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Challenges and recommendations

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The need for environmental regulation of tires: Challenges and recommendations☆

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ABSTRACT

The interest in tire wear particles (TWPs), generated from abrasion of tires, have gained traction over the past few years, both in regards to quantifying particulate emissions, leaching of different compounds, toxicity, and analytical methods. The life of a tire, from cradle to end-of-life, crosses over different scenarios during its lifetime and transcends environmental compartments and legislative areas, underlining the need for a collective approach. Sustainability for a tire encompasses the use of raw materials, recycling of raw materials, circular economy and material sourcing. The tire industry is currently making significant efforts towards a greener and more sustainable production considering reduction of CO_2-emissions, recycling, material sources and implementing the use of biomass from plants rather than oil-derived alternatives. In this paper, we aim to analyze and discuss the need for environmental regulation of tires in order to provide a series of targeted recommendations for future legislation. Our study shows that the numerous regulations related to tires focus on chemicals, manufacturing, raw materials, use of tires on roads, waste handling, safety and polycyclic aromatic hydrocarbons (PAHs) in different life cycle stages of a tire. However, none directly addresses the contribution of TWPs to the environment. Despite the overall good intentions of the existing regulations, there is a lack of focus on the compounds that partition from the tire and disperse in the environment, their mixture effects, and the transformative products from the parent compounds in the environment. Therefore, a renewed focus is needed on risk assessment of complex mixtures like TWPs. Thus, transparency in regard to use of chemicals in TWP, mixtures, minimization of emissions, and capture of particulate pollution should be a priority.

1. Introduction

The interest in tire wear particles (TWPs), generated from abrasion of tires, have gained traction over the past few years, in regard to particulate emissions (Baensch-Baltruschat et al., 2021), leaching of different compounds (Halsband et al., 2020; Kolomijeca et al., 2020; Tian et al., 2021), toxicity (Khan et al., 2019; Capolupo et al., 2020; Halle et al., 2021), and analytical methods (Peter et al., 2018; Wagner et al., 2018; Klöckner et al., 2019; Goβmann et al., 2021). Furthermore, literature on generation of TWPs (Baensch-Baltruschat et al., 2020) and detection of TWPs in the environment (Rausch et al., 2022; Rødland et al., 2022) has been published in the past years. An estimated average of 0.8 kg (ranging from 0.2 to 5.5 kg depending on country) of TWPs per year is transferred to the environment per capita (Kole et al., 2017). The car tire production in the EU was 300 million in 2020 (ETRMA, 2020a), and around 3.2 million tonnes of end-of-life tires (ELTs) result every year in the EU (ETRMA, 2018). Around 43% of ELTs are used as recycled granules of which 21% are used for artificial turf, that is 600 million tons of crumb tire granulate estimated to be produced and spread out as turf per year (RecyBEM, 2015). Most recently, the distribution of tire-road-wear-particles (TRWPs) from German roads was estimated. Between 12 and 20% of the TRWPs was found to be released to surface

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waters, 66–77% being transported to road banks and soils near roads and finally, 5% of TRWPs went into the fine air-fraction (Baensch-Baltruschat et al., 2021). Chemicals commonly used in tire manufacturing, such as aniline, 1-octanethiol, 6PPD and benzothiazole, and their derivates, have been shown to be toxic and have on many occasions be found to be present in tires, tire particles and leachate (Marwood et al., 2011; Halle et al., 2021; Tian et al., 2021). These substances only comprise a minute part of the complex tire matrix, underlining the multiplicity and scale of the issue at hand.

The complete lifespan of tires comprises five stages: raw materials, production, use, ELTs and repurposing (Fig. 1). First, the raw materials are harvested and produced on process plants where more than 200 raw materials can be used to produce a tire (ETRMA, 2020a). The main raw material in tires is polymeric substances including natural rubber. Substances often added in tire production processes, apart from the main raw materials, natural and synthetic rubbers (butyl, styrene-butadiene rubber, butyl-rubber), include a diverse suite of chemicals such as, trace metals, oils, fillers (silica, carbon black), sulphur, resins, anti-aging agents (antioxidants) and vulcanization accelerators (Piotrowska et al., 2020). Furthermore, textile cords are also part of the tire production, consisting of weaves of numerous ultra-thin viscose, nylon, aramid and polyester fibers (Piotrowska et al., 2020). In raw materials and production phases, the focus for a circular system, has primarily been to reduce waste, employ raw materials sustainably, and replace materials that can hinder recycling efforts downstream (ETRMA, 2020a).

During the tire use on the road, it will generate micronized rubber particles from abrasion, where they will mix with other materials and particulates deposited on the road (e.g. minerals, metals and salts) (Kreider et al., 2010; Unice et al., 2013; Kovochich et al., 2021). Estimates suggest that 10–17% of a tire is transferred into the environment as TWPs due to abrasion (Lassen et al., 2015; Unice et al., 2019a, 2019b). These particles have different fates depending on the environmental compartment they enter (Halle et al., 2020) and can thus end up in water, soil or air (Wik and Dave, 2009; Baensch-Baltruschat et al., 2021). To optimize tire use different technologies have been implemented to help consumers, e.g. indication of low tire pressure. Furthermore, it has been suggested that an improved driving pattern, e.g. proper tire pressure and mindful acceleration and cornering, can minimize the amount of particulate debris derived from driving (Andersson-sköld et al., 2020). Retreading of truck tires is also an effort to reduce overall consumption as one tire can be re-treaded three times, however, a decline in the use of re-treaded tires has been observed between 2011 and 2020 (ETRMA, 2021).

Finally, worn tires are recirculated back as ELTs through different recycling management systems in the EU. To date, there are three different recycling management measures in the EU, where the extended producer responsibility (EPR) is the most common. A handful of countries use a liberal system, and finally, Denmark and Croatia have a tax system, and thus, are part of a governmentally controlled system. The Nordic countries, Finland, Sweden and Norway started the EPR ELT management back in 1996, and since then many countries followed, the latest being Ireland in 2017 (ETRMA, 2022a,b). Around 3.2 million tonnes of ELTs are used every year in the EU (ETRMA, 2018). Of these, approximately 33% was used in energy recovery and 62% in material recovery (ETRMA, 2022a,b). ELTs contain energy that can be recovered through incineration, as have been done for e.g. cement kilns, where they have been used as primary or secondary fuel sources in the production of steam, electricity, cement, lime, paper and steel (Dabic-Miletic et al., 2021). Pyrolysis is another type of incineration that has a higher energy recovery value than regular incineration (70%) and it is

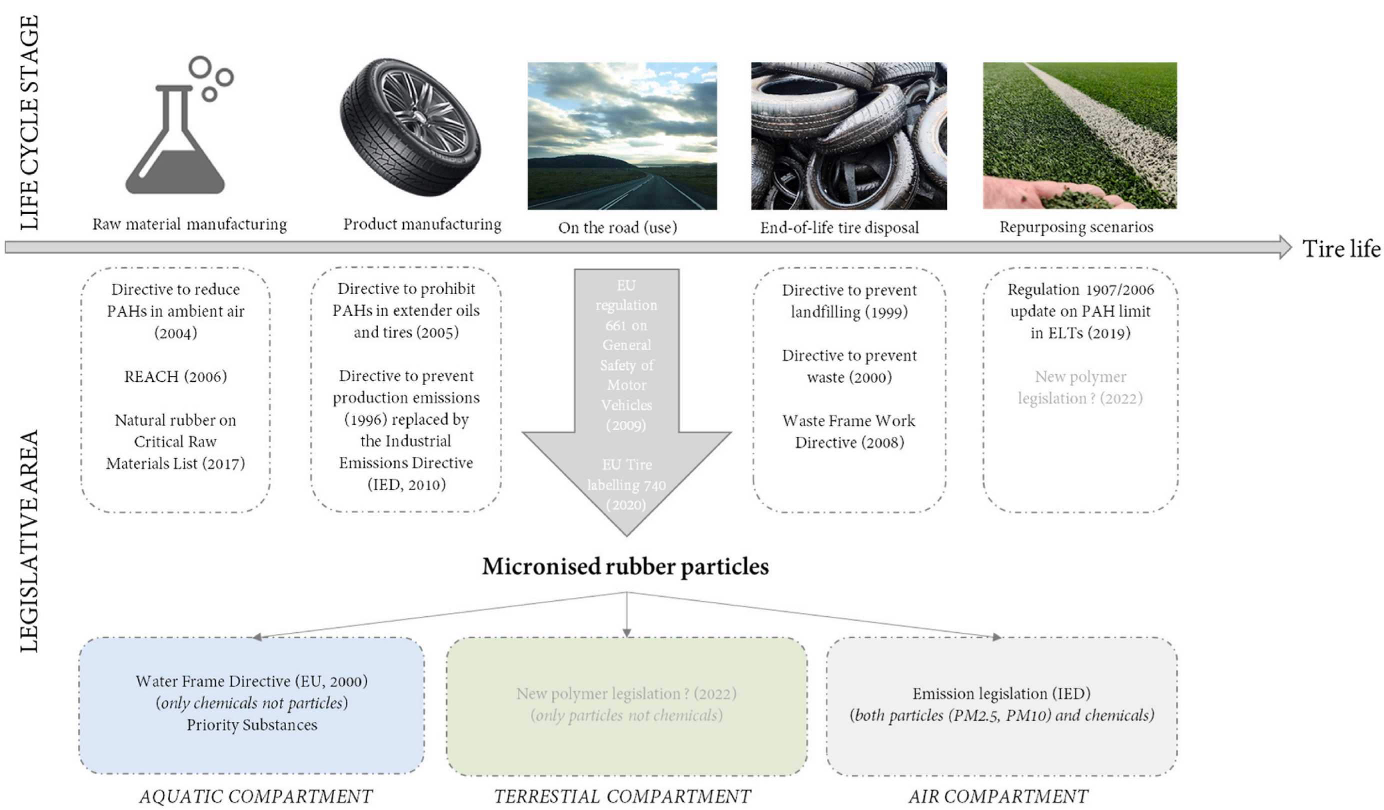

Fig. 1. The lifespan of a tire is illustrated as five major events, from raw material manufacturing, to product manufacturing, lifetime on the road, end-of-life tire disposal and finally as repurposing scenarios. Each lifecycle stage is governed by different legislative areas, complicating the overall risk assessment of potential hazard to the environment. Some legislations overlap several life stages of a tire (e.g. Water Frame Directive, IED and possibly the new polymer legislation) albeit legislation regarding and directly targeting micronized rubber particles in different environmental compartments is amiss or unfulfilling by not targeting both particulate matter and the specific chemicals related to wear and tear of tires.

considered by some as one of the most eco-effective technologies for the treatment of ELTs (Xu et al., 2020). That said, any actual energy efficiency have not been confirmed by data, and many operational and technical problems need to be solved before pyrolysis is considered both reliable and economically feasible (European Parliament, 2017). During pyrolysis, ELTs can be reprocessed into recovered carbon black and tire-derived oil that can be used as input feedstock for chemical plants and other industries (Weibold Consulting, 2022). This has led to an increased focus on how to most effectively recycle the rare and/or expensive elements of a tire. For example, an average 10 kg car tire contains about 3 kg carbon black (RCB, 2022). However, burning 1 kilo of rubber corresponds to burning 1 kilo of oil, although 6 kilos of oil have been used in the process of producing 1 kilo of tires. Consequently, several authors have argued that only a small percentage of the initial cost incurred in producing a tire is regained in the incineration process and that burning ELTs is a waste of valuable raw materials (BANREC, 2022). In regard to the material recycling, ELTs can be mechanically sheared into shreds (25–300 mm in size) and be used in civil engineering applications. This granulate is called Tire Derived Aggregate (TDA) and has many functions from foundation for roads and railways to draining material and insulation (ETRMA, 2022a,b).

From the above, it is clear that many different legislative areas are in work over the course of a tire's lifespan. In this paper, we aim to analyze and discuss the need for environmental regulation of tires in order to provide a series of targeted recommendations. We will first map the regulations that apply along the life cycle of tires in the EU and discuss advantages and disadvantages from a scientific-technical perspective. Secondly, we will couple environmental risk assessment parameters to these regulations to understand where and to what extent which regulation applies in order to identify and analyze knowledge gaps. Lastly, we discuss the complexity of the tire matrix in relation to risk assessment and regulations, and provide a series of recommendations.

2. Regulation of tires along life cycle

In order to analyze the regulation of tires throughout their life cycle, an overview of the most relevant legislations covering tires and tire components is provided in Table 1. Fig. 1 illustrates the life cycle of a tire from raw material to ELT and pinpoints some of the main legislative events at each life stage. In the following sections the regulations affecting each life stage will be analysed.

2.1. Regulation of raw materials

Natural rubber has been recognized as a "critical raw material" by the European Commission since 2017, and is subjected to the EU Raw Materials initiative (EC, 2017a; 2020a). The list of critical raw materials is used by the European Commission to support policy development for instance with regard to identifying investment needs and when guiding research and innovation under EU's research programs (ECHA, 2020a). The list of critical raw materials is also specifically mentioned as being relevant for the circular economy and the European green deal's circular economy action plan. The action plan aims to decouple growth from resource use, through sustainable product design and mobilization of potential secondary raw materials in order to minimize use of pristine raw materials (EC, 2020b).

The production of synthetic rubber falls under the scope of the Industrial Emissions Directive (IED) as the main EU instrument to regulate emissions of pollutants from industrial installations (EC, 2010). The IED aims to achieve a high level of protection of human health and environment in particular through the use of Best Available Techniques (BAT). Around 50000 installations undertaking the activities listed in Annex I of the IED are required to cooperate in accordance with a permit granted by the member states authorities. The IED is based on several pillars. One is that an interrogated approach has to be taken, meaning that permits have to take into account the whole environment of the

Table 1
Chronologically lists the main legislative interests spanning a tire's life cycle. The majority of legislation affects the production stage and re-use or re-purposing scenarios, with a focus on ELT granulates.

Year	Legislation	Description	Reference
1996	Council Directive 96/61/EC (IPPC Directive, Article 16(2)) Replaced in 2010 by the Industrial Emissions Directive (IED)	Measures to prevent or reduce emissions to air water and land from activities covered by the Annex I of the Directive, including measures concerning waste, in order to achieve a high level of protection of the environment.	EC (2010)
1999	Directive 1999/31/EU	To prohibit landfilling of waste tires.	EC (1999)
2000	Directive 2000/53/EU	To prevent waste from vehicles and their components.	EC (2000a)
2000	Water Framework Directive	EU directive committing EU member states to achieve good qualitative and quantitative status of all water bodies.	EC (2000b)
2004	Directive 2004/107/EC PAHs in ambient air	Target value for benzo(a) pyrene, is 1 ng/m^3, expressed as the total content in the PM_{10} fraction averaged over a year.	EC (2004)
2005	Directive 2005/69/EC PAHs in extender oils and tyres	To prohibit the presence of PAHs in extender oils used to produce tires. The directive prohibits marketing and use of extender oils in tire production, if they contain more than 1 mg/kg Benzo (a)pyrene (BaP), or more than 10 mg/kg of the sum of the 8 listed PAHs in Annex I.	EC (2005)
2006	REACH, the European chemical legislation	Individual substance information requirements are determined according to tonnage. Tires are seen as whole products, referred to as 'articles'. Polymers are exempted from registration obligations under REACH, but not from authorization and restriction. Requires importers and suppliers to collect information from their suppliers about the chemicals in the tires, with specific attention to whether any of the chemicals are on the European Chemicals Agency's (ECHAs) REACH Candidate List as substances of very high concern (SVHCs).	EC (2006)
2007	Polymers of low concern	OECD expert group decides that polymeric materials generally have low hazard potential.	OECD (2009)
2008	Waste Framework Directive	EU initiative to protect the environment and human health by preventing or reducing adverse impacts of waste generation and management.	ECHA (2008)
2009	EU Regulation 661/2009		EC (2009)

(*continued on next page*)

Table 1 (*continued*)

Year	Legislation	Description	Reference
	General safety of motor vehicles	To fulfill demands of tires in use in the EU.	
2009	EU Regulation 2020/740 Tire labelling, updated 2020	Serves to better inform and empower consumers when buying tires. Two additional parameters have been added per 2021, both related to the use in extreme climate conditions.	(ECHA, 2020)
2017	Natural Rubber recognized as a "critical raw material" by EC	Subject to the EU raw material initiative, used to support policy development and relevant for circular economy and the Green Deal's Circular Economy Action Plan.	(EC, 2017a; EC, 2020b; EC, 2020a)
2019	Limit of PAH content in ELTs was implemented (Annex XV, Regulation (EC) No 1907/2006).	Limit of 20 mg/kg of PAHs in granules used as infill, the limit will apply from August 10th' 2022.	EC (2021)
2022	REACH polymer legislation?	Development of a possible proposal for registration of certain kinds of polymers, mandate has been extended to late 2022.	(EC, 2022a,b)

installation covering e.g., emissions to air, water and land, generation of waste, use of raw materials, energy efficiency and prevention of accidents. The Environmental Limit Values included in the permit must be based on BAT. A BAT reference document (BREF) has been prepared entitled "Best Available Techniques for the Production of Polymers" as required under Article 16(2) of Council Directive 96/61/EC (IPPC Directive) (EC, 2007). BREFs are prepared by a multi-stakeholder process coordinated by EU IRC Seville however the BREF on production of polymers has not been updated since 2007 and does not include any consideration of TWPs. The BAT-conclusions are adopted by the Commissions as Implementing Decisions and the IED required that these BAT-conclusions are the reference for setting permit conditions. The pollutant to be assessed into air and water are listed in Annex II of the IED and this includes a general reference to all substances listed in Annex X of the Water Frame Directive (Directive, 2000/60/EC). Either Annex II of IED or Annex X of the WFD mentions TWPs.

Often, polymers are tagged as polymers of low concern (PLC), and by 2007, the OECD Expert Group on Polymers agreed that, *"Polymers of low concern are those deemed to have insignificant environmental and human health impacts"* (OECD, 2009a,b). Thus, there was agreement within the OECD that polymeric chemicals meeting these criteria have a low hazard potential (Henry et al., 2018). Furthermore, Section 3.2 of the Guidance for monomers and polymers states: *"Following Article 2(9) of REACH, any polymer meeting the criteria of Article 3(5), whether natural polymers or not, does not have to be registered"*. Due to the high molecular weight of polymer molecules they are generally regarded as representing a low concern, and are exempted from registration and evaluation under REACH. This consequently applies to both natural and synthetic rubber. In 2019, the European Centre for Ecotoxicology and Toxicology of Chemicals (ECETOC) developed a framework for polymer risk assessment (ECETOC, 2019), and in 2020, "the Wood report" was finalized for the European Commission to propose criteria for the identification of polymers requiring registration (PRR) under REACH (EC, 2020c). Lohmann et al. (2020), specifies that there is not sufficient evidence to consider a group of polymers, the fluoropolymers, as being of low concern as the group is too diverse to warrant a full exemption from regulatory review. Furthermore, they recommend that the assessment and management of fluoropolymers should consider the whole life cycle, not just the use phase (Lohmann et al., 2020), as could be relevant for polymeric tire materials.

Under the European chemical legislation, REACH, manufacturers and importers have a general obligation to register and provide information on the substances that they manufacture or import on their own in mixtures or in articles (REACH Regulation Art. 5). This obligation applies for substances used in the manufacturing of tires as well. REACH aim to ensure that manufacturers, importers and downstream users must provide information regarding manufacture, place on the market, and assess whether any adverse effect on human health or the environment can be expected. Under the REACH Regulation, any manufacturer or importer of a substance, either on its own, or in one or more mixtures, in quantities of one tonne or more per year shall submit a registration to the European Chemicals Agency (ECHA) (REACH Regulation Art. 6) unless they meet the exemption criteria laid out in Article 2 of the Regulation. Polymers, for instance, are exempted until a practicable and cost-effective solution for selection of polymers posing a risk to human health or the environment can be found. This means that although natural and synthetic rubber fall under the scope of REACH, these are exempted from the registration and evaluation obligations under REACH, but not from authorization and restriction under REACH. Consequently, ECHA and EU Member States could decide to initiate an authorization and/or restriction process under REACH, but they would not have access to the health and environmental information provided by the registrants on which such initiatives would normally be based.

2.2. Regulation of tire production

REACH applies to all substances used in industrial processes, and therefore, by default applies to the substances used to produce tires (EC, 2006). REACH works with tonnage-triggered information requirements, meaning that the higher the production volume of a substance, the more information must be provided about the substance upon registration (EC, 2005). REACH does not only apply to individual substances, but also to so-called 'articles'. Tires fall under this definition of an article, and companies that import and/or supply tires to the European market are therefore covered by REACH. An article is defined as "*an object which during production is given a special shape, surface or design which determines its function to a greater degree than does its chemical composition*" (EC, 2006). The registration of an article under REACH has to be supplemented with a technical dossier on physicochemical, ecological and toxicological data. Furthermore, product use, potential for exposure to human health or the environment, and classification, labelling, and safe use for each application must be provided (REACH Regulation Art. 10 (a)).

One of the key legislations relevant when it comes to production of tires is Directive 2005/69/EC (EC, 2005) regarding marketing and use of PAHs in extender oils and tires. The directive prohibits the presence of some PAHs in the extender oils used to produce tires if they contain more than 1 mg/kg Benzo(a)pyrene (BaP), or more than 10 mg/kg of the sum of the 8 listed PAHs in Annex I, including e.g., BaP, Benzo(e)pyrene (BeP) and Benzo(a)anthracene (BaA). PAHs can be integrated into the rubber upon production and thereby be present in the final product. The presence of PAHs means that many extender oils have been classified as carcinogenic, mutagenic and toxic to reproduction (EC, 2005). REACH also requires importers and suppliers to collect information from their suppliers about the chemicals in the tires, with specific attention to whether any of the chemicals are on the ECHAs REACH Candidate List as substances of very high concern (SVHCs). If there are chemicals present in the tires that are on the Candidate List, exceeding a concentration of 0.1% and are imported in quantities of more than 1 tonne per year, then a notification must be given to ECHA and certain safety information must be provided to the customer. Similarly, tire suppliers are required to provide information to the customers if the tires contain chemicals on the Candidate List at concentrations above 0.1%. The information from the Candidate List should as minimum include the name of the chemical. A number of PAHs are listed on the Candidate List, including, among others, anthracene (ECHA, 2021; HSA, 2021). To get on the candidate list a chemical must possess certain hazard properties, such as being carcinogenic, mutagenic, toxic for reproduction, persistent bio accumulative and toxic (PBT), or very persistent and very bio accumulative (vPvB) (ECHA, 2022a).

Currently, there does not seem to exist any quantified estimates on the potential air emissions of PAHs specifically from tire production. However, in general, if PAH's is emitted to the air, Directive 2004/107/EC of December 15, 2004 (EC, 2004) is relevant to consider as it sets out requirements to a list of substances in ambient air, including PAH's. It follows from the directive that Member States are obliged to make sure that the target value for BaP, which is used as a marker for "*the carcinogenic risk of polycyclic aromatic hydrocarbons*", is not exceeded in ambient air. The target value is 1 ng/m^3, expressed as the total content in the particulate matter (PM), PM_{10}, fraction averaged over a year.

2.3. Regulation of tire use

When tires are in use in the EU, they have fulfilled the demands from the 'general safety of motor vehicles' Article (EU Regulation 661/2009). Furthermore, a tire labelling regulation (EC2020/740) has been applied since 2009 and was re-evaluated in 2020 (EC, 2020d). The tire labelling serves to better inform and empower consumers when buying tires on a range of parameters, namely, fuel efficiency (rolling resistance), safety (wet grip) and noise reduction. Two additional parameters have been added per 2021, both related to the use in extreme climate conditions. These are depicted as the alpine symbol (3PMSF) for snowy conditions and the ice stalagmite, used in the Nordic countries, for icy conditions. This label is produced via the European Product Database for Energy Labelling (EPREL), where industry uploads information to the database.

Due to rolling resistance, tires are responsible for 20–30% of the fuel consumption in passenger cars. Rolling resistance is also the main factor responsible for the emission of tire wear particles from abrasion during driving. The upcoming polymer legislation under REACH may or may not incorporate micronized rubber particles, specifically in the form of artificial turf, in their legislation. As forementioned, tire wear contributes significantly to the flow of anthropogenic polymer particles to the environment by emission in road environments and distribution via various routes (air, rainwater, runoff, water courses etc.) (Baensch-Baltruschat et al., 2020). It is estimated that 12–20% of micronized rubber particles (TWPs and TRWPs) end up in aqueous environments (Baensch-Baltruschat et al., 2021). Here, chemicals from the particles will leach out depending on the ambient environment. However, there is no overlap between the substances known to leach out from tires, e.g. aniline (Marwood et al., 2011) and benzothiazoles or 1-indanone (Halle et al., 2021), and the Water Framework Directive priority list (EC, 2013). Therefore, these substances are not searched for or monitored on a state level in aqueous environments at present. Table 2 shows the information available from the ECHA database on four different rubber-related compounds. It is worth noting that the PBT criteria does not apply for any of these compounds, since the respective Bioconcentration Factors (BCFs) are below the threshold of 2000. None of the compounds are labeled as SVHC, and are therefore, not candidates for phasing out (i.e., on the Candidate list).

2.4. Regulation of end-of-life-tires (ELTs)

To regulate or reduce the environmental pollutants, standards and guidelines for the tire industry have been released, especially concerning ELTs. A series of directives were published in Europe, such as Directive 1999/31/EC (to prohibit landfilling waste tires) and Directive 2000/53/EC (to prevent waste from vehicles and their components) (EC, 1999, 2000a). According to Dabic-Miletic et al. (2021) the European landfill directive (1999) has been the main driver for improving ELT management, and many countries established corresponding management systems or standards for increasing resource efficiency and reducing negative environmental impacts (Sienkiewicz et al., 2017). In 2021, a limit of PAH content in ELTs was implemented (EC, 2021), in addition, there are regulations on the eco-labelling of tires from 2009 which were recently updated (EC, 2020d).

2.4.1. Regulations on ELT as a secondary raw material

The European action plan for a circular economy sets out to boost the market for so-called secondary raw materials, which are materials that upon recycling are "*injected back into the economy as new raw materials thus increasing the security of supply*" (EC, 2015). The action plan does not mention ELTs specifically, however, the European Commission's website highlights secondary raw materials from ELTs in connection with a Raw Material Commitment (EC, 2017b). The purpose of the commitment is to foster recycling and recovery of ELTs through standardization. In order to do this, the technical committee CEN/TC 366 has developed a technical specification ("CEN/TS 14243:2010," 2010) of categories and methods for determining dimensions and impurities of materials produced from ELTs, which however needs to be further developed (EC, 2017b). These initiatives are in accordance with the World Business Council for Sustainable Development that has proposed that ELT-derived products are recognized by the legislation as secondary raw

Table 2
Lists some of the information available from the ECHA database on four rubber-related compounds (6PPD, 1-octanethiol, aniline and benzothiazole). Each compound behaves differently in the environment as the BCF and LogKow indicates, yet none of the compounds apply to the PBT criteria, has a high enough BCF, are envoked on the SVHC list or is regulated in relation to tires besides from in REACH depending on individual tonnage levels. This serves to illustrate one of the main complexity issues regarding tires and their derivatives, each individual component might not pose a risk for each individual parameter. However, complete mixture effects, knowledge on which compound can be found in which environmental compartment in the different life stages of a tire, and metabolites of compounds are not investigated properly to ensure an environmentally sound exposure of this many-faced multi-component pollutant.

Chemical Parameter	1-Octanethiol *(111-88-6)*	6PPD *(793-24-8)*	Aniline *(52-63-3)*	Benzothiazole *(95-16-9)*
Persistent, Bioaccumulative and Toxic (PBT)	No	No	No	No
Bioconcentration Factor (BCF)	11.83 L kg^{-1} *(in ww sediment)*	569 *(from read-across)*	>1 and 2.6 ± 0.06 *(in Lumbriculus variegatus and Danio rerio, respectively)*	2.1–5.1 and > 4.1–7.5 *(in fish)*
Biodegradation	Not readily biodegradable *(from read-across)*	Not Readily biodegradable	Readily biodegradable *(often used as reference substance for degradation tests)*	Readily biodegradable
SVHC Candidate List	No	No	No	No
$LogK_{OW}$	4.21	4.68	0.91	2.01
Regulated in REACH	Yes *(tonnage is ≥ 1 to < 10)*	Yes *(tonnage is ≥ 10000 to < 100000)*	Yes *(tonnage is ≥ 1,000,000 to < 10,000,000)*	Yes *(tonnage is ≥ 10 to < 100)*
Regulated in Water Framework Directive	No	No	No	No
Regulated in Waste Framework Directive	No	No	No	No
Reference	ECHA (2022a)	ECHA (2022b)	ECHA (2022c)	ECHA (2022d)

materials (or alternative energy sources). Here, standards are also mentioned as an important tool to support such recognition (World Business Council, 2010). Ciccu and Costa (2012) investigated a waterjet technology to produce rubber granulates as a secondary raw material from ELTs. Waterjet was found to be both technically and economically promising as method for disintegrating tires into new applications, including e.g. municipal water filtration and manufacture of paving and building elements (Ciccu and Costa, 2012).

2.4.2. Regulation of ELTs used for energy recovery and pyrolysis

End-of-life tires are classified in the EC Decision on EU list of wastes (2001/118) under entry 16.01.03 (EC, 2000b, EC, 2000c). When it comes to regulation of the use of ELT for energy recovery, the most important aspect to note is that energy recovery is considered the second-worst option according to the waste hierarchy of the EU Waste Framework Directive. Only, landfilling is considered a worse environmentally damaging end-of-life option. Incineration of waste is regulated under the Industrial Emission Directive (IED). Chapter IV of the IED contains special provisions for waste incineration plants and waste co-incineration plants. These provisions include conditions that have to be met in order to obtain for instance a permit and complying with emission level values.

The IED Chapter IV does not apply to gasification or pyrolysis plants if the gases resulting from the thermal treatment of waste are purified to such an extent that they are no longer a waste prior to their incineration and they can cause emissions no higher than those resulting from the burning of natural gas (IED, article 42). The products most commonly manufactured from pyrolysis of ELTs are recovered carbon black and tire-derived oil. ECHA defines chemical recyclers as manufacturers of substances who must comply with chemicals legislations, REACH and the classification, labelling and packaging of substances and mixtures (CLP) (Manzuch et al., 2021). Under CLP, carbon black has not been classified by any suppliers (ECHA, 2022b), whereas tire-derived oil from waste rubbers and tires has been classified by most suppliers as carcinogenic, mutagenic, or toxic for reproduction (CMR) and environmentally acute and chronic toxic. Recovered carbon clack would be a so-called mono constituent under REACH assuming that the concentration is over 80% w/w.

Tire-derived oil from pyrolysis need additional processing to be used and as this is usually upgraded in refineries, it falls under the criteria of intermediate substances under REACH and it has been registered as such (Manzuch et al., 2021Manzuch et al., 2021).

2.4.3. Reuse and re-purposing scenarios of ELTs

The high turnover rate of car tires produces a significant fraction of waste with limited options for closed loop recycling. This has resulted in alternative recycling paths for ELTs, e.g. infill on artificial sports fields, of which approximately 21% of ELTs are recycled to, in Europe (Verschoor et al., 2021). A recent risk assessment conducted by EU authorities concluded that this form of recycling result in 16,000 tonnes of microplastics being released into the environment per year and that the total of intentionally added microplastics will eventually pose an environmental risk. As a result, ECHA has proposed a ban on placing artificial turf on the market after a transition period of six years and the mandatory use of risk management measures (such as fences, brushes) to prevent the loss of infill from the pitches after a transition period of three years (ECHA, 2020). ECHA's environmental estimates and conclusion has been challenged by Verschoor et al. (2021), who argues that estimates of release to the environment are overestimated, and that leaking from artificial fields can be controlled. Regardless of whether restrictions of this form of recycling will be imposed or not, it remains a challenge that this repurposing is essentially a down-cycling and thus does not keep the materials within the value chain, which is the aim of the circular economy plan in EU (EC, 2020b).

Another suggested use of ELTs is use as part of coastal structures to protect against tsunamis and other storm water events (Hazarika and Fukumoto, 2016). This reuse scenario has been widely applied for many years, as tires have good properties for this purpose, although this form of recycling is also a down-cycling and thus it does not fit optimal in a circular economy context. Leachates of hazardous chemicals from car tires used in coastal management has been raised as a concern, and differing salinities impact the degree of leaching (Hartwell et al., 1998, 2000), although generally reduced release over time has been documented (Collins, 2021). However, a recent study demonstrated a synergistic mechanism of toxicity on rotifers when exposed to 6PPD and road salt, underlining the importance of mixture effects (Klauschies and Isanta-Navarro, 2022). An alternative recycling pathway of ELTs is to use crumb rubber as a binder in asphalt to improve performance. Application of crumb rubber in asphalt reduces noise from friction and improves durability of the material. In addition, incorporating crumb rubber will increase the amount of available rubber in a road context, that can be potentially abraded upon vehicle circulation on the road. Most of the particles created during tire-road friction are stemming from the road surface (i.e. minerals, bitumen, and in this case crumb rubber). This means, that more rubber would be emitted and transported through the air into the environment. However, this is dependent on a series of parameters such as replacement ratio and temperature requirements, and is thus not straight forward (Milad et al., 2020).

3. Discussion

3.1. Mixture effects and low probability of becoming a candidate list chemical lead to important knowledge gaps

When assessing the legislative framework in relation to tires and TWPs in the EU, various considerations need to be made. Currently, polymers are exempted from registration under the REACH regulation. However, Article 138(2) of REACH expects a possible further review to extend the registration requirements to polymers. Considering that the first research paper on emission and identification of rubber particles in road dust emerged in the late sixties (Thompson, 1966) it seems counterintuitive that more detailed identification and environmental regulation of the product and it's by-products is still amiss. The REACH definition of polymers covers substances taking part in the polymerization reaction, together with additives necessary to preserve, batch-impurities, reaction-by-products and catalysts. Therefore, it has been suggested that polymers are treated as mixtures in the context of hazard assessment (Rochman et al., 2019). Adding to this, TWPs may act as a carrier of other toxic contaminants, such as metals retrieved from brake wear on the road surface (Wagner et al., 2018; Hüffer et al., 2020; Rausch et al., 2022), Recently, Daellenbach et al. (2020) demonstrated that metallic particles are major constituents of the oxidative potential in PM despite relatively low concentrations of metallic particles in the PM_{10} fraction, underlining how low concentrations within mixtures may aid in increased toxicity.

Another problem is that REACH does not ensure transparency about which kinds of chemicals are present in a given tire. It is only recently that derivatives of tire chemicals, specifically a derivate of 6PPD, have come into focus (Tian et al., 2021). This has the potential to widen the known toxicological impacts from tires and TWPs and is currently under investigation. It also serves well as an example to a previously overlooked compound that is part of tire. More focus is needed on the constituents of articles such as tires, their mixture effects, and their transformation products.

3.2. Assessing the hazard potential of TWPs

Abrasion of particles and leaching of chemicals during various stages of tire life has been demonstrated, underlining the need to understand both hazards of polymeric materials as well as incorporated chemicals, and their transformation products. Screening a complex mixture matrix for each of the possible chemical components in particles and leachate that could act as drivers of toxicity is a challenging and time-consuming endeavor. For instance, it took Tian et al. (2021) > 15 years to pinpoint a transformation product of 6PPD, as *one* causative agent for the toxic effects seen on coho salmon. Clearly, it is not possible to assess the hazard for each chemical compound that can be identified in the around 120000 different tires in the EU alone.

Even if it was possible there are several issues which are not accounted for in the current particle hazard assessment paradigms (Mitrano and Wohlleben, 2020). For example, only few OECD Test Guidelines are applicable to particles, and larger particles (microplastic up to 5 mm) often outsize the standard test organisms used. An issue previously addressed in regard to waterborne particulate contamination (Khan et al., 2017). To overcome this, scientists must resort to non-standardized testing using common sense and all their scientific training to rethink the actual exposure scenarios and how to best depict that in a closed laboratory environment, e.g. Khan et al. (2019), Capolupo et al. (2020), Kolomijeca et al. (2020), Halle et al. (2021), and Kim et al. (2021). The lack of standardized guidelines e.g. for TWP or leachate preparation, furthermore complicates later comparison between studies as each study uses their own methods. This hinders a global effort to streamline results and has been debated within both microplastics and microrubber groupings when it comes to analytical methods, ecotoxicology and environmental fate (Wagner et al., 2018; Rochman et al., 2019; Halle et al., 2020; Baensch-Baltruschat et al., 2020; Kovochich et al., 2021; Rausch et al., 2022; Rødland et al., 2022).

3.3. The challenges of read-across

There seems to be a discrepancy between individual chemical constituents in tires and TWPs and the different regulative measures in place for different life stages of a tire. Although the individual constituents are regulated under REACH in regard to raw materials and production, they are not considered as part of TWP pollution, and many of the chemicals are not accounted for. Secondly, the EU legislation generally makes it difficult to regulate complex mixtures. The toxicological information available through ECHA on aniline, states a 48-h EC_{50} of 0.16 mg L^{-1} and a 21-d NOEC of 0.004 mg L^{-1} for *Daphnia magna*. Similarly, a 48-h LC_{50} of 0.024 mg L^{-1} and a NOEC of 0.004 mg L^{-1} was determined for *D. magna* using 1-octanethiol. When examining these additives, each compound on their own do not fulfill the criteria of SVHCs or PBT. Partly because of the sometimes high value of the cut off criteria (e.g., 2000 for B under PBT) and sometimes because they have been read-across from a similar looking group of compounds due to lack of specific data (See ECHA database, references from Table 2). Thus, tires and TWPs are indirectly deemed non-toxic, despite annual production of the constitutional chemicals in the many-tonnage range, with compounds that have toxic potential in low concentrations.

Lastly, there are many chemicals in tires that are not actively searched for in the environment. Table 2 illustrates, as an example, how four chemical compounds found in tires (1-octanethiol, 6PPD, aniline and benzothiazole) are scored in relation to legislative criteria. Each individual chemical does not seem to pose a threat to the environment or human health as they are scored as not PBT or vPvB, with a low BCF, and are not present on the Candidate Lists for SVHC. Adding to that, the chosen limits for the PBT and BCF criteria implies that only the most problematic substances will be added to a candidate list. Some compounds present in TWPs are on the Candidate List, including but not limited to: phenol pyrene, phenanthrene, fluoranthene, benzo(k)fluoranthene, lead, benzo(ghi)perylene, chrysene, benz(a)anthrazene, BaP, cadmium and anthracene. However, the full Candidate List totals at 219 chemicals (ECHA, 2022c), representing chemicals from all industries and sectors across Europe, and the fact that some of these happen to overlap with chemicals from tires and TWPs is very likely to be more coincidental than intentional. Even though many different chemicals are in use throughout the manufacture of a tire, only a small fraction of these are listed as SVHCs, increasing the possibility of overlooking effects from problematic substances when taking the whole life cycle of a tire into consideration. Examples could be compounds such as aniline, benzothiazole, hexamethomethylmelamine and other non-PAH organics (Marwood et al., 2011; Capolupo et al., 2020; Halle et al., 2021; Johannessen and Parnis, 2021; Tian et al., 2021). Complete mixture effects, knowledge on which compound can be found in which environmental compartment in the different life stages of a tire, and metabolites of compounds are not investigated properly to ensure an environmentally sound exposure of this many-faced multi-component pollutant. Thus, read-across from chemical or polymer risk assessment is not a sufficient tool for assessing the hazard potential of TWPs. Overall, one of the main issues that drive these knowledge gaps is the sheer amount of chemical components used in or around tire manufacturing, and the many shapes they may take on before, under and after use.

3.4. How new measures and recommendations can step in to address the challenges

The tire industry is making significant efforts towards a greener and more sustainable production, considering emission of CO_2, recycling, material sources and implementing the use of biomass from plants rather than oil-derived alternatives. When talking about sustainability in a tire context the usual interpretation is on the use of raw materials, recycling of raw materials, circular economy and material sourcing (ETRMA, 2020a). Rolling resistance should be the parameter to improve (Andersson-sköld et al., 2020), as it is linked to performance, and improved performance is by default more sustainable. The sustainable thoughts do somehow not yet encompass a lower chemical load, lower abrasion, or transparency of ingredient use.

A new regulation in the European Union is under development which will, if adopted, likely have impact on polymer pollution from tires. The initiative is proposed by the European Commission and is titled "Measures aiming to reduce the presence in the environment of unintentionally released microplastics from tires, textiles and plastic pellets". As the title indicates, the initiative aims to address unintentional microplastics release to the environment and will among others focus on release from tires. One of the intentions of the initiative is to develop "labelling, standardisation, certification and regulatory measures on unintentional release of microplastics, including to increase the capture of microplastics at all relevant stages of products' lifecycle". The public consultation of the regulation proposal ended in May 2022 and the current time table for the initiative suggests adoption of the initiative in the fourth quarter of 2022 (EC, 2022a,b).

One way to curb restrictive regulation could be for the tire industry to open up about their ingredient use. This is already in part covered by the global automotive declarable substance list (GADSL) organized by the Global Automotive Stakeholders Group (GASG), that is a combined effort by the automotive industry, automotive part suppliers and the chemical and plastic industries. This is done in order to facilitate communication and exchange substance information on automotive products throughout the supply chain. It should be noted that the list comprises all aspects of an automobile, not just the tires and breaks that are of particular interest in this context. On the GADSL, the declarable substances *expected* to be present in a material or part that remains in a vehicle at point of sale is listed (GASG, 2022). This gives a quick overview of any prohibited or declarable substances and lists approximately 270 substances. Some of the substances found in TWPs are present on the list, including aniline, 2-mercaptobenzothiazole, copper, and lead. However, metabolites of substances and substances *expected* to be used up in chemical reactions are not listed, and could be of higher importance when it comes to environmental regulation of substances. The amount of substances on the list is furthermore debatable, as ETRMA states that more than 200 raw materials are usually used for the production of a tire (ETRMA, 2019) and in the EU alone there are 120000 different tires (ETRMA, 2020b). How come that a list entailing all substances relating to a car, is only a fraction longer than what is supposedly in the tire itself. Therefore, a higher degree of transparency in relation to substances associated specifically to tire and break wear would be favorable and allow for more precise risk assessment of the few possibly problematic tire constituents that could perhaps be substituted or removed. Lastly, in an effort to address regulatory challenges, specific TWP legislation that aims directly at the use-scenarios for this specific type of polymer could be developed and implemented. Collection of anthropogenic polymer particles throughout the tire life cycle could be improved to minimize spill risks during raw material manufacturing, production, use and when shredding for repurposing scenarios. Specifically for the tire use scenario, a collecting device was recently designed to capture tire emissions at the source, thus minimizing the amount of particles reaching the environment (TTC, 2020).

4. Conclusion

In many cases, one-point solutions to pollution resulting in legislative action is a fine tool to use. However, when dealing with a many-faced mixture pollutant, like tires and TWPs, the different use-scenarios throughout their lifecycle, and the consequent hazard potentials need to be better defined in order to properly handle sub-sequent risk assessment. Therefore, transparency in regard to use of chemicals in complex mixtures should be a priority. As this paper compiles, there are numerous regulations relating to tires, chemicals, manufacturing, raw materials, use of tires on roads, waste handling, safety and PAHs in different life cycle stages of a tire. However, none directly target the contribution of TWPs and their chemical constituents to the environment. Examining the legislative framework affecting tires and TWPs, we found no overlapping or duplicate regulations. Rather, more gaps than redundancies were found when analyzing the different European legislative measures, specifically when it comes to TWPs released into different environmental compartments. Priority should be given to addressing complex mixtures like TWPs that disperse in the environment so that we better understand their mixture effects and transformative products.

Author contributions

LLT: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Writing - original draft; Writing - review & editing. **MBN**: Investigation; Methodology; Data curation; Formal analysis; Validation; Writing - original draft; Writing - review & editing. **SFH**: Investigation; Methodology; Data curation; Formal analysis; Validation; Writing - original draft; Writing - review & editing. **KS**: Investigation; Methodology; Validation; Writing - original draft; Writing - review & editing. **KK**: Funding acquisition; Project administration; Supervision. **FRK**: Conceptualization; Investigation; Methodology; Validation; Funding acquisition; Project administration; Supervision; Writing - original draft; Writing - review & editing. **AP**: Conceptualization; Validation; Funding acquisition; Project administration; Supervision; Writing - review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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