between 40,000 to 50,000 km (Prielli, 2021).

The tyre composition can vary depending on the type of tyre as well as on the tyre producer. Car tyres are mostly composed of synthetic and natural rubbers, accounting for 24.1% and 18.2% respectively, both including chemical additives. Carbon black, a fine black powder essentially composed of elemental carbon, (19%), coated steel wires (11.4%), precipitated silica (9.7%), oil (6.1%), textiles (4.7%), zinc oxide (1.6%), sulfur (1.3%), stearic acid (1%), and recycled rubber (0.5%) are other main tyre compounds (Piotrowska et al., 2019). Additionally, there might be other components such as vulcanization agents that may contain traces of lead and cadmium oxides (USEPA, 2019).

After the usage phase, and when tyres are no longer suitable to be used on a vehicle any longer, tyres become EOL tyres. Waste tyres are a large waste flow in Sweden, which corresponds to approximately 90.000 tons of tyres per year (Svensk Däckåtervinnings, 2021a). Additionally, there is an increase in the consumption of tyres, which will also lead to an increase in the EOL tyres that need to be managed. Thus, it is important to identify waste management solutions that are environmentally efficient and sustainable. In Sweden, approximately 60% of EOL tyres were used as an energy source for energy production or in the cement industry, 22% were reused as blasting mats, 17% used for material recycling, and 1% were exported (Ragn Sells, 2021).

Extended producer responsibility is the most popular model for managing waste tyres in Europe (Winternitz et al., 2019). In this model, the management of the waste tyres is the responsibility of producers and importers that put the tyres on the market. The approach has been very successful reaching at times percentages around 100% of tyre collection. Sweden was one of the first countries to adopt this management system back in 1994 under the national regulation (1994:1236).

We are also reaching a point, that circular economy is becoming a fundamental topic to be considered when wastes are being managed. In November 2020, Naturvårdsverket was commissioned by the government to identify and propose measures to increase material recycling of EOL plastics, including EOL tyres (M2020 / 1898). Circular economy practices can lead to several environmental gains, for instance, the reduction of the amount of resources extracted from nature or the reduction of the energy used in the production phase. Therefore, innovative high-efficiency processes to manage EOL products present a crucial priority for the European market.

Nevertheless, there are also some concerns about using EOL tyres. The main discussions have been on the tyre's materials content as well as the potential spread of microplastics into the Nature. For example, the European Union (EU) is discussing a ban, in which granulated rubber cannot be used in artificial fields. This is motivated by the fact that these compounds are perceived as problematic for the environment and specific ecosystems. At times microplastics end up in the wastewater systems, and eventually in aquatic ecosystems. However, there is also the possibility to implement solutions to reduce the amount of rubber dispersed into the environment.

This report aims to analyse EOL tyre management in Europe and Sweden in particular. Additionally, the report investigates the recycling technologies available in the market to manage EOL tyres. Furthermore, the expected environmental impacts for EOL tyres, in general, are investigated. The report is written based on a literature review, as well as short interviews with relevant actor's such as universities, research institutes, companies, and other institutions.

The remainder of the report is structured as follows: Section 2 presents state of the art regarding waste hierarchy in Circular Economy. Section 3 presents common tyre composition as well as substances of concern. In Section 4, the state of EOL tyre management for Europe is analyzed, with particular focus on the situation in Sweden. Currently available reuse and recycling techniques are presented in Section 5. Environmental impacts are presented in Section 6. Finally, the report finishes with a Discussion chapter (Section 7) and a conclusions chapter (Section 8).

2. Waste hierarchy in Circular Economic

Circular Economy has gained a lot of attention as a concept to improve the environmental performance of goods, services, infrastructures, among other systems. It is a relatively new concept that has been developing through the years. In (2018) Reike et al. performed an extensive literature review, and presented a framework that summarizes Circular Economy strategies, which is an evolution of the 3R-imperatives of "Reduce, reuse, recycle". The new framework is composed of a 10R topology and is presented fully in Supplementary Table 1. Campbell-Johnston et al. (2020) adapted the framework to EOL tyres, and selected 8 circular economy strategies, which are presented in Figure 1, and described in this section.

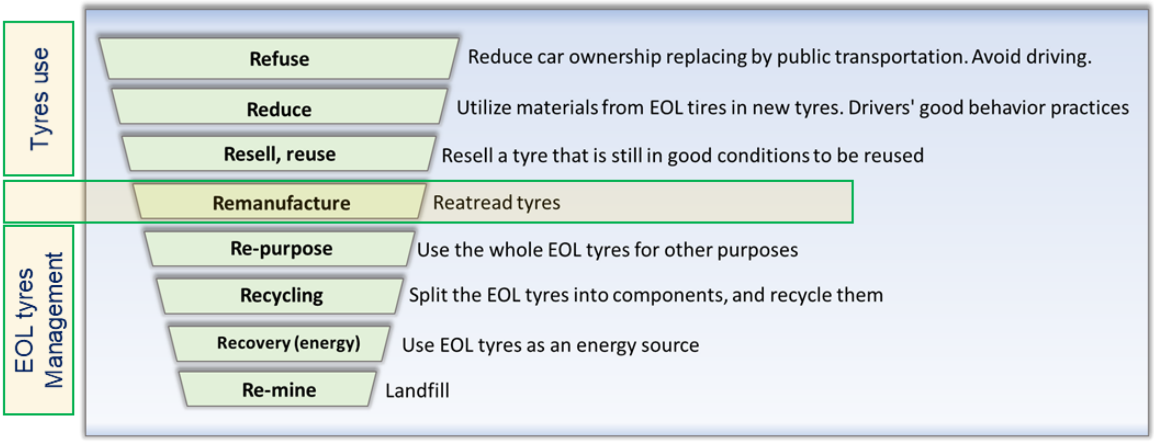

Figure 1. Hierarchy of Circular Economy options for EOL tyres adapted from (Reike et al., 2018) and (Campbell-Johnston et al., 2020)

Before entering the EOL phase, many strategies can be applied to reduce tyres environmental impact. In Figure 1 the first four strategies are closer to the consumers. The first strategy "*Refuse*" implies the reduction of tyres usage by utilizing alternatives to car ownership such as public transportation or car sharing. The second strategy ("*Reduce"*) can be applied to both consumers and tyre manufactures. Tyre consumers can extend the use of lifespan of the tyres, by inflating the tyres properly, checking the alignment of the tyres, rotating the tyres regularly, inspecting the wheel and suspension components, and avoiding rough terrains (Truebil, 2021). Additionally, the consumer should choose durable tyres. The producers can apply different strategies to reduce the environmental impact of production, such as recycling materials from EOL tyres in the production of new tyres or utilizing green energy sources. Additionally, the production of durable tyres also plays a very important role. One must have in mind, that all the materials used in tyre manufacture, will as well affect all the implementation of EOL tyres management strategies. For example, if the manufacturing industry uses toxic chemicals, the EOL tyre might not be possible to use as raw material in the production of kids' playgrounds tiles.

The "*Remanufacture*" strategy, is right in the border between the usage and EOL phase. For tyres remanufacture is represented by tyre retreading. Retreading is simply the reconstruction of an old tyre. It saves many resources and energy, and the tyre can be used again. It is at this stage that we leave the usage phase, and we enter in the EOL of tyres management phase, which starts with "*Re-purpose*" strategy. This consists of using the entire end-life tyre, without any chemical or mechanical transformation. This is a common practice in the application of tyres for civil engineering purposes, such as soil stabilization. Other examples can be to use whole EOL tyres in racing tracks or swings. "*Recycling*" is the next strategy. Here the EOL tyres are mechanically or chemically transformed, and the obtained materials are recycled or reused. One example is the gridding process, which splits the tyre into rubber, steel, and textiles fibres. "*Recycling*" is followed by "*Energy recovery*". EOL tyres have high energy content and can be used as an alternative fuel. Finally, the last strategy is "*Landfill*", which in many countries is not an option anymore.

It is important to highlight that, in theory, and from a circular economy perspective, strategies that are placed at the top of the hierarchy should be prioritized. However, it is also very important to have a systemic approach, to analyse and understand the implications of the implementation of a specific strategy. Particularly the impacts of that strategy may have in other systems. There could be situations that a strategy that is placed at the top of the hierarchy may have a higher environmental impact when compared to a strategy that is at the bottom of the hierarchy. Therefore, it is important to analyse the different alternatives that are available to manage end-of-life tyres. The successful implementation of Circular Economy concepts and strategies requires the involvement and collaboration of several different stakeholders, including consumers, industries, policymakers, etc. (Selman, 2000).

2.1. Remanufacturing – Retread

It is important to clarify that retreading technology is not part of EOL tyres management. However, it is a technology that may have a contribution in reducing the number of EOL tyres. Therefore, the authors found it important to include this technology in the report, as a strategy to improve material circularity and reduce waste generation.

Retread allows that the tyre serves the same function that it has been designed from the beginning. The reformulation of the tyre must be performed with a cautious process, regulated by specific technical standards (UN ECE Regulation 108 for cars and UN ECE Regulation 109 for commercial vehicles). Tyre retreading uses the structure of an old tyre. The first steps consist of testing if the EOL tyre can be used for retreading purposes. Not all EOL tyres can be used, mostly due to structural feature problems. After the tyre is selected, the tyre is polished, a layer of buffer rubber is pasted, and then the tread rubber is further pasted. The process is finished with vulcanization (Qiang et al., 2020).

There are two techniques for retread: hot retreading and pressure "cold" retreading. Hot retreading involves the vulcanization of a tyre in a mould at a temperature of around 150 °C. This technique is suitable for all tyre types, but a separate mould is required for each tread and size. This technique requires high investment costs. Cold retreading involves vulcanization without a mould at a temperature of between 95 °C and 110 °C. Less investment is required (Aircrafttyres, 2021). Cold retreading can be used for truck tyres, but not for car tyres.

When compared to the production of a new tyre, tyre retreading uses 70% less new material and 80% less energy (European Commission, 2015). Additionally, it is considered a practically waste-free process. The main by-product obtained is pulp rubber, which can be used in the construction industry to produce polymer composites (Sienkiewicz et al., 2012). Tyre retreading is more common among truck tyres. This is explained by the fact that it needs lower investment costs (cold retreading technique), and because it has been a common practice among tyre truck users for many years. According to a study performed by ETRMA retreaded tyres represented 37% of all the truck tyres sold in France, Italy, Germany, Spain, and the United Kingdom in 2010. However, this value decreased to 30% in 2015, mostly due to high competition for imported tyres. The same report also highlights that a retreaded tyre supports 4.3 times as many jobs as a non-retread imported tyre (ETRMA, 2016). The situation in Sweden is not different with the number of retreading companies being reduced from a maximum of 50 to a little bit more than 10 in 2019 (Däckdebatt, 2019). According to BIPAVER (Retread industry's trade association), the reduction of the number of retreaded tyres has three main reasons: difficulties to compete with new tyres with lower quality and cheap prices; public acceptance of used products in general, and; lack of a tyre retreading label so that previous reservations can be invalidated.

A premium truck tyre can be retreaded up to 2 times. The same does not apply to new tyres with low quality, which most of the time cannot be used to be retreaded. Therefore, if the new tyres market would be mostly composed of low-quality tyres, the retread process would not be possible to be performed. Therefore, eco-design plays an important role in retreading because a tyre cannot be reused if it was not initially designed for retreading. It seems very important to have more links between tyre manufacturing and retreading industry so that they can collaborate more in the future.

One of the main challenges of the retreading industry is that historically retreaded tyres have a reputation of being a lower quality product (Azemi & Lindblom, 2016). However, this is not necessarily true. To be accepted for retreading, a tyre must be of good quality. As stated before, tyres with low quality cannot be retreaded. Also, the current technology ensures that the retreading process will assure a quality very similar to the quality of a new tyre. To overcome this problem, it seems fundamental to develop a retreading label, that would assure more trust from the consumer side. Additionally, it seems also fundamental to create an understanding for the consumer, that retreaded tyres are safe and can save a lot of resources and energy. From a circular economy perspective and to close the material loops, there would be a benefit if more EOL tyres would be retreaded. Therefore it is important to create links between tyre producers and recyclers so that tyres can be easier to remanufacture (Campbell-Johnston et al., 2020).

According to BIPAVER (Retread industry's trade association), it is important to study some strategies that may increase the number of retreaded tyres in the future, including: Municipalities to act as role models, with minimum retreading quotas in vehicle fleets such as public services transport, public transport; Introduction of a tyre label for retreaded tyres; Constructive design for a "multi-life strategy" for the new tyre manufacturer; Consistent transfer of the legal framework on the new tyre side to retreads; or; Financial incentives for retreaded tyres user. Therefore, the tyres retread in Sweden should be the subject of detailed analysis in the future to evaluate possible contributions for material circularity. These future studies should as well analyse other important variables, such as: what is limiting the retreading market in Sweden; why consumers prefer new tyres instead of retreads; the safety of retreads in comparison with new tyres, or; fuel consumption of vehicles using retread tyres in comparison to a new tyre.

3. Tyres composition and substances of concern

Natural and artificial rubber are the main components of tyres. Other major components include steel and textile (styrene-butadiene rubber). Additionally, tyres contain a broad range of components and additives, namely filler systems (carbon black, clays, silicas, calcium carbonate), stabilizer systems (antioxidants, antiozonants, waxes), cross-linking agents (sulfur, accelerators, activators) and secondary components such as pigments, oils, resins and short fibres (Halsband et al., 2020). Other chemical components may be found such as Polycyclic aromatic hydrocarbons (PAHs), phthalates, sulfenamides, guanidines, thiazoles, thiuams, dithiocarbamates, sulfur donors, phenolics, phenylenediamines, and heavy metals as summarised in (Halsband et al., 2020). In a study by Cheng et al. (2014) it was found that tyre rubber granulate may contain heavy metals and organic contaminants that leach into percolating water posing a potential risk to the environment and human health (Cheng et al., 2014). Several of the chemical components of tyres have also been found in their leachates (Seiwert et al., 2020)as well as in the run-off, storm water and sediments in the road environment where tyre wear is a likely source (Björklund et al., 2009; Järlskog et al., 2021; Polukarova et al., 2020). A recent study also identify, and show toxic concentrations, of substances such as 6PPD-quinone in road runoff (Tian et al., 2021).Tyres composition is mostly dependent on the type of application. For example, passenger cars have higher amounts of synthetic rubber, truck tyres have a higher percentage of natural rubber, and tyres used in heavy-duty vehicles do not contain synthetic rubber in their composition (Grammelis et al., 2021). Likewise, the tyre composition differs between winter and summer tyres and on the manufacturing company. Tyres may therefore contain potentially hazardous compounds, and it is of importance that they are managed correctly.

Table 1 gives an overview of the elements and compounds classified as hazardous waste by Basel convention in tyres. Zinc is the main metal of concern, found in the form of Zinc oxide at a level around 1 to 2%. Zinc oxide is not generally considered a toxic metal. However, due to the high concentrations of this compound in tyres, there is a risk for potential soil and water contamination. Heavy metals oxides such as cadmium, lead, and arsenic are found at low levels (<0.005%w). Some mineral oils used as plasticizers may contain polycyclic aromatic hydrocarbons (PAH). PAH contains a large group of hydrocarbons, which are not fully investigated, but some are known to have carcinogenic effects. In the EU there has been a significant reduction in the amounts of carcinogenic PAH compounds in tyres (Edeskär, 2006). This was a consequence of the ban of certain chemicals in the manufacture of tyres in Europe. This ban was introduced by REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) following entry no. 50 of Annex XVII, Regulation (EC) 1907/2008. The regulation included a restriction on the use of 8 PAHs in tyres and extender oil, which sum cannot be higher than 10mg/kg.

Table 1. Elements and compounds classified as hazardous waste by Basel convention in tyres (UNEP (2000))

Constituent	***Remarks***	***Content (% weight)***
Copper compounds	Alloying constituent of the metallic reinforcing material	~ 0.02
Zink compounds	Zinc Oxide, retained in the rubber matrix	~ 1
Cadmium	On trace levels as Cadmium compounds attendant substance of the Zinc Oxide	Maximum 0.001
Lead/lead compounds	On trace levels, as an attendant substance of the Zinc Oxide	Maximum 0.005
Acidic solutions/acids in solid form	Stearic acid, in solid form	~ 0.3
Organohalogen compounds	Halogen butyl rubber (tendency: decreasing)	Maximum 0.1

4. EOL Tyres in Europe and Sweden

This chapter provides an overview of the waste management practices for EOL tyres in Europe and Sweden in particular.

As with many other wastes, EOL tyres management in Europe has registered very significant improvements. This is the result of the collaboration of the actors involved in the whole tyre life cycle, as well as the specific legislation by the commission. One of the turning points happened 1999 (Council Directive 1999/31/EC) when the commission banned EOL tyres landfill with effect from 2003. In Supplementary Table 2, one can see a historical overview of the European legislation concerning the treatment of EOL tyres management.

In Europe, there are three models to regulate and improve supervision of EOL tyre management namely: Management model based on Extended Producer Responsibility (EPR), Tax system, and free-market system (ERTMA, 2010). The most popular model is the Extended Produced Responsibility (EPR) which has been implemented in 21 of the 28 EU member states, including Sweden (ETRMA, 2017). In this model, the management of used tyres is the responsibility of the producers and importers who put the tyres on the market. The management should ensure the legally required levels of recovery and recycling of these wastes (Sienkiewicz et al., 2012). This model is acknowledged to have helped the improvement of the management of EOL tyres in Europe. Figure 2 shows a historical overview of the waste management practices for EOL tyres in Europe. As can be seen in Figure 2, landfilled EOL tyres were reduced from 49% in 1996 to approximately 5% in 2011.

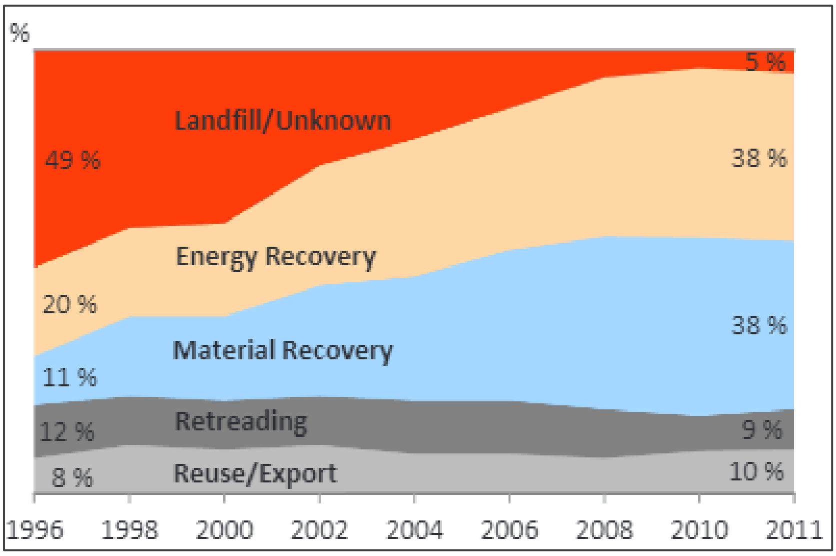

Figure 2. Evolution of used tyres recovery routes in Europe (ETRMA, 2015)

In Figure 3 data on EOL tyres management by country in Europe compiled by European Tyre & Rubber Manufacturers Association (ETRMA) for 2019 is presented. In total, more than 3,1 million tons of waste tyres were generated in the EU28. Approximately 50% (1.5 million tons) were recycled, by being granulated to be used as raw material for different purposes. From this, half was estimated to be used as infill artificial turf and 30% to produce rubber tiles (Verschoor et al., 2021). Energy recovery was also a common waste management alternative for EOL tyres in Europe, with approximately 39% of the total EOL tyres (1.2 million) tons received, both in cement kilns (75%) and urban heating and power plants (25%). Finally, a small part (2%) was used for engineering purposes, including highway sound barriers and surface structures. From Figure 3, one can see that most of the countries have similar EOL tyre management. There are some exceptions, such as Finland, Denmark and Belgium. In Finland, most of the EOL tyres were reused in civil engineering, including the use of shredded tyres for highway sound barriers and surface structures at landfill sites (Tana, 2021). In Denmark, the tyres were granulated or sent for pyrolysis (Daekbranchens Miljoefond, 2021). In

Belgium, most of the tyres were recycled, and the granulated rubber was used in artificial fields and rubber tiles (Recytyre, 2021).

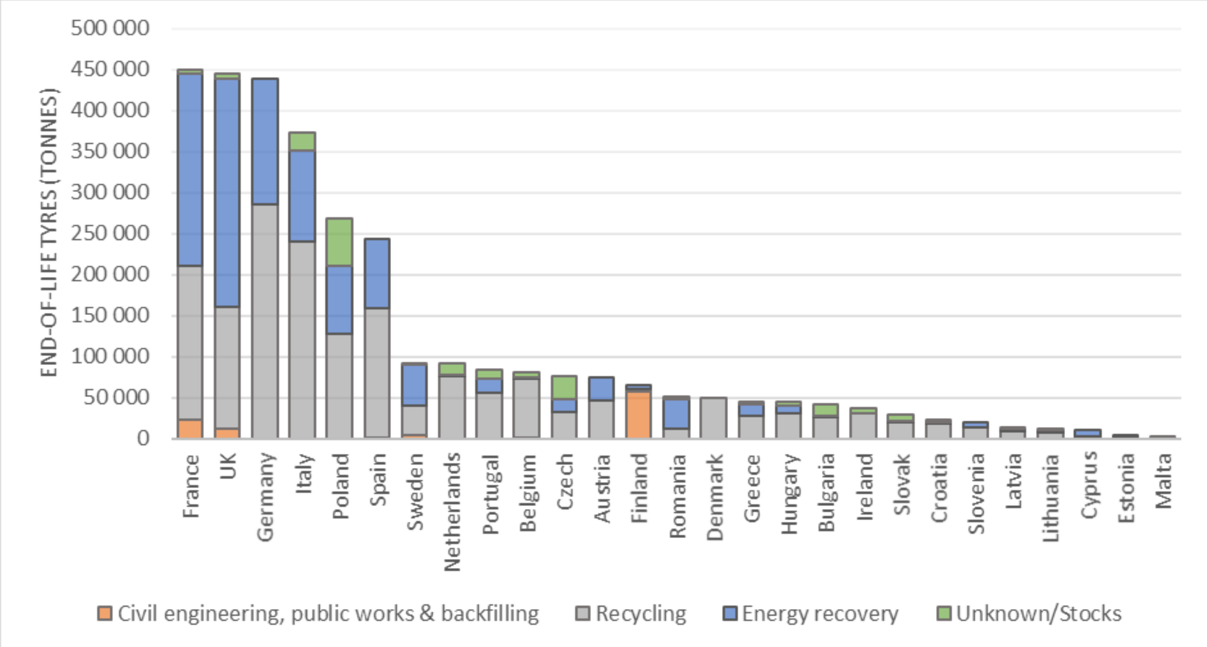

Figure 3. EOL Tyres Management in EU28 in 2018 (based on ETRMA data)

In Sweden, the entity responsible for collecting and managing EOL tyres is Svensk Däckåtervinning. The entity was established in 1994, under the national regulation (1994:1236). Before that EOL tyres were mostly sent to landfill (Naturvårdsverket, 2020). After the establishment of Svensk Däckåtervinning, EOL tyres recovery rates have rapidly increased to values close to 100% (Svensk Däckåtervinning, 2021b). In 2020 there were a total of 84,574 tons of EOL tyres generated in Sweden, according to the Svensk Däckåtervinning statistics (Svensk Däckåtervinnings, 2021d). From that, 41% (35,053 tons) of the EOL tyres were used as an energy source in the cement industry and the ashes and steel were thereafter used as raw materials for cement production. Approximately 24% (20,427 tons) of the EOL tyres were as well used as an energy source but in coal burners of thermoelectric power stations to generate energy. Therefore, in total 65% of EOL tyres were used as an energy source. Considering that the exportation of EOL tyres represents approximately 1% (982 tons), 34% of the EOL tyres were therefore reused or recycled. It includes 9% (7,290 tons) re-used to produce blasting mats, 1% (883 tons) recycled and used has granulated rubber, and the remaining 24% (19,939) recycled in other ways. It is important to clarify that retreated tyres are not considered in these statistics. This is explained by the fact that most of the retreaded tyres are not accounted for as EOL tyres. A scheme with EOL tyre management for Sweden can be found in Figure 4.

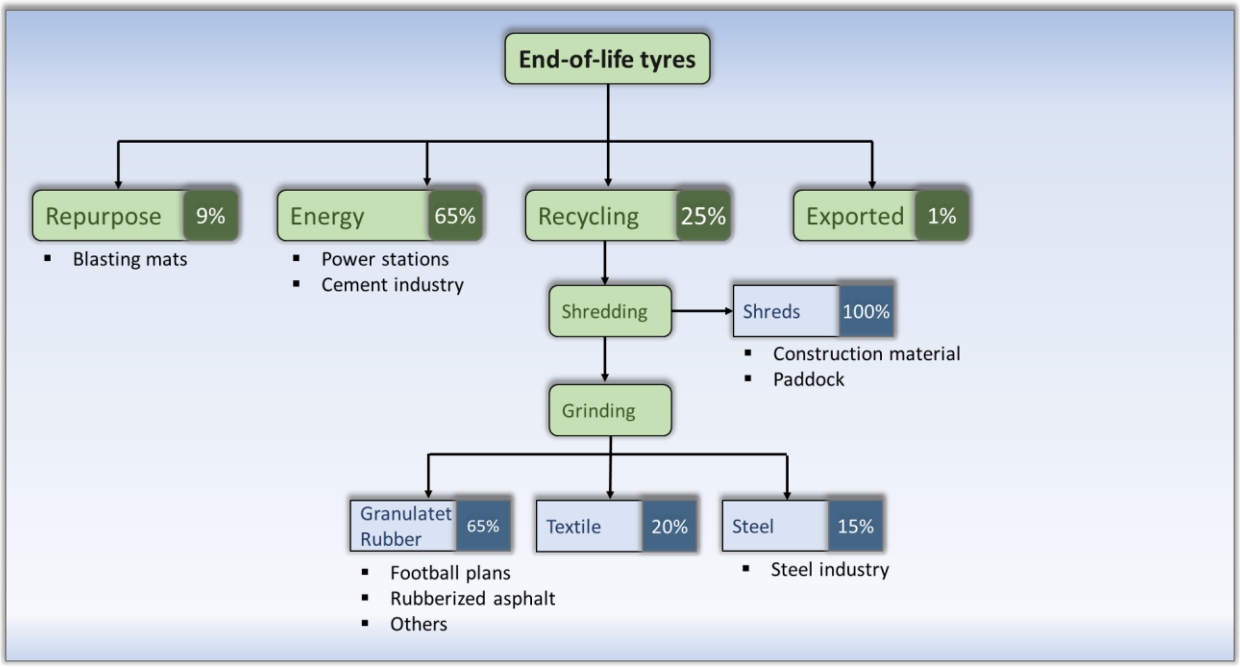

Figure 4. Handling of end-of-life tyres in Sweden - based on Svensk Däckåtervinning statistics for 2020 (Svensk Däckåtervinnings, 2021d) (note: in figure 3, blasting mats are included in recycling)

EOL waste management in Sweden has registered some changes in the last 5 years (Figure 5). The main change can be found in the use of granulated rubber, that from 2016 to 2020 there has seen a significant usage decrease, from 13% (10,521 tons) to 1% (883 tons) respectively. According to Svensk Däckåtervinning this is mostly due to the reduction of granulated rubber used in artificial fields, which is justified with a negative connotation that these materials might be a source of microplastics spreading to the environment (Svensk Däckåtervinning, 2021b). On the other hand, the number of tyres used as an energy source registered an increase, from 52% in 2016 to 65% in 2020.

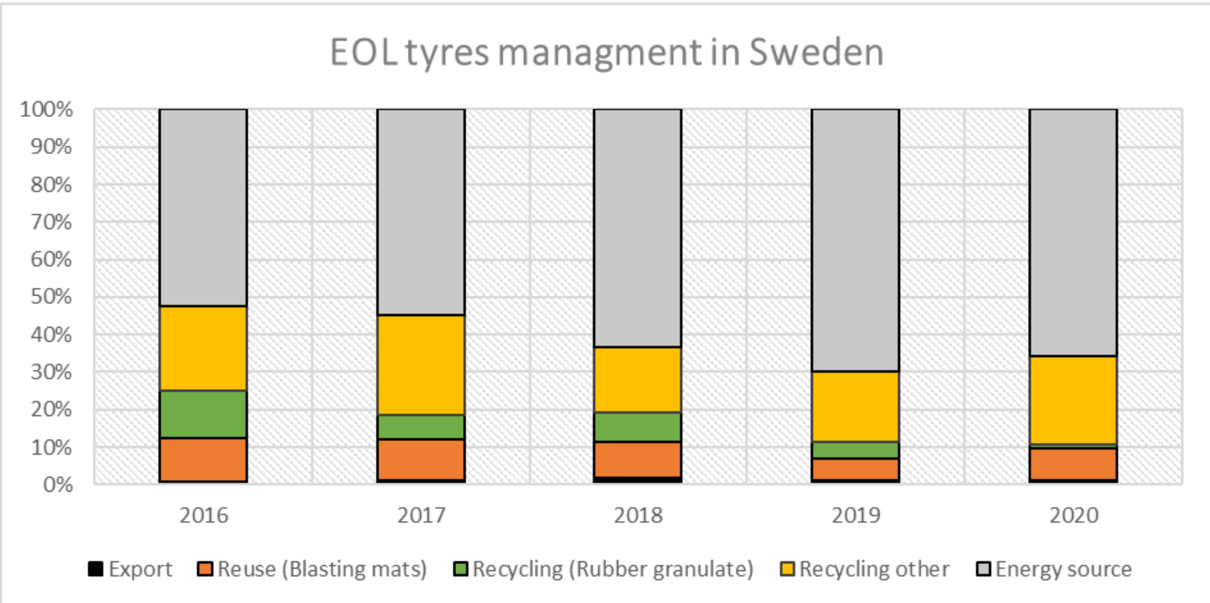

Figure 5. Management of end-of-life tyres in Sweden between 2016 and 2020 - based on Svensk Däckåtervinning statistics (Svensk Däckåtervinnings, 2021d)

5. Currently Available Reuse and Recycling Technologies

EOL tyre reuse and recycling possibilities are manyfold. In this section, an overview of the available reuse and recycling technologies is presented, based on a literature review. The technologies descriptions can differ in depth. This is just dependent on the information available in the literature and does not mean that alternatives with more information should be prioritized. The technologies are divided into two main categories, namely: material recycling and, energy recovery. Figure 6 gives an overview of the technologies described in this study, as well as the obtained products and the potential product applications.

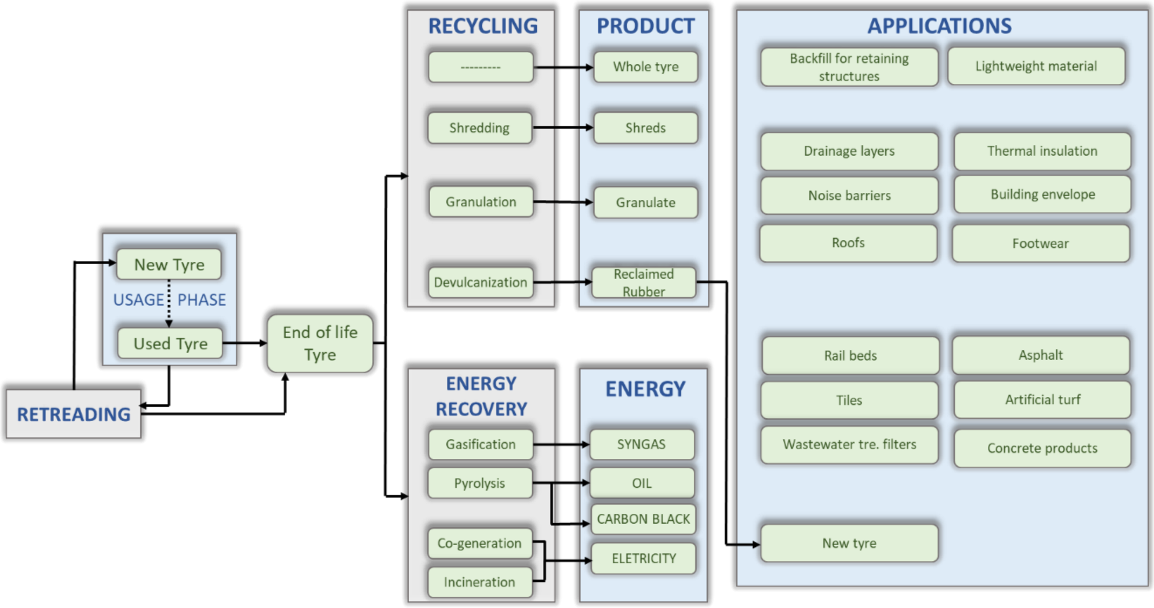

Figure 6. Waste management alternatives for EOL tyres

5.1. Product recycling

EOL tyres recycling is a challenging process. This is mostly explained by the fact that tyres are a complex material composed of multiple compounds. The presence of various additives and the complex crosslinked structure make their reprocessing difficult (Fazli & Rodrigue, 2020b). However, due to EOL tyres characteristics, there are multiple recycling applications available in the literature. Tyre recycling has several application alternatives. A simpler application is to recycle the EOL tyre in its original form or modified into shreds. In this alternative, the tyre is mostly used for engineering applications. A second alternative is to recycle the tyres into main components and thereafter utilize them as raw materials in multiple industrial processes. However, one has to have in mind, that the process of recycling tyres, and in particular rubber can be considered difficult, mostly due to the three main reasons (Lapkovskis et al., 2020):

- the presence of a three-dimensional network formed during vulcanization;
- the variety of formulations of rubber compound;
- the complex structure of rubber products.

5.1.1. EOL Tyre derived products

Product recycling consists of using the tyre in its original form or mechanically/chemically modified into smaller components. Shredding consists of cutting the tyre into smaller parts (50 – 300 mm). The shredding process results in the exposure of steel belt fragments along the edges of the tyre shreds (Edeskar, 2006). The process can be composed of a one or two-stage processing process, that depends on the size of the shred that aims to be obtained. Shreds can also be denominated as Tyre Derived Aggregates (TDA). There are two types of TDA, Type A with a maximum size of 75 mm and Type B with a maximum size of 305 mm (Scraptirenews, 2021). Table 1 presents the designation for sizes of processed tyres in Europe as well as in the USA.

Table 2. Designation for sizes of processed tyres in Europe and USA (Birkholz et al., 2003)

prEU 1423:2004 (Europe)		**ASTM D 6270-98 (USA)**	
Designation	**Size**	**Designation**	**Size**
Fine powder	<500 µm	Ground rubber	425 µm -2 mm
Powder	<1 mm	Granulated	425 µm -12 mm
Granulate	1-10 mm	Chip	12-50 mm
Chip	10-50 mm	Shred	50-305 mm
Shred	50-300 mm	Rough Shred	50*50*50<X<762*50*100

5.1.2. Material Recycling – Grinding

The main goal of the grinding process is to cut the tyres into small pieces to produce granulate rubber. The process aims at separating the rubber from the metal and fabric components of the tyre. In this process, there is no complete decomposition of the polymers, which makes it possible to preserve the valuable properties of the elastomers rubber (Lapkovskis et al., 2020). The obtained granulate rubber has multiple applications, including being used as turf in an artificial field or to be used as raw material for cement production. There are two main mechanical granulation methods, normal temperature, and cryogenic temperature. The biggest difference between the technologies is the size and shape of the individual pieces of rubber, which can have an impact on the type of use of the obtained rubber. The gridding technology to be used is therefore largely dependent on the type of application of the end products.

Mechanical grinding at normal temperature

There are multiple mechanical grinding technologies, including abrasion, compression, cutting, and impact (Lapkovskis et al., 2020). It is a multi-step process that mostly uses a series of granulators and cracker mills. Metals are separated from the rubber using magnets and fibres are separated using air separators. The final granulate rubber has approximately 0.3 mm in size. The obtained rubber has rugged edges, which among other applications, makes it ideal to be used in rubber-modified asphalt, due to more surface area to bond to the asphalt (Ecogreenequipment, 2021). The use of recycled tyre rubber in asphalt pavements is increasing due to its properties such as reducing the permanent deformation of flexible pavements and enhancing the resistance to rutting, reducing pavement construction and maintenance costs, and improving the resistance to fatigue damage (Alfayez et al., 2020).

Mechanical grinding at cryogenic temperature.

This method uses liquid gases to freeze the rubber. Liquid nitrogen is the most common liquid gas used, but there are other alternatives such as liquid carbon dioxide. Thereafter the rubber is shattered as it passes through a hammer mill. The final rubber has a rather uniform texture because it breaks along smooth lines. Compared to normal temperature grinding, cryogenic grinding benefits from a higher production rate and lower milling energy consumption (Fazli & Rodrigue, 2020a). The method also includes the absence of thermal or oxidative destruction, fire and explosion safety, and the high efficiency of the separation of metal and textiles from granulate rubber (Lapkovskis et al., 2020).

One of the main challenges of griding recycling technologies is the quality of the obtained textile fibres, which in most cases are contaminated with rubber. At the time, there is no feasible process that allows the obtention of a pure product, economically and qualitatively usable. Additionally, there is a lack of information on the composition of the textile fibres, as well as a market that justifies the effort to purify them. Therefore the most common final destination of the textile fibers is incineration (Landi et al., 2016).

Material recycling –Chemical Processing – Devulcanization

This process aims to produce devulcanized rubber that can be mixed with virgin rubber, without generating a significant decrease in mechanical and physical properties. The devulcanization process causes the selective breakup of the sulfur-sulfur (S-S) and carbon-sulfur (C-S) chemical bonds without breaking the backbone network and without degrading the material (Asaro et al., 2018). The process must be preceded by one of the grinding processes described above. The devulcanization technologies are still under development, and more research is needed.

5.2. Recycling materials applications

5.2.1. Backfill for retaining structures (Whole tyres and shreds)

Tyre bales are used in civil engineering. Tyre bales are composed of EOL tyres compressed into a rectangular shape. Usually, they have around 100 tyres and weigh about 1 ton. Tyre bales are mostly used when unstable conditions exist, and they replace materials such as query aggregate, gravel, or gabion baskets. They work as reinforcement elements. Examples of tyre bales applications include road sub-base, construction of breakwaters and dams, or river and stream banks (Hylands & Shulman, 2003). Tyre bales are particularly important in areas with poor soil conditions. The application of tyres as a structural material is not limited to tyre bales. Whole tyres or even tyre shreds or granulated rubber are also common materials used (Figure 7). They are usually mixed with construction materials such as gravel and sand. There are many advantages including frost resistance, insulation, stabilization, or drainage.

The shreds can also be used to build cellular embankment structures. These are walls or banks of stone build to hold a structure. To achieve the desired mechanical characteristics, these structures are filled with different materials, and one possibility is tyre shreds mixed with sand. An example of application is the use of tyre shreds in rockfall protections embankment designed to dissipate the energy of a falling rock block (Hennebert et al., 2014). Hennebert et al., 2014 performed a study, in which they analyze the environmental impact of these structures when containing tyre shreds. They have concluded a significant release of zinc, total hydrocarbons, and aniline. However, the concentrations measured in the laboratory rapidly decrease, and concentration limits, set for road applications, were not exceeded. The most critical issue is related to the post-fire environmental impacts of the tyre shreds and sand mixture. According to the authors, fire is not a direct threat to the embankment structure itself. But the tyre shreds and sand mixture should be correctly managed in the EOL phase. The authors conclude that shredded tyres mixed with soil to build embankments will have a limited impact on the environment.

5.2.2. Lightweight material in road construction (Whole tyre and shreds)

Tyres shreds can be used as lightweight material due to the low bulk density. The tyre shreds are inexpensive lightweight materials when compared to conventional backfill aggregates (Birkholz et al., 2003). Additionally, shreds have good thermal insulation, good drainage/hydraulic conductivity, and are compressible. They can be used in a wide variety of engineering projects, including retaining structures in embankments, backfill to integral bridge abutments, or slope repair and stabilization (Hylands & Shulman, 2003). One of the most common applications is to use tyre shreds to reduce the weight of the road embankment to reduce settlements in the substrate (Birkholz et al., 2003). The aim is to reduce the overall ground pressure and therefore reduce the settlement and the risk of slope and foundation failure (Hylands & Shulman, 2003). The application can also be performed using whole tyres. A good example can be found in the USA, in which a company called Mechanical Concrete uses whole tyres as a foundation for roads. These geocilinders are filled with other construction materials. The advantages of using these cylinders include the reduction of risk of collapse, retaining wall facing, and reduced rutting. Some disadvantage is the potential leaching risk (further discussed in Section 6).

5.2.3. Blasting mats (Whole tyres)

Blasting mats can be defined as a heavy carpet manufactured with truck tyres bound together with ropes, cables, or chains. The main purpose of this product is to contain fly rocks that happen after an engineered blast. The use of blasting mats is widespread in Sweden. An important aspect of this application is that if EOL tyres would not be used, a virgin material would be needed (Andersson and Diener, 2020).

5.2.4. Drainage layers (Shreds)

Tyres shreds have good draining properties and therefore can be used as raw material. Shred tyres drain 10 times better than well-graded soil and provide 8 times better insulation than gravel (ETRMA, 2010). For example, drainage shreds may be used in landfills for drainages purposes. However, in that case, water the leaching properties must be considered. Low pH tends to increase leaching of metals and alkaline condition results in increased leaching of organic compounds. Additionally, zinc and phenols need to be considered under neutral pH conditions (Edeskar, 2006).

5.2.5. Thermal insulation purposes (Shreds and rubber granulates)

Shred tyres are known to have low thermal conductivity. This makes this material a good option to be used as a thermal insulation material to limit frost penetration, and frost heave inroads. Thermal insulation applications include road and street structures, fill in pipeline construction, or fill for housing (Hylands & Shulman, 2003). Materials that would be replaced if this technology is used include expanded polystyrene or lightweight clay aggregate.

5.2.6. Noise barriers - Soundproof glazed screens (Shreds, rubber granulates and textile fibers)

There is extensive research on using EOL tyres as a resource to produce durable noise reduction barriers. These new technologies have been using whole tyres and shreds. Additionally, granulated rubber can also be used to produce mats that can be implemented as absorption media in noise-reducing walls (Hylands & Shulman, 2003). There are some examples of companies that already use this technology. For example, in the Czech Republic, mmcité+ produces walls to fix along railways or highway infrastructure to reduce vehicle noise using EOL tyres. With 4 tyres is possible to produce one square meter of noise-reducing wall.

Figure 7. Examples of EOL tyre recycling options (Retaining structure and rubber asphalt)

5.2.7. Rubber in concrete (Rubber granulates)

Tyre rubber can be seen as a partial substitute for aggregates in high-performance concrete. This is a technology that is under development. There are several studies in the literature that have shown promising results on producing lightweight rubber aggregate concrete for some special purposes (Thomas & Gupta, 2016). The advantages of using this technology include good sound insulation, shock absorption, and lighter concrete products. Rubber has potential in concrete production, but its weak inherent strength and poor bond performance hinder its usage in large quantities (Roychand et al., 2020). Additionally, there are some concerns related to the rubber high flammability that should be taken into consideration. On one hand rubberized concrete is more durable, less ductile, has greater crack resistance, but on the other hand, has a low compressive strength (Alam et al., 2015).

The product application is manyfold. It can be used for instance in road barriers, improving road safety, or in house construction to reduce sound attenuation and insulation. There are also some experiments using rubber concrete mixes as shock absorbent on bike lane pavements, which would allow safer bike lanes. A study performed in Sweden, in a collaboration between RISE and CBI Betonginstitutet tested modified concrete pavement by replacing coarse aggregates and sand with rubber chips and rubber granulates (Kraft et al., 2015). The obtained results showed an elastic modulus two magnitudes lower compared to ordinary concrete and still maintain a sufficient load-bearing capacity for cyclists and pedestrians.

5.2.8. Tyre Rubber in road pavements (Rubber granulates)

Polymer-modified binders consist of bitumen blended with a synthetic polymer or granulate rubber (Figure 7). They are used to enhance the performance of binders on heavy trafficked or distressed pavements (Austroads, 2021). The use of reclaimed polymers is growing as an alternative source of polymer-modified binders, as well as to extend the service life of the asphalt pavements (Brasileiro et al., 2019). Reclaimed polymers can be incorporated into the bitumen using two main processes: the wet or the dry process. In the wet process, the added percentages of tyre rubber range from 1.75% to 25.0% by weight of bitumen, with the most used being 10%. The rubber sizes used are between 0.15 and 0.60 mm. For the dry process, tyre rubber percentages vary between 1% and 10% of the total weight of the mixture, with the most common being 1%. The size of the particles range from 0.6 to 3.0 mm (Brasileiro et al., 2019). Advantages of using this technology include increased durability, decreased maintenance, and improved driving safety. However, there are some application challenges, as temperature requirements are more critical (Karagiannidis & Kasampalis, 2010). A literature study performed by Hellman et al. (2017) indicates that rubber-modified asphalt has high fatigue resistance, which can be an advantage for Swedish conditions.

The use of rubber asphalt is well implemented in countries like USA, Portugal, Spain, or Italy. In Sweden, asphalt rubber is still in an early stage of implementation, even though it has been used for a long time. Additionally, in the wintertime studded tyres are used by many drivers, and the road constructions are characterized by relatively thin bitumen-bound layers. Therefore research is needed to evaluate and analyze rubber asphalt technology's performance, environmental benefits, and economic prerequisites (Hellman et al., 2017). In 2015, rubber-modified asphalt in Sweden was 20 to 30% more expensive than conventional asphalt. However, this can be compensated by the expected longer rubber asphalt lifetime when compared to conventional asphalt (Karri & Hellwig, 2015).

From the environmental perspective, when compared with conventional asphalt, rubberized asphalt production is a high energy-consuming process due to a higher mixing temperature. On the other hand, the higher mixing technology can lower the mixing temperature of rubberized asphalt mixture which in turn can lead to fuel savings of 20–25%. In the use phase, rubberized asphalt allows noise reduction (Wang et al., 2018). Ragn Sells has performed a study in which the authors perform a Life Cycle Assessment to compare and analyze the environmental impacts of three asphalt rubber pavements and a conventional asphalt pavement without rubber modification in the Swedish context. The difference between the rubber asphalt pavements is their thickness. The study concludes that asphalt rubber pavements with similar constructions had a slightly higher environmental impact than conventional pavements when the asphalt lifespan is not considered. Construct thinner pavements decrease the environmental impact of asphalt rubber in a life cycle perspective. Additionally, asphalt rubber pavements seem to have a longer lifespan when compared to conventional asphalt, which would as well reduce environmental impacts (Johansson, 2018). The study does not consider the asphalt use phase and EOL phase, which could be the subject of study in the future. Research is also needed to evaluate the impact of the dispersed asphalt rubber into nature, in comparison with the conventionally used asphalt.

Another interesting object of study would be to analyze the leaching of both asphalt types. A study performed by Gheni et al. (2018) has analyzed the environmental impact of using rubber aggregate in chip seal pavement in terms of leaching under different pH conditions. The study has concluded that for pH between 4 to 10, toxic heavy metals leached from the rubberized chip seal were below that of the EPA drinking water standards. It would be interesting to perform a similar study but in the Swedish context. Rubberized asphalt is also known to have a larger lifespan, which also should be an object of study in the Swedish context in the future, particularly considering the usage of wintertime studded tyres.

Noise reduction is one of the advantages that can be obtained with the use of rubber in asphalt. Sandberg (2010) did a study in which he has analyzed the sound properties of asphalt rubber in Sweden, in comparison to the conventional Stone Mastic Asphalt (SMA) and porous asphalt pavements. The conclusion was a reduction of the 1-3 dB; mainly due to low-noise-optimized texture. The author has verified that the indications of the use of rubber asphalt after two years of traffic exposure suggest that the noise advantage might become greater with time and age.

5.2.9. Vibration - Train and tram rail beds or rail ties (Shreds and rubber granulates)

Tyre-derived materials have been applied in railway engineering to reduce the vibration transmitted by the trains moving on the railway track (Montella et al., 2012). They can be used in the underlying layer of the ballast or used to produce the rail ties in which rails are bedded into (ERTMA, 2005). This application is under development and several research projects have been studying different alternatives. For example, Cho et al. (2007) observed environmental vibration reduction after utilizing tyre shreds in Honam and Gyeongbu rail lines. Two tyre shred layers were used with 0.20-meter thickness for 23-Hz and 33-Hz vibrating sources, and vibrations were reduced by 16% and 30%, respectively. The shreds can also be mixed with ballast material to increase the track resiliency, improve the damping properties, and decrease the breakage and wear of ballast particles (Fathali et al., 2019). One of the main advantages of using EOL tyres as train and tram rail beds is the longer lifespan of this material when compared to the traditional timber used.

5.2.10. Roofs (Rubber granulates)

Research on the potential use of rubber granulates to produce roofs is in progress. Some studies have shown that the rubber granulates can be used as a drainage layer, without changing the performance of the system. One possibility is to produce roofs by mixing the granulated rubber with cement and sand. The advantages of the technique include a lower density of the final product, which in turn reduces the load on the roof, and the higher flexibility of the materials that also reduces cracking (*Kaushal Kishore, et al., NA*). With this technology, rubber granulates would replace porous stones currently used, such as expanded clay, pumice, natural puzolana, etc.(Vila et al., 2012). With that, a reduction in the extraction of raw materials would be achieved, as well as a potential reduction in energy consumption.

Figure 8. Examples of EOL tyre recycling options (Rubber used as artificial turf, used in train and tram lines, and flooring, outdoor tiles)

5.2.11. Backfill for retaining walls and building envelope (Shreds, rubber granulates)

Shredded tyres can be used as insulation or as backfill material for retaining walls. The main idea is to take advantage of some of the tyre shred attributes, namely lightweight and durability. Djadouni et al. (2019) performed an LCA comparison between a traditional method involving a retaining wall backfilled with sand, and an alternative method involving a retaining wall backfilled with shredded tyres. Results showed savings of around nearly 19% of concrete and 65% of reinforcement steel of the shredded tyres solution in comparison with the traditional solution.

Another potential application is to use rubber tyres as backfill material for buildings envelope. In a study performed by Rashid et al. (2018) the authors conclude that EOL tyres can be very effective material to be used in building walls for reducing indoor air-conditioning demand in extreme climatic conditions. Tyre rubber is very promising regarding the reduction of indoor heating demand.

A potential application of both rubber and textile fibre obtained from the recycling process (mechanical grinding) is to produce absorbent soundproofing materials. Maderuelo-Sanz et al. (2012) performed a study in which they compared sound insulation behaviour of recycled rubber particles, textile fibres (from tyres), and their combination. The single material layers were compared with commercial sound-absorbing materials such as glass-wool, and it was found that the new materials had equal or better sound absorption properties.

The main concerns about this application are the possibility for internal combustion as well as the potential groundwater contamination (Djadouni et al., 2019). Yoon et al. (2006) have analyzed the potential groundwater contamination of an embankment structure filled with tyre shred–sand mixture, by analyzing the potential contamination of metals. The authors have concluded that except for manganese, all metal levels were well below the standard limits prescribed for secondary drinking water defined by the United States Environmental Protection Agency.

5.2.12. Footwear (Rubber granulates)

There are examples of industries that use rubber granulates as raw materials used for the manufacturing of rubber footwear and other rubber products. In footwear manufacturing, granulate rubber is mostly used for out-sole production. Some advantages of using this material include good water resistance as well as a long-life span.

5.2.13. Tyre rubber used on artificial turf (Rubber granulates)

In the last decades, there has been an exponential increase in the number of synthetic turf pitches in Europe (Figure 8). Granulate rubber is one of the most used infill materials. Other examples include ethylene-propylene-diene monomer rubber (EPDM), thermoplastic elastomer (TPE), cork, or mixtures of granulated rubber from EOL tyres with various synthetic and natural materials (JOHANSSON, 2019).

The dispersion of microplastics, including tyre particles, is a matter of concern regarding the impact that it may cause to environmental systems. For that reason, there was a discussion in the EU for a potential ban on the use of rubber granulate in the fields. In 2017, SWECO performed a material flow analysis over dispersal routes for artificial turf from Älvsjö AIK FF's from four artificial turf pitches for one year (SWECO, 2017). Assuming average values, 4 fields are estimated to have approximately 220 tons of granulated rubber. A refill of 6 to 10 tons of granulate rubber is necessary every year. This is because turf rubber is dispersed via plowing, by players in shoes and socks (home or changing rooms) or dispersed into nature. The model shows that more than half of the dispersed rubber turf ends up in the urban runoff. Additionally, a large part of the rubber is dispersed into the surrounding nature as illustrated in Figure 9.

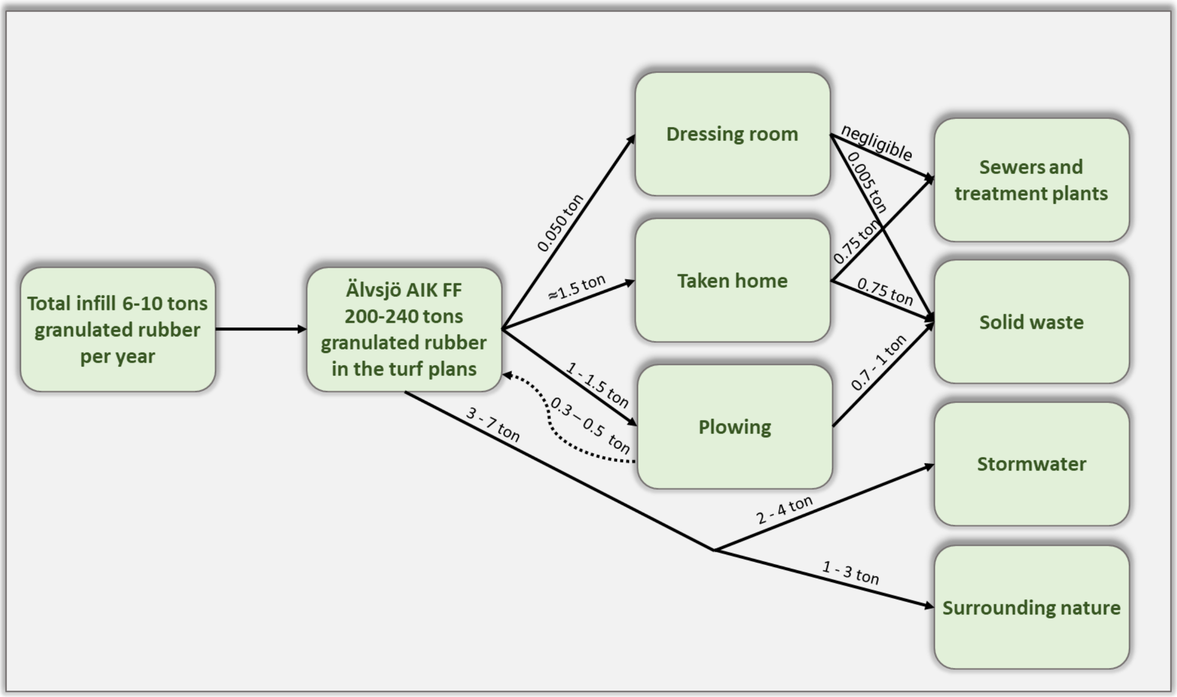

Figure 9. Material flow model overspreading of granulated rubber in four Älvsjö AIK FFs turf fields per year (SWECO, 2017)

There are also suggestions on potential solutions to avoid turf rubber dispersion and potentially avoid the ban. For instance, the installation of physical barriers around the pitch, installing player "brush down” areas, or to install or retrofit filters to the drains to avoid that the rubber enters the surface water drainage system (3P Technik, 2019). The installation of filters in the drainage system has proved to be an effective measure of reducing the dispersion to less than 1 kg per year (Regnell ,2019). In the case of snow, it is recommended that the snow is stored in designed areas with a paved surface. After the snow is melted, granulates can either be reused on the fields or disposed of as solid waste. The drainage system draining the paved surfaces surrounding the artificial turf needs to be cleaned regularly (Verschoor et al., 2021).

Ragn Sells has performed an LCA study, in which they compared the use of 4 granulated infill materials used in artificial football fields in Sweden, namely rubber granulate from tyres, ethylene propylene diene monomer rubber (EPDM), thermoplastic elastomers (TPE), and expanded cork (Johansson, 2018). The results have shown that EPDM and TPE accounted for 15 and 28 times as much greenhouse gases as granulated rubber, respectively. Additionally, due to the short life span, cork has larger carbon and water footprint when compared to granulated rubber.

There have been some concerns about potential health risks for the practicians (further discussed in section 6.). However, no conclusions can be obtained from the literature review. While some studies have proven that the use of end-of-life tyres materials is safe for the environment, others have shown a potential release risk of metals and PAHs. For example, Celeiro et al., (2021) analyzed 40 target compounds determined in 50 synthetic football pitches, concluding that chemicals such as PAHs, plasticizers, antioxidants, and vulcanization agents were reaching concentrations above the limit. However, other studies have shown that it is safe to play sports on pitches with the rubber infill (e.g. Echa (2017), (Pronk et al., 2020)). A study performed by Pronk et al. (2020), has identified that even though there are some carcinogenic, mutagenic or reprotoxic substances such as PAHs, phthalates and benzothiazoles, BPA and metals like cadmium, cobalt, and lead), all tested pitches the rubber granulate comply with the concentration limits set for mixtures of substances in Europe (Pronk et al., 2020). In 2015, Magnusson (2015) analyzed the potential environmental and health risk of different infill materials used in artificial fields, including rubber from EOL tyres. The study was based on an extensive literature review and the performance of leaching tests for metals, chloride, fluorine, sulfate, distillable phenols and DOC for each filler. The author concluded that environmental risk characterizations vary, but most of the analyzed studies have shown that the local environmental risk is generally low for rubber. From the analyzed studies, two studies have indicated potential zinc leaching that could be a possible risk to the environment. Regarding health aspects, studies analysied by Magnusson (2015), have demonstrated that the health risks with rubber are small (see Table 3 and respective references). Regarding the leaching tests, the results have revealed that all detected concentrations were below the limits for drinking water standards and in parity with stormwater. Another conclusion of the study was that rubber was the infill material with more available studies both for environmental and health risks compared to the other infill materials. Magnusson (2015), gives a summary of the analyzed studies, which is presented in Table 3. Nevertheless, it is important to define regulations to establish scientifically and risk based limit values for some substances in granulated rubber used in artificial turfs.

Table 3. Environmental and health risk assessment of artificial turf fillers (Magnusson, 2015)

Health Risks	**Granulated tyre rubber**	**TPE**	**EPDM**	**R-EPDM**
Skin contact	Minimal[1 2 3 4 5] Potential allergy risk[6]	Minimal[2 6]	Minimal[3] Potential allergy risk[6]	Unknown
Swallowing	Minimal	Minimal[6]	Minimal[6]	Unknown
Effect on Children (Pica)	Not minimal[5]	Unknown	Not minimal[5]	Unknown
Inhalation, outdoors	Minimal[1 2 3 4 7 8]	Minimal cancer risk[2]	Minimal[3 6]	Unknown
Inhalation, indoors	no increased cancer risk[7 9]	Unknown	Unknown	Unknown

Environmental Risks	**Granulated tyre rubber**	**TPE**	**EPDM**	**R-EPDM**
Ground water	Potential risk[10] Small impact[4 5 6]	Unknown	Unknown	Unknown
Surface water	Potential risk/ Impact[4 10] Small risk/Impact[6 11]	Unknown	Small risk[6]	Unknown
Soil	Potential risk[10] Small risk[11]	Unknown	Unknown	Unknown

5.2.14. Flooring, outdoor tiles (Rubber granulates)

Recycled rubber can be blended as filler to produce new composites. For example, the tyres granulated can be mixed with polyurethane to produce synthetic floor tiles (Figure 8). These tiles are now common floor materials used in outdoor and indoor playgrounds and recreational grounds. They offer

[1] Pavilonies et al., - From (Magnusson, 2015)

[2] Ruffino et al., 2013 – From (Magnusson, 2015)

[3] Kim et al., 2012 – From (Magnusson, 2015)

[4] New York State, 2009 – From (Magnusson, 2015)

[5] State of California, 2007 – From (Magnusson, 2015)

[6] Danish EPA, 2008 – From (Magnusson, 2015)

[7] Ginsberg 2011 – From (Magnusson, 2015)

[8] Menichini et al., 2011 – From (Magnusson, 2015)

[9] Norwegian Institute of Publich Health and the Radium Hospital, 2006 – From (Magnusson 2015)

[10] RIVM Report 2007 – From (Magnusson, 2015)

[11] Birkholz et al., 2003 – From (Magnusson, 2015)

elasticity and reduce vibrations. The technology is well established, and the tiles are widely used in children's playgrounds in many countries, including Sweden.

In the last years, some studies have analyzed the environmental impacts of recycled rubber use to produce different materials, including outdoor tiles produced with EOL tyres materials. The outdoors tiles had special attention due to the possible exposure of children to toxic materials. The results differ from study to study. Llompart et al. (2013) has tested commercial pavers and has observed a high content of toxic chemicals, in particular PAHs. Additionally, the vapour phase above the samples has confirmed the volatilization of many of those organic compounds. In another study performed in (2014) Celeiro et al., has investigated the presence of polycyclic aromatic hydrocarbons (PAHs) and other hazardous organic chemicals in an indoor recycled tyre playground surface with limited ventilation. The conclusion was that fourteen out of the sixteen EPA priority PAHs were identified. Additionally, the authors have identified nine PAHs in the vapor phase above the playground sample. Another study in Sweden, performed by Stockholm municipality in 2018, has analyzed and compared granulated rubber from tyres as virgin granulated rubber, to be use in used as filling material on artificial turf and cast-in-place (Kemikaliecentrum, 2018). The study concludes that tyres granulated should not be used where children can be in contact with them. This is because the material had varying amounts of PAHs. Additionally, it contained elevated levels of cobalt, both in comparison with toy directives and with guideline values for sensitive land use. However, this problem can be overcome, with the establishment of regulatory limit values for given substances in rubber granulate to be used to produce outdoor tiles for children.

5.2.15. Wastewater treatment filters (Shreds)

Pilot tests are on the way to apply rubber shreds as filters in wastewater treatment plants or constructed wetlands. As exemplified in Figure 10 this can be an applicable solution as rubber clips, can be regarded as inert waste under the EU waste classification rules for landfill waste (NFS 2004:10) (Ulinder, 2018). The filters can be applied both for large-scale, or small-scale wastewater treatment. The advantages are that the rubber shreds retain their drainage capacity for longer than natural materials, such as sand or gravel where the pores are clogged by sand and smaller particles (Ennuwa, 2021). The results from a ground bed study indicate that the ground bed purifies to the same extent as a conventional ground bed (Ulinder, 2018). The ground bed purification of phosphor was 83% and the bed also met the percentage reduction requirements at a high level of protection for BOD7 and nitrogen. Over the ground be COD was reduced by 87 % and after the ground bed the concentrations of BTEX, aliphates, aromatics and PAH were found below, or near, the detection limit. Several metals were found at lower concentrations after bed than before, but zinc, iron, cobalt and nickel were found at higher levels. Iron was significantly higher at the first sampling and subsequently decreased. The concentrations of zinc after the bed increased when sludge depletion was not performed as planned. The separation of coliform bacteria over the ground bed was found to be 73 % and >87% (two analyses). The effectiveness of the bed in relation to a conventional bed was, however, not compared but would be beneficial to evaluate the two types of beds, and their pros and cons in relation to each other.

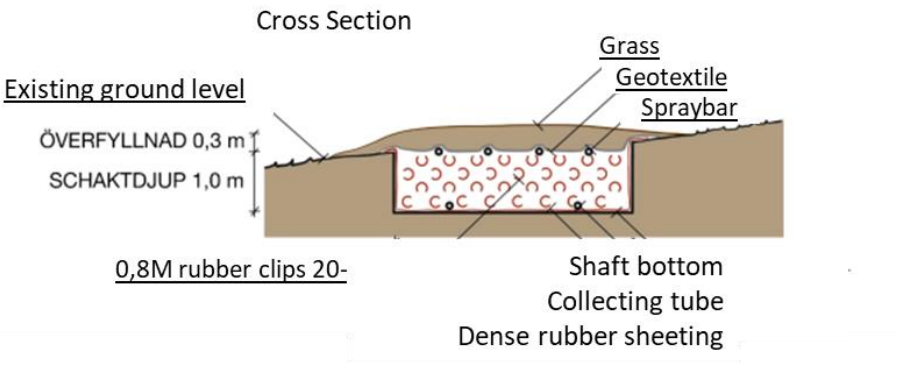

Figure 10. Example of the use of EOL tyre shreds in a wastewater treatment plant (Ulinder, 2018)

Rubber shreds can also be used in other constructions as alternatives to sand and gravel, glass foam (Hasopor), foams such as Styrofoam (Frigolit), rock wool and other mineral wools. In underground constructions the main advantage is that the pores do not clog, thereby retaining the drainage capacity (Ennuwa, 2021). Other advantages are the long-term purification capacity and improved soil conditions such as increased number of nematodes (related to long heat retention) which can be applied to multiple wastewater treatment options. The barrier for improvements on the market, especially for wastewater treatments is the acceptance of the method and lack of demands on purification capacity of for example phosphor but also other pollutants (Ennuwa, 2021). Further studies of rubber shreds in different types of constructions would be beneficial to evaluate its potentials and risks in relation to conventional materials.

5.2.16. Molded products - plastic materials

In this technology, granulate rubber is combined with a urethane binder to produce molded products. The process is simple and allows the products of low-tech products such as livestock mats, railroad crossings, speed bumps, etc. (Reschner, 2008)

5.3. Used as an alternative fuel

EOL tyres have been widely used as an alternative fuel source in many industrial processes. Because they are composed of fossil fuel derivates, used tyres have a high calorific value. Table 4 gives a summary of the caloric values of several combustible materials. From the table, one can see that EOL tyres heating value is slightly lower than crude oil but higher than coal. EOL tyres have a calorific value 6 times higher than municipal solid waste.

Table 4. Calorific values of several combustible materials (Laboy-Nieves, 2014)

Source	kJ/kg
Municipal Solid Wastes	5,800
Mixed Biomass	15,100
Paper	17,400
Textiles	18,600
Bituminous Coal	26,200
Scrap Tyres	31,400
Crude oil	39,500

There are multiple technologies in which EOL tyres are used as a fuel source. EOL tyres can be directly used to produce energy or heat, or they can be converted into fuels and after used as raw material. In the next subsections, four alternatives are presented, namely energy recovery through incineration, co-processing, pyrolysis, and gasification.

5.3.1. Incineration

Tyres are mostly composed of rubber materials. Therefore, there is the possibility of using EOL tyres as an alternative fuel in some energy recovery processes, as Tyre Derived Fuel (TDF). An advantage of the method is that tyres can be directly used without any other previous pre-treatment. Tyres shreds can also be used as TDF. Incineration takes place in thermoelectric power stations. The utilization of EOL tyres in coal plants, beyond recovery energy, also reduces the oxides of nitrogen (NOx) emissions (Singh et al., 2009). The use of tyres as an alternative fuel in incinerators is a common practice in Sweden has been shown in Section 3.

The main advantage of this technology is that the use of EOL tyres replaces fossil fuels that otherwise would be used. Therefore, if green energy sources are not available the use of EOL tyres can be seen as a valid alternative for fossil fuels. Additionally, many authors account for part of the CO_2 emissions from energy recovery using tyres as from biomass origin. This is supported by the fact that tyres are composed of natural rubber. Mora et al. (2021) has identified that on average the use of EOL tyres avoids 30% of the total CO_2 emissions, considering that amount of biomass (natural rubber) in the scrap tyres matches the CO_2 neutral emissions. However, there are some environmental challenges that one should be aware of. The main environmental challenge with the incineration of EOL tyres is the emissions into the atmosphere. Even though tyre combustion allows the use of recovered energy it also generates emissions of undesired pollutants such as dioxins, PAHs, VOCs, etc. Some studies compare the use of scrap tyres instead of coal. In 2006, (Gieré et al., 2006) presented a study in which the authors performed a comparison between medium-sulfur bituminous coal and a mixture of 95 wt.% coal plus 5 wt.% tyre-derived fuel in a power station. An increase of Zn from 15 g/h to nearly 2.4 kg/h when coal + tyre-derived fuel was combusted result in the high Zn content of the shredded tyres. Additionally, emissions of most other metals and metalloids, as well as those of HCl increased when tyre-derived fuel was used. On the other hand, emissions of CO decreased and of NO_x, SO_2, and the total particulate matter remained virtually unchanged. Another study performed in 1996 (Levendis et al., 1996), compared emissions (SO_2, NO_x, CO, and PAHs) from pulverized bituminous coal and ground waste automobile tyres combustion. The SO_2 emissions from the combustion of steady-flow clouds (aerosols) of tyre and coal particles were comparable (within a factor of 2), the NO_x emissions of tyres were lower than those of coal by a factor of 3−4 and individual gas-phase PAH emissions of tyres were 1.5−2 times higher than those of coal. However, one must have in mind that the report was written in 1996, and tyres composition has been changing throughout the years. This is particularly important for tyres produced after 2010, with lower specific PAH amounts.

5.4. Co-processing

EOL tyres can be used in cement furnaces for energy production. If applied in the cement industry, the ash obtained after the combustion can be used to be bound to the clinker (Pipilikaki et al., 2005). The high temperatures and the oxidizing atmosphere in the kiln (1500-1600°C) allows the complete combustion of the tyre, including the volatile matter produced during the combustion (Amari et al., 1999). The volatized iron oxide can be used to be incorporated in the clinker, replacing supplemental iron. European legislation regulates and limits the number of tyres used as an alternative fuel in the manufacture of cement, with a maximum of 20% of the total fossil fuel used in the process (Ramos et al., 2011). Pulp and paper mill industries can also use tyres as an alternative fuel source. In this case, tyres are used as a heat source for drying and the generation of steam for electric power (Amari et al., 1999). The use of EOL tyres in pulp and paper mills is not a common practice in Europe (Ramos et al., 2011). The use of tyres in the co-process is a well establish technic in Sweden, particularly in the cement industry as shown in Section 3.

There are two main advantages of using tyres as an alternative fuel in the cement industry. First, the replacement of fossil fuels, and second the utilization of the steel enriched ashes in the cement. Therefore, as explained in the incineration process, CO_2 from fossil fuel origin can be reduced due to natural rubber content, which will depend on the content of natural rubber of the used EOL tyres.

As with incineration, the main environmental concern with co-processing technology is the air emissions. Albino et al. (2011) have performed a literature review in which they analyze environmental, social, technical, and economic impacts of using alternative fuels in cement kilns including the use of end-of-life tyres as an alternative fuel. From the analyses, the authors have concluded that there are no clear conclusions on the effect of the use of tyres in cement kilns. The process is very dependent on multiple factors such as the industry technology, the type of EOL tyres used, etc. However, Albino et al. (2011) have found that more studies have experienced a reduction of the emissions of NO_x when EOL tyres were used as alternative fuels in cement kilns.

5.4.1. Pyrolysis

Pyrolysis is a thermochemical process in which EOL tyres are recovered into energy and chemical commodities. The process uses shred or granulated tyres. In this process elastomers contained in the rubber are decomposed under high temperatures of 400-700 °C and in the absence of oxygen (Sienkiewicz et al., 2012). The heating rate of the tyre directly after the product yield as well as the quality of the product, and the reaction time can take from minutes to hours depending on the used technology (Martínez, 2021). The process end products are liquid pyrolysis oil, pyrolytic carbon char, metal, and synthetic gas or syngas (CO and H_2) (Ramirez-Canon et al., 2018).

One of the main challenges in pyrolysis technology is that, even though the obtained products hold a lot of promise, they are still in a nascent stage (Martínez, 2021). The type and composition of the EOL tyre, as well as the technological maturity of the pyrolizer, strongly affect the quality of the liquid pyrolysis oil and pyrolytic carbon char.

Regarding the potential product applications, liquid pyrolysis oil has been found to potentially be used as a promising substitute for petroleum-derived products, such as heating oil or motor fuels (Martínez, 2021). However, and to fulfil fuel standards established for such uses liquid pyrolysis oil demands some upgrading stages. The pyrolytic carbon char can be used to replace virgin carbon black, but this demands some refining process, depending on the type of application. The syngas, which is composed of hydrogen (H_2), hydrogen sulfide (H_2S), carbon oxides (CO_x), and light hydrocarbons (C1 - C6), can be used as fuel in the pyrolysis process, or co-generation technologies (López et al., 2011).

Research has been in place to develop tyre pyrolysis in Sweden. At the time, there is one company in Sweden (Enviro) which owns a pyrolysis technology for EOL tyres. The company has implemented a pilot facility in Åsensbruk with the capacity to recycle 15.000 tons of tyres per year. There are also plans to implement a new facility in Uddevalla, with a maximum capacity of 60.000 tons per year. A research project between Enviro and IVL (Swedish Environmental Research Institute) concluded that recovered carbon black leads to CO_2eq emissions that are 79-84 percent lower than the emissions from the production of virgin carbon black. Additionally, in 2017, another research project between Enviro and RISE assessed three different approaches for upgrading pyrolysis oil. They have found no significant differences between upgrading pure fossil oil and oil with 20 percent pyrolysis oil. For this reason, the pyrolysis oil can be used in petrochemical industries to reduce their consumption of fossil oil. Each ton of EOL tyre produces 500 kg of pyrolysis oil (ENVIRO, 2021). Further research on other technics for pyrolyze oil purification is needed, to make it economically viable to produce other high-value petroleum-derived products, which would increase the market value of the pyrolyze oil.

Pyrolysis is a high-energy demanding process. The energy demand can be significantly reduced if the syngas generated in the process is used as an energy source. Another possibility is to use solar energy by focusing on solar irradiations with the help of photoactive catalysts (Dick & Agboola, 2020). The main environmental challenge of pyrolysis is air emissions. In the pyrolysis process, several pollutants may be released, including PAHs, particulate matter (PM), oxides of nitrogen (NO_x), oxides of sulfur (SO_x), dioxins and furans, hydrocarbon (HC) gases, metals, carbon dioxide (CO_2), and carbon monoxide (CO). These elements need to be captured before they are discharged into the ambient air (Chen et al., 2007). A very important aspect is that pyrolysis technologies and processes have been developing significantly in the last years, both in what concerns the quality of the obtained products, as well as reduction of the emissions into the atmosphere. For those reasons, pyrolysis is considered one of the most promising technologies for EOL tyre processing.

5.4.2. Gasification

As with the pyrolysis process, gasification is a waste-to-energy thermochemical process in an oxygen-deprived environment. It is an endothermic reaction to produce mainly syngas (CO and H_2). The process produces other by-products, namely carbon dioxide, light hydrocarbons, and char (Leung & Wang, 2003). Syngas yield depends on the technology, fuel, and gasifying agent used but it can represent a yield of approximately 63% by weight (Ramos et al., 2011). The solid part is composed of carbon black and steel. The process has shown high potential to produce high-quality syngas, but it needs technological development particularly in reducing amounts of energy required to break down the feed material (Nkosi et al., 2021). The environmental issues described in the pyrolysis processes are approximately the same experienced by the gasification process.

5.5. Applications summary

The previous subsections have shown many potential applications for EOL tyre-derived products. In Table 5 a summary of the described technologies is presented, with the type of EOL tyre-derived product that is used, the main advantages as well as the identified challenges.

5.5.1. Summary of potential tyres recycling applications and remarks

Table 5. EOL tyre-derived products applications and respective advantages and challenges. In addition to those, there are also challenges related to public procurements, regulations, lack of classifications and perceptions for all the technologies

Technology	Material type	Advantages	Challenges
Rubber in asphalt pavments	Rubber granulates, Textile Fibers	▪ Noise reduction (usage phase) ▪ Replaces aggregates (gravel) ▪ Longer lifespan when compared with conventional asphalt	▪ Not all contractors are familiar with the technology ▪ Difficult to compete with other materials that are more economically accessible ▪ Potential leaching risks (?)
Rubber in concrete	Rubber granulates, Textile Fibers	▪ More resilient ▪ More durable	▪ Not economically feasible ▪ Low compressive strength ▪ Technology is under development
Rubber used as artificial turf	Rubber granulates	▪ Well implement and widespread technology ▪ Good impact resistance ▪ Limited maintenance (no watering, etc)	▪ Dispersion of microplastics. Rubber may end up in the stormwater system and aquatic ecosystems ▪ Potential toxic risk for users (?)
Playground surfaces and Sport surfaces	Rubber granulates	▪ Well implemented in the marker ▪ Playgrounds allow easy accessibility (wheelchairs) ▪ High impact resistance - Lower rate of injury on rubber granulate surfaces (Llompart et al., 2013) ▪ High durability ▪ Facilitated maintenance	▪ Potential toxic risk for users (mainly children) (?) ▪ Heat retention •
Devulcanization (reclaimed rubber)	Rubber granulates	▪ Potential use of the rubber as raw material to produce new tyres	▪ Technology is under development ▪ Not economically feasible ▪ The quality of the end products needs to be improved (properties of the recycled rubber not as good as virgin rubber) ▪ High energy consumption ▪ Uncertain commodity market
Footwear manufacturing	Rubber granulates	▪ Good water resistance ▪ Replace plastics such as PU, TPU or EVA Foam	▪ Not a common practice •
Sound Absorbing Materials	Tyre Shreds, Textile Fibers	▪ High potential to replace other materials ▪ Good sound-absorbing properties	▪ Technology under development ▪ Potential leaching risks (?) ▪ Potential fire risks (?)

Technology	Material type	Advantages	Challenges
Molded products	Rubber granulates	▪ Replacement of virgin plastic materials •	▪ Limited market
Production of steel	Steel	▪ Technology well established ▪ Reduction of iron ores extraction	•
Blasting mats	Whole tyre	▪ Technology well established ▪ Reduces the amount of virgin materials used	▪ Limited market
Thermal isolation	Tyre Shreds	▪ Potential replacement of expanded polystyrene or lightweight clay aggregate ▪ Low thermal conductivity	▪ Requires stiffer superstructure ▪ Potential leaching risks (?)
Lightweight fill	Tyre Shreds	▪ Increased load-carrying capacity ▪ Improved drainage ▪ Replacement soil, clean fill, drainage aggregate, expanded shale or polystyrene insulation blocks ▪ Low density	▪ Potential leaching risks (?)
Building envelope (walls)	Tyre Shreds	▪ Reduction of indoor heating	▪ Technology under development ▪ Potential fire risks (?)
Roof tiles	Rubber granulates	▪ High water drainage capacity ▪ Low density and high permeability ▪ Replacement of virgin materials	▪ Technology under development ▪ Potential leaching risks (?) ▪ Potential fire risks (?)
Draining layers	Whole tyre, Tyre Shreds	▪ High water drainage capacity ▪ Replacement of gravel	▪ Potential leaching risks (?) •
Vibration attenuation (train and trams lines)	Tyre Shreds	▪ Longer lifespan when compared to wood ▪ Noise reduction ▪ Vibration attenuation	▪ Technology under development ▪ Not a common practice ▪ More expensive when compared to wood chips ▪ Potential leaching risks (?)
Stress-reduction fill over preexisting buried pipes	Tyre Shreds	▪ Vibration attenuation ▪ Minimize stress on pipes •	▪ Not a common practice ▪ Potential leaching risks (?)

Technology	Material type	Advantages	Challenges
Retaining walls, road-base reinforcement, erosion protection	Whole tyre, tyre bales	▪ Replacement of concrete blocks and/or polyethylene blocks ▪ Low density, high permeability, and high porosity ▪ In some cases, the whole tyre can be used, avoiding energy use in material processing ▪ Low transportation costs	▪ Potential leaching risks (?)
Wastewater filters	Rubber granulates	▪ Replace plastic materials and gravel	▪ Technology under development
Pyrolysis	Whole tyre	▪ Improves material circularity ▪ Replacement of virgin carbon black ▪ Pyrolysis oil can be used as a fuel source	▪ Technology under development (there is a pilot factory 6.000 tons in Sweden) ▪ Air emissions of GHG and toxic pollutants (?) ▪ Energy consumption (can be reduced if pyrolysis gas is used)
Incineration with energy recovery	Whole tyre	▪ Technology well established ▪ High energy content ▪ Energy generation ▪ Fossil fuels replacement	▪ Air emissions of greenhouse gases and toxic pollutants
Co-processing	Whole tyre	▪ Technology well established ▪ High energy content ▪ Recovery of energy ▪ Steel can be used in cement ▪ Fossil fuels replacement	▪ Air emissions of greenhouse gases and toxic pollutants
Gasification	Rubber granulates	▪ Syngas can be used in multiple applications ▪ Maximum heat recovery	▪ Technology under development ▪ Air emissions of GHG and toxic pollutants (?) ▪ High operational costs

6. Environmental impacts of tyre recycling

In this section, potential environmental impacts of tyre reuse and recycling in general and based on literature review are presented. This is a follow-up of some of the impacts that were already presented in the previous section when the technologies and applications were presented. In this section, environmental impacts are divided into four main categories namely resources and energy reduction, air emissions, leaching and toxicity.

6.1. Resources and energy reduction

EOL tyres hold many technical unique characteristics that make them versatile, including elastic modulus, water absorption, or tensile strength. As shown in chapter 5 multiple applications make EOL tyres a good material to replace other virgin materials. Additionally, the use of EOL tyres use may not only save many resources but also can save a large amount of energy that would be needed to extract or produce the materials that they might be replacing.

In the literature, there are multiple examples of studies, that compare the different end of life management options for tyres from a Life Cycle perspective (e.g.(Bianco et al., 2021)). Even though these studies are an important contribution, there is also a need to have access to more studies, in which EOL tyres are compared with raw materials that they might replace. Such an example is the study performed by Clauzade et al. (2010), in which the authors have performed a Life Cycle Assessment for nine recovery methods for EOL tyres, including cement works, foundries, steelworks, urban heating, retention basins, infiltration basins, moulded objects, synthetic turfs and equestrian. The study was performed in France, following the methodological prescriptions developed in the ISO 14 040 and ISO 14 044. The environmental impact was accessed by analysing the impacts avoided through the substitution effect, namely the replacement of traditional raw materials and energy reduction. The environmental impacts for EOL tyres were negative for almost all the nine technologies and the eight studied environmental indicators. One example of the results can be found in Figure 11, in which (Clauzade et al., 2010) shows the Greenhouse gas effect indicator - generated impacts and avoided impacts of the studied methods. From the graph, it is clear a clear reduction in greenhouse gas emissions for all the studied alternatives.

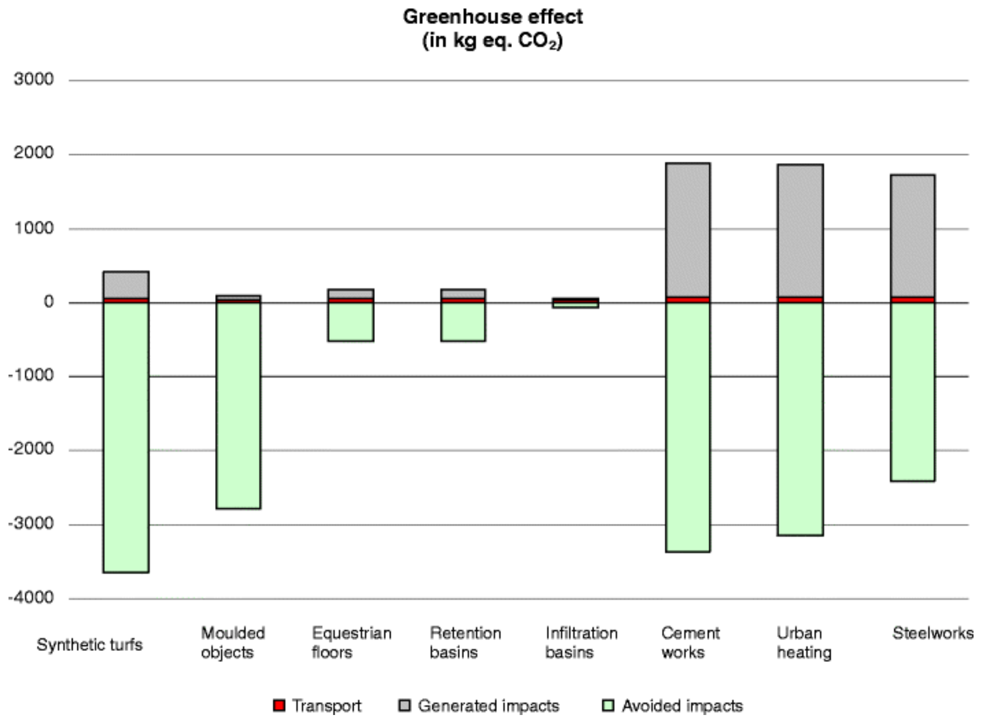

Figure 11. Greenhouse gas effect indicator -for 9 EOL tyres recovery methods studied (Clauzade et al., 2010)

The main benefits of using EOL tyres are reduced energy and resource use. But in the literature, other potential health and environmental impacts are also discussed, which are further described below.

6.2. Air emissions and microplastics dispersion

Air emissions are mostly originated from the energy recovering processes. This topic was already widely discussed in Section 5.4 when the energy recovery technologies were described. In summary, the energy recovery process may generate emissions of undesired pollutants such as dioxins, NO_x, SO_x, PAHs, VOCs, etc. In addition to that, greenhouse gases are also emitted such as CO_2. Additionally, some end-of-life tyres applications may cause microplastics to spread to Nature.

Air emissions may also arise from reused materials due to the wearing of the new products. This may, for example, arise from the wearing of asphalt, when the tyre containing asphalt material is applied in the wearing layer of the road. The wearing is not likely to occur when used in the lower asphalt layers.

6.3. Leaching

One recognized concern in using EOL tyres, shreds, or granulate rubber as raw material or structural product is the potential overtime leaching of tyre constitutes. Tyres contain a variety of substances to achieve the properties of the rubber that are in demand (e.g: rolling resistance, mechanical abrasion, temperature intensity, etc). To understand the leaching risk that granulate rubber may cause to the environment, a literature review was performed for articles or reports published after 2010, the year in which the PAHs ban was implemented in Europe. In this search, we have considered all the EOL tyre products, namely whole tyres, tyre shreds, or tyre granulates. This plays a significant role due to the material composition or contact surface. For instance, tyre shreds include steel tyre wire, and therefore more risk for metals leaching when compared to tyre granulates. On the other hand, tyre granulates have more contact surface area and therefore a potential higher risks for leaching PAHs. The investigation does not include a risk assessment, i.e. changes in leachability and bioavailability due to vulcanisation. We think further studies on environmental impacts due to leaching, bioavailability, exposure and toxicity are essential to do a proper risk assessment. Leaching will also depend on how the end-of-life tyre products will be used in the new application, and more studies for the specified uses are necessary.

The results of the literature study can be found in Table 6. Some studies have experienced no significant impact of EOL tyres and components in the environment. For example, Duda et al. (2020) has analyzed the effect of leaching in tyre bales and analyzed the presence of metals, PAHs, phthalates, selected anions, or cations. The wastewater arising was not enriched significantly in impurities and was below the standards imposed for wastewater discharged to either waters or soil. Maeda (2016) obtained similar results, but this time using tyre-derived aggregates, concluding that the number of potentially harmful compounds leaching was limited, and the rate of leaching is sufficiently low that the concentrations of these compounds in the surrounding waters did not pose any environmental degradation. On the other hand, some studies have identified potential environmental risks. For instance Kalbe et al. (2013) have analyzed the release of zinc and PAHs leached from components of sports surfaces containing recycled rubber granules. Kalbe et al. (2013) has verified concentrations of zinc and PAHs (sum of 15 EPA PAH) partly above the threshold values for the soil-groundwater pathway of the German Federal Soil Protection.

As it can be seen in Table 6, there are slight differences in the results obtained in the studies. However, there are also some similarities between some of the studies. For example, some studies have identified a decrease in release over time and suggest pre-washing of tyres before the reuse applications which can significantly reduce the leaching of dissolving organic and inorganic constituents, e.g: Selbes et al. (2015) suggests a pre-washing of around 12 h. Another common result from some of the studies is that neutral PH areas traditionally lower leaching risks.

Table 6. Literature review on EOL tyre leaching studies after 2010

Study	Goal	Results
Selbes, Meric, et al. "Leaching of DOC, DN, and inorganic constituents from scrap tyres." Chemosphere 139 (2015): 617-623.	▪ Different sizes of tyre chips and granulate rubber were exposed to leaching solutions with pH's ranging from 3.0 to 10.0 for 28 days. ▪ Examined the leaching of dissolved organic carbon (DOC), dissolved nitrogen (DN), and selected inorganic constituents.	▪ Leaching of DOC and DN were found to be higher for smaller size tyre chips. ▪ Leaching rates showed that components associated with the rubbery portion of the tyres (DOC, DN, zinc, calcium, magnesium, etc.) exhibited an initial rapid followed by a slow-release. ▪ Neutral pH conditions should be preferred for reuse applications. ▪ Pre-washing of tyres (e.g., for a duration of 12 h) prior to reuse applications can significantly reduce the leaching of dissolving organic and inorganic constituents. ▪ Removal of wires from the tyres will significantly reduce the release of iron.

Study	Goal	Results
Maeda, Richela K. "Water quality evaluation of tyre derived aggregate." (2016).	▪ Investigate the rate that potential water quality contaminants leach from tyre-derived aggregate (TDA) as a function of time of 83 constituents.	▪ The laboratory experiment suggests that, of the 83 tested constituents, benzene, methyl isobutyl ketone (MIBK), cadmium, zinc, iron, manganese, total phosphate, and total suspended solids (TSS) are leached from TDA and dissolved oxygen (DO) is altered by TDA. ▪ For the eight constituents suspected to leach from TDA, a decrease in release over time was observed. ▪ The number of potentially harmful compounds leaching from the TDA is limited, and the rate of leaching is sufficiently low that the concentrations of these compounds in the surrounding waters do not pose any environmental degradation.
Duda, Aleksander, et al. "Application of material from used car tyres in geotechnics—an environmental impact analysis." PeerJ 8 (2020): e9546.	▪ Tyre bales were placed in the water for 120 days, with emerging leachate analyzed after set intervals of time.	▪ Wastewater arising was not enriched significantly in impurities (be these metals, PAHs, phthalates, selected anions or cations), and there were therefore no exceedances of standards imposed for wastewater discharged to either waters or soil.
Kalbe, Ute, et al. "Development of leaching procedures for synthetic turf systems containing scrap tyre granules." Waste and Biomass Valorization 4.4 (2013): 745-757.	▪ The release of zinc and polycyclic aromatic hydrocarbons (PAH) leached from components of sports surfaces containing recycled rubber granules was considered.	▪ The concentrations of zinc and PAH (sum of 15 EPA PAH) were partly above the threshold values for the soil-groundwater pathway of the German Federal Soil Protection and Contaminated Sites Ordinance

6.4. Toxicity

Multiple factors are determining the adverse effects of toxic agents, including the intrinsic toxicity, the dose, the exposure conditions (e.g. total concentrations, leachability, bioavailability in its different applications), and the response of the host (European Comission, 2021). In this subsection, we focus on presenting some literature studies, that have analyzed the dose of some toxic agents that can be found in tyre-derived products. In Table 7 we present the goals and conclusions of 4 different literature studies. Most of the studies found in the literature analyze the health risk of synthetic turf pitches with rubber granulate infill. It is important to highlight, that synthetic turf pitches also have other plastics than granulated rubber. The results from the studies can vary in what concerns potential risks for the users. Pronkt el al. (2020) have analyzed 45 (all samples) or 79 substances (a subset) in granulate samples from 100 Dutch synthetic turf pitches, and have concluded that the rubber granulate comply with the concentration limits set for mixtures of substances in Europe. Celeiro et al. (2021) have analyzed 40 target compounds determined in 50 synthetic football pitches, and have concluded that chemicals such as PAHs, plasticizers, antioxidants, and vulcanization agents were reaching concentrations above the limit. Schneider et al. (2020) have analyzed 46 substances and substance groups from 86 EOL tyres and 10 non-EOL tyres infill samples 14 European countries. They have concluded that the average concentration of REACH PAHs was below 10 mg/kg, but other substances such as Al, Co, benzothiazoles, 6PPD, DPG, and 4-tert-octylphenol were found at higher concentrations. Therefore, the literature analysis does not allow to have any specific conclusions on the potential toxicity risks (dose of some toxic agents) of the tyre-derived products. The available information and current knowledge on toxicity in relation to environmental and health exposure is not enough to take any conclusions.

Table 7. Literature review on amount of some toxic agents that can be found in tyre-derived products

Study	Goal	Results
Celeiro, Maria, et al. "Investigation of PAH and other hazardous contaminant occurrence in recycled tyre rubber surfaces. Case-study: restaurant playground in an indoor shopping centre." International Journal of Environmental Analytical Chemistry 94.12 (2014): 1264-1271.	▪ Investigated the presence of polycyclic aromatic hydrocarbons (PAHs) and other hazardous organic chemicals in a recycled tyre playground surface (in an indoor restaurant of a shopping centre with limited ventilation)	▪ Fourteen out of the sixteen EPA priority PAHs were identified and quantified in the investigated recycled tyre rubber playground surfaces. The analytical measurements also confirmed the presence of other harmful compounds including phthalates, adipates, antioxidants and benzothiazole among others, in some cases at high concentration levels (DEHP> 3000 µg g−1). ▪ HS-SPME studies demonstrated the presence of nine PAHs in the vapour phase above the playground sample, showing that these chemicals could reach the surrounding air. Consequently, PAHs would likely be accessible by inhalation increasing the risk to children.
Pronk, Marja EJ, Marjolijn Woutersen, and Joke MM Herremans. "Synthetic turf pitches with rubber granulate infill: are there health risks for people playing sports on such pitches?." Journal of exposure science & environmental epidemiology 30.3 (2020): 567-584.	▪ Rubber granulate samples from 100 Dutch synthetic turf pitches were analysed for 45 (all samples) or 79 substances (a subset).	▪ A study have identified that even though there are some carcinogenic, mutagenic or reprotoxic substances such as PAHs, phthalates and benzothiazoles, BPA and metals like cadmium, cobalt, and lead), all tested pitches the rubber granulate comply with the concentration limits set for mixtures of substances in Europe.
Celeiro, Maria, et al. "Evaluation of chemicals of environmental concern in granulate rubber and water leachates from several types of synthetic turf football pitches." Chemosphere 270 (2021): 128610.	▪ In this study 40 target compounds, including polycyclic aromatic hydrocarbons (PAHs), plasticizers, antioxidants and vulcanization agents were determined in 50 synthetic football pitches of diverse characteristics to estimate environmental risks.	▪ Results revealed the presence of most of the target PAHs in granulate rubber at total concentrations up to 57 µg g−1, next to a high number of plasticizers and vulcanization agents. Runoff water collected from the football pitches contained up to 13 PAHs as well as other chemicals of environmental concern. In addition, continuous leaching of chemicals from the granulate rubber to the surrounding water was demonstrated. The transfer of target chemicals into the runoff water poses a potential risk for the aquatic environment.
Schneider, Klaus, et al. "ERASSTRI-European risk assessment study on synthetic turf rubber infill–part 1: analysis of infill samples." Science of The Total Environment 718 (2020): 137174.	▪ 86 ELT and 10 non-ELT infill samples 14 European countries were investigated. ▪ Concentrations of 46 substances and substance groups in ELT granules are reported	▪ The average concentration of REACH PAHs is below 10 mg/kg. ▪ Al, Co, benzothiazoles, 6PPD, DPG, and 4-tert-octylphenol found at higher concentrations ▪ Benzothiazole, MIBK and other volatiles evaporate from infill.

7. Discussion

This section discusses the main findings obtained from the study.

Improve circularity for EOL tyres is a challenging and complex process. Nonetheless, EOL tyres hold multiple characteristics that make them a very versatile product, as presented in section 5. For example, EOL tyres drainage properties make them a good raw material to be used in technologies such as roofs production or in construction used as drainage layers. The elastic modulus allows the EOL tyres to be used for vibration attenuation in road construction, or in train or trams rail beds. The potential applications are even more important if we consider resources scarcity and the good indications of the high potential that EOL tyres hold to replace a large variety of virgin materials, as shown in Section 6.1. Although advances have been done to improve the material circularity there is still a need for further research and more technical implementations, so that potential users understand the environmental and economic potential for each technology. On top of that, EOL tyres must be managed anyhow. Export EOL tyres does not seem to be a valid alternative because of the negative impacts of the transportation and that it implies lost control of how the EOL tyres are managed including the costs and benefits of potential management strategies.

From our study, we have seen that it is difficult to find detailed information for many EOL tyre recycling technologies. Above all, there is a lack of information that makes it difficult to carry out risk analysis. This requires more lab. and field studies regarding bioavailability, leachability and toxicity for the different technologies and their applications (i.e., the whole context). However, the benefit of re-use and recycling is huge and therefore scientifically and risk-based classifications/regulations and procurement opportunities for re-use also need to be reviewed.

There would be potential circular economy benefits if the components from EOL tyres would be used in the production of new tyres. As shown in this report, multiple technologies make already possible the separation of the EOL tyres into components (Section 5.1.2). The metal, which represents around 11% of the total weight of a tyre, can easily be reused by melting and recasting. The granulated rubber is more challenging to reuse due to its vulcanized structure. Rubber recycling to be used again in new tyres is still in an early stage, mostly due to economic and environmental challenges. The devulcanization process is still being developed and more research is needed so that more recycled rubber can be used in new tyres, as pointed in Section 5.1.2. To repurpose EOL tyres, giving them a new life by adapting to another function is also a good circular economy alternative. Many repurpose alternatives were presented in this report, nonetheless, repurpose market seems limited. However, in Sweden, there are many tyres that are reused to produce blasting materials, avoiding the need for the utilization of other virgin materials (Section 5.2).

Another possibility that is growing in the last decades, is to use/incorporate the EOL tyre components into new materials, and therefore improve material circularity. Many technologies have been using recycled rubber, by directly using it as a product or as raw materials to produce other products. This report has shown many application examples, such as the use of rubber in concrete products, as turf in artificial fields, or in rubberized asphalt among others (Section 5.2). One of the main advantages of these applications is that using EOL rubber avoids the use of other virgin materials that otherwise would be needed. Therefore, there is a need to brand the possible applications of EOL tyre-derived products.

There are multiple recycling possibilities for granulated rubber. The same applies to steel, which can easily be recycled. Nevertheless, this is not the case for textile fibres extracted from the EOL tyres. Textiles have always been one of the main challenges in tyres recycling. In most cases, they are contaminated with rubber, which makes it difficult to recycle. Additionally, when processed, the textiles can generate dust that may affect the environment as well as lead to potential health risks. Tyre textile recovery technologies are being developed, including application in concrete production, or to be used as an energy source (ETRMA 2015).

One of the main challenges to foster material circularity is to link two value chains that have never cooperate in the past. This happens even in cases that technologies have proven to be viable. Taking the example of road construction, rubber might be used as a resource in asphalt. For this to be a reality, there is a need to link rubber recyclers as well as the asphalt manufacturing industry or even the contractors. Probably there will be a need for the asphalt manufacturing industry to adapt to new technologies. Therefore, linking actors that could benefit from EOL tyres recycling presents an important step to improve EOL tyre management. It seems fundamental, more research studies, in which EOL tyres are evaluated with a risk assessment performed in the Swedish context, so that contractors may see the environment and economic potential. The studies should be performed for each of the EOL tyres applications.

It seems also important to link multiple stakeholders from different supply chains, to improve EOL tyre's management efficiency. In theory and from the circular economy, strategies that are on the top of the circular economy hierarchy should be prioritized (Section 2). For example, a used tyre can be remanufactured to be used again, after it can be used to produce blasting mats, which in turn can be converted into granulated rubber to be used as turf, and finally used in the pyrolysis process to produce energy products. Of course, this is not possible to be performed on all the tyres, but the main point here is to highlight the importance of creating links between different supply chains, that can cooperate. This is as well one of the suggestions found in the Däckbranschen plan for 2020-2030 period and defined as the "Symbiotic Recycling" strategy (Däckbranschens, 2021b).

An important step in the future is that EOL tyres or products are not catalogued as waste and that a system perspective is applied. As it has been shown in this report, EOL tyre-derived products such as shreds, or components such as granulated rubber and steel, are materials with value in the market and can be used in several applications. This is a topic that ETRMA and ETRA have been working on in the last years. An example is that in 2010, materials standards were created according to the CEN/TC 366, which defines parameters and test methods for EOL tyres cuts, shreds, chips, granulate and powders (Dekkretur, 2021). This is directly related to the improvement of the acceptance of EOL tyred derived products as a potential resource and not a waste. However, there is a necessity for additional standards, in particular the standardization of relevant physical and chemical properties of tyre-derived materials. ETRMA (2015) points out the lack of standards to work to has been one of the barriers for new facilities that produce high-quality materials using EOL tyres. According to ETRMA (2015), there is a committee working on three main topics:

- specific physical characteristics of tyre-derived materials;
- specific chemical characteristics of tyre-derived materials;
- quality criteria for the selection of whole tyres, for recovery and recycling processes.

The chemical characteristics of tyre-derived products are extremely important for some applications. For example, if granulated rubber from tyres is meant to be used in places in which children might be in contact, they must fulfil the requirements for substances that might be dangerous for the users and the environment. There are already some rules that restrict hazardous substances in chemical products and goods, such as REACH regulations. But there is a need for specific regulations that establish scientifically and risk-based limits on chemical substances, for recycled granulated rubber used in artificial turf or children's playgrounds. This regulation would possibly allow better trust for the contractors. The same principle is applied if the tyre derived products that might be in contact with soil or water sources.

As stated before, the European Commission is analysing a potential ban on the use of granulated rubber in artificial turfs. The granulated market has registered a significant reduction in usage in the last 5 years in Sweden (Section 4). This report introduces several practices to be implemented in artificial fields, that help the reduction of microplastics dispersed into Nature, and with that avoid the ban. The practices include the introduction of the installation of physical barriers around the pitch, installing player “brush down” areas, or installing or retrofit filters to the drains to avoid that the rubber enters the surface water drainage system (Section 5.2). It is therefore necessary that the artificial fields implement the previous practices. A potential solution would be the introduction of notification obligations for facilities using artificial grass, to comply with the suggested practices (VTI, 2021). However, it is also important to highlight that the notification obligation should be applied to all the artificial grass facilities, and not only the ones using granulated rubber from tyres.

A very important aspect is that eco-design also takes into consideration potential EOL tyres reuse and recycling. As referred before, it seems of great importance that new tyres are produced in a way that they can be retreaded. But eco-design is not just applicable for the retreading technology. For example, some tyres can have in their composition foams for noise reduction or containing sealants to make them puncture-free (EuRIC, 2021). This can lead that these tyres may contaminate other EOL tyres. This highlights the importance of linking manufacturers with potential EOL tyre recyclers.

Regarding the quality of EOL tyres, separation on the final collection points also may play an important role so that EOL tyres do not get contaminated. According to Kilander (2019) in 2018 EOL tyres in Sweden were not sorted in the collection point. Sorting EOL tyres can be of importance because the composition of the tyres may vary, allowing the increase of EOL tyre's reusability.

8. Conclusions and further research

This section presents the main findings of this report.

In Sweden, end-of-life tyres accounted for approximately 85,000 tons in 2020. 65% were used as an energy source for energy production or in the cement industry, 34% were recycled or reused, and 1% were exported. The numbers for 2018 for EU28 show that 37% of the total EOL tyres (1.2 million) were used as an energy source, 55% (1.7 million tons) were recycled, by being granulated to be used as raw material for different purposes and 3% was used for engineering purposes. The remaining 5 % were unknown.

EOL tyres have multiple unique characteristics that make them versatile and suitable to be used as raw material in several different applications, which are presented in this report. Examples include rubber asphalt, rubber in artificial turfs, used as a lightweight material, etc.

Granulated rubber has registered a significant reduction in usage in the last 5 years in Sweden, due to the reduction of usage in artificial fields. This report introduces several practices to be implemented in artificial fields, that help the reduction of microplastics dispersed into Nature. A potential solution would be the introduction of notification obligations for facilities using artificial grass, to comply with the suggested practices. The notification obligation should be applied to all the artificial grass facilities, and not only the ones using granulated rubber from tyres. However, there is also the need to assure that rubber does not expose any risk to the users.

Regarding the environmental analysis, the use of these end-of-life tyres may reduce the extraction of virgin materials as well as a reduction in energy use. However, tyres may contain toxic substances; thereby the human and environmental risks, in the different applications have not yet been studied enough to draw conclusions regarding health and environmental impacts. Our suggestion is, therefore, the performance of more risk assessment studies, for each EOL tyres application, as well as a sustainability assessment showing and evaluating the positive and negative health and environmental impacts. Another suggestion is the implementation of scientifically and risk-based regulations that define substances limits for tyre-derived products; it would potentially allow that user's and contractors to have more trust and safety to use EOL tyre products.

EOL tyres are perceived as waste material, instead of potential raw material. The use of EOL tyres needs to be branded among potential users and contractors. The suggestions from this study are:

- The creation of standards with specific physical and or chemical characteristics of tyre-derived materials;
- More environmental and economical studies in which EOL tyres applications are compared to virgin materials that are replaced;

Finally, the benefits of EOL tyre reuse and recycling are huge but need more lab and field studies that show and measure the potential benefits and evaluates the potential associated environmental and health risks from a holistic and systemic approach.

Referenser

Alam, I., Mahmood, U. A., & Khattak, N. (2015). Use of rubber as aggregate in concrete: a review. *International Journal of Advanced Structures and Geotechnical Engineering*, *4*(2), 92–96.

Albino, V., Dangelico, R. M., Natalicchio, A., & Yazan, D. M. (2011). alternative energy sources in cement manufacturing. *Network for Business Sustainability*, 1–139.

Alfayez, S. A., Suleiman, A. R., & Nehdi, M. L. (2020). Recycling tire rubber in asphalt pavements: state of the art. *Sustainability*, *12*(21), 9076.

Amari, T., Themelis, N. J., & Wernick, I. K. (1999). Resource recovery from used rubber tires. *Resources Policy*, *25*(3), 179–188. https://doi.org/10.1016/S0301-4207(99)00025-2

Asaro, L., Gratton, M., Seghar, S., & Hocine, N. A. (2018). Recycling of rubber wastes by devulcanization. *Resources, Conservation and Recycling*, *133*, 250–262.

Azemi, Q., & Lindblom, E. (2016). *Cirkulär ekonomi i däckbranschen*.

Bianco, I., Panepinto, D., & Zanetti, M. (2021). End-of-Life Tyres: Comparative Life Cycle Assessment of Treatment Scenarios. *Applied Sciences*, *11*(8), 3599.

Birkholz, D. A., Belton, K. L., & Guidotti, T. L. (2003). Toxicological evaluation for the hazard assessment of tire crumb for use in public playgrounds. *Journal of the Air & Waste Management Association*, *53*(7), 903–907.

Björklund, K., Cousins, A. P., Strömvall, A.-M., & Malmqvist, P.-A. (2009). Phthalates and nonylphenols in urban runoff: Occurrence, distribution and area emission factors. *Science of the Total Environment*, *407*(16), 4665–4672.

Brasileiro, L., Moreno-Navarro, F., Tauste-Martínez, R., Matos, J., & Rubio-Gámez, M. del C. (2019). Reclaimed polymers as asphalt binder modifiers for more sustainable roads: A review. *Sustainability*, *11*(3), 646.

Campbell-Johnston, K., Calisto Friant, M., Thapa, K., Lakerveld, D., & Vermeulen, W. J. V. (2020). How circular is your tyre: Experiences with extended producer responsibility from a circular economy perspective. *Journal of Cleaner Production*, *270*(May), 122042. https://doi.org/10.1016/j.jclepro.2020.122042

Celeiro, M., Armada, D., Ratola, N., Dagnac, T., de Boer, J., & Llompart, M. (2021). Evaluation of chemicals of environmental concern in crumb rubber and water leachates from several types of synthetic turf football pitches. *Chemosphere*, *270*, 128610.

Celeiro, M., Lamas, J. P., Garcia-Jares, C., Dagnac, T., Ramos, L., & Llompart, M. (2014). Investigation of PAH and other hazardous contaminant occurrence in recycled tyre rubber surfaces. Case-study: restaurant playground in an indoor shopping centre. *International Journal of Environmental Analytical Chemistry*, *94*(12), 1264–1271.

Chen, S.-J., Su, H.-B., Chang, J.-E., Lee, W.-J., Huang, K.-L., Hsieh, L.-T., Huang, Y.-C., Lin, W.-Y., & Lin, C.-C. (2007). Emissions of polycyclic aromatic hydrocarbons (PAHs) from the pyrolysis of scrap tires. *Atmospheric Environment*, *41*(6), 1209–1220.

Cheng, H., Hu, Y., & Reinhard, M. (2014). Environmental and health impacts of artificial turf: a review. *Environmental Science & Technology*, *48*(4), 2114–2129.

Cho, S. D., Kim, J. M., Kim, J. H., & Lee, K. W. (2007). Utilization of waste tires to reduce railroad vibration. *Materials Science Forum*, *544*, 637–640.

Clauzade, C., Osset, P., Hugrel, C., Chappert, A., Durande, M., & Palluau, M. (2010). Life cycle assessment of nine recovery methods for end-of-life tyres. *The International Journal of Life Cycle Assessment*, *15*(9), 883–892.

Dick, D. T., & Agboola, O. (2020). Pyrolysis of waste tyre for high-quality fuel products: A review. *AIMS Energy*, *8*(5), 869–895.

Djadouni, H., Trouzine, H., Correia, A. G., & da Silva Miranda, T. F. (2019). Life cycle assessment of retaining wall backfilled with shredded tires. *The International Journal of Life Cycle Assessment*, *24*(3), 581–589.

Duda, A., Kida, M., Ziembowicz, S., & Koszelnik, P. (2020). Application of material from used car tyres in geotechnics—an environmental impact analysis. *PeerJ*, *8*, e9546.

Edeskar, T. (2006). Use of tyre shreds in civil engineering applications: technical and environmental properties. *Theses*. http://epubl.ltu.se/1402-1544/2006/67/index-en.html

Edeskär, T. (2006). *Use of tyre shreds in civil engineering applications: technical and environmental properties*. Luleå tekniska universitet.

Fathali, M., Esmaeili, M., & Nejad, F. M. (2019). Influence of tire-derived aggregates mixed with ballast on ground-borne vibrations. *Journal of Modern Transportation*, *27*(4), 355–363.

Fazli, A., & Rodrigue, D. (2020a). Recycling waste tires into ground tire rubber (GTR)/rubber compounds: A review. *Journal of Composites Science*, *4*(3), 103.

Fazli, A., & Rodrigue, D. (2020b). Waste rubber recycling: A review on the evolution and properties of thermoplastic elastomers. *Materials*, *13*(3), 782.

Gheni, A., Liu, X., ElGawady, M. A., Shi, H., & Wang, J. (2018). Leaching assessment of eco-friendly rubberized chip seal pavement. *Transportation Research Record*, *2672*(52), 67–77.

Gieré, R., Smith, K., & Blackford, M. (2006). Chemical composition of fuels and emissions from a coal+ tire combustion experiment in a power station. *Fuel*, *85*(16), 2278–2285.

Grammelis, P., Margaritis, N., Dallas, P., Rakopoulos, D., & Mavrias, G. (2021). A Review on Management of End of Life Tires (ELTs) and Alternative Uses of Textile Fibers. *Energies*, *14*(3), 571. https://doi.org/10.3390/en14030571

Halsband, C., Sørensen, L., Booth, A. M., & Herzke, D. (2020). Car tire crumb rubber: Does leaching produce a toxic chemical cocktail in coastal marine systems? *Frontiers in Environmental Science*, *8*, 125.

Hellman, F., Eklöf, I., & Kraft, L. (2017). *Återvinning av däck i anläggningskonstruktioner: bättre resursutnyttjande av ett högvärdigt material*. Statens väg-och transportforskningsinstitut.

Hennebert, P., Lambert, S., Fouillen, F., & Charrasse, B. (2014). Assessing the environmental impact of shredded tires as embankment fill material. *Canadian Geotechnical Journal*, *51*(5), 469–478.

Hylands, K. N., & Shulman, V. (2003). *Civil engineering applications of tyres*. Viridis.

Järlskog, I., Strömvall, A.-M., Magnusson, K., Galfi, H., Björklund, K., Polukarova, M., Garção, R., Markiewicz, A., Aronsson, M., & Gustafsson, M. (2021). Traffic-related microplastic particles, metals, and organic pollutants in an urban area under reconstruction. *Science of the Total Environment*, *774*, 145503.

Johansson, K. (2018). Life cycle assessment of two end-of-life tyre applications: artificial turfs and asphalt rubber. *Ragn-Sells Däckåtervinning AB*.

JOHANSSON, M. (2019). *Designperspektiv och konstruktion-Hur konstrueras en sluten hållbar konstgräsplan för fotboll?*

Kalbe, U., Krüger, O., Wachtendorf, V., Berger, W., & Hally, S. (2013). Development of leaching procedures for synthetic turf systems containing scrap tyre granules. *Waste and Biomass Valorization*, *4*(4), 745–757.

Karagiannidis, A., & Kasampalis, T. (2010). Resource recovery from end-of-life tyres in Greece: A field survey, state-of-art and trends. *Waste Management & Research*, *28*(6), 520–532.

Karri, A., & Hellwig, S. (2015). *Comparing rubber modified asphalt to conventional asphalt. Assessment of Trafikverket's road survey tool*.

Kilander, S. (2019). *How can artificial intelligence-based sorting solutions support the realisation of circular economy and closed loop recycling of scrap tyres: A case study at Ragn-Sells*.

Kraft, L., Rogers, P., Eriksson Brandels, A., Gram, A., Trägårdh, J., & Wallqvist, V. (2015). Experimental rubber chip concrete mixes for shock absorbent bike lane pavements. *3rd International Conference on Best Practices for Concrete Pavements, 28-30 October. 2015. Bonito, Brazil: IBRACON and USP*.

Laboy-Nieves, E. N. (2014). Energy recovery from scrap tires: A sustainable option for small islands like Puerto Rico. *Sustainability (Switzerland)*, *6*(5), 3105–3121. https://doi.org/10.3390/su6053105

Landi, D., Vitali, S., & Germani, M. (2016). Environmental analysis of different end of life scenarios of tires textile fibers. *Procedia Cirp*, *48*, 508–513.

Lapkovskis, V., Mironovs, V., Kasperovich, A., Myadelets, V., & Goljandin, D. (2020). Crumb Rubber as a Secondary Raw Material from Waste Rubber: A Short Review of End-Of-Life Mechanical Processing Methods. *Recycling*, *5*(4), 32.

Leung, D. Y. C., & Wang, C. L. (2003). Fluidized-bed gasification of waste tire powders. *Fuel Processing Technology*, *84*(1–3), 175–196.

Levendis, Y. A., Atal, A., Carlson, J., Dunayevskiy, Y., & Vouros, P. (1996). Comparative study on the combustion and emissions of waste tire crumb and pulverized coal. *Environmental Science & Technology*, *30*(9), 2742–2754.

Llompart, M., Sanchez-Prado, L., Lamas, J. P., Garcia-Jares, C., Roca, E., & Dagnac, T. (2013). Hazardous organic chemicals in rubber recycled tire playgrounds and pavers. *Chemosphere*, *90*(2), 423–431.

López, F. A., Centeno, T. A., Alguacil, F. J., & Lobato, B. (2011). Distillation of granulated scrap tires in a pilot plant. *Journal of Hazardous Materials*, *190*(1–3), 285–292.

Maderuelo-Sanz, R., Nadal-Gisbert, A. V, Crespo-Amorós, J. E., & Parres-García, F. (2012). A novel sound absorber with recycled fibers coming from end of life tires (ELTs). *Applied Acoustics*, *73*(4), 402–408.

Maeda, R. K. (2016). *Water quality evaluation of tire derived aggregate*.

Magnusson, S. (2015). *Systemanalys av konstgräsplaner: Miljö-och kostnadsaspekter*. Luleå tekniska universitet.

Martínez, J. D. (2021). An overview of the end-of-life tires status in some Latin American countries: Proposing pyrolysis for a circular economy. *Renewable and Sustainable Energy Reviews*, *144*(April), 111032. https://doi.org/10.1016/j.rser.2021.111032

Montella, G., Mastroianni, G., & Serino, G. (2012). Experimental and numerical investigations on innovative floating-slab track including recycled rubber elements. *Proceedings of ISMA2012-USD2012, Belgium*, 2869–2879.

Mora, P., Alarcón, A., Sánchez-Martín, L., & Llamas, B. (2021). Biomass Content in Scrap Tires and Its Use as Sustainable Energy Resource: A CO2 Mitigation Assessment. *Sustainability*, *13*(6), 3500.

Nkosi, N., Muzenda, E., Gorimbo, J., & Belaid, M. (2021). Developments in waste tyre thermochemical conversion processes: gasification, pyrolysis and liquefaction. *RSC Advances*, *11*(20), 11844–11871.

Piotrowska, K., Kruszelnicka, W., Bałdowska-Witos, P., Kasner, R., Rudnicki, J., Tomporowski, A., Flizikowski, J., & Opielak, M. (2019). Assessment of the environmental impact of a car tire throughout its lifecycle using the LCA method. *Materials*, *12*(24), 1–25. https://doi.org/10.3390/MA12244177

Pipilikaki, P., Katsioti, M., Papageorgiou, D., Fragoulis, D., & Chaniotakis, E. (2005). Use of tire derived fuel in clinker burning. *Cement and Concrete Composites*, *27*(7–8), 843–847. https://doi.org/10.1016/j.cemconcomp.2005.03.009

Polukarova, M., Markiewicz, A., Björklund, K., Strömvall, A.-M., Galfi, H., Sköld, Y. A., Gustafsson, M., Järlskog, I., & Aronsson, M. (2020). Organic pollutants, nano-and microparticles in street sweeping road dust and washwater. *Environment International*, *135*, 105337.

Pronk, M. E. J., Woutersen, M., & Herremans, J. M. M. (2020). Synthetic turf pitches with rubber granulate infill: are there health risks for people playing sports on such pitches? *Journal of Exposure Science & Environmental Epidemiology*, *30*(3), 567–584.

Qiang, W., Li, J., Yunlong, W., Xiaojie, Q., & Guotian, W. (2020). Discussion on Tire Retreading and Reuse Technology. *IOP Conference Series: Earth and Environmental Science*, *512*(1). https://doi.org/10.1088/1755-1315/512/1/012146

Ramirez-Canon, A., Muñoz-Camelo, Y. F., & Singh, P. (2018). Decomposition of used tyre rubber by pyrolysis: Enhancement of the physical properties of the liquid fraction using a hydrogen stream. *Environments - MDPI*, *5*(6), 1–12. https://doi.org/10.3390/environments5060072

Ramos, G., Alguacil, F. J., & López, F. A. (2011). The recycling of end-of-life tyres. Technological review(). *Revista de Metalurgia (Madrid)*, *47*(3), 273–284. https://doi.org/10.3989/revmetalm.1052

Rashid, Y., Alnaimat, F., & Mathew, B. (2018). Energy performance assessment of waste materials for buildings in extreme cold and hot conditions. *Energies*, *11*(11), 3131.

Reike, D., Vermeulen, W. J. V, & Witjes, S. (2018). The circular economy: new or refurbished as CE 3.0?—exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. *Resources, Conservation and Recycling*, *135*, 246–264.

Reschner, K. (2008). Scrap tire recycling: A summary of prevalent disposal and recycling methods. *Retrieved from. Acesso Em*, *10*.

Roychand, R., Gravina, R. J., Zhuge, Y., Ma, X., Youssf, O., & Mills, J. E. (2020). A comprehensive review on the mechanical properties of waste tire rubber concrete. *Construction and Building Materials*, *237*, 117651.

Sandberg, U. (2010). Asphalt rubber pavements in Sweden: noise and rolling resistance properties. *INTER-NOISE 2010-39th International Congress on Noise Control Engineering 2010, 15-16 June 2010, Lisbon, Portugal*, 7379–7388.

Schneider, K., de Hoogd, M., Madsen, M. P., Haxaire, P., Bierwisch, A., & Kaiser, E. (2020). ERASSTRI-European risk assessment study on synthetic turf rubber infill–part 1: analysis of infill samples. *Science of The Total Environment*, *718*, 137174.

Seiwert, B., Klöckner, P., Wagner, S., & Reemtsma, T. (2020). Source-related smart suspect screening in the aqueous environment: search for tire-derived persistent and mobile trace organic contaminants in surface waters. *Analytical and Bioanalytical Chemistry*, *412*(20), 4909–4919.

Selbes, M., Yilmaz, O., Khan, A. A., & Karanfil, T. (2015). Leaching of DOC, DN, and inorganic constituents from scrap tires. *Chemosphere*, *139*, 617–623.

Selman, P. (2000). A sideways look at Local Agenda 21. *Journal of Environmental Policy and Planning*, *2*(1), 39–53.

Sienkiewicz, M., Kucinska-Lipka, J., Janik, H., & Balas, A. (2012). Progress in used tyres management in the European Union: A review. *Waste Management*, *32*(10), 1742–1751. https://doi.org/10.1016/j.wasman.2012.05.010

Singh, S., Nimmo, W., Gibbs, B. M., & Williams, P. T. (2009). Waste tyre rubber as a secondary fuel for power plants. *Fuel*, *88*(12), 2473–2480. https://doi.org/10.1016/j.fuel.2009.02.026

Thomas, B. S., & Gupta, R. C. (2016). A comprehensive review on the applications of waste tire rubber in cement concrete. *Renewable and Sustainable Energy Reviews*, *54*, 1323–1333. https://doi.org/10.1016/j.rser.2015.10.092

Tian, Z., Zhao, H., Peter, K. T., Gonzalez, M., Wetzel, J., Wu, C., Hu, X., Prat, J., Mudrock, E., & Hettinger, R. (2021). A ubiquitous tire rubber–derived chemical induces acute mortality in coho salmon. *Science*, *371*(6525), 185–189.

USEPA. (2019). *Synthetic Turf Field Tire Crumb Rubber Research Under the Federal Research Action Plan Final Report Part 1 – Tire Crumb Rubber Characterization Appendices*. *2*(July), 1–456. https://www.epa.gov/sites/production/files/2019-08/documents/synthetic_turf_field_recycled_tire_crumb_rubber_research_under_the_federal_research_action_plan_final_report_part_1_volume_2.pdf

Verschoor, A. J., van Gelderen, A., & Hofstra, U. (2021). Fate of recycled tyre granulate used on artificial turf. *Environmental Sciences Europe*, *33*(1), 1–15. https://doi.org/10.1186/s12302-021-00459-1

Vila, A., Pérez, G., Solé, C., Fernández, A. I., & Cabeza, L. F. (2012). Use of rubber crumbs as drainage layer in experimental green roofs. *Building and Environment*, *48*, 101–106.

Wang, T., Xiao, F., Zhu, X., Huang, B., Wang, J., & Amirkhanian, S. (2018). Energy consumption and environmental impact of rubberized asphalt pavement. *Journal of Cleaner Production*, *180*, 139–158.

Winternitz, K., Heggie, M., & Baird, J. (2019). Extended producer responsibility for waste tyres in the EU: Lessons learnt from three case studies – Belgium, Italy and the Netherlands. *Waste Management*, *89*, 386–396. https://doi.org/10.1016/j.wasman.2019.04.023

Yoon, S., Prezzi, M., Siddiki, N. Z., & Kim, B. (2006). Construction of a test embankment using a sand–tire shred mixture as fill material. *Waste Management*, *26*(9), 1033–1044.

Online References:

Aircrafttyres, 2021. https://aircrafttyres.com/2-uncategorised/248-retreading-cold-or-hot-explained

Andersson and Diener, 2020. Life Cycle Assessment of Resource Effectiveness in a Business Ecosystem of Heavy-Duty Truck Tires. https://www.ri.se/sites/default/files/2020-05/2020.03.Cirkd%C3%A4ck.LCA_Final_0.pdf

Austroads, 2021. Polymer Modified Binder (PMB). Available at: https://austroads.com.au/publications/pavement/agpt04k/selection-of-treatments/binders/polymer-modified-binder-pmb

BIPAVER (Retread industry's trade association), 2021, Yorick Lowin, personal communication 210623

Daekbranchens Miljoefond, 2021. https://www.daekbranchens-miljoefond.dk/english

Dackdebatt, 2019. Det våras för regummerade däck. https://www.dackdebatt.se/foretagaren/e/162/det-varas-for-regummerade-dack/

Dekkretur, 2021. How to make it work. https://www.dekkretur.no/media/1022/pioneers_of_producer_responsibility_150213.pdf

Däckbranschens, 2021. https://www.dackinfo.se/statistik/marknaden/

Däckbranschens, 2021b. Väggen mot hålbarhet inom Däckbranschen Sverige.

https://www.sdab.se/media/1652/vaegen-mot-haallbarhet-inom-daeckbranschen.pdf

Echa (2017) Recycled rubber infill causes a very low level of concern: https://echa.europa.eu/sv/-/recycled-rubber-infill-causes-a-very-low-level-of-concern

Ecogreenequipment, 2021. Ambient vs. Cryogenic Rubber Grinding. Ambient vs. Cryogenic Rubber Grinding (ecogreenequipment.com)

Ennuwa, 2021, Andreas Pettersson., personal communication 210622

ENVIRO, 2021. https://www.envirosystems.se/en/news/rise-project-oil-from-EOL-tyres-as-fuel-well-on-its-way-to-profitability/

ETRMA- European Tyre & Rubber Manufacturers' Association (Belgium), 2016. The socio-economic impact of truck tyre retreading in Europe The circular economy of tyres in danger. https://www.etrma.org/wp-content/uploads/2019/09/201611-ey_retreading_lr.pdf

ETRMA - European Tyre & Rubber Manufacturers' Association (Belgium), 2015. End-of-life Tyre REPORT 2015. https://www.etrma.org/wp-content/uploads/2019/09/elt-report-v9a-final.pdf

ETRMA - European Tyre & Rubber Manufacturers' Association (Belgium), 2010. A Valuable Resource with Growing Potential 2010 edition. Report downloaded from (May 2011)

ETRMA - European Tyre & Rubber Manufacturers' Association (Belgium), 2017. Annual Report 2017: Moving innovation that cares [WWW Document]. Annu. Rep. URL http://www.etrma.org/uploads/Modules/Documentsmanager/20170905---etrma-annual-report-2016-17---final.pdf.

EuRIC, 2021 – EuRIC Comment on tyre Eco-design to bost circular economy. https://www.euric-aisbl.eu/position-papers?filter_45=5

European Comission, 2015. Labels to show how retreaded tyres stack up against new tyres | Horizon 2020 (europa.eu)

European Comission, 2021.Introduction to toxicology. https://ec.europa.eu/health/ph_projects/2003/action3/docs/2003_3_09_a21_en.pdf

Eur-Lex, 2005. EC Directive 2005/69. Official Journal of the European Union, European

Commission, Brussels.

Naturvårsverket, 2020. Extended Producer Responsibility in Sweden. Extended Producer Responsibility in Sweden ISBN 978-91-620-6944-5. (naturvardsverket.se).

Pirelli,2021. How to maximise a tire life. https://www.pirelli.com/global/en-ww/road/how-many-kilometres-can-a-tyre-cover

Svensk Däckåtervinnings, 2021a. Svensk Däckåtervinnings Årsrapport för 2019 tryckt och klar - Svensk Däckåtervinning (sdab.se)

Svensk Däckåtervinnings, 2021b. https://www.sdab.se/en/facts/sdab/

Svensk Däckåtervinnings, 2021c. Eco-friendly water treatment with tyre rubber - Utility - Svensk Däckåtervinning (https://www.sdab.se/en/utility/undersidor-utility/eco-friendly-water-treatment-with-tyre-rubber-utility/)

Svensk Däckåtervinnings, 2021d. https://www.sdab.se/om-oss/statistik/

Scraptirenews, 2021, Tire Derived Aggregate. https://www.sdab.se/media/1550/tire-derived-aggregate-scrap-tire-news.pdf

Recytyre, 2021. https://www.recytyre.be/fr/chiffres-cles-de-recytyre

Regnell F, 2019. Dispersal of microplastic from a modern artificial turf pitch with preventive measures—case study Bergaviks IP, Kalmar, Ecoloop: 27. https://www.genan.eu/wp-content/uploads/2020/02/MP-dispersal-from-Bergavik-IP-Kalmar-Report.pdf

Radial Vs Bias and Region. Global Tire Market (2020 to 2025) - by Vehicle Type, Demand (globenewswire.com)

Ragn Sells, 2021. Däckets väg i återvinningsprocessen (ragnsellstyrerecycling.com)

Rengaskierratys, 2021. How to make it work. https://www...com/files/90/How_to_make_it_work_2014.pdf

Research and Markets, 2020. Global Tire Market (2020 to 2025) - by Vehicle Type, Demand Category, Tana, 2021. https://tana.fi/stories/finland-recycles-tyres/

Truebil, 2021. 7 Simple tips to extend the life of your tires. https://www.truebil.com/blog/7-simple-tips-to-extend-the-life-of-your-tires

UNEP, 2000. Technical guidelines on the identification and management of used tyres. Report. Basel Convention series/SBC No. 02/10, Secretariat of the Basel Convention, Châtelaine.

Ulinder, E., 2018, Rening av hushållsavlopp i markbädd uppbyggd av gummiklipp – Slutrapport efter 18 månaders drift, RISE Rapport, 2018-06-29, Referens JX57113-02, Rapportmall reningseffektivitet enligt EN 12566-3.docx (sdab.se)

VTI, Swedish National Road and Transport Research Institute 2019. Bindemedel [Binding agents]. https://www.vti.se/sv/Forskningsomraden/Bindemedel/

VTI, Swedish National Road and Transport Research Institute 2021. Potentiella styrmedel och åtgärder mot mikroplast från däck- och vägslitage

Kaushal Kishore et al., (NA). Waterproofing of Roff with discarded tyre rubber Crumb. Available at: https://www.engineeringcivil.com/waterproofing-of-roof-with-discarded-tyre-rubber-crumb.html

Kemikaliecentrum, 2018. Kemisk analys av gummigranulat. Available at: 32-2018-1511-Bilaga-5-Kemisk-analys-av-gummigranulat.pdf (bekogr.se)

3P Technik, 2019. HOW TO STOP MICROPLASTICS FROM ARTIFICIAL TURF SPORTS PITCHES POLLUTING OUR OCEANS. How to stop Microplastics from Artificial Turf Sports Pitches Polluting our Oceans - 3P Technik UK

Bilaga 1

Supplementary Information Table 1 - 10 Value Retention Options in CE (Reike et al., 2018)

Downcycling						
R#	**CE concept**	**Object**	**Owner**	**Function**	**Key activity customer**	**Key activity market actor**
R9	Re-mine	Landfilled material	Local authorities; Land owner	New	Buy and use secondary materials	Grubbing, cannibalizing, selling (South)/ high-tech extracting, reprocessing (North)
R8	Recover (Energy)	Energy content	Collector, municipality, energy company, waste mgt. company	New	Buy and use energy (and/or distilled water)	Energy production as by-product of waste treatment
R7	Re-cycle	Materials	Collector, processor, waste mgt. company	Original or new	Dispose separately; buy and use secondary materials	Acquire, check, separate, shred, distribute, sell
R6	Re-purpose (ReThink)	Components in composite products (new product with old parts)	New user	New	Buy new product with new function	Design, develop, reproduce, sell

Product upgrade						
R#	**CE concept**	**Object**	**Owner**	**Function**	**Key activity customer**	**Key activity market actor**
R5	Re-manufacture	Components in composite products (old product with new parts)	Original or new customer	Original, upgraded	Return for service under contract or dispose	Replacement of key modules or components if necessary, decompose, recompose
R4	Re-furbish	Components of composite products (old product with new parts)	Original or new customer	Original, upgraded (large complex products)	Return for service under contract or dispose	Replacement of key modules or components if necessary
R3	Repair	Components of composite products (old product with new parts)	1st or 2nd consumer	Original	Making the product work again by repairing or replacing deteriorated parts	Making the product work again by repairing or replacing deteriorated parts

Client/user choices						
R#	**CE concept**	**Object**	**Owner**	**Function**	**Key activity customer**	**Key activity market actor**
R2	Re-sell/Re-use	Product	Consumer	Original	Buy 2nd hand, or find buyer for your non-used produced/possibly some cleaning, minor repairs	Buy, collect, inspect, clean, sell
R1	Reduce	Product	Consumer	N.a.	Use less, use longer; recently: share the use of products	See 2nd life cycle Redesign
R0	Refuse	Product	Potential consumer	N.a.	Refrain from buying	See 2nd life cycle Redesign

Supplementary Information Table 2 - European legislation concerning treatment of End of Life Tres from:(Grammelis et al., 2021)

Year	Title—Reference	Content
1975	Council Directive 75/442/EEC (modified by Directive 2008/98/EC)	ELTs characterized as non-hazardous wastes
1993	Council Regulation (EEC) No 259/93	ELTs characterized as non-hazardous wastes
1999	Council Directive 1999/31/EC	Prohibition of tires disposed in landfills (whole tires 2003-shredded tires 2006)
2000	Commission Decision 2000/532/EC	End-of-life vehicles are coded as “16 01 03”
2000	Directive 2000/76/EC	Specific emission standards for the cement industry with effect from 2002
2000	Directive 2000/53/EC	Recovery of 85% of vehicles to be disposed off, with effect from 2006, with compulsory removal of tires from the vehicle
2001	Directive 2000/53/EC	ELTS classification code 16.01.03, (from 1 January 2002)
2005	Directive 2000/53/EC	Features the need for additional actions in order to determine the optimal environmental options and targets for wastes. Includes the principle of producer responsibility
2008	Directive 2008/98/EC	Basic principles of waste management (“the polluter pays” & “waste management hierarchy”). Introduces the waste end principle.
2009	Directive 2009/28/EC	Mandating the levels of renewable energy use within the European Union from 2009 to 2021
2010	CEN TS 14,243 “Materials produced from end of life tires—Specification of categories based on their dimension(s) and impurities, and methods for determining their dimension(s) and impurities”	Mandating the levels of renewable energy use within the European Union from 2009 to 2021
2018	CEN TS 14,243 “Materials produced from end of life tires—Specification of categories based on their dimension(s) and impurities, and methods for determining their dimension(s) and impurities”	Amendments to Directive 2008/98/EC on waste (incl. legislation for treatment of waste)

ABOUT VTI

The Swedish National Road and Transport Research Institute (VTI), is an independent and internationally prominent research institute in the transport sector. Our principal task is to conduct research and development related to infrastructure, traffic and transport. We are dedicated to the continuous development of knowledge pertaining to the transport sector, and in this way contribute actively to the attainment of the goals of Swedish transport policy.

Our operations cover all modes of transport, and the subjects of pavement technology, infrastructure maintenance, vehicle technology, traffic safety, traffic analysis, users of the transport system, the environment, the planning and decision making processes, transport economics and transport systems. Knowledge that the institute develops provides a basis for decisions made by stakeholders in the transport sector. In many cases our findings lead to direct applications in both national and international transport policies.

VTI conducts commissioned research in an interdisciplinary organisation. Employees also conduct investigations, provide counseling and perform various services in measurement and testing. The institute has a wide range of advanced research equipment and world-class driving simulators. There are also laboratories for road material testing and crash safety testing.

In Sweden VTI cooperates with universities engaged in related research and education. We also participate continuously in international research projects, networks and alliances.

The Institute is an assignment-based authority under the Ministry of Infrastructure. The Institute holds the quality management systems certificate ISO 9001 and the environmental management systems certificate ISO 14001. Certain test methods used in our labs for crash safety testing and road materials testing are also certified by Swedac.

vti

Swedish National Road and Transport Research Institute • www.vti.se • vti@vti.se • +46 (0)13–20 40 00