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A marine pollution governance assessment framework - the case of emerging tyre wear particles governance in the European Union

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ABSTRACT

Despite global regulatory efforts over the last 50 years, marine pollution remains a persistent challenge. Its transboundary nature requires a multifaceted governance approach that encompasses land-based sectors as well as pathways of pollution from land to sea. Understanding why marine pollution governance struggles to be effective requires examining actor interactions and power dynamics that shape regulatory outcomes.

This article therefore develops a marine pollution governance assessment framework (MAPGAF) based on two key components: 1) A *life cycle* perspective that considers pollution sources from product creation to their end-of-pipe emissions, and 2) an analysis of *governance arrangements* including rules of the game, discourse and power dynamics between actors. The MAPGAF is applied to the emerging governance of tyre wear particles (TWPs) within the European Union (EU), a new focal area recognized in the European Green Deal Zero Pollution Action Plan.

The analysis highlights that different regulatory developments are emerging along the lifecycle of tyres and the end-of-pipe emissions of TWPs. EU governance arrangements addressing different life cycle stages thus interact, shaping overarching regulatory, power and discursive trends. Most importantly, while on the one hand recent EU regulations are expected to foster a more preventive approach to TWP emissions by enhancing tyre design, the power of the tyre (and car) manufacturers is increasing. Recognising these interactions is key to strengthening marine pollution governance in the EU, by addressing industry influence, integrating a life cycle perspective, and ensuring that governance arrangements are ambitious and enforceable.

1. Introduction

Despite 50 years of global regulatory efforts to limit marine pollution - starting with the creation of the United Nations Environmental Programme (UNEP) and the Stockholm Declaration in 1974 - high levels of pollution persist [7]. This includes the marine environment, which remains under threat from nutrient, plastic and chemical pollution [73,78]. Mitigating marine pollution is challenging because of its transboundary nature requiring coordinated efforts both within and between countries [33,74]. Marine pollution also has a strong land-sea interaction, as most pollution is generated on land, reaching the marine environment via waterways [36,78]. Recently, there has been increased attention for addressing pollution at its source, including curtailing plastic production to reduce (micro)plastic pollution – an issue highlighted in the failed negotiations for the Global Plastic Treaty [14,53,8]. Addressing marine pollution therefore requires a multifaceted governance approach that integrates land-based sectors, consumer behaviour, and waste(water) management systems.

The fluid and interconnected nature of marine pollution challenges conventional ways of assessing and understanding marine pollution governance efforts in two key ways. First, given the scale of pollution across terrestrial, aquatic and marine environments and the multitude of sources, governance efforts should not be assessed in isolation [33,73,78]. Scholars frequently publish overviews to understand how the global governance landscape of marine pollution governance is evolving, especially when it comes to plastic pollution (see e.g. [17,23,76]). They

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often take institutional characteristics as a starting point – such as the type of institution (state, market, or civil society) or governance level (international, regional, national, or local), and highlight the complexity and fragmentation of existing efforts [34,74,77]. However, such analyses should also consider how governance efforts address not only pollution pathways and sources (e.g., disposal and waste management) but also product design and use [73], which is something that is increasingly emphasised in studies on governing plastic items (see e.g. [12,65,71]).

Second, understanding actor interactions and power dynamics is essential for explaining why marine pollution governance remains highly complex and fragmented [73,78]. Some scholars highlight the role of powerful (industry) actors in resisting efforts to make marine governance more integrated and rigorous [19] as well as the socio-technical and financial lock-ins of petrochemical and plastic production and consumption [64,68]. Greater attention is needed for actor interactions and power dynamics across governance efforts, from pollution sources to different stages of pollution control, and across multiple governance levels. For instance, several studies show regulation disproportionately focuses on consumption and waste management of plastic products [49,57], while reducing virgin plastic and petrochemical production remains largely unaddressed [19,68,73].

To address both challenges, this article develops and applies a governance assessment framework for fluid marine pollutants, such as plastics or chemicals. This framework combines a focus on the full product life cycle - including end-of-pipe leakage to the (marine) environment - and the governance and power dynamics that shape policy ambition and focus. The product lifecycle perspective enables identifying the various land-based sources of pollution. Consequently, sources are *production* of materials and products, *use* of materials and products, and *end-of-life* of materials and products. Pollution occurs at each of these stages, resulting in *end-of-pipe* emissions. Additionally, the governance assessment framework uses the concept of a governance arrangement as the unit of analysis, to enable an examination of actor interactions under institutional rules, discourses, and power dynamics. A governance arrangement is defined as the temporary stabilisation of actors, institutions, and policy decisions within a policy domain [4,5]. With a more explicit focus on governance dynamics that span across lifecycle stages, this framework enhances assessing how governance architectures and power relations affect governance efforts that target a pollutant's source-to-sea trajectory.

To illustrate the insights that can be generated with this framework, the article examines how the European Union (EU) is governing Tyre Wear Particles (TWPs), a major source of unintentional microplastic pollution (alongside textiles and the degradation of larger plastic items) [48,54,62] and an emerging issue area within the EU. TWPs, shed from vehicle tyres during road use, is transported via rain, urban runoff, and atmospheric deposition into both terrestrial and aquatic environments [60,11]. In December 2019, the EU adopted the European Green Deal (EGD), which aims to make the EU climate-neutral. As outlined in the Zero Pollution Action Plan, the EU targets a 30 % reduction in microplastic emissions by 2030. Using the marine pollution governance assessment framework, this article analyses EU's set of regulatory responses to TWP pollution, focusing on governance dynamics across the life cycle of tyres, as well as the end-of-pipe TWP emissions.

In the next section, the marine pollution governance assessment framework is introduced. After that, the methodology used for the case study of the emerging EU governance of TWPs is presented in Section 3. Section 4 analyses the governance arrangements of TWPs during production, use, end-of-life of tyres and the end-of-pipe stage in which pollution occurs. Section 5 presents the outcomes of the assessment of emerging EU governance of TWPs in terms of its regulatory and power dynamics. This article ends with a concluding discussion about the assessment framework, in Section 6.

2. Marine pollution governance assessment framework

The marine pollution governance assessment framework (MAPGAF) is based on four stages which are introduced in the following section. Three of these stages relate to the life cycle of a product, while one focuses on pollution of the environment. The main unit of analysis of the framework is a governance arrangement, a concept which is introduced in Section 2.2.

2.1. Life cycle and pollution stages

The stages used as a basis for the MAPGAF help pay attention to the way in which governance efforts not only aim to reduce end-of-pipe or existing emissions to the marine environment, but also emissions at source, i.e. along the lifecycle [57,73]. Four stages characterize the path that pollution takes from land-based sources to the marine environment: production, consumption and use, end-of-life, and end-of-pipe leakage (see Fig. 1). The scope for this typology builds upon the lifecycle perspective, which assumes that marine pollution is related to the production of raw materials and products that include chemicals and other substances. For example, the design of products has implications for their use, end-of-life and end-of-pipe stages, i.e. in terms of which pollutants leak into the marine environment and through which pathways.

The production stage entails the composition, design and manufacturing of products, usually using complex chemical substances and an energy-intensive industrial process. However, already during production, substances can leak into the environment, e.g. through industrial wastewater discharges or loss of materials during transport (see Fig. 1). In these instances, production practices directly relate to end-of-pipe emissions, without materials and products making it to the Use stage. Governance targeting production include the banning of substances or products for production and putting them on the market, or the redesign of products [12,73].

Consumers and users of products can be both households and industry, e.g. when using packaging for equipment, food used by producing companies, or vehicle use in transport in an economic sector. Use is a source of pollution because it can already lead to direct pollution of the (marine) environment during use, e.g. through abrasion of tyres during use, or disposal of waste directly in the environment (see Fig. 1). Use of products, however, also determine what materials and products move to the End-of-Life stage. Governance approaches include the banning of substances and products to be used, or incentive schemes to reduce use of products and substances [12,23,73].

The end-of-life of materials and products range from the moment of disposal to waste treatment of products and chemicals. Mismanagement of waste is seen as a source because it leads to leakage of materials and products into the (marine) environment. The End-of-life stage involves both public and private waste management actors but can also include users such as households when it comes to separation and proper disposal of waste. Governance approaches could be reducing or eliminating direct disposal into the environment by improving separation of waste, banning of dumping, and improving waste management and treatment [12,73]. By improving waste management, recovery and recycling of materials becomes possible, preventing these from ending up in the environment.

Substances that leave the production, use and end-of-life cycle stages and that are entering the (marine) environment are considered to fall in the end-of-pipe category. Governance approaches that target the end-of-pipe stage focus on addressing the leakage of substances to environmental domains after emissions have already been generated. They can focus on capturing emissions just before or shortly after they are released. Examples include wastewater treatment that removes pollutants. Wastewater treatment can take place at a production site, from wastewater of households and users, but can also be linked to the end-of-life waste management. Actors targeted through these governance approaches often are a mix of public and industrial actors.

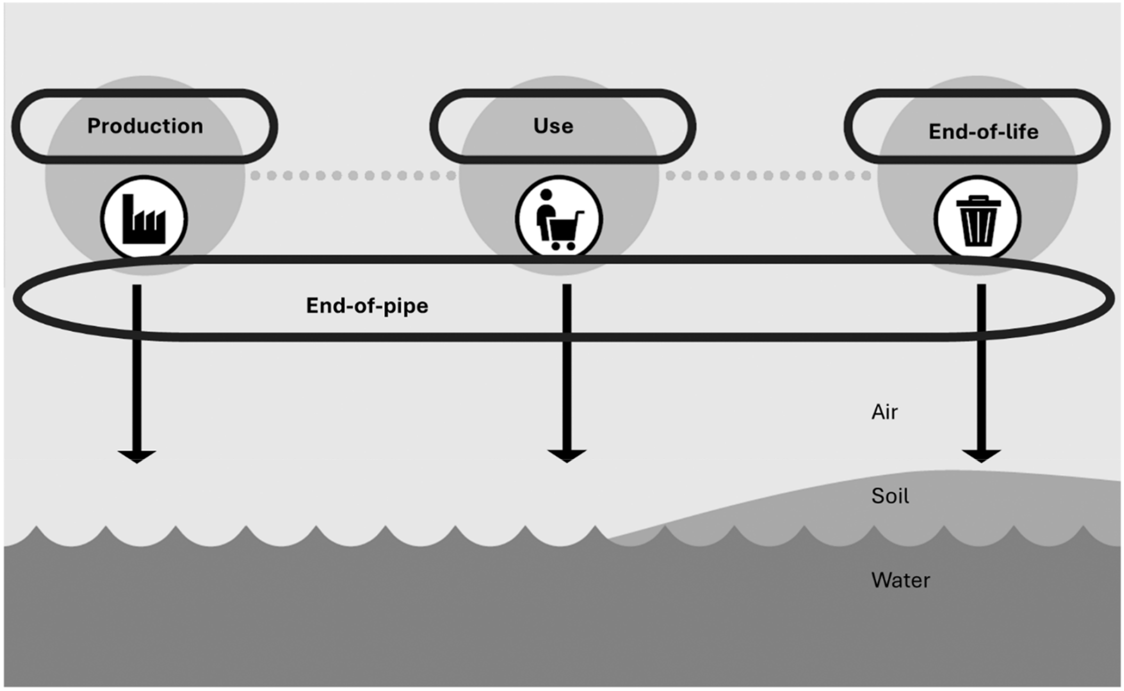

Fig. 1. Lifecycle and pollution stages in the marine pollution governance assessment framework (based on [73]).

2.2. Governance arrangement

To go beyond identifying whether a governance approach falls within which stage, this article combines the stages with the concept of governance arrangement. The concept originates from the policy arrangement approach, which offers a framework to study the institutionalization of governance arrangements, i.e. the process leading to the formation, deformation and reformation of governance arrangements [3,75]. "Institutions, no matter how stable they appear at first sight, are subject to continual change and adjustment, deconstruction, and reconstruction" ([4], p. 96). The main aim of the policy arrangement approach is to understand and analyse the ongoing institutionalisation of governance arrangements, which is the result of the interplay between the interactions of actors participating in putting policy into practice on the one hand, and processes of social and political change (political modernisation) on the other hand [4,6].

A key concept used within this approach is that of the governance arrangement, which refers to the temporary stabilisation of the organisation and substance of a policy domain within which actors take and implement decisions [4,5,6]. The organization and content of a governance arrangement determine how actors develop and implement policies and regulations to govern a certain policy domain. A policy domain refers to the issue area for which a group of actors interact in a relatively stable institutional setting to develop and implement policies and regulations. Stability in the organization and substance of a governance arrangement is based on the actors involved, rules-of-the-game that guide actors' behaviour and expectations, power resources and relations between actors, and discourses that specify the different interpretation schemes that frame actors' preferences [4,5,6].

How these dimensions are defined is presented in Table 1. Table 1 also details the set of potential power asymmetries and manifestations that were used to assess the power of different actors in the emerging EU governance of TWPs [45]. This includes a combination of having a formal position in decision making and/or informal and lobbying access to decision making actors. It also includes the use of knowledge, financial and legal resources to shape decision making processes. And finally, to reflect that governance arrangements across lifecycle stages are interlinked, the involvement in multiple governance arrangements is considered a manifestation of the power of an actor. The assumption is that the more of these resources and manifestations of power an actor uses, the more powerful its position is vis-à-vis other actors in a governance arrangement.

Table 1
Definitions of the dimensions of a governance arrangement (based on [6,4,5,45]).

Governance Arrangement dimension	Definition
Policy Domain	An issue area for which a configuration of actors interacts to develop and implement policies and regulation
Rules of the Game	The institutional setting of policy making and implementation; those norms and rules that define the expectation of behaviour during policy making and implementation in a policy domain
Actors	Any organization involved in or affected by policymaking and implementation in a policy domain
Discourses	Expressed ideas about the issue area's problem definition, its causes and possible solutions
Power & Resources	Resource asymmetries and manifestation of power through: • Formal positions in decision making and implementation processes (as defined by the rules of the game) • Lobbying and access to actors in formal positions in decision making and implementation processes • Knowledge asymmetry between actors • Financial resources asymmetry between actors • Ability to litigate actors • Being included in multiple governance arrangements that span linked issue areas at the same time

3. Methodology

As outlined in this section, the methodology of the application of the MAPGAF is based on a case study approach, with qualitative data collection and analysis methods.

3.1. Case study research design and scope

Based on the MAPGAF's lifecycle and pollution stages, four governance arrangements around the lifecycle of a tyre and associated emissions of TWPs were identified: (1) production, (2) use (abrasion), (3) end-of-life (tyre as waste), (4) end-of-pipe (TWPs in the environment). The focus is on the whole tyre wear particle, which means that road wear particles, as well as particulate matter were not included in the scope of this research. As such, tyres as source of macroplastic pollution were excluded from the scope of the case study.

Examining governance across the whole value chain of tyres and TWPs fulfils the criteria of a case study research design. Case study research seeks to achieve complex and rich explanations of phenomena [58]. Yin [80] defines the case study research methodology as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident and in which multiple sources of evidence are used." The case study of the four governance arrangements that ultimately make up EU TWP governance focuses on a real-life context; allows for in-depth exploration through comparing four governance arrangements; attempts to be holistic; explores processes as well as outcomes; investigates the context and setting of a situation; and consist of multiple levels and stakeholder groups. A case study can gain credibility by thoroughly triangulating the descriptions and interpretations, not just in a single step but continuously throughout the research.

3.2. Data collection methods

Two overarching methodological strategies to collect data have been used.

1. Reviewing existing evidence by exploring and capitalizing on data that already exist:
   Relevant EU policies and governance issues related to tyres and TWPs were identified for each governance arrangement through a document analysis. The researched evidence consists of legal and policy documents such as EU directives, action plans and strategies; peer-reviewed publications, media coverage, blog posts, EU websites, public consultations, and studies, assessments and reports between 2018 and 2023. For EU legislation, the main data source was EUR-Lex, as well as the websites of relevant European institutions. This broad representation of using multiple sources of existing data surfaced relevant information and made it possible to develop an in-depth and holistic case study overview.
2. Gathering primary data by conducting semi-structured interviews:

Semi-structured interviews were conducted using a topic list (see supplementary material) based on the four governance arrangement dimensions of rules of the game, actors, discourses and power relations. Nine representatives from the tyre and recycling industry, environmental non-governmental organisations and European Commission Directorate-Generals (DG) were purposefully selected for their expertise in one or more of the identified governance arrangements and lifecycle stages, see Table 2. The interviews took place in June 2023.

Researcher and methodological triangulation were guaranteed by using different data collection methods and by carrying out all research activities in pairs by an experienced team of researchers from various research institutions. Throughout the data collection process, stakeholder autonomy was respected, and the ethical guidelines were ensured. Ethical consideration was approved by SIKT in Norway to fully follow GDPR guidelines on involving stakeholders in the study.

3.3. Data analysis and validity

The analysis started with a focus on the existing governance landscape related to the reduction and prevention of pollution from TWPs. A key objective was to determine the main policy domains and how emissions and pathways of TWPs are governed. Policy domains were determined based on identifying the rules of the game, actors, discourses, and power manifestations involved in governing tyres and TWPs during different lifecycle and pollution stages. The different stages were followed by an analysis of the identified and selected governance arrangements, defining how actor interaction is shaped by rules of the game, discourses and power relations within identified governance arrangements. In the analysis, a balance has been sought between examining interaction within and identifying governance dynamics across the four governance arrangements.

Table 2
List of expert interviews.

Stakeholder group	Organisation
EU policy makers	DG Environment DG Energy
Car and Tyre producing industry	Car manufacturer Tyre manufacturer European Tyre and Rubber Manufacturers Association (ETRMA)
Recycling Industry	The European Recycling Industries' Confederation (EURIC)
Water (treatment) Industry	European Federation of National Associations of Water Services (EurEau) / Dutch Water Board
Environmental Non-Governmental Organisation	ECO standard Transport and Environment

To carry out the analysis, qualitative data analysis methods were applied, including manual coding to identify key concepts, their interrelationships, and themes [32]. This allowed for a comparison between the responses from the different interviewees on the same governance arrangement and lifecycle stage. In an additional step, a thematic analysis based on the codes was applied to identify emerging themes, best practices and constraints, as well as linkages.

Triangulation was also ensured in the data analysis phase, as different researchers together reflected and discussed the preliminary findings, the coding process and the relevant steps in the analysis.

4. Marine pollution governance of TWPs in the European Union

This section first introduces the EU's regulatory background of microplastics, including TWPs, before analysing the four governance arrangements along their life cycle stages from production to end-of-pipe. Each arrangement is assessed in terms of the 4 dimensions of a governance arrangement: rules of the game, actors, discourses, and power dynamics.

4.1. Regulatory background of protecting the marine environment from microplastics pollution in the EU

The EU's objective of 30 % reduction of microplastics released into the environment by 2030 has been set as part of the EGD's Zero Pollution Action Plan in 2021. The Marine Strategy Framework Directive (MSFD, 2008/56) already included microplastics (called micro-litter in the MSFD) within its scope, aiming to maintain levels that do not cause harm to the coastal and marine environment or that do not adversely affect the health of the species concerned. The MSFD targets the spatial distribution of micro-litter across the coastline, surface layer of the water column and in the seabed sediment and the ingestion of micro-litter by marine animals [21].

To complement the MSFD, the EU is enhancing microplastic monitoring across various water bodies through directives such the Water Framework Directive (2000/60/EC), the revised Urban Wastewater and Treatment Directive (UWWTD, 2024/3019), and the proposed EU rules on soil monitoring. Additionally, microplastics are included in the updated watch list of substances as part of the Environmental Quality

Standards Directive (2008/105/EC), contributing to regulatory frameworks that guide pollution control measures such as the Water Framework Directive. These efforts provide the foundation for sector-specific governance approaches, including the regulation of tyre production, which plays a critical role in limiting TWP emissions.

4.2. Governance arrangement for tyre production

In Europe, 4.2 million tonnes of tyres were produced in 2020 [25]. The production stage involves tyre design, composition, and manufacturing. Natural and synthetic rubber are the main raw materials used for tyres, yet tyres also consist of various chemicals, metals, carbon black and oils [46,71]. Its governance focuses on improving these aspects to reduce the abrasion rate and limit the harmful chemical emissions [59].

EU regulatory *actors*, who have the *power* to develop regulation, in particular the three European Commission Directorate-Generals (DGs) for the Environment, Mobility and Transport, as well as Energy set the tone for the development of *rules of the game* in terms of policies and legislation for tyre design. Generally, these EU processes relate to existing tyre legislation. This includes the Tyre Approval Regulation (2019/2144) which sets minimal requirements for tyres to being placed on the EU market, the Tyre Labelling Regulation (2020/740) setting information requirements for users, and the Euro 7 regulation (2022/0365/COD) which ultimately aims to ban the worst-performing tyres from being sold on the EU market, based on a still to be developed tyre abrasion measurement method. For the manufacturing process, the Industrial Emission Directive (2024/1785) establishes obligations for industrial installations – which are outside the scope of this study -, while for the chemical composition the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation (1907/2006) is the legislative instrument manufacturers must comply with [71], see Fig. 2 for an overview of relevant regulation across the four lifecycle stages.

Currently, the policy *discourse* related to tyre production focuses on how to best address TWPs through measures aimed at improving tyre design. This includes expanding the scope of the Regulation on Eco-design for Sustainable Products (ESPR, 2024/1781) to include tyres and setting eco-design requirements for tyre design. While this measure indirectly addresses the amount of TWPs, it does not target the chemical composition of tyres or the manufacturing process. Moreover, tyre industry argues that reducing tyre friction and thus abrasion, will reduce road safety [39].

Within the governance arrangement for production, the tyre industry is a key *actor*, as manufacturers can modify tyre characteristics and composition, such as improving energy efficiency or changing the tyre tread, using less harmful chemicals and choosing more sustainable materials for tyre production. At the EU level, the tyre industry is primarily represented by the European Tyre and Rubber Manufacturers Association (ETRMA) and the European Tyre and Rim Technical Organization (ETRTO), which significantly influence EU and other processes due to their expertise and experience with the chemical composition of tyres, the use of alternative materials, and the design of for example a wider tread [47,61,38].

In an effort to improve the composition and design of tyres, tyre and car manufacturers collaborate with universities, research institutes, engineering companies and start-ups on topics outside the tyre industry's expertise, e.g. toxicity or technologies including enzymatic recycling of plastics [44,38]. These partnerships help to develop the science, technology and chemicals needed. While there is a general understanding of what a tyre is composed of, only the respective tyre manufacturers know the exact composition of their tyres due to market competition and antitrust regulation. This provides them with a powerful position in the policy development and decision-making process. Not only does the tyre and car industry have the capacity to engage in different policy processes, e.g. through representation in different

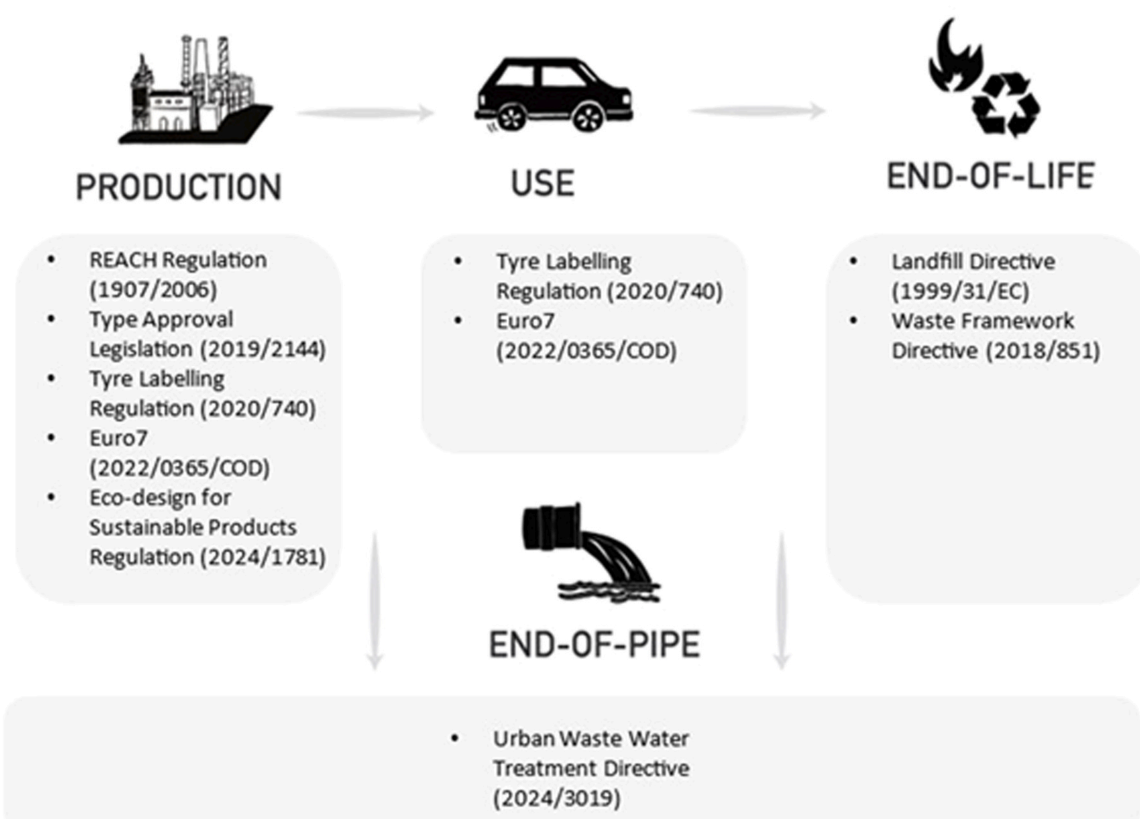

Fig. 2. EU legislation for tyres during production, use, and end-of-life and end-of-pipe TWP emissions.

forums, but they also have access to financial and knowledge resources that provide them with an overall advantage not only on the market but also in decision-making processes. In turn, Non-Governmental Organisations (NGOs) and civil society organisations with limited capacity and resources have turned to EU institutions to set clear regulations and incentives for the tyre and car industry to act on tyre design to reduce tyre abrasion [20,27]. While regulatory developments, such as eco-design requirements for tyres under the ESPR are underway, there is currently no existing incentive for tyre manufacturers in place.

4.3. Governance arrangement for tyre use

Approximately 1.2–6.7 kg of TWPs are produced during a tyre's life span, which makes up 10–16 % of the weight of the tyre [55,66]. It is estimated that between 360.000 and 540.000 tonnes of TWPs were released in the environment in 2019 [29]. As such, the governance arrangement in the use stage is inextricably linked to the governance arrangement in the production stage, as tyre design and composition have an impact on the abrasion rate of the tyre, occurring during tyre use on the road. Consequently, policies targeting the increasing amount of passenger cars like the Sustainable and Smart Mobility Strategy complement existing *rules of the game*, such as Euro 7 and Tyre Labelling Regulation.

As part of the Tyre Labelling Regulation, information requirements will cover the classification according to emissions of microplastics (abrasion) and kilometres run (mileage), which will guide the consumer when purchasing a tyre in addition to the existing classifications (rolling resistance, noise, wet grip, snow and ice conditions) depicted on the tyre label. It can only do so, however, once reliable testing and measuring methods are available [40]. In addition, the most significant features considered by consumers when comparing tyres were found to be mileage, grip and purchase price [40]. The study, which was conducted by the European Commission, also found that abrasion was not considered relevant [72]. Therefore, it remains to be seen how the new classification may increase consumer awareness and choices in the future.

As such, the establishment of minimum requirements covering non-exhaust emissions under Euro 7 constitutes a significant policy development [43], as it sets legal thresholds for emissions from tyres to be sold on the market. These legal thresholds depend on the tyre abrasion measurement method [41], which is currently being developed under Regulation No. 117 by the United Nations Economic Commission for Europe World Forum for Harmonization of Vehicle Regulations (UNECE WP29). The methodology, which is reflected in the Euro 7 regulation, will apply gradually from July 2028 for C1 class tyres (passenger cars), 2030 for C2 class tyres (light trucks) and 2032 for C3 class tyres (heavy trucks). Euro 7 is the first regulation addressing non-exhaust emissions and will set abrasion limits for tyre manufacturers to comply with when tyres are sold on the market. As a result, this regulation will ultimately influence the tyre material composition, as well as the manufacturing process.

In this vein, *discourses* on tyre abrasion focus on different aspects influencing tyre wear. For example, vehicle weight and torque are discussed as factors impacting TWP release, due to the trend towards heavier vehicles and increased road traffic [2,81,44]. Other factors discussed to impact tyre wear are the role of individual driving behaviour, road characteristics, weather conditions when driving, tyre pressure and speed [2,13,31,52,70,38]. Tyre wear particle emission is also seen as an intrinsic and essential part of car mobility and necessary for safe vehicles [39].

In recent years, research projects (with car and tyre industries participating in these projects) have emerged to enhance knowledge on these issues, e.g. the RAU project focusing on tyre wear in the environment [9], the KI-RAM project focusing on AI-based solutions to reduce abrasion and traffic-related microplastic emissions [10], and the LEON-T project, investigating particulate and noise emissions from tyres [50]. Within these projects, the tyre industry acts as either a project partner or project coordinator. A further example of increased engagement and collaboration among *actors* is the European Tyre and Road Wear Particles Platform, bringing together tyre producers, the road and automotive sectors, as well as chemical suppliers and the wastewater sector [15]. Given the different factors that have to be taken into consideration to reduce TWP emissions, the platform served as a first attempt to discuss and exchange best practices, ways to improve the capture and removal of TWPs, as well as options for cross-sectoral collaboration [31]. Nevertheless, the European Commission relies heavily on the expertise of the tyre industry which not only holds relevant knowledge resources and financial capital to advance technological development, but is also well represented in the UNECE WP29, contributing to the development of a harmonized tyre abrasion measurement method.

4.4. Governance arrangement for tyres' end-of-life

The end-of-life stage involves the collection of disposed tyres, and their material recycling or energy recovery. Disposed tyres do not include tyres which are retreaded or exported for reuse. Exporting used tyres to non-OECD countries will become prohibited under the EU Waste Shipment Regulation (2024/1157) as of May 2026. The management of end-of-life tyres that remain within the EU is of great importance for the zero pollution objective for TWP emissions, since tyres are a significant source of waste [18] and an important secondary source of microplastic and chemical pollution from leachate. Since the Landfill Directive (1999/31/EC) the disposal of tyres in landfills is illegal in the European Union from 2006 onwards. According to ETRMA [26], in 2021, 97 % of all EoL tyres were collected (with the remaining 3 % unknown or kept in stocks). Following the Waste Framework Directive (2018/851), tyre collection is organised in some EU Member States under an Extended Producer Responsibility scheme which incentivizes producers to collect end-of-life tyres [79]. Extended Producer Responsibility schemes cover approximately 60 % of the 3 Million tons of annually generated end-of-life tyres [28].

The European Tyre and Rubber Manufacturing Association is a key *actor* representing producers. They estimate that currently 40 % of tyres are used in energy recovery, mainly in coal plants and cement kilns [26], while 55 % of tyres are used in recycling. Within the recycling category, 70 % consists of infill of granulated rubber, and 25 % consists of inorganic content use for cement manufacturing [24]. The *rules of the game* are evolving. The granulated rubber infill in synthetic sports pitches and playgrounds is being phased out under the REACH regulation on intentionally added microplastics, increasing the need to find alternative recycling methods that minimize negative impacts on human health and the environment. In response to this ban, the recycling industry *actors* highlight a need for more circularity [42].

In their *discourses* the recycling industry points to the need for better end-of-waste criteria in the Waste Framework Directive, to facilitate the recycling of tyre materials, including in tyre production [39,42]. They also highlight the need for eco-design of tyres, which could facilitate material recovery and minimise the need to resort to energy recovery in which the material is lost [42]. Tyre producers' discourses do not reflect the end-of-life considerations but rather highlight high collection rates of end-of-life tyres. They prioritise design criteria related to use, such as safety, grip, and roll resistance. The discourses of environmental NGO's align with those of the recycling industry as they argue that the current implementation of the Extended Producer Responsibility of producers to address pollution from car tyres is insufficient [43,42].

Governance of the end-of-life stage has underwent a transition from regarding tyres as waste going into landfills or exports, to encouraging energy recovery, material recovery and closed loop recycling of tyres as part of a circular economy [28,45]. This last transition remains, however, challenged by the lack of a market for tyre-derived materials, as well as the high level of technical innovation needed to remove toxic chemicals such as PAHs from tyres.

4.5. Governance arrangement for end-of-pipe TWP emissions

The governance arrangement for the end-of-pipe stage includes wastewater, stormwater, and road runoff management and treatment to retain abrased TWPs before these reach open water bodies [48,59]. In some wastewater treatment facilities, microplastic particles can be removed before the effluent is released into the environment [22,51], with microplastics being captured in sewage sludge [67]. Given the environmental impact of TWP pollution, there is a need to develop effective methods for capturing these particles during waste water treatment [41]. Microplastics from sewage sludge might still enter the environment through incomplete incineration [63] or the application of sewage sludge on agricultural land [16,35].

The *rules of the game* for the governance of end-of-pipe emissions of TWPs are mainly laid out in the Urban Waste Water Treatment Directive. Directives give guidance and flexibility for Member States for implementation leading to variation between countries, e.g. Germany setting limits for microplastics in sewage sludge used in agriculture and implementing a monitoring program to track the levels of microplastics in sewage sludge while most EU countries do not [37]. Following the recent revision, the UWWTD mentions microplastics for the first time, primarily in relation to monitoring. The central *actors* are the wastewater authorities of Member States, who set national requirements for wastewater treatment facilities, and the European Federation of National Associations of Water Services (EurEau). EurEau represents Europe's water services sector and has significant influence on legislative developments at the EU level such as the revision of the UWWTD [42].

The end-of-pipe governance in the EU can be characterised as a 'captive market' with limited *power* for users to choose a wastewater operator [30]. As a result, the wastewater treatment sector is primarily reactive to legal requirements rather than being driven by market forces. The *discourses* surrounding microplastic capture in wastewater treatment facilities are usually focused on finding the most effective and efficient technologies for capturing these particles [1,67]. EU regulation hinges on agreement on methodologies for monitoring of TWPs and microplastics in water and sewage sludge, which renders *power* to researchers such as the Joint Research Centre of the EC as well as rubber-producing industries who increasingly invest in studies on TWPs (see e.g. [56]).

The water industry and water authorities point out that end-of-pipe measures alone are insufficient to address TWP pollution and argue for a source-based approach where possible [42]. Wastewater treatment will only target run-off from roads that go to the sewage system, however not all countries have wastewater treatment facilities that include road run-off. The required time and investment associated with changes to road infrastructure and wastewater treatment capability are significant, limiting the responsiveness of end-of-pipe measures to address TWP emissions [42]. Wastewater operators are very supportive of the newly introduced Extended Producer Responsibility (EPR) schemes for wastewater treatment and consider them an effective way to involve industries in the discussion of water quality. They emphasize the importance of shared responsibility in dealing with emerging pollutants and argue that treatment plants cannot be solely responsible for removing all substances ([56]).

5. Assessment of emerging EU TWP governance

Based on the governance arrangement analysis, this section will assess the way in which EU governance of TWPs is evolving, first in terms of regulatory dynamics within and between lifecycle and pollution stages, and second in terms of power and discourse dynamics. This section will end with an overarching assessment of EU TWP governance.

5.1. Regulatory dynamics in the emergence of EU TWP governance

The analysis of the EU governance arrangements affecting emissions of TWPs shows that rules and regulations to reduce TWPs have only recently been adopted (see Fig. 2). Within the EU, TWP pollution is an emerging policy domain that touches on all four lifecycle and pollution stages (see Table 3). As such, EU TWP governance are an acknowledgement that measures to improve and change design, use, and end-of-life of tyres, and end-of-pipe emissions of TWPs are all needed to achieve the EU's ambition of a 30 % reduction of microplastics to the environment.

Regulations that target a specific lifecycle or pollution stage include the Euro 7 and ESPR, which target the design and production of tyres, while the UWWTD focuses on improving end-of-pipe capture of TWPs. In addition, the stage that receives least attention is the consumption and abrasion during use of tyres [71]. Only labelling to allow consumers to make more informed buying decisions are currently under development, although it should be noted that the Euro 7 legislation does affect which tyres consumers can chose from, because they provide thresholds

Table 3
Regulatory and power dynamics in emerging EU TWP governance.

Life cycle or pollution stage	Regulatory developments	Power and discourse dynamics
Production	Preventing the most environmentally harmful tyres from entering the market (Euro7) Linking use- and end-of-life concerns with design and production to prevent abrasion, encouraging tyre circularity (ESPR)	Power of EU policymaking institutions to develop regulations to reduce tyre abrasion Power of tyre producing industry in setting abrasion methodologies and standards Eco-design discourse is emerging and contested for tyres
Use	Labelling to allow informed consumer decision-making and encourage eco-design (Tyre Labelling Regulation)	Power of EU policymaking institutions to develop regulations to reduce tyre abrasion Power of tyre producing industry in setting abrasion methodologies and standards Discourse of inevitability and essentiality of tyre wear for safe vehicle mobility
End-of-Life	Reducing end-of-life microplastic emissions from crumb rubber infill and encouraging alternative material recovery solutions (REACH and Waste Framework Directive)	Recycling industry lacks power to influence tyre design Discourse of circular economy to prevent material loss emerging shared between recycling industry, EU policymaking institutions, industry and NGOs Differing discourse about effectiveness of Extended producer responsibility between producing industry and NGOs
End-of-Pipe	Defining microplastics as a priority substance for wastewater treatment (UWWTD) Extended Producer Responsibility puts responsibility for wastewater treatment on producers (UWWTD)	Wastewater operators are generally supportive of extended producer responsibility schemes. EU institutions and Member States are powerful actors laying out the rules of the game. NGOs like EurEau have power in influencing EU policy making. Discourses revolve around technological solutions for improving capture of pollutants through wastewater treatment

for placing tyres on the market. Moreover, efforts to reduce car mobility are included in a different policy domain, i.e. that of mobility and climate change. Other rules and regulation that affect use of tyres, i.e. improving public transport, are thus not considered in relation to TWPs (yet) [45]. In fact, a particular challenge related to the increased use of electric vehicles, which are promoted to reduce fuel use and greenhouse gas emissions, is that these are heavier, leading to higher levels of tyre wear and thus emissions of TWPs [69]. As a consequence incoherence exists between EU TWP governance that aims to reduce TWP emissions and mobility and climate governance that promotes the use of electric vehicles.

The analysis also shows how most of the current regulatory developments span multiple stages and are generating linkages between governance arrangements, see Table 3. For example, incorporating tyres in the ESPR may facilitate material recycling of tyres, which has become more urgent due to the infill ban under the updated REACH regulations as part of the end-of-life governance arrangement. Similarly, extended producer responsibility for wastewater treatment will connect producers to the end-of-pipe of TWPs, and potentially provide an incentive to improve tyre design. Finally, the updated tyre labelling requirements that include tyre abrasion rates in the use stage, in combination with the Tyre Approval Regulation and Euro 7, can potentially impact design and producer decisions too. While there thus appears to be a coherent set of policies that create linkages between life cycle stages, some of these are still only in development. For example, including abrasion rate in labelling is being aimed for, but is dependent on the agreement on harmonized abrasion measurement methodologies. Similarly, increasing reuse of mechanically recycled tyre granulate is hampered by technological and economic challenges of ensuring this granulate is safe and cheap to enable reuse in tyre production.

5.2. Power and discourse dynamics in the emergence of EU TWP governance

The analysis also shows that governance efforts are dominated by EU policymaking institutions, EU Member States and the tyre producing industry, see Table 3. EU institutions and Member States have a formal position in the regulatory process as well as access to financial and knowledge resources. Yet, EU institutions and Member States rely on the tyre industry for access to knowledge about tyre design and composition, knowledge that is protected by competition laws. This industry therefore has an influential role in the development of methodologies to determine abrasion rates in the UNECE WP29, which are used for Euro 7 and the Tyre Labelling Regulation. Their influence extends therefore also to how a synergetic link between consumer buying choices and improved tyre design is aimed for based on the abrasion measurement methodologies.

In addition to this influence, the rubber, tyre and car producing industries have access to financial resources, know their way in lobbying EU institutions and policy makers and are involved in multiple governance arrangements around the production, use and end-of-life of tyres. This combination gives them a very powerful position within EU TWP governance. NGOs are involved in multiple arrangements too, but have less access to financial and knowledge resources. Other actors have a more influential role within a single governance arrangement, e.g. recycling industry in the end-of-life governance arrangement, and the wastewater treatment industry in the end-of-pipe governance arrangement.

Added to these power dynamics are differences in discourses between these actor groups, particularly between industry and NGOs, see Table 3. There is a common discourse around eco-design, which is particularly favoured by the NGOs, the recycling industry and expressed in high-level EU ambitions, but this discourse is challenged by the tyre producing industry. The Tyre Labelling Regulation is a shared interest between regulators and the tyre and rubber industry, but the extent of the potential gains from this regulation is being questioned by NGOs. Tyre and car producers argue for an approach in which other factors beyond tyre design, such as road design, are considered and highlight the trade-offs between e.g. safety from changing tyre design to reduce TWP emissions. The intricate link between TWPs and toxic chemicals is similarly brought forward by the end-of-life actors and NGOs but largely avoided by regulators and the tyre and rubber producers. It remains to be seen how industry and NGOs are able to use their power resources to entrench their discourses within the further development and implementation of EU TWP regulations.

5.3. EU TWP governance assessment and recommendations

Overall, we can conclude from the assessment that the zero pollution action plan and the associated revisions of regulations foster a more preventive approach to TWP emissions. Various regulations together seek to enhance tyre design to reduce emissions during use or the end-of-life of tyres. The tyre abrasion standards and eco-design have the most potential in terms of preventing TWP emissions (in addition to reducing the use of vehicles altogether). However, as a consequence, the role of the most powerful actors, i.e. the tyre (and car) manufacturers, in implementing and working towards reducing TWPs becomes only more important. The extended producer responsibility for wastewater treatment under the UWWTD also adds to the attention and pressure going to these industries. The tyre producing industry's powerful position could, however, lead to design and abrasion rates being watered down and efforts being pushed to issue areas downstream, i.e. in later stages of the life cycle. In that sense, the increasingly powerful role of the rubber, tyre and car producing industry embodies a risk of regulatory capture of EU institutions. This will ultimately depend on how successful industry (and other actors) are in lobbying policy makers, influencing the development of abrasion methodologies and standards, and using discursive arguments around addressing other factors than tyre design in shaping EU TWP governance.

In addition, while technological developments offer potential for improved end-of-pipe TWP governance, they require not just significant regulatory changes, but also costly long-term planning and investment on roads infrastructure and wastewater treatment facilities. It would take at least a decade for such technological and infrastructural improvements to result in meaningful reductions of microplastic emissions into waterways. Addressing TWP emissions through design and use as well as end-of-pipe measures is therefore vital to achieve EU ambitions to reduce microplastic emissions by 30 % by 2030.

Based on the assessment, several recommendations for improving EU TWP governance can be provided. First, in order to strengthen EU TWP governance, it is important to safeguard the preventive approach to governing TWPs, with attention for prevention of emissions at source and the role of tyre production and design for emissions later in tyre lifecycle. The interaction of different regulations across the lifecycle and pollution stages is therefore relevant to monitor, especially given the power of the tyre producing industry which is expanding to governance arrangements across the whole lifecycle. Providing transparency of decision making processes, supporting NGOs and inclusivity in stakeholder engagement, and reducing possibilities for industry lobbying are some ways to reduce the risk of regulatory capture. Second, the analysis also shows that further efforts to address use of tyres, including the increase of tyre wear in use of electric vehicles should be considered. This requires ensuring more coherence between EU TWP governance and the policy domains of mobility and climate change. Finally, given the role of both road and wastewater infrastructure, more attention should be paid to the financial implications of developing and implementing technological and infrastructural improvements for public agencies involved in managing roads and wastewater treatment facilities and infrastructure.

6. Concluding discussion

In this article, a MAPGAF was developed to allow for an assessment of governance approaches not in isolation, but collectively, by assessing the way in which multiple governance efforts address lifecycle and pollution stages of products and substances that leak into the marine environment. In addition, the MAPGAF focuses on how rules of the game, actors and their discourses and power resources affect how marine pollution is governed. Based on the application of the framework to the emerging EU governance of TWPs, this section draws conclusions about the societal and theoretical relevance of the MAPGAF.

First, our case study of emerging EU governance of TWPs shows that the MAPGAF is not only relevant for understanding governance dynamics within each governance arrangement, but lays bare how interaction between lifecycle and pollution governance arrangements are shaped by regulatory, power and discursive trends in marine pollution governance that go beyond an individual policy domain. Notably, attention to power and discourse dynamics added depth to the assessment. This was evident first, because it became clear that power relations are not only based on available resources but also accumulate when an actor is involved in multiple governance arrangements. Second, shared and competing discourses influence synergetic or competing regulatory dynamics across different governance arrangements. For example, while some governance arrangements and actors advocate and stimulate eco-design of tyres, others emphasize how other factors that shape the use of tyres influence abrasion rates and thus TWP emissions. These insights were also reflected in the recommendations, which highlighted the need to ensure policy developments create synergistic linkages between lifecycle and pollution stages and reduce the increasingly powerful role of the tyre manufacturing industry.

However, while the framework includes four lifecycle and pollution stages, additional stages could be incorporated depending on the pollutant addressed. For example, the stage of production can be further differentiated into production of raw materials and manufacturing of products (see e.g. [65,71]). Similarly, a stage of remediation could be envisaged after end-of-pipe, where pollutants are recovered from the (marine) environment [73]. Moreover, in some cases, certain lifecycle stages might be less relevant; for instance, fertilizers may not have an end-of-life stage since they are directly absorbed into the environment during use. The stages presented in this framework should therefore be viewed as a heuristic example rather than a rigid structure and can be adapted to the policy domain and type of pollutant studied. Future research should broaden the application of this framework to other pollutants to further insights into how interaction between governance arrangements addressing lifecycle stages and pollution reinforce ambitious ways to reduce marine pollution. This then also includes refining which stages are most relevant to distinguish in marine pollution governance assessments.

CRediT authorship contribution statement

Astrid Hendriksen: Writing – original draft, Methodology, Conceptualization. **Linda Del Savio:** Writing – review & editing, Writing – original draft, Formal analysis. **Emily Cowan:** Writing – review & editing, Formal analysis. **Judith van Leeuwen:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Freddy van Hulst:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2025.107023.

Data availability

The data that has been used is confidential.

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