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Review article

A comprehensive assessment of plastic remediation technologies

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ABSTRACT

The global presence of plastic litter and its accumulation in the environment has become an issue of concern to the public and policymakers. This concern has triggered innovators in past decades to design and develop a multitude of remediation technologies to prevent plastic from entering the environment, or to clean up legacy litter. This study aims to (i) systematically review the current scientific literature on plastic remediation technologies, (ii) create a 'plastic clean-up and prevention overview' illustrating 124 remediation technologies and 29 characteristics, (iii) qualitatively analyse their key characteristics (e.g., fields of application, targeted plastic), and (iv) investigate challenges and opportunities of clean-up technologies for inland waterways (e.g., canals, rivers) and ports. We identified 61 scientific publications on plastic remediation technologies, until June 2022. Thirty-four of these studies were published within the last three years, demonstrating a growing interest. The presented overview indicates that inland waterways are, so far, the preferred field of application, with 22 technologies specifically designed for cleaning up plastics from inland waterways, and 52 additional ones with the potential to be installed in these locations. Given the importance of clean-up technologies in inland waterways, we highlighted their strengths, weaknesses, opportunities, and threats (SWOT). Our results indicate that, despite the challenges, these technologies provide essential prospects, from improving the environmental quality to raising awareness. Our study is instrumental as it illustrates an up-to-date overview and provides a comprehensive analysis of current in design phase, testing, and in use plastic remediation technologies.

1. Introduction

Plastic is the most extensively used human-made material (Worm et al., 2017), and its persistence, together with poor waste management, facilitate its accumulation in the environment. Due to its key characteristics, such as durability, lightweight, and low production costs (Sigler, 2014) plastic materials are suitable for a wide range of products (Derraik, 2002). However, the same attributes contribute to making plastic waste generated from mismanaged plastic an environmental issue of concern (Catarino et al., 2021). Once in the environment, macroplastics (greater than5 mm) can persist for decades (Ryan et al., 2009) and, when subjected to the action of wind, waves, and sunlight, break into smaller pieces, currently identified as microplastic (<5 mm, Thompson et al., 2004) and nanoplastics (1 nm to 1000 nm; Gigault et al., 2018). Plastic contaminates ecosystems and is described as an emerging pollutant, due to the potential negative effects in organisms, and recognized as an urgent and global problem in policy documents and strategies (e.g., European Commission, 2021; UNEA, 2022). This widespread environmental accumulation of plastic litter has raised concerns on their effects in organisms, ecosystems services and human health.

Plastics have the potential to entangle, suffocate, starve marine, terrestrial, and freshwater life (Gola et al., 2021; Khalid et al., 2020; Li, 2018), particularly in accumulation zones, i.e. hotspots. Plastic litter can not only act as an artificial substrate and transport invasive species across habitats (Welden, 2020) but macroplastic litter, can also physically harm terrestrial and aquatic fauna via entanglement or ingestion (Collard and Ask, 2021; Curtis et al., 2021; Roman et al., 2022; Thrift et al., 2022). Ingested macroplastic litter can lead to malnutrition, injuries, and occasionally death (Wright et al., 2013). Despite the overall

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knowledge on the risk of microplastics remains low in most areas of the ocean (Everaert et al., 2020), studies have investigated the effects of plastic pollution in marine, terrestrial and freshwater environments (Bucci et al., 2019). Moreover, although the interactions are not yet fully known and should be investigated with realistic scenarios and within a changing environment (Catarino et al., 2022), evidence suggests that ingested microplastics, in addition to individual issues, can have effects on higher level of organisation, such as population, community and food web (Everaert et al., 2022; López-Martínez et al., 2021; Nelms et al., 2018). Plastic has the capacity to sorb hydrophobic organic contaminants (HOCs) (Koelmans et al., 2016) and as such cause indirect effects to organisms of which the impact depends on the trophic level of the recipient species (Diepens and Koelmans, 2018). Overall, a growing body of evidence points to a broad range of potential detrimental effects of plastic (Lau et al., 2020). These scientific findings and the underlying public perception together with the precautionary principle has triggered innovators for action.

Due to the magnitude and significance of the issue, plastic has now gained considerable awareness from researchers, policymakers, and the general public. However, this issue has been long recognized, and the presence of plastic in the environment has been studied since the late 1960s, (Carpenter and Smith, 1972; Kenyon and Kridler, 1969; Fig. 1). In recent years, with support of scientific studies, pro-environmental information campaigns, and non-profit (NPO) and community initiatives, authorities have been stimulated to propose legislation (Catarino et al., 2021) and to promote the development of technological solutions to minimize the impact that plastic might have on ecosystems (Lohmann, 2017). An example of a treaty introduced to reduce anthropogenic waste is the London Convention, which, although not specifically directed at plastic litter was a first step in preventing pollution of seas from dumped waste. In addition, in May 2021, as part of the European Green Deal, the European Commission approved the 'Zero pollution action plan' (COM (2021) 400) aiming at reducing pollution in air, water and soils. In recent years we have started seeing policies effectively directed at reducing, recycling, and controlling plastic waste and its pollution (Diana et al., 2022; Fig. 1). For instance, the recently signed United Nation (UN) plastic pollution treaty UNEA (2022). However, policies alone cannot reverse the rising trend of plastic pollution and therefore combined post-consumption solutions are necessary (Lau et al., 2020). The first record of a plastic remediation technology was dated from 1995 (Schmaltz et al., 2020), and just a few years later a technology to target waste from the environment was firstly described in the scientific literature (Phillips, 1999). Since then, numerous other remediation technologies have been developed to clean up existing plastic from the environment and are defined in the current study according to Schmaltz et al., 2020 as collection or clean-up technologies. In addition to removing legacy plastics, some remediation technologies further aim at preventing more plastic from entering the aquatic environment and have been defined as prevention technologies (Schmaltz et al., 2020). As the potential risk of plastics is especially relevant for hotspots areas (Høiberg et al., 2022; Everaert et al., 2018) and considering that macroplastics not removed can eventually break down into smaller particles (Alimi et al., 2018), deploying these technologies in accumulation areas can be especially relevant to indirectly reduce micro and nanoplastic. Moreover, by reducing plastic accumulation, these technologies indirectly lower the probability of encounter for organisms (Shim and Thomposon, 2015).

With increased awareness of the potential effects of plastic, the number of technological solutions to target plastic and prevent debris accumulation in the environment will likely keep increasing. Due to its novelty, the scientific literature on the topic of plastic remediation technologies is quickly developing with a few recent studies providing an overview (e.g., Schmaltz et al., 2020, Bellou et al., 2021; Moulaert et al., 2021; Helinski et al., 2021). This review aims at providing additional clarification with an up-to-date overview and analysis to the current state of the art of plastic remediation technologies. In particular, the objectives of the present study were to: (i) provide a 'plastic clean-up and prevention overview', i.e., a list of in use, testing, and in design phase plastic clean-up and prevention technologies and their related characteristics, (ii) determine the current scientific and innovation progress on plastic remediation technologies, (iii) examine the geographical distribution of scientific studies and countries of development and deployment of remediation technologies, (iv) consider the different fields of application of the technologies, (v) investigate strengths, weaknesses, opportunities, and threats (SWOT) of clean-up technologies currently deployed or tested in inland waterways (e.g., rivers, canals) and ports, and (vi) discuss the knowledge gaps on plastic remediation technologies such as their potential environmental impact and policies. In addition, the current state of the scientific knowledge on the benefit as well as new risks of plastic clean-up technology is especially complex due to multiple interacting parameters (e.g., environmental conditions, type of plastics) (Leone et al., 2022). Therefore, this study presents additional inventory and critical analysis on plastic remediation technologies, their characteristics, and their classification. In addition, we provide information to better understand the benefits and opportunities that these innovative technologies offer and identify their possible challenges and disadvantages.

2. Methods

2.1. Systematic literature review

A systematic literature review was performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses

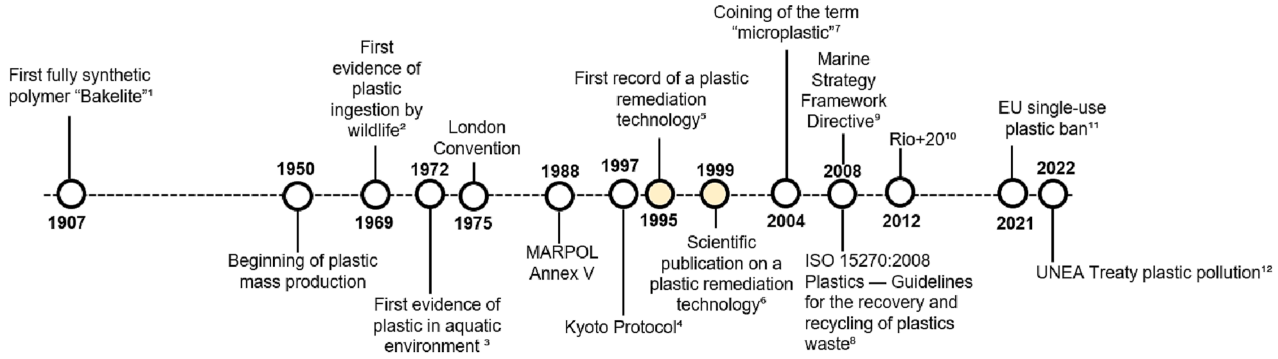

Fig. 1. Timeline depicting of important events in the plastic production and pollution with highlights on policies for prevention of litter in the environment, the development of plastic clean-up technologies and their presence in the scientific literature. **1**:Thompson et al., 2009 **2**: Kenyon & Kridler, 1969 **3**: Carpenter & Smith, 1972 **4**: Kyoto Protocol, 1997 **5**: Schmaltz et al., 2020 **6**: Phillips, 1999 **7**:Thompson et al., 2004 **8**: ISO, 2008 **9**: MSFD, 2008 **10**: Rio+20, 2021 **11**: European Commission, 2021 **12**: UNEA (2022).

(PRISMA) 2020 statement (Page et al., 2021), on the 29th of June 2022. The aims of this systematic literature search were: (i) to evaluate the state of the art in plastic remediation technologies, (ii) to determine if the number of studies focusing on the topic is changing over time, and (iii) to assess where research on systems and technologies to collect or prevent plastic pollution has been executed. In line with policy documents (e.g., European Commission, 2021), we used the term ‘pollution’ to refer to plastic that is contaminating the environment and potentially inducing negative effects. To perform this search, we developed a series of search terms based on keywords found in the scientific literature on plastic pollution and remediation technologies (Table 1). The search words were synonyms or types of plastic pollution paired with the Boolean search siring ‘AND’ synonyms of technology ‘AND’ synonyms of collect or prevent. The selected terms (Table 1) were searched in the electronic database Scopus (Elsevier, The Netherlands, https://www.scopus.com) within the field ‘Abstract title, Abstract, and Keywords’.

The initial systematic literature search in Scopus resulted in 1033 papers in English, to which two extra papers found from other sources (e.g., via references) were added. After removing one duplicate, 1034 titles and abstracts were read to determine the eligibility of each document. Studies were included or discarded based on the following two eligibility criteria: (i) discussing or mentioning plastic clean-up or prevention technologies expressly designed to target plastics before it reaches the environment or that are already in it, (ii) describing parts of clean-up or prevention technologies in detail (Table 2). The term “prevention” in this study refers to solutions that aim at preventing plastic from entering the environment rather than technologies focused on recycling and waste reduction. In fact, recycling is not aimed at directly blocking plastics from leaking into the environment or collecting them from it. The terms “collection” or “clean-up”, refer to solutions aiming at cleaning up plastics already present in the environment (Schmaltz et al., 2020) rather than sampling techniques. Studies discussing the role of technologies that can be combined with clean-up or prevention devices (e.g., algorithms, remote sensing, recycling) were not included in the final analysis unless the collection procedure of plastic litter was also assessed and sufficiently described. In addition, studies investigating the role of wastewater treatment plants (WWTP) or dams in trapping microplastics were discarded as both dams and WWTPs are not novel concepts created to collect existing plastic litter or prevent plastic from entering the environment. If a study described a new invention to trap plastics from dams or WWTPs that is not relying on the current and existing filtration steps, the paper was included. Similarly, any study only discussing the role of recreational or volunteering work in collecting plastic litter (e.g., volunteering beach clean-up, volunteering collection of plastics from fishing vessels) was not included in the final analysis. If in doubt over the eligibility of a study while screening the title and abstract, the paper was included in the full-article screening. Following the title and abstract screening, 110 studies were fully read to further confirm their eligibility based on the above-mentioned criteria. This last screening resulted in 61 papers that were used for the analysis (Fig. 2).

Table 1
Overview of the Boolean search strings and terms used in the systematic literature search performed on the 29th of June 2022 on Scopus (Elsevier, The Netherlands).

Search terms
Plastic waste OR plastic litter OR plastic pollution OR plastic debris OR marine debris OR marine litter
AND
Tech* OR invent* OR solution* OR boom* OR trap* OR remediation* OR barrier* OR device*
AND
Cleanup* OR clean-up* OR collect* OR capture OR prevent

Table 2
Inclusion and exclusion criteria to assess the eligibility of each study included in the systematic literature review performed on the 29th of June 2022 in the electronic database Scopus (Elsevier, The Netherlands).

	Inclusion criteria	Exclusion criteria
Study type	Article, Conference paper, Review, Book chapter, Note, Conference review, Letter, Book, Data paper	Article collection
Study content	Description or discussion of plastic clean-up or prevention devices, or their parts, explicitly developed or conceived to collect or prevent plastic from entering the environment	Attitude changes, plastic recycling or disposal, volunteering clean-up, monitoring, use of existing systems to trap plastics (e.g., dams, WWTP), legislations
Time period	No restriction	
Language	English	
Availability full study	Available online or from the authors	

2.2. Non-systematic review

To complement the systematic (cfr 2.1) search on scientific literature, a non-systematic review using the search engine Google was further performed to ensure a complete overview of available technologies. By adapting the methodology of Moulaert et al. (2021), we conducted a free web search, using the following terms: ‘remove’, ‘collect’, ‘catch’, ‘marine debris’, ‘marine litter’, ‘marine plastic’, ‘marine waste’, ‘ocean plastic’, ‘plastic’, ‘waterway’, ‘inland waterway’, ‘river’, ‘ocean’, ‘system’, ‘technology’, ‘trap’, and ‘booms’. For the non-systematic review if a new technology was found on Google, independently from the precise source such as databases, websites, grey literature, YouTube videos or social media, it was always included in the overview.

2.3. Compilation of the ‘plastic clean-up and prevention technologies overview’

The ‘plastic clean-up and prevention overview’ (Leone et al., 2023) was compiled by merging the searches from the systematic and non-systematic reviews. For each plastic remediation technology included in the final overview, a list of 29 characteristics was assembled (Fig. 3). The overview of plastic remediation technologies was manually revised to remove duplicate technologies or information.

2.4. SWOT analysis

A SWOT analysis is a strategic planning and management technique widely used for projects and operations which aims at identifying their Strengths, Weaknesses, Opportunities, and Threats. As defined by (Gürel, 2017), strengths and weaknesses are factors internal to the project or operation that can either bring advantages or disadvantages, while threats and opportunities are intended as external factors that might be harmful or valuable to the project or operation. This particular methodology has been previously used and proved successful to investigate clean-up technologies (Morrison et al., 2019).

In this study, we focused the SWOT analysis on technologies listed in the ‘plastic clean-up and prevention overview’ (Leone et al., 2023) that are currently in the testing phase or are already in use. To be able to provide a harmonized way of discussing the technologies, the ranges of technological readiness levels (TRL), were provided (Bellou et al., 2021). Moreover, in line with the classification given by Schmaltz et al. (2020) and Helinski et al. (2021), we have classified the technology maturity as: in use, testing phase, design, not in use. Since the development of a technology can quickly move from a design stage to a testing and in use one, and the search has been carried out in 2022, the ranges included in the overview represent the stage at which a technology was

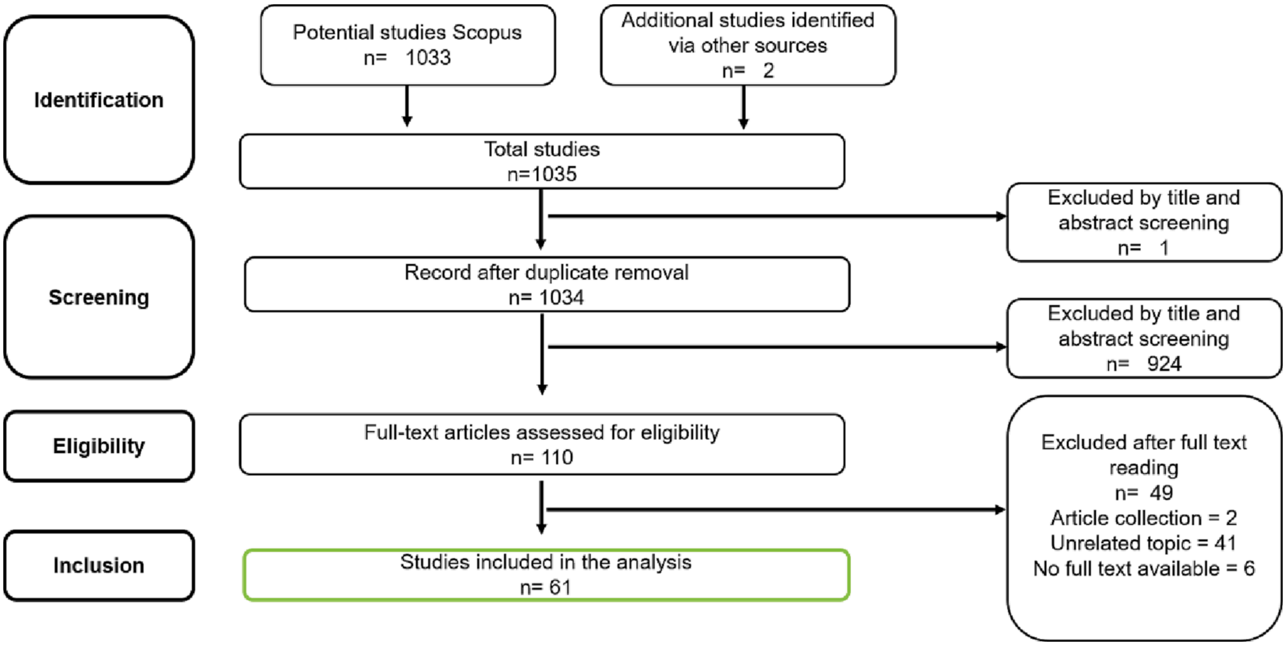

Fig. 2. Flow diagram of the systematic search performed in this study on the database Scopus (Elsevier, The Netherlands), adapted from PRISMA 2009 Flow Diagram" by Moher et al. (2009), and done on the 29th of June 2022.

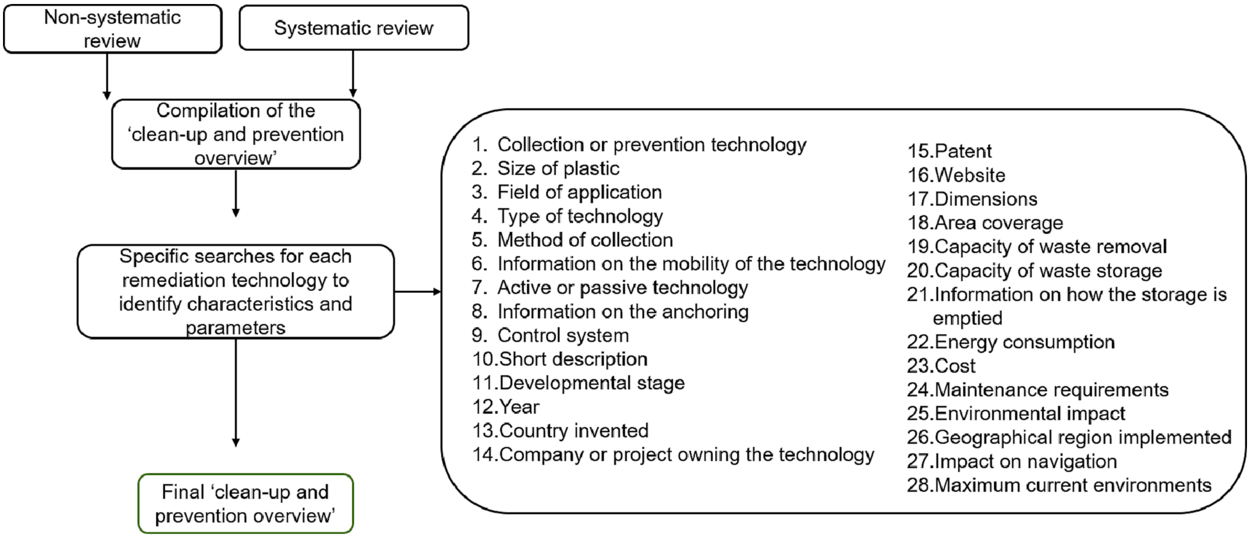

Fig. 3. Flow diagram to illustrate the process used in the creation of the'plastic clean-up and prevention overview'.

when the search was carried out. In addition, we performed the SWOT analysis on technologies that are or can be used in inland waters, since that is where they are mostly applied (Moulaert et al., 2021). Furthermore, we categorised this subset of technologies according to the devices' collection strategy. Prior to the SWOT analysis, we made an important distinction between the collection mechanism and the actual removal of plastic from the environment. The collection mechanism is the way plastic is gathered (e.g., booms or nets), whereas the removal mechanism is the action of retrieving the gathered debris (e.g., via crane, wheel). To perform the SWOT analysis, clean-up technologies have been grouped based on their collection mechanisms, which can impact the suitability, deployment, and use of a device. To group the technologies, three decision rules were theoretically identified and followed. Firstly, we have classified the clean-up systems according to their mobility into two categories: "mobile" and "stationary". By mobile system, we mean technologies that can move around to collect plastic while stationary are systems that are deployed in a fixed location. Following this classification, stationary systems were further divided into "active" and "passive". The category "active" includes all the systems that, following the definition provided by Helinski et al. (2021), require external power to function, while the category "passive" refers to systems that do not require external power and, therefore, rely, for instance, on natural flows or currents to gather plastic litter. Finally, systems were categorised based on the control system. Stationary systems, (both passive and active), are autonomous i.e. can operate without direct human control. Mobile systems are all active and are further divided into autonomous, crewed (require people on board to operate), and uncrewed (remotely operated).

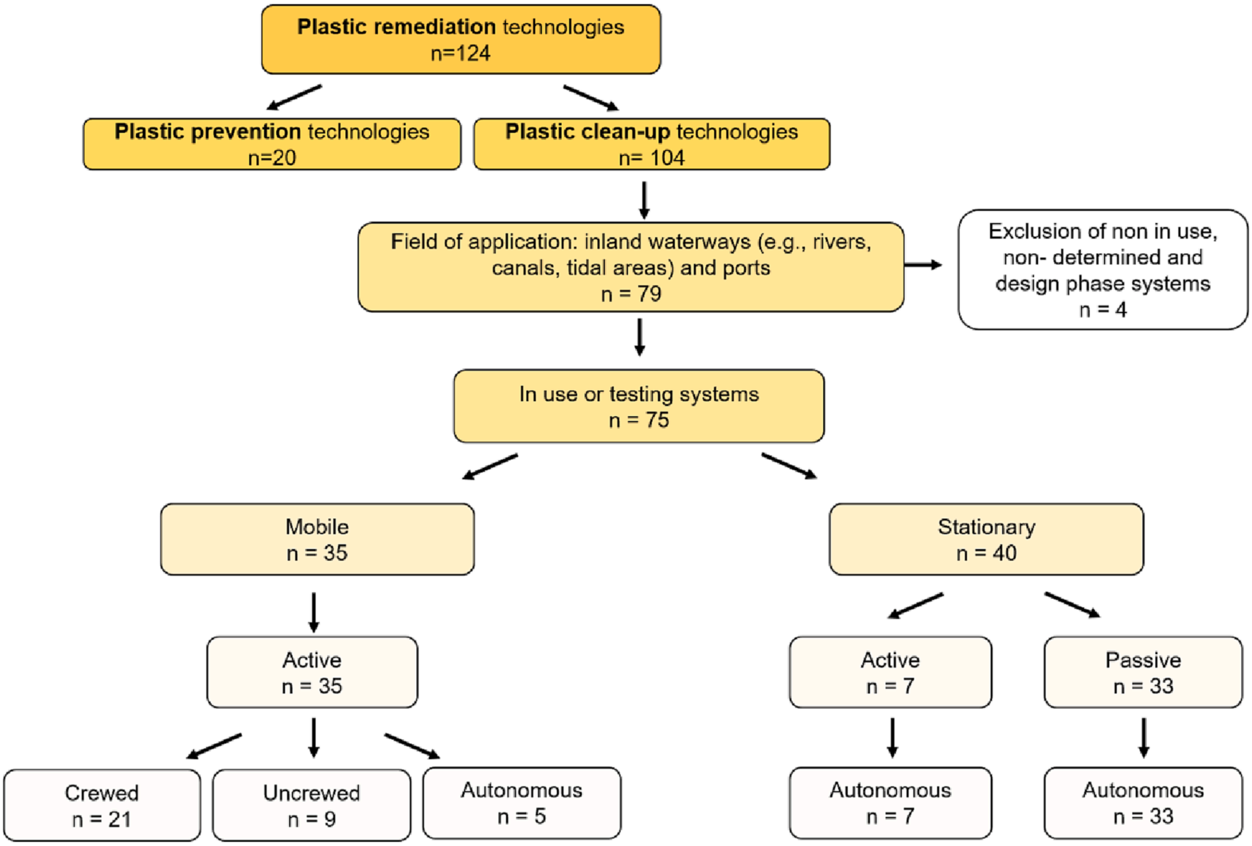

Fig. 4. Diagram of the classification system used in this study to perform the Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis of clean-up technologies from the'plastic clean-up and prevention overview' (see Fig. 3).

3. Results & discussion

3.1. *Scientific and innovation progress of plastic remediation technologies*

A total of 61 scientific publications on plastic remediation technologies were identified between 1999 and 29th of June 2022 (Fig. 5). The first scientific publication describing the use of a remediation technology to collect debris, including plastic, from urban drainage systems, was Phillips (1999). Our results indicate a global growing interest from the scientific community in plastic remediation technologies with more than 50% of the studies on the topic of plastic remediation technologies having been published only in the past three years, from the beginning of 2020. The relatively small number of studies published in the year 2022 (n = 5) compared to the 18 of 2021 can be explained by the fact that the presented results include publications only until half of 2022. When looking at the proportion of plastic clean-up and prevention

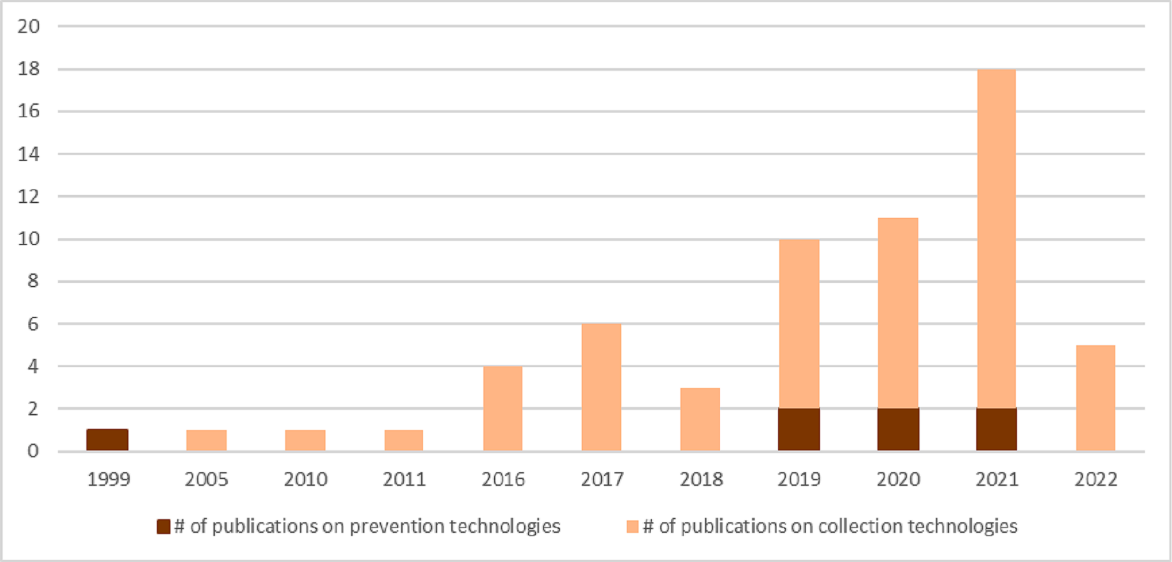

Fig. 5. Scientific publications retrieved using a systematic review (until June 2022) on the topic of plastic clean-up and prevention technologies per publication year.

technologies, we observed that papers investigating clean-up technologies constitute 89% of studies on plastic remediation technologies. This result is in line with the design and development of remediation technologies. In fact, 84% of the technologies listed in the ‘plastic clean-up and prevention overview’ (Leone et al., 2023) aim at cleaning up plastics already present in the environment. Similarly, Schmaltz et al. (2020) found that 38 technologies out of the 52 listed in their Plastic Pollution Prevention and Collection Technology Inventory are a collection technology.

The ‘plastic clean-up and prevention overview’ (Leone et al., 2023) contains information retrieved from both scientific and grey literature on technologies that aim to remove or prevent plastic from entering the environment. Even though this novel field of innovation is rapidly growing, the majority of the remediation technologies for which information is currently available online are in the design phase (TRL 1–3), already in the testing phase (TRL 4 to 6) or in use (TRL 7–9). Of the 124 technologies listed in the overview, 86% were, at the time of the systematic and non-systematic search, deployed (in use or in testing; Fig. 6). The presented result is in line with what previously shown by Schmaltz et al. (2020) where they observed that 88% of the technologies listed in their Plastic Pollution Prevention and Collection Technology Inventory are devices in testing phase or already in use. Similar conclusions have been drawn by Helinski et al. (2021), where 62.5% of the devices analysed to clean-up plastics from inland waterways is in use and 20% of the technologies were being tested. The number of systems presented in our results may however be underestimated, and there are multiple reasons for this. A first potential reason relates to the fact that concept ideas might not be yet publicly available and therefore not retrievable online. Therefore, it is possible that, globally, the number of technologies being conceptualize is larger than those listed in the present overview. A second reason refers to the category ‘not in use’. Websites or online information describing remediation technologies that are not anymore in use might have been already deleted (Helinski et al., 2021). Lastly, the search we performed was mainly limited to the English language. It is anticipated that there may be various systems deployed globally for which information may be only available in the local language. Furthermore, communities may also develop simplified solutions to collect waste in water streams, which have no web presence. Since globally there is a continuously increasing number of devices being developed and deployed, the overview might be non-exhaustive list of the technologies available that only accounts for the information available until July 2022. To be able to follow the development of a particular technology, from the design phase to the fully developed product, companies should disclose and make the technological readiness level (TRL) of their technology openly available. By addressing the TRL the comparison between technologies would become clear and efficient (Bellou et al., 2021). Moreover, as plastic remediation technologies are novel technological innovations, attention to the societal readiness level (SRL; Innovation Fund Denmark, n.d.), should also be consider as effort should be made to improve SRL and to reach societal acceptance.

Independently from the developmental stage, 78% of all the remediation technologies listed in the overview is targeting exclusively macroplastic litter, while 14% were for micro and macroplastics and only 8% if for microplastics. In their study, Schmaltz et al. (2020) have also observed that, more than 50% of the technologies analysed, aimed at collecting only macroplastics. Creating systems that target plastic of 5 mm or less is technologically more challenging than targeting plastic items that are visible to the naked eye. In addition, prevention technologies, defined as solutions explicitly created to prevent plastics from entering the environment, can be found in households (e.g., laundry balls or filters). Therefore, they can rely on the general public for use, while clean-up technologies are usually a collaboration between the company producing the device and the government or administration of a certain location. Macroplastics wrongly discarded in the environment undergo mechanical, chemical and biological modification, breaking them into smaller particles (Julienne et al., 2019). Thus, given the formation of microplastics from larger plastic items, clean-up technologies collecting macroplastics mitigate the presence of microplastics in the environment. In fact, if preventing plastics from entering the environment directly contributes to the possible effects of plastics on organisms, cleaning up reduces the number of secondary microplastics. As the number concentration of plastic grows for smaller sizes (Koelmans et al., 2022), and as many effect mechanisms for aquatic biota necessitate for plastic to be ingested (Koelmans et al., 2022), the removal of macroplastic is extremely relevant to indirectly reduce the potential consequences of microplastics on organisms. In particular when considering that so far, due to the analytical challenges, most of the technologies target macro plastics, with only a few focusing on microplastics (Schmaltz et al., 2020) and only some recent experimental work investigating nanoplastic prevention (Ben-David et al., 2023). As such, clean-up technologies targeting macroplastics do prevent micro and nanoplastic presence in an indirect manner.

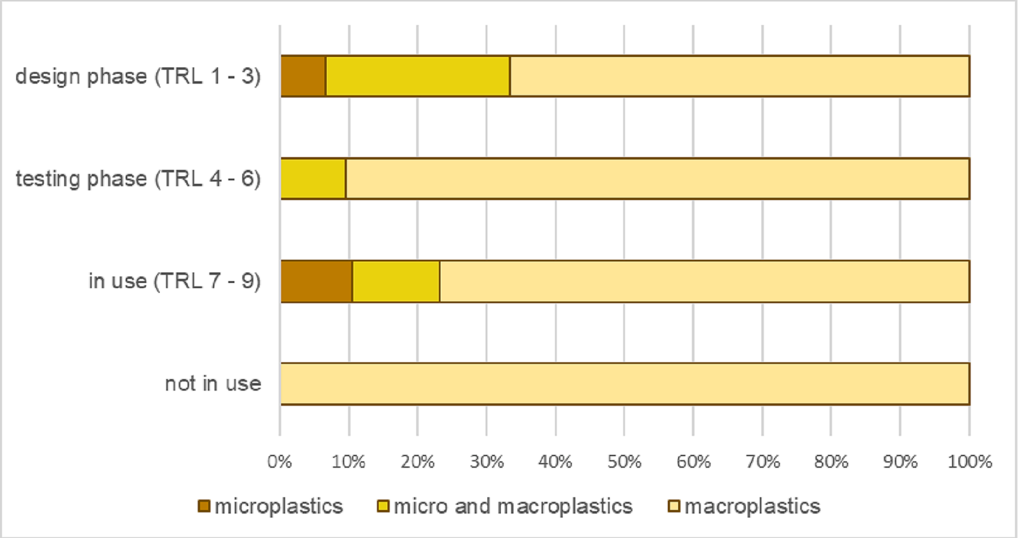

Fig. 6. Plastic size category targeted by plastic remediation technologies based on their development phase.

3.2. Geographical distribution: scientific studies, companies, and in use or testing plastic remediation technologies.

At the continental level, Europe is leading the research literature on plastic remediation technologies with 54% of the 61 papers published from 1999 to the 29th of June 2022 coming from first authors affiliated with a European institution (Fig. 7). The Netherlands is the country with the highest number of publications on plastic remediation technologies (18%) and at the same time is also the country, within Europe, in which 12% of the 124 companies producing plastic remediation technologies are registered (Fig. 7). From the studies published by an author affiliated at a Dutch institution, more than a half is assessing parts or systems (n = 9) from The Ocean Cleanup (https://theoceancleanup.com/), a Dutch based company. In the United States of America (USA) 26% of the total 124 companies listed in the overview are registered. However, only three scientific publications have been published on plastic remediation technologies from authors affiliated with an American institution (i.e. Chrissley et al., 2017; Helinski et al., 2021; Schmaltz et al., 2020). Moreover, although 13% of scientific studies issued on plastic remediation technologies were published in China, only one technology reported in the ‘plastic clean-up and prevention overview’ (Leone et al., 2023) is from an institution registered in the country. Our results show that number of scientific publications issued from a specific country does not always reflect the number of companies or non-governmental organizations (NGOs) working in the industry of remediation technologies registered in that same area. However, it is possible that additional studies, as well as remediation technologies, might be available, but not retrieved in this review because of language barriers, or lack of web presence.

The information about where a company is producing or developing a clean-up or prevention system is registered and was mostly accessible and available for in use and testing technologies as well as the ones in the design phase (i.e., 2 non-determined out of 124 technologies). However, we observed that information about the countries in which the remediation technologies are deployed is not always available. Out of 107 in use or testing clean-up technologies, information on at least one deployment location is available only for 58 technologies. Of these, one floating debris barrier technology is, according to the owner’s website, already deployed in several locations around the world on three continents (https://www.desmi.com/products-solutions-library/enviro-enhancer/) and two beach cleaners (Barber SandMan and Barber SurfMan; https://www.hbarber.com/) are used worldwide. For 40 of the technologies in the testing phase or in use, no information was available about the location in which the technologies are deployed.

As plastic litter is non-uniformly widespread, companies might tend to deploy remediation technologies, and in particular plastic clean-up technologies, in the hotspot areas independently from their home country. For instance, as Asiatic rivers are highly contributing to the transport of plastic (Meijer et al., 2021), twelve technologies out of the 58 for which the deployment location was available, are deployed in Asia. For example, The Ocean Cleanup (https://theoceancleanup.com/) has deployed one of their Interceptors on the Malaysian river Kang, estimated to be the 4th in the top 50 predicted plastic emitting rivers (Meijer et al., 2021). Besides Asia, also West Africa is considered one of the main hotspots for plastic litter (Meijer et al., 2021). However, information was available only for one technology deployed in Nigeria. We can observe a discrepancy in the countries in which technologies are designed and conceptualized and the countries in which they are tested or deployed (Fig. 8). For instance, when looking at in use or testing technologies 30% have been designed in North America. However, of these 107 in use and testing technologies, 15% are actually deployed in this continent. As previously mentioned, additional technologies might be developed or deployed, and no online record is currently available or not retrieved because of the language barrier.

3.3. From near land to open ocean: fields of application of plastic remediation technologies

Each particular technology is designed to be used in one or more fields of application. For instance, a clean-up technology using a water bubble curtain (e.g., Great Bubble Barrier, https://thegreatbubblebarrier.com/) can be deployed in multiple areas (e.g., canals, rivers, and tidal zones). From the presented overview of 124 remediation technologies, all prevention technologies available from the ‘plastic clean-up and prevention overview’ (Leone et al., 2023) are suitable for residential waters and 11 for stormwater drains (Fig. 9). In fact, these technologies prevent plastic from our households and stormwaters from entering the environment. The vast majority (n = 104) of the technologies are clean-up technologies, collecting plastics from the environment, and 22 can target plastic exclusively in inland waterways.

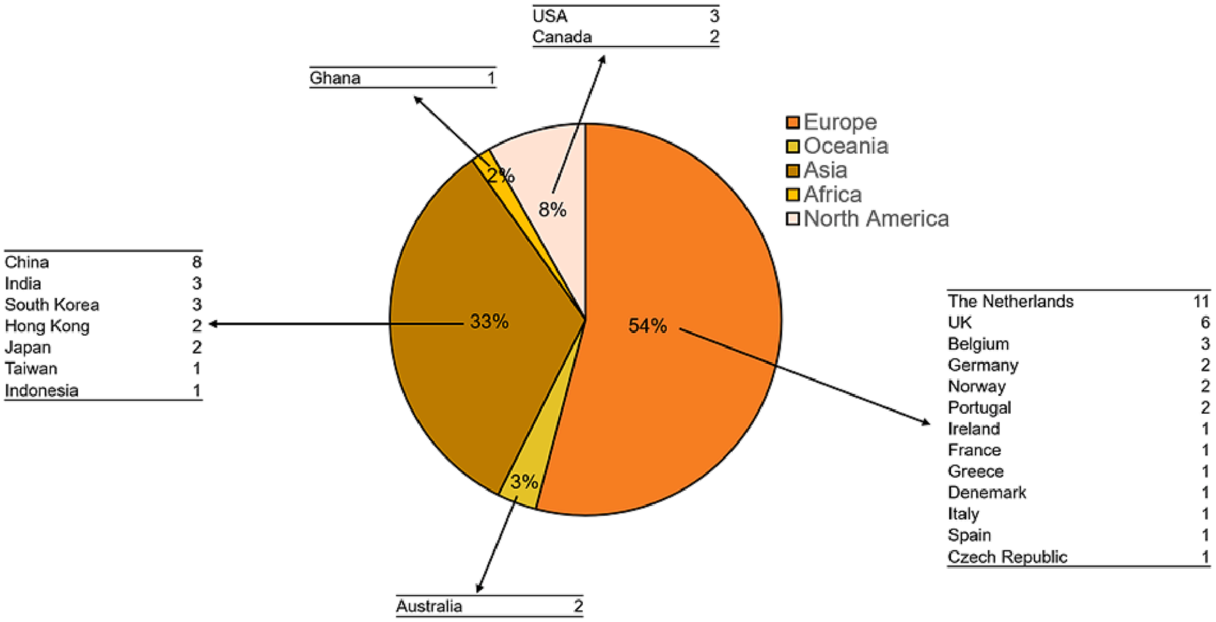

Fig. 7. Pie chart indicating the number of scientific publications per continent and country retrieved from the systematic search performed on the electronic database Scopus on the 29th of June 2022.

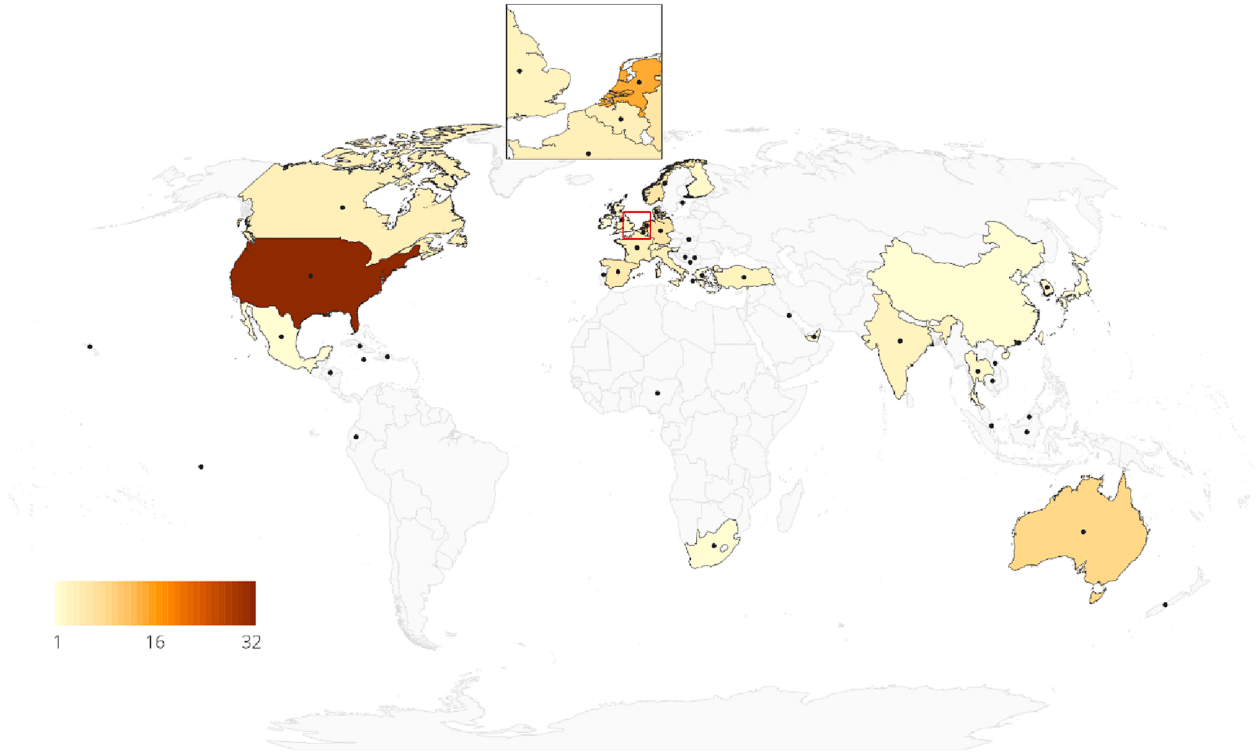

Fig. 8. Countries in which remediation technologies companies are registered with a reference to their total number (colour gradient from 1 (yellow) to 32 (orange)). Black dots indicate the countries in which at least one plastic clean-up technology is being tested or is already in use. Map made by Flanders Marine Institute (VLIZ) using QGIS version 3.16. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

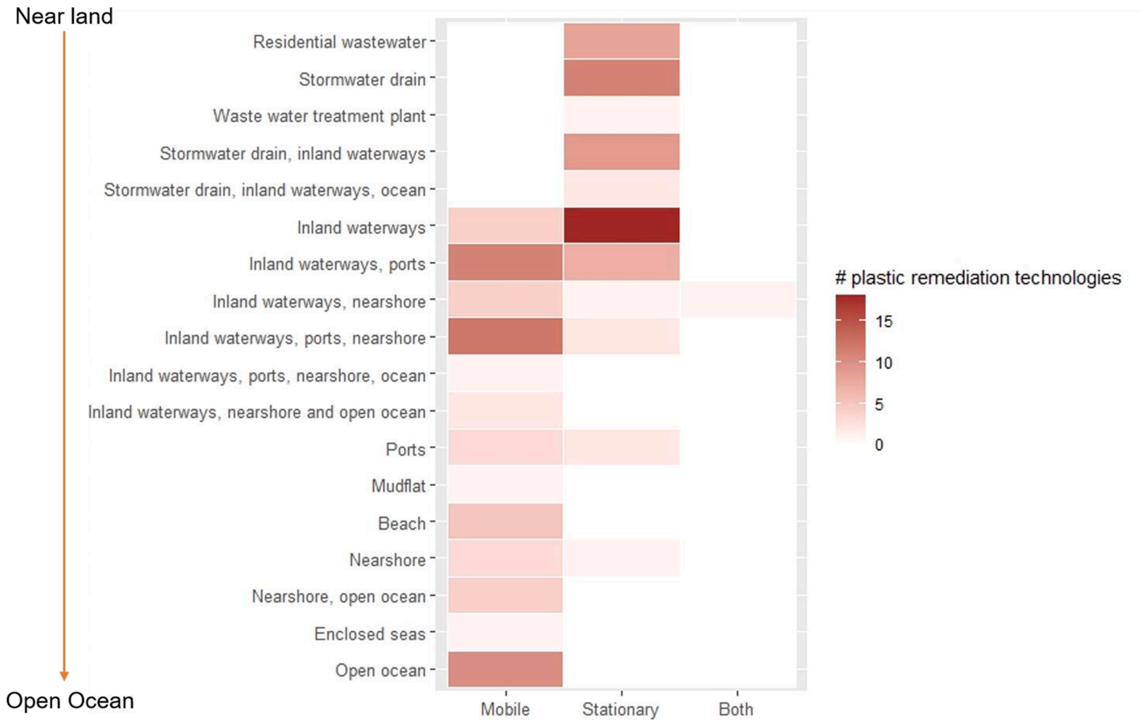

Fig. 9. Field of application of all plastic clean-up and prevention technologies ordered from land to the open ocean and the collection mechanism (i.e., mobile, stationary, both (micro and macroplastics)). Figure made using the R studio software version 2022.02.03 build 492.

However, with 52 additional technologies that have the potential to be installed in these areas, the total number of technologies that can be deployed and function in inland waterways is 74 (Fig. 9), making this field of application the most addressed. With rivers being one of the main pathways for the transport of plastic from inland, near the source, to the marine environment (Lebreton et al., 2017; Rochman, 2018) mitigation strategies such as clean-up technologies aim at collecting plastics in these locations. So far, there is a discrepancy in the number of technologies that can function in inland waterways compared to other fields of application, such as the open ocean (n = 10). Targeting plastic in smaller water bodies is technologically easier than removing plastics from the open ocean where, due to a dilution effect, it is more challenging to remove. However, new evidence indicates that plastic in the open ocean, such as in the Great Pacific Garbage Patch, is largely due to fishing activities (Lebreton et al., 2022). Therefore, clean-up technologies in seas and oceans can positively contribute to the removal of plastic deriving from wrongly discharged fishing items as well as the waste brought from the land. Post-consumption strategies, such as the implementation of remediation technologies in hotspot countries and areas, together with pre-consumption mitigation plans, could reduce plastic accumulation (Lau et al., 2020). In addition, given the globality of the issue, combining clean-up and prevention technologies is necessary to target plastics at different locations, from households to the ocean greys.

3.4. Strengths, weaknesses, opportunities and threats (SWOT) of plastic clean-up technologies for inland waterways and ports

The presented SWOT analysis investigated the strengths, weaknesses, opportunities, and threats of in use and testing clean-up technologies deployed in inland waterways and ports (Table 3). New evidence highlights the role of rivers in transporting and accumulating plastic litter (Meijer et al., 2021). These are extremely dynamic ecosystems (Meire et al., 2005) and some of the world's most exploited natural systems offering essential ecosystem services (Boerema and Meire, 2017). For example, they serve as nursery grounds for commercially relevant species (Vasconcelos et al., 2009). Given the significance of these areas and the negative effect that plastic accumulating in inland waterways might have on the overall health of the ecosystems, clean-up technologies to remove plastics are currently being deployed. However, these novel technologies are human-made. To do so, a SWOT analysis can help evaluate the prospect and possible threats. This type of analysis has been previously used for assessing the potential of clean-up technologies (Morrison et al., 2019). However, where Morrison and colleagues focus their analysis only on one specific clean-up project (i.e., The Ocean Cleanup, https://theoceancleanup.com/), we present a more comprehensive analysis by comparing multiple clean-up technologies. The SWOT analysis in this study indicates that both stationary and mobile systems (Fig. 4) share common threats and opportunities (Table 3 & S3). All clean-up technologies have the opportunity to raise awareness and bring attention to the plastic pollution issue. At the same time, clean-up technologies might be perceived by the local communities as 'the solution' to the problem. Therefore, more plastic might be discarded into the environment due to the wrongful perception that plastic clean-up technologies will then remove it.

Table 3
Summarized SWOT analysis for stationary and mobile plastic clean-up technologies that can be deployed in inland waterways. For full table see Table S3 in the supplementary material.

	Stationary	Mobile
Strengths	• No continuous attendance required during deployment.	• They can actively navigate to areas of known accumulation of debris
Weaknesses	• It is limited to the part of the waterway in which it is deployed • Need for an external security system • Need to assess how the system is perceived by the community • Deployed in areas where waste collection will be accessible (e.g., from margin using low-dimension cranes) • Collected debris requires extra infrastructure to be carried away to shore	• Energy consumption •Sensitive to extreme weather conditions
Opportunities	• Local improvement for life and environmental quality • Raising awareness on plastic pollution • Jobs opportunities • Data collection • Reducing the amount of plastic in the environment and as such reducing the environmental risk	
Threats	• People might see plastic clean-up technologies as unique solution and discard more plastic in the environment	

When looking only at stationary technologies, independently from being active (i.e., relaying on external power) or passive (i.e., do not rely on external power), they both share one strength, and five weaknesses (Table 3). The main strength is that these particular technologies do not necessarily need to be operated to gather plastic litter once deployed in the environment. However, these stationary technologies are, for instance, only limited to the portion of the waterways where they are initially deployed. In addition, one of the five shared weakness is that collected debris requires extra infrastructure to be carried away. Despite the similarities, active and passive clean-up technologies have unique challenges and prospects. Stationary active systems could be efficient in areas such as ports or canals where, due to a high passage of vessels and usually low water flow, they can actively collect plastic litter without disrupting local shipping traffic. However, the same systems might lose their efficiency when placed in areas of high river flow where, due to strong currents, the action of the motor can be overpowered. Mobile technologies have three common weaknesses and one opportunity (Table S3). All mobile technologies rely on energy consumption to gather plastic litter, and, although this energy can come from electricity or fuel consumption, these clean-up technologies open the possibility of using green energies (e.g., solar, and wind energy). As information regarding the type of energy used or the energy consumption is mostly not fully disclosed by companies, calculating the carbon footprints of each device is not currently possible. To clarify the environmental impact of cleanup devices, we recommend that companies, when possible, disclose the energy source used to power the technology. We need an objective method to measure the energy consumed by the systems, need for an intercalibration exercise to align the output data of different sensors and sources of energy.

Similar to stationary systems, crewed, uncrewed and autonomous systems have their own strengths, weaknesses, opportunities, and threats. For example, in waterways with a particularly high flow, uncrewed clean-up technologies can be safely controlled from the shore (Table S3). In the same condition, an autonomous system might be damaged by the high flow, and a long time might pass before the device is checked, resulting in a lower uptime. Therefore, the deployment of a particular mechanism (mobile or stationary) is conditioned by multiple internal (strengths and weaknesses) and external factors (opportunities and threats). Every single case needs to be addressed independently, based on the environmental parameters of the location of deployment of the clean-up system or the costs.

However, the presented SWOT analysis can provide stakeholders with some insights into the possible strengths, weaknesses, opportunities, and threats of plastic clean-up systems for inland waterways and ports.

3.5. Knowledge gaps: potential environmental impact and current policies

The assessment of the environmental impact of a remediation technology is crucial to ensure that benefits are greater than the potential negative effects. This is particularly true for clean-up technologies because they are deployed in natural environments such as rivers, beaches, estuaries, and oceans. According to Bellou et al. (2021) none of the solutions they analysed reported information of their environmental impact. Similarly, Helinski et al. (2021), highlight multiple uncertainties surrounding the potential environmental long- and short-term effects of plastic clean-up technologies.

Many of clean-up technologies are in use or testing in environments, such as inland waterways. Rivers and estuaries, for example, serve as spawning and nursing grounds for commercially relevant species (Dai et al., 2020) and, by being at the transition zone between aquatic and terrestrial habitats, provide fundamental nutrient cycling (Elsdon et al., 2009). The impact that a particular technology can have on the environment can be direct by for instance removing biota from the environment, or indirect where next to capturing plastic they might remove organic material such as wood or reed from upstream (Helinski et al., 2021). While the removal of some invasive vegetation species such as water hyacinth (CABI, 2020), often associated with plastic transport (Schreyers et al., 2021), might be beneficial, the transport of some of the organic material is necessary for the structure, productivity and function of the riverine ecosystem (Wipfli et al., 2007). Therefore, when a clean-up technology is deployed special attention should be paid to assessing the unintended bycatch of biota and organic material. Better established developers might have the means to voluntarily address and investigate the possible environmental impact of their technologies (e.g. see CSA, 2018), however we speculate that many young start-ups may not have yet the resources to outsource or even conduct environmental impact assessments (EIA). Despite many policies currently in force to reduce plastic pollution (Diana et al., 2022) there is still a lack of legislation to guide new emerging companies in monitoring the potential environmental impact or their systems as well as related costs. For instance, who is economically responsible for the plastic once collected, and if a country downstream is deploying a clean-up system is the country upstream partially responsible for the costs of cleaning up? With plastic pollution being a global problem, collaboration is essential, and careful consideration must be made when choosing which system to deploy in a given area. To date, research is being conducted in the development of framework to support stakeholders in their decision-making process when choosing an efficient yet sustainable clean-up technology (Leone et al., 2022). However, with more clean-up systems being deployed globally, research and scientific validation are necessary to minimize any of their potentially negative effects. For instance, ecological models, supported by experimental and observational data, could help in the assessment of the impact of plastic clean-up technologies (Egger et al., 2021).

3.6. Significance and future prospects for plastic remediation technologies

To date, there is still a lack of knowledge on the state, flux and fate of plastic (Horton, 2022). To improve the cost-efficiency of plastic remediation technologies more research is needed on the transport and fate of plastic in the environment. With an estimate that more than 1000 rivers could contribute to over 80% of the annual global emission of plastics to coastal and open ocean waters (Meijer et al., 2021) catching these debris from small streams to larger rivers is an efficient way to remove plastic. However, recent research suggests that riverbeds, lakes and estuaries can act as reservoirs of plastic (van Emmerik et al., 2022), which will require further removal, to avoid degradation and negative consequences in lacustrine and estuarine ecological communities. Indication of plastic in the water column (Rowley et al., 2020) demonstrate the need for further research into targeting plastics at various levels of the water column, which is necessary to efficiently remove this persistent litter. In addition, novel evidence of plastic litter originating from land mainly being found nearshore (Lebreton et al., 2022) suggest that efforts in removing plastic waste from inland waterways, before they reach the shore, should be prioritized. Moreover, although WWTPs were tested for plastic removal, they currently rely on filtration systems not specifically designed for this purpose. Due to the importance of removing plastic particles in WWTPs, before they are discharged into the environment (Freeman et al., 2020), technologies specifically developed to target plastic within WWTPs should be further investigated. An example of such a technology is the GoJelly project.

Plastic pollution is a global and an extremely complex issue to which remediation technologies aiming at preventing or collecting plastic from the environment are a crucial key, but not unique, solution. Only with multidisciplinary, multi-stakeholders and global efforts we can hope to achieve a significant decline of plastic litter. For instance, important improvements of remote sensing techniques for the detection and observation of plastics are crucial also in the objective assessment of the removal efficiency of the plastic remediation technologies, which is so far not always reported or assessed. To allow comparability between similar clean-up or prevention mechanisms, the efficiency of a removal technology should be disclosed by the companies, and the latter preferably being quantified in line with (to be developed) international agreed standards and protocols. In addition, observation of plastic fluxes and identification of hotspot areas are fundamental in supporting future plastic prevention and clean-up (van Emmerik et al., 2020). Due to the novelty and interdisciplinarity of many of the plastic remediation technologies, as discussed by Bellou et al. (2021) the collaboration between different partners is crucial to ensure the reduction of plastic litter, with minimal environmental side-effects. Even though technological solutions such as plastic remediation technologies are fundamental to achieve the ambitious goal of reducing plastic litter (Borrelle et al., 2020), other innovative solutions such as new materials, improved waste management and recycling should be implemented (Schmaltz et al., 2020). Technological innovation alone will not be sufficient to solve all issues related and caused by plastic litter (Cordier, 2019). Additional research is needed to assess the effectiveness of deploying plastic remediation technologies together with enhanced waste management and novel policies (Worm et al., 2017). Moreover, education about plastic remediation technologies and their advantages and limits should be given to the general public to avoid the false impression that, if a remediation technology is deployed, plastic can be discarded in the environment. However, if well regulated, plastic remediation technologies have the potential to reduce the load of environmental plastic and minimize more plastic from leaking into the environment.

4. Conclusions

Plastic remediation technologies, aiming at preventing plastic waste from entering the environment or at cleaning up legacy plastic, are a key step to minimize plastic flux in the environment and the consequent potential negative impacts. This study aimed at providing an overview of the currently available plastic remediation technologies to researchers, innovators, stakeholders and policymakers. Our overview of 124 technologies shows that inland waterways are the field of application of most and our analysis indicates that location is key for a successful deployment with minimum impact in the environment. We demonstrate that there is a growing scientific interest on plastic remediation technologies, but our SWOT analysis indicates that there are still crucial knowledge gaps in the field of plastic clean-up technologies. Our results show that, despite the challenges, these technologies provide a promising pathway to assist in improving the environmental quality (via plastic removal) but also in raising awareness on plastic litter. To create a framework where plastic remediation technologies contribute most effectively to reducing plastic pollution in the environment, we advise that more information be made accessible on the effectiveness and potential impacts of using plastic remediation technologies.

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Declaration of Competing Interest

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

Data availability

The data is uploaded in the online repository Marine Data Archive (Leone et al., 2023).

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2023.107854.

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