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Exploring a Source to Sea approach for plastic pollution policy integration in the European Union: the case of tyre wear particles

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ABSTRACT

The European Green Deal marks a shift in policy-making, aiming to transform the European economy and society to achieve sustainability and climate neutrality. Its zero-pollution ambition, outlined in the Zero Pollution Action Plan, provides an opportunity to address marine pollution in the European Union in a more integrated manner, setting the ground for new governance requirements to address existing challenges, and drive the integration of previously separate policy domains. In this context, the Source to Sea concept is explored to assess plastic pollution policy integration with regard to tyre wear particles, a form of unintentionally released microplastics. In this vein, the article considers the life cycle stages and pathways of tyre wear particle pollution across land, freshwater, and the marine environment to identify key actors, including responsible authorities, and policies that govern them. In applying a Source to Sea approach to the tyre wear particles case, the assessment highlights cooperation and conflicts among actors, conflicting policy objectives and how tyre wear particles are covered under the European Green Deal. This assessment offers a perspective to explore opportunities for policy integration regarding marine pollution and for future research avenues into policy integration, including through the application of empirical studies.

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1. Introduction

Marine plastic pollution is a complex governance challenge. Due to its transboundary nature, plastic pollution can have major environmental implications across international borders and extends across different legal jurisdictions managed by various administrative bodies (Ferraro & Failler, 2020; Hoof et al., 2012; Van Leeuwen et al., 2014; Maes et al., 2023a, 2023b; Soma et al., 2015). For example, plastic litter released on the coast of one country may wash up on the coast of another. In such instances, multiple legally-mandated authorities, including local public authorities

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responsible for waste management (e.g. municipalities, port authorities), national public authorities (e.g. ministries of environment, fisheries, tourism), sectoral agencies (e.g. environment or waste agencies) and regional sea bodies (e.g. Regional Sea Conventions) may be involved in marine litter pollution management (Hedlund et al., 2023; Maes et al., 2023). Human activities, including on land and at sea, further contribute to this governance challenge due to their impact on interconnected ecosystems, which are connected through river flows and ocean currents (Harris et al., 2023; 2021; Nyberg et al., 2023). Ultimately, plastic pollution that ends up in the marine environment can be the result of any number of multiple point and diffuse sources and could have travelled via several pathways before being detected (Harris et al., 2023). Multiple governing bodies, actors, policy initiatives, and instruments have emerged to prevent marine plastic pollution (Maes et al., 2023; Van Leeuwen et al., 2022; Vince & Hardesty, 2018), however, the challenge of plastic pollution persists. An effective governance response to plastic contaminants requires a coordinated approach that integrates key considerations and knowledge about sources, pathways, relevant interlinkages between actors, management approaches, and policies to foster joint action and identify appropriate measures (Cowan et al., 2025). The present stagnation in the negotiations on a Global Plastic Treaty is indicative of the difficulties in consolidating international efforts to address plastic pollution. As such, recent developments of plastic pollution governance at the EU level represent a significant contribution to this process.

The European Green Deal, presented in 2019, marks a shift in EU policy-making, aiming to transform the European economy and society to achieve sustainability and climate neutrality. Its zero-pollution ambition provides a unique opportunity to address marine plastic pollution in the EU in an integrated manner. The European Green Deal, including the 2021 Zero Pollution Action Plan and 2020 Circular Economy Action Plan, which in conjunction with the previously established 2018 Plastics Strategy and 2008 EU Marine Strategy Framework Directive (MSFD) sets priorities for policy and governance to address existing challenges with plastic. With this development in EU marine pollution policy, a first step towards integrating previously separate policy domains is attempted. Despite these efforts, current policies are not significantly addressing the sources of unintentionally released microplastics, which contribute to marine plastic pollution. Moreover, there remains a lack of fit-for-purpose marine litter, plastic and microplastic monitoring approaches that enable the accurate and robust assessment of the effectiveness of implemented mitigation actions (Galgani et al., 2022; 2025). The often-conflicting objectives and priorities of actors and the disconnect between institutional arrangements in different regions, as well as across life cycle stages of specific forms of plastic pollution, add to the complexity of the problem and inhibit the effectiveness of current policies to adequately address marine plastic pollution.

The EU has been widely studied as a case of policy integration (Kaplaner et al., 2025; Maltby, 2013; Rietig, 2013; Ugland & Veggeland, 2004). Numerous understandings and definitions of policy integration exist, and they all primarily focus on the 'cooperation of actors from different policy domains or policy sectors' (Tosun & Lang, 2017). From this standpoint, policy integration is not a goal that can be achieved, but an ongoing political process which requires continuous and targeted efforts to resist the 'pull toward sector-specific problem definition, policy-making, implementation and evaluation'(Cejudo & Trein, 2023; Maes et al., 2023). Policy integration is recognised as a mechanism for incorporating environmental objectives into sector-specific policies, a process that, within the EU is guided by the ambitions outlined in the European Green Deal (Dupont & Jordan, 2021). While policy integration is broadly recognised as an important approach to better understand policy-making, its practical application in policy design and implementation remains challenging, partly due to the lack of effective tools for assessing policy integration in practice

(Lafferty & Hovden, 2003; Nilsson & Persson, 2003). In addition, sectoral silos, conflicting interests, institutional fragmentation, the lack of political will, the complexity of issues, and capacity constraints further impede effective policy implementation. However, to address and improve policy integration, it is important to accurately identify and ultimately target gaps, inconsistencies and overlaps within policy domains (i.e. policy mixes) (Howlett et al., 2017; Maes et al., 2023).

Despite marine plastic pollution being recognised as a critical health and environmental issue under the European Green Deal, particularly under the Zero Pollution Action Plan, current governance approaches and policies are largely fragmented and insufficient to effectively address the complex sources, pathways, and impacts of microplastic pollution, specifically emerging contaminants like tyre wear particles (TWPs) in the EU. This lack of integrated marine plastic pollution governance in the EU hinders the effective implementation of the European Green Deal's zero-pollution ambition. Thus, a novel approach to governance that considers the interconnectedness of sources, pathways, and actors involved in marine plastic pollution is needed. Based on the Source to Sea concept, which is presented in the following chapter, this article assesses EU plastic pollution policy integration in the case of TWPs. TWPs were selected as an explorative case study, as they represent an emerging contaminant of growing relevance within EU environmental governance and exert impacts across terrestrial, freshwater, and marine ecosystems. Microplastics, such as TWPs, can infiltrate groundwater through pathways including wastewater treatment plants and urban runoff during storm events, thereby affecting interconnected water bodies like rivers, estuaries, wetlands, and oceans. Tyres constitute a significant source of microplastics that are unintentionally released into the (marine) environment throughout their lifecycle and use phase (Booth et al., 2024; Lau et al., 2020; Mattsson et al., 2023). As such, this study provides an opportunity to generate insights into the application of the Source to Sea approach as a means to enhance policy integration in addressing marine plastic pollution within the framework of the European Green Deal. The article aims to address the following research question: How does a Source to Sea approach contribute to assessing the integration of existing policies for governance of marine plastic pollution from TWPs within the context of the European Green Deal? In doing so, the article examines the interconnections between established concepts of plastic pollution governance, such as the circular economy and the life cycle of plastics, through the lens of a Source to Sea approach, offering insights and contributing to the EU policy integration literature.

2. A Source to Sea approach to policy integration

The policy integration literature, revealing compartmentalised and sector-specific policy-making, has provided different perspectives on policy issues, for example through multi-level governance (Howlett et al., 2017; Zepa & Hoffmann, 2023), mostly focusing on assessing horizontal policy integration (Bergmann & Müller, 2024) and in a limited manner also vertical policy integration (Vargas et al., 2019; Zepa & Hoffmann, 2023). Horizontal policy integration refers to the level of coherence between (sectoral) policies and vertical policy integration links bottom-up and top-down policy dynamics (Vargas et al., 2019).

This chapter explains how this article uses the Source to Sea concept to assess plastic pollution policy integration between policy domains relevant for Source to Sea pathways in the case of TWPs. The section first explores how the Source to Sea concept relates to identifying both pathways of pollution from Source to Sea, as well as the variety of upstream sources of TWP pollution. It will then discuss how policy integration requires identifying both policies and actors across the life cycle stages and pathways of TWP pollution.

2.1. The Source to Sea concept

The Source to Sea concept emerged as a way to balance conflicting and diverse governance and management objectives and arrangements between freshwater and marine systems (Michels-Brito et al., 2023). It offers a means to consider the entire water system, as a continuum from rivers, lakes, deltas, and estuaries to coastlines, nearshore waters, adjoining seas, continental shelves, and the ocean (Granit et al., 2017) (Mathews & Stretz, 2019). As such, the concept has been applied to better understand the interlinkages between freshwater and marine management (Liss Lymer et al., 2018; Michels-Brito et al., 2023; Wang et al., 2021) or in the context of freshwater and sediment management of lakes, rivers, and river deltas (Belete et al., 2021). In the context of pollution governance and management, the Source to Sea concept has been applied in the case of marine litter management (Francis & Herat, 2020), as well as to identify the occurrence, sources, degradation, fate, transport, and pathways of different contaminants, such as pharmaceuticals (White et al., 2019; Zandaryaa & Frank-Kamenetsky, 2021), microplastics in waste water treatment plants (Freeman et al., 2020), nano plastics (Gangadoo et al., 2020), Tyre and Road Wear Particles (Mattsson et al., 2023), and plastic litter (Lima et al., 2022), among others. Within these studies, the Source to Sea concept highlights the relevant interlinkages between land, freshwater, coastal and marine systems (Weinberg et al., 2021), where the river is the central focus. In a similar vein, Francis and Herat (2020) combine a Source to Sea perspective with circular economy principles based on Mathews and Stretz' framework for marine litter prevention (Mathews & Stretz, 2019).

While the term 'Source to Sea' occurs in scientific articles of the 1990s and 2000s (Adams & Evans, 1990; Baker & Spencer, 2004; Castelo, 1994; Packett et al., 2009), its use as a concept within governance and management frameworks to increase cross-sectoral coordination and upstream-downstream (or land to sea) cooperation amongst actors only appeared from 2017 onwards (Francis & Herat, 2020; Graham, 2023; Granit et al., 2017; Michels-Brito et al., 2023; Weinberg et al., 2021). Beyond scientific literature, the Source to Sea concept has been applied in various contexts. For instance, the Food and Agriculture Organisation, during the 2023 UN Water Conference, introduced the Source to Sea approach as a dynamic interface between land and oceans that offers a framework for integrated planning that enhances the implementation of water resource management (Food and Agriculture Organisation, n.d.; Granit et al., 2017; Mathews & Stretz, 2019). At the regional seas level, Regional Sea Conventions, such as the Barcelona Convention, explore possible ways to apply the Source to Sea approach as presented in the framework by Mathews and Stretz (Mathews & Stretz, 2019; UNEP-MAP, 2023). Regarding plastic pollution, UNEP uses a Source to Sea description in its programme of work, the Clean Seas Campaign, Global Commitment, Global Partnership on Plastic Pollution and Marine Litter (United Nations Environment Programme, 2021). While these examples provide insights to the level of context within which the Source to Sea concept appears in the policy field, the term itself has been used without any specific guidance or recommendation on how this concept should be applied or implemented. For example, UNEP's review of technical solutions 'from Source to Sea' focuses on technologies for the prevention of wastewater contamination, treatment of wastewater and run off, as well as downstream technologies for microplastics removal from drinking water and wetlands (Nikiema et al., 2020). Similarly, the recent European Environment Agency report on marine litter contains recommendations for a more holistic approach 'from Source to Sea', addressing the mismanagement of waste and rivers as the major pathways (European Environment Agency, 2024). However, these examples are downstream (i.e. marine) focused and do not differentiate between different sources of contaminants, revealing that the Source to Sea concept is often applied in a limited way.

Although it remains a loosely applied and defined concept with limited utilisation across marine and pollution governance in the EU, the Source to Sea concept within water and pollution governance demonstrates a growing shift towards integrating land and sea, and upstream and downstream considerations across science and management to integrate previously disconnected policy domains.

Building on previous Source to Sea conceptualisations (Francis & Herat, 2020; Granit et al., 2017; Mathews & Stretz, 2019), this article adopts a more extended Source to Sea approach by including sources of marine plastic pollution along the life cycle stages of plastic products, while recognising the interconnectedness of geographical segments from land to sea. In order to assess policy integration, it is necessary to identify policy objectives and actors involved in the design and implementation of these policies, since a range of state and non-state actors, as well as stakeholders, are involved in policy integration (Vince et al., 2024). The Source to Sea approach presented here can serve as a useful tool for this purpose.

2.2. Applying a Source to Sea approach to assess policy integration

In the case of TWPs, a Source to Sea approach for the assessment of plastic pollution policy integration combines two elements: Pollution pathways and lifecycle stages (ref. Figure 1).

The first element (pollution pathways) considers policy integration of plastic pollution as a cross-cutting issue in policies across pollution pathways based on the Source to Sea approach. Figure 1 shows how pollutants move through the environment, from their initial generation to their ultimate impact on coastal and marine ecosystems. The pathways illustrate the different routes

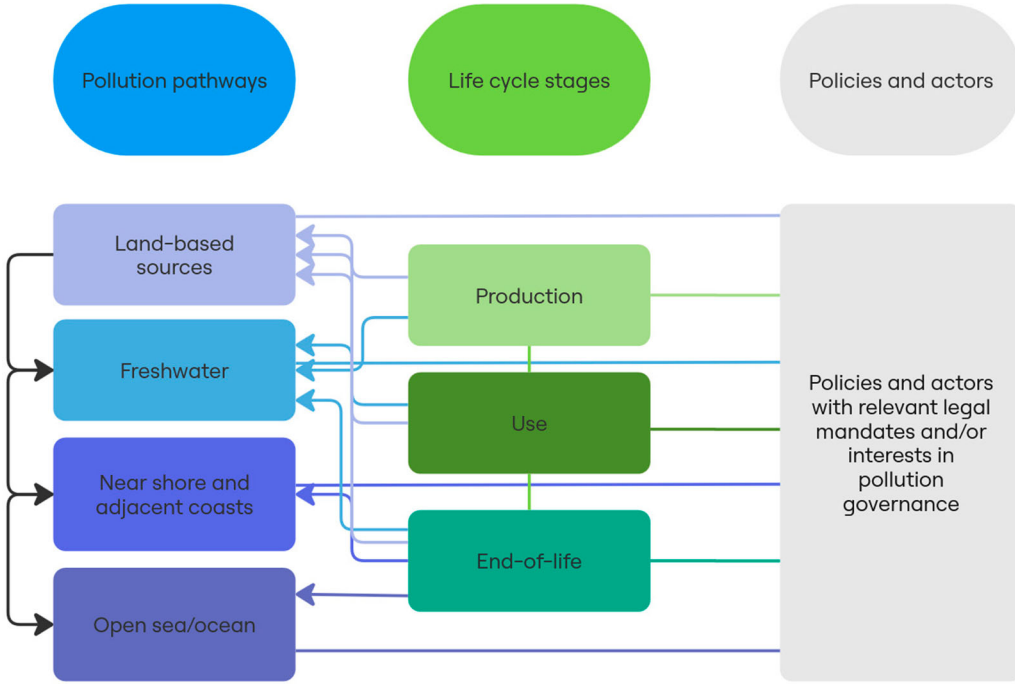

Figure 1. Source to Sea approach.

contaminants and pollutants can take, and the policies and actors involved at each stage highlight the potential for intervention and management.

The second element (life cycle stages) considers policy integration of plastic pollution as a cross-cutting issue in policies across the life cycle stages of a product. The life cycle perspective, including the production (manufacturing, design and composition), use and end-of-life stage of a product, is closely linked to the stages of pollution generation and transport and has relevant implications for pollution policy integration (ref. Figure 1).

In order to assess policy integration, a third cross-cutting element is important, i.e. that of policies and subsystem involvement (Candel & Biesbroek, 2016; Cejudo & Trein, 2023). Subsystem involvement can vary from low to high amounts of policy integration and can be conceptualised along two indicators: (1) which subsystems are involved in the governance of a cross-cutting issue and (2) the density of interactions (Candel & Biesbroek, 2016). In accordance with the conceptualisation outlined above, the present article identifies the relevant actors (as well as those who are not involved), their respective roles, and the degree of interest they have in marine plastic pollution, with a view to assessing policy integration. Consequently, the policy objectives and the relevant actors involved at each life cycle stage and pathway segment of TWP pollution are identified (see Figure 1). The Source to Sea approach serves as a means to operationalise which policy domains are relevant for TWP pollution and to assess policy integration dynamics.

In this article, policy integration dynamics are understood as the translation of the 'high-level' policy goals of the European Green Deal along the life cycle stages of a product and geographical segments (i.e. pollution pathways) from land to sea, while considering the key policies and actors tasked with implementing the EU's zero pollution ambition. Five steps were taken to apply this approach to policy integration. First, a case study pollutant was identified and selected for the assessment of policy integration. In the second step, a pollutant profile was developed based on the scientific literature. The third step consisted of mapping out the identified pollutant characteristics across the Source to Sea framework, tracing the sources and pathways of the selected pollutant. In the fourth step, a mapping exercise of the EU policy landscape was carried out using the Source to Sea approach to map out policies across different life cycle stages of the selected pollutant (source, transport, and sinks). This step provided a baseline understanding of the policy landscape and identified which policies address each stage of the pathway. This step further included mapping out key stakeholders involved in each stage of the lifecycle and pollutant pathway to identify their involvement in the selected policies. Finally, the last step included assessing the policies and actors against the life cycle stages and pathway segments, pertaining to the level of coherence between (sectoral) policies and subsystem involvement in the governance of TWPs and the density of interactions.

Data collected through the SOS-ZEROPOL2030 project[1] was used in each of these steps and included the life cycle categories (production, use, end-of-life), which guided the data collection process (Van Leeuwen et al., 2023). In particular, for steps one and two, data from document analysis (Devriese et al., 2023; Van Leeuwen et al., 2026) was used and for step three data from qualitative interviews (Van Leeuwen et al., 2023) was applied. By assessing the relevant EU policies, as well as the role of various actors (e.g. institutions, networks, organisations, individuals) across the Source to Sea continuum, the framework provides a means to assess policy integration. It provides a structured and visual approach to consider policy integration related to pollution, enabling a comprehensive understanding of the challenges and opportunities for effective governance. It allows for an integrated view of the problem, from source to impact, and facilitates the identification of key areas for improvement.

3. Exploring the Source to Sea approach in the case of tyre wear particles (TWPs)

While TWPs were chosen as an explorative case study, the focus of this article is on the marine environment; consequently, airborne particle emissions and soil pollution are beyond the scope of this research, although their contribution to marine plastic pollution is recognised. Along with other specific types of microplastic pollution such as textile fibres and pellets, for example, TWPs[2] are a form of microplastic with a clearly defined source (i.e. car tyres). TWPs are generated during tyre use due to the friction between the tyre and the road (Kreider et al., 2010). TWPs vary in size and shape (with the majority being <100 μm and into the nanoscale) and as such can travel through air, water, and soil where they may pose risks to human health and the environment (Barboza et al., 2020; Knight et al., 2020). While it is a significant challenge to elucidate the primary drivers of observed TWP toxicity, recent studies indicate the additive chemicals present in vehicle tyres, and by extension TWPs, are the primary driver of their toxicity (Cheong et al., 2023). Comparative studies have demonstrated that chemical leachates derived from vehicle tyres are more toxic than those from many thermoplastic consumer products (Sørensen et al., 2023), while the aging of TWPs through environmental degradation processes appears to increase their toxicity (Lv et al., 2024).

As such, TWPs present a complex governance challenge and an interesting case for the application of the Source to Sea approach. This application is outlined in the following section, by mapping out policies and actors across different stages of the TWP life cycle (source, transport, sink) and pathways of TWPs from Source to Sea (freshwater, coastal waters and open sea) to identify which policies address which stage of the pathway and key stakeholders involved in each life cycle stage and pathway segment and consider their level of involvement in policy-making, as well as to highlight gaps and overlaps in policy coverage and areas where integration is lacking (ref. Table 1).

The results (ref. Table 1) show how inextricably linked land-based sources of pollution are to the life cycle stages of tyres as a consumer product and not solely to the sources pertaining to the water system (rivers, lakes, etc.). Consequently, through the visualisation and application of the Source to Sea approach (ref. Table 1) three relevant implications for policy integration were identified: (1) cooperation and conflicts among actors, (2) conflicting policy objectives, and (3) how TWPs are covered under the European Green Deal.

3.1. Actors: cooperation and conflicts

Across the presented EU policy landscape, the main actors with a role in TWPs governance include the European Commission (DG GROW, DG ENV, DG MOVE, DG RTD and DG ENER), ECHA, the tyre industry, civil society (NGOs) and research institutes (ref. Figure 2). Tyre manufacturers play an important role in attaining the goals of the EU Zero Pollution Action Plan, as they are responsible for the composition, design, re-tread and reuse of tyres. Consequently, their expertise in chemical formulations and rubber materials, influences the discourse concerning abrasion rate, road safety and other key aspects of tyres. Due to this expertise, the tyre industry contributes to the development of a tyre abrasion measurement method under the Euro 7 regulation proposed by DG GROW. Developing this method contributes to the zero-pollution goal by establishing a threshold that prevents the worst-performing tyres from being sold on the EU market. This is in line with and reflected in the Sustainable and Smart Mobility Strategy, which acknowledges the problem of microplastic pollution from tyres and the importance of promoting high-performing tyres

Table 1. Applying the Source to Sea approach to tyre wear particles (TWPs).

Considering pollution from Source to Sea: identify the life cycle stages (source, transport, sink) and pathways (fresh-water, coastal water, open sea) of TWPs	**Considerations from management:** understanding current system of governance (policies and actors) of TWPs Policies	Actors
Land-based source – production: TWPs are emitted due to friction on the road causing tyre wear and tear. Tyre abrasion is closely linked to tyre production including tyre design, composition and manufacturing processes, impacting the abrasion rate of the tyre (Van Leeuwen et al., 2023).	The chemical legislation **Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)** establishes mandatory registration and information requirements for tyre manufacturers and importers when placing the tyre (product) on the market and in manufacturing processes.[a]	The REACH Regulation of the EU falls under the authority of the **European Chemical Agency (ECHA).** **Tyre manufacturers, suppliers, distributors and importers**, have to register and provide information on the manufactured/imported substances used in tyre manufacturing to ECHA except for polymers (e.g. natural and synthetic rubber) which are exempted (REACH Regulation Art. 2 (9), 5, 6; (Trudsø et al., 2022)).[b] **Directorate-General Environment (DG ENV) and Directorate-General Internal Market, Industry, Entrepreneurship and SMEs** (**DG GROW**) are responsible for the REACH regulation, restrictions of specific hazardous chemicals and authorisations for continued use of chemicals. **Directorate-General for Research and Innovation** (DG RTD) is responsible for EU policy on research, science and innovation, overseeing Horizon Europe and EU Missions Programmes.[c]
	The 2010/75/EU Industrial Emission Directive sets rules to reduce pollutant emissions from industrial installations by requiring permits based on Best Available Techniques (BAT), e.g. BAT for the production of polymers with implications for the production of synthetic rubber used for tyre manufacturing (Directive (EU), 2010; Trudsø et al., 2022).	**DG ENV** is responsible for implementing the Directive, which applies to industrial installations. Approximately 50000 industrial installations operate under a permit granted by EU Member State authorities (Trudsø et al., 2022).
	The **Eco-design for Sustainable Products Regulation (ESPR)** provides a framework for setting eco-design requirements. Tyre-specific requirements could be set through implementing and delegated acts as per the Commissions working plan (Regulation (EU) 2024/1781 of the European Parliament and of the Council Establishing a Framework for the Setting of EcodesingRegulation (EU) 2024/1781 of the European Parliament and of the Council Establishing a Framework for the Setting of Regulation (EU) 2024/1781 of the European Parliament and of the Council Establishing a Framework for the Setting of Ecodesingg Directive 2009/125/EC 2024).	**DG ENV** is tasked with the new regulation.
	The **Tyre Labelling Regulation (TLR)** allows for informed purchase of tyres based on energy parameters (rolling resistance, wet grip, external noise) depicted on the tyre label. While tyre abrasion is not currently a parameter, it is being considered under the TLR.	**DG ENER** is tasked with this regulation. Tyre and car manufacturers represented at EU level through associations such as **ETRMA, ETRTO, EUCAR and ACEA** are actively engaged in the EU policy-making process. **Environmental NGOs like Transport & Environment** develop policy recommendations and communicate scientific knowledge to

		protect environmental and consumers' interests. **Research institutes/companies** like Emissions Analytics provide a database with information on organic compounds found in tyres, tyre models and test results from over 40 tyre manufacturers (Van Leeuwen et al., 2023).
	The Plastic Strategy provides strategic orientation to reduce marine litter and transform the design, production, use and recycling of plastic products.	**EU Member States** are encouraged to create incentives for the use of safe and energy-efficient tyres, indirectly affecting TWP emissions.
Land-based source – use: TWPs are emitted due to friction on the road causing tyre wear and tear. The tyre abrasion rate is closely linked to individual driving behaviour, road characteristics, weather events, speed limits, among others.	The **Euro 7 Regulation** sets thresholds for tyre abrasion and the development of a harmonised tyre abrasion measurement method. Ultimately, this will impact tyre design and composition, as the worst-performing tyres will be banned from being sold on the market.	**DG GROW** proposed Euro 7 and UNECE World Forum for Harmonisation of Vehicle Regulations (WP.29) is tasked with developing an abrasion measurement method which will be applied in Euro 7. The tyre and car industries are actively engaged in the UNECE and Euro 7 process.
	The **TLR** allows for informed purchase of tyres based on energy parameters (rolling resistance, wet grip, external noise) depicted on the tyre label. While tyre abrasion is not currently a parameter, it is being considered under the TLR.	**DG ENER** is tasked with this regulation. Tyre and car manufacturers represented at the EU level through associations such as **ETRMA, ETRTO, EUCAR and ACEA** are actively engaged in the EU policy-making process. **Environmental NGOs like Transport & Environment** develop policy recommendations and communicate scientific knowledge to protect environmental and consumers' interests. **Research institutes/companies** like Emissions Analytics provide a database with information on organic compounds found in tyres, tyre models and test results from over 40 tyre manufacturers (Van Leeuwen et al., 2023).
	The Plastic Strategy provides strategic orientation to reduce marine litter and transform the design, production, use and recycling of plastic products.	**EU Member States** are encouraged to create incentives for the use of safe and energy-efficient tyres, indirectly affecting TWP emissions.
	Sustainable and Smart Mobility Strategy aims to improve public transport systems, infrastructure and technology, recognising the need for coherent rules for environmental, energy and safety performance of tyres to reduce tyre abrasion.	**DG Transport and Mobility (DG MOVE)** is responsible for the Strategy.
Land-based source – End of life:	**The 2008/98/EC Waste Framework Directive** establishes a waste hierarchy, Extended Producer Responsibility and end of waste criteria for recycling.	**DG ENV** is tasked with this directive, and **tyre producers** are responsible for collecting end-of-life tyres.
Freshwater: TWPs enter the aquatic environment due to stormwater runoff or wastewater discharges from roads (road runoff, Parker-Jurd et al., 2021). TWPs can also be released through the disposal of sewage sludge and its use in agriculture (ibid.).	**The 2020/2184/EU Drinking Water Directive** sets standards for water quality and establishes a new methodology to measure microplastics in EU drinking water.	**DG ENV** is tasked with this directive. The **Joint Research Centre** developed the methodology to monitor microplastics in tap water across the EU. **Drinking water operators and associations** are actively engaged with policy developments.
	The revised **91/271/EEC Urban Waste Water Treatment Directive (recast UWWTD)** sets standards for emerging pollutants, including microplastics (Art. 18), and introduces monitoring obligations for microplastics in wastewater	**DG ENV** is tasked with this directive. **Wastewater operators and associations like EurEau** have been actively engaging in the proposal for the recast of the UWWTD. The **Joint Research Centre** develops models on water quality and quantity which have been adapted in policy updates of the

	treatment facility inlets and outlets, as well as sewage sludge (Van Leeuwen et al., 2023).	UWWTD. **EU Member States** or their municipalities may set stricter water quality standards within end-of-pipe operations (Van Leeuwen et al., 2023).
	The **86/278/ECC Sewage Sludge Directive** regulates the quality and use of sewage sludge produced from urban wastewater treatment without currently addressing microplastics.	**DG ENV** is tasked with this directive.
	2000/60/EC Water Framework Directive guides monitoring and management of surface and groundwater water quality and defines environmental quality standards. Microplastics may be considered priority substances once a monitoring methodology is available.	**DG ENV** is tasked with this directive.
Nearshore and adjacent sea (coastal waters): Treated wastewater effluent and surface runoff via storm water drainage are considered the three principal routes of TWPs to the marine environment (Parker-Jurd et al., 2021).	**The 2000/60/EC Water Framework Directive** (WFD) encourages sustainable use of water and protects coastal waters with the aim of achieving good ecological and chemical status.	**DG ENV** is tasked with this directive.
	The 2008/56/EC Marine Strategy Framework Directive (MSFD) requires monitoring of marine litter under Descriptor 10 and applies to coastal waters as defined by the WFD.	**DG ENV** is tasked with this directive.
Open Sea/Ocean: TWPs can be transported directly to the ocean through the atmosphere or carried by rainwater into rivers and sewers, where they can pass through the water treatment process (Parker-Jurd et al., 2021). Emissions at open sea are highest in coastal cities and where main highways run alongside the coast.	**The 2008/56/EC MSFD**, under Commission Decision 2017/848, requires Member States to consider Priority Substances as defined under the WFD also beyond territorial waters if these may still give rise to pollution effects (Tornero et al., 2021).	**DG ENV** is the responsible body for this directive.

[a]It must be noted that the REACH restriction on microplastics only applies to intentionally added microplastics. Unintentionally released microplastics (e.g., TWPs) are not covered under REACH.
[b]It must be noted that while polymers are exempt from registration/evaluation under REACH Art. 2(9), they may still be regulated by other provisions, e.g., restrictions.
[c]DG RTD has a cross-cutting role, and as such, is a relevant actor across all policies and source-to-sea categories of this table.

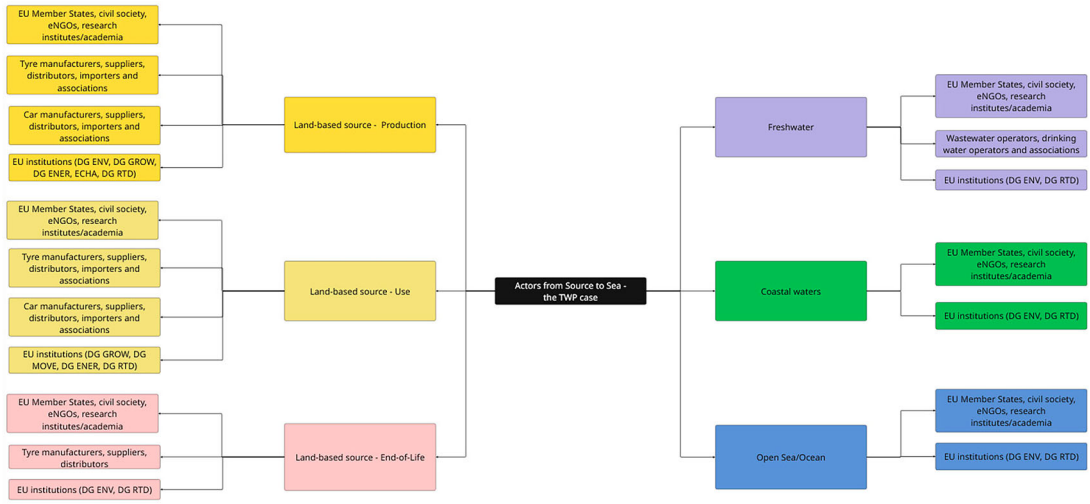

Figure 2. Map of actor groups from Source to Sea in the TWPs case study.

(COM(2020)789 Final Smart Mobility Strategy, 2020). Despite the tyre industry's influential role, research institutes and academia are important contributors to technology and research development, as they provide insights into the possibility of producing low-wearing tyres that still meet the required performance and safety criteria (Jung & Sodano, 2020; Mattsson et al., 2023; Weng et al., 2020; Zhao & Qin, 2018). Tyre manufacturers primarily highlight individual driving behaviour, speed limits, road pavement, vehicle weight (van Broekhuizen et al., 2022) and drainage systems as influencing factors on the amount of TWP emissions.

The analysis shows that while tyre manufacturers are relevant actors across all life cycle stages of tyres, they seem not to be primarily involved in processes and technology developed related to TWPs capture and removal from terrestrial and aquatic environments (ref. Figure 2). Following this observation, and in consideration of the polluter pays principle, tyre manufacturers could play a stronger role in facilitating collaboration and contributing with their expertise to capture and remove TWPs from the environment. TWPs' removal is being addressed under the amended EU Urban Waste Water Treatment Directive (UWWTD), which by 2045 will not only require Member States to remove micropollutants from urban wastewater before it is released into the environment, but also to implement the polluter pays principle that requires companies to cover costs of data collection and evaluation of their products' impact on wastewater (COM(2022)541 Final Urban Wastewater Treatment Directive (Recast), 2022). At the same time, many wastewater treatment plants face challenges related to the increasing complexity of parameters, rising costs for monitoring, and implementing three treatment stages (Wasser 3.0, 2024).

While the tyre industry is primarily involved in the production, use, and end-of-life cycle stages of the tyre product, DG ENV and local authorities, as well as the respective EU Member States, are only involved once TWPs enter the (marine) environment. As such, the analysis reveals the disconnect between upstream and downstream stakeholders in addressing TWPs from Source to Sea. So far, examples to increase interactions among stakeholders include the European Road and Tyre Wear Particle Platform, the Zero Pollution Stakeholder Platform, as well as different Horizon Europe projects contributing to TWPs research. However, research and stakeholder platforms

applying a Source-to-Sea approach are still rather limited. Local authorities, coastal cities, and municipalities should be further included in these exchanges, as they are the most impacted by TWP pollution (Mattsson et al., 2023).

Coordination among the different European Commission Directorate Generals (DGs) adds to the complexity of TWPs and consequently marine pollution governance in the EU, as different DGs are tasked with one specific aspect of the problem. While DG MOVE is tasked with policies on sustainable mobility and transport, DG ENER is tasked with tyre labelling and eco-design requirements under the Eco-design for Sustainable Products Regulation (ESPR) impacting tyre design (Devriese et al., 2023). DG RTD is responsible for EU policy on research, science and innovation, with a view to helping create growth and jobs, and tackling the biggest societal challenges. It oversees the current EU research and innovation funding programme Horizon Europe, as well as EU Missions. DG GROW is responsible for the EU Work Programme – UNECE Activities Proposals and as such suggested the tyre abrasion measurement method. DG ENV is tasked with the Microplastic Initiative, which focuses on the unintentional release of microplastics, such as from tyres, and seeks to develop an integrated approach for TWPs, including eco-design requirements, labelling and standardisation measures, as well as methods for measuring the release of microplastics from tyres. While there are different policy initiatives to target TWPs, there is strong potential for better coordination among the European Commission DGs to further integrate and combine efforts to effectively address TWP pollution.

3.2. Conflicting policy objectives

The analysis further reveals conflicting objectives among policies. For example, while the Sustainable and Smart Mobility Strategy acknowledges microplastic pollution from tyres, it aims to increase the number of and transition to zero-emission cars, including vans, buses and heavy-duty vehicles (e.g. trucks, buses and coaches) to reduce the amount of greenhouse gas emissions (COM(2020)789 Final Smart Mobility Strategy, 2020). This stands in contrast to the zero-pollution objective, as battery-powered electric vehicles are typically heavier than their equivalent internal combustion engine vehicles, and thus can contribute to increased TWP emissions from tyres (Beddows & Harrison, 2021; Timmers & Achten, 2016; Woo et al., 2022). Another example in the case of TWPs is the use of recycled materials (e.g. PET bottles) in tyre design and composition. While this contributes to the EU's circularity and sustainability objectives, it does not contribute to the EU's environmental objective under the Zero Pollution Action Plan, as it does not reduce the amount of TWP emissions and thus microplastics unintentionally released into the environment. It is thus essential to integrate environmental objectives into sectoral policies or there is a risk of pursuing climate targets at the expense of other policy goals (e.g. healthy seas).

3.3. How TWPs are covered under the European Green Deal

Currently, existing EU legislation only indirectly applies to TWPs by regulating either the tyre or microplastics, posing a challenge to effective regulation and governance of TWP pollution. Policies related to tyre composition, design, and abrasion, such as the chemical legislation REACH, the Industrial Emission Directive, ESPR, Euro 7, and Tyre Labelling Regulation, are relevant mechanisms for preventing TWP emissions. However, the current policy design might hamper policy integration. For instance, although polymers are classified as substances under REACH, they are not subject to registration, and there is no requirement to report health and environmental information

to ECHA (ref. Table 1). As such, the European Commission and EU Member States lack a sound baseline for a future restriction process under ECHA (Trudsø et al., 2022). Furthermore, environmental monitoring of microplastics in the EU currently focuses on the marine environment through the MSFD, with microliter criteria for Member States to establish target levels that do not cause harm or do not adversely affect the health of the marine environment (Devriese et al., 2023; 2025; Gago et al., 2016). The MSFD covers aspects not addressed by the WFD, which include marine litter under Descriptor 10 (Devriese et al., 2023; 2025; Galgani et al., 2010; Galgani et al., 2013). Many monitoring programmes from EU Member States do not include TWPs specifically, as they are one of the most challenging forms of microplastics to isolate and quantify in environmental samples (Parker-Jurd et al., 2021). The methodological assessment standards for monitoring TWPs among Member States could be better coordinated and harmonised, as elements and parameters currently differ (Banfi et al., 2021a; 2021c; 2021b; Devriese et al., 2023). Furthermore, to ensure effective implementation, Member States' strategies under the WFD and MSFD should be coherent and coordinated across each marine region or subregion. This is to some extent achieved through established mechanisms, including the Regional Sea Conventions, which play a key role in promoting and facilitating harmonised monitoring and assessment programs across countries.

Another aspect to be drawn from this analysis, is the potential benefit for policy integration from including considerations from both science and management across the Source to Sea continuum. Scientific insights are important for informing policy developments about the varying shapes, sizes and chemical content of TWPs, which consequently affect the transportation and dispersion of particles into the aquatic environment (van Broekhuizen et al., 2022). This in turn needs to be reflected in management responses across land, freshwaters and sea. As such, research serves as a prerequisite for policy integration. Especially in the case of TWPs, advancing methods for their accurate identification and quantification, as well as their transport and dispersion into the marine environment can help not only to advance polymer developments but also policies and regulations (Mattsson et al., 2023).

4. Conclusion

The application of the Source to Sea approach to the case of TWPs presented within this work provided new insights into the dynamics of plastic pollution policy integration under the European Green Deal. The assessment revealed the benefits of a redefined approach to policy integration, incorporating policy considerations across spatial scales, encompassing sources, pathways, and sinks of plastic pollution. In providing a better understanding of how policies and actors interact and engage from Source to Sea, the unique challenges and transboundary nature of marine plastic pollution can be acknowledged in policy-making and implementation, which was demonstrated within this exploratory research.

By mapping policies and actors across the entire life cycle of TWPs, policy coherence, as well as vertical and horizontal fragmentation, were visualised. In particular, the lack of coordination between policy sectors (i.e. transport, environment, waste management), as well as the disconnect between upstream and downstream actors, hence the disconnect between the EU regulation level and implementation at the organisational level were highlighted. Based on these findings, the TWP case does neither present a success story nor a failure of policy integration but a case of unrealised potential, as the analysis highlights significant challenges in translating the ambitious goals of the European Green Deal into concrete, coordinated action. Despite the European Green Deals' emphasis on integration, governance remains highly fragmented, as policies addressing TWP

sources (i.e. tyre manufacturing, road construction, wastewater treatment) remain largely disconnected from policies addressing transport, circular economy, the marine environment and pollution. As such, the case demonstrates the challenges of the horizontal and vertical integration process. While this research focuses on the EU and the Green Deal, similar challenges can be observed at the international level. The recently stalled Global Plastic Treaty negotiations illustrate the complexity of reaching agreement on the regulation of diffuse and unintentional sources of plastics, with implications for horizontal and vertical policy integration. Slow progress and the lack of global harmonisation of approaches and regulations, may undermine individual, as well as collaborative efforts to address plastic pollution. This also emphasises the need for the establishment of universal bans on harmful substances and the alignment of testing methods to assess the safety of substances and plastic products, including tyres (Maes et al., 2023). Moreover, due to existing gaps in current regulatory frameworks, implementation of source-specific measures will largely depend on national and regional initiatives (Mattsson et al., 2025). In this regard, the EU's zero pollution ambition serves as a notable example of proactive policy action.

The Source to Sea approach presented within this work, not only serves as a tool to map out and assess policy integration but also serves as a means to collaborate, by bringing together different actors to discuss and exchange on the pollutant of concern according to their respective roles across life cycle stages and pathways. This could take the form of a Source to Sea forum, bringing together actors across the approach to strengthen connections between stakeholders and to foster coordinated efforts for effective policy implementation. Such an initiative could also contribute to raising public awareness of the often invisible yet pervasive problem of unintentionally released microplastics.

The approach has the potential to highlight new opportunities for policy integration, thereby enhancing the governance of marine and freshwater resources. For example, at the horizontal level, the MSFD could make use of existing measures within the WFD, since many measures and objectives also deliver MSFD targets. The Source to Sea approach places new emphasis on land-based pollution sources and allows for the visualisation and understanding of how contaminants travel not only from 'Source to Sea' but across policies, legal mandates, and actors (i.e., responsibilities). The TWP case shows how the Source to Sea approach identifies conflicting objectives, conflicts, and cooperation between actors and how TWPs are covered under the European Green Deal, using the concept as a means to operationalise which policy domains are relevant for plastic pollution governance of TWPs. It may also be applied to future emerging contaminants, incorporating Source to Sea considerations into policy design as new pollutants are identified and regarding emerging contaminants sadvances.

These results further offer a basis and perspective for future research avenues through the application of such an approach to empirical studies. For example, while our analysis focuses on policy integration for the European Green Deal, hence at EU level, regional actors, such as river basin management organisations, e.g. the Danube Commission or Regional Sea Conventions, could be considered in future work. Moreover, the framework with its emphasis on mapping life cycle stages, pathways as well as relevant policies and actors, may provide an adaptable tool to be tested and explored in different contexts and at different scales, highlighting the interconnectedness of different components with implications for policy integration. While other types of microplastics (e.g. from textiles, paints or coatings) or pollution (e.g. chemical contaminants) could serve as case studies for further exploration of the Source to Sea approach, the concept is also applicable to other policy sectors and domains within the European Green Deal. For example, in the context of the Farm to Fork Strategy, policy integration could be assessed in the case of food systems,

revealing disconnects in sustainable food production, inefficiencies in supply chains, food waste hotspots, and highlighting the need for integrated policies which promote agroecology, food waste reduction and support of local food systems. Ultimately, considering policies in an integrated manner will help support progress towards multiple policy goals, as established within the European Green Deal. Moreover, the Zero Pollution Action Plan calls for increased integration across space so that actors can make more informed decisions. Thus, the Source to Sea approach strengthens EU plastic pollution governance by recognising the interconnectedness of the natural systems and promoting the integration of policies across the entire lifecycle of plastics. In doing so, it supports the realisation of a sustainable EU, as envisioned in the European Green Deal.

Notes

1. The Source to Sea – Zero Pollution 2030 (SOS-ZEROPOL2030) project is a Horizon Europe project aiming to develop a holistic zero pollution framework to guide the EU towards zero pollution in European Seas. Key deliverables include the D2.1 Report titled The EU Zero Pollution Ambition (Devriese et al., 2025) and the D2.2 Report titled The EU Governance Landscape for Zero Marine Pollution (Van Leeuwen et al., 2023).
2. TWPs must be differentiated from tyre and road wear particles (TRWPs), as this term refers only to the tyre components and excludes material derived from abrasion of the road surface (e.g., asphalt and road markings).

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