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Review article

Plastic pollution solutions: emerging technologies to prevent and collect marine plastic pollution

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ABSTRACT

As plastic waste accumulates in the ocean at alarming rates, the need for efficient and sustainable remediation solutions is urgent. One solution is the development and mobilization of technologies that either 1) prevent plastics from entering waterways or 2) collect marine and riverine plastic pollution. To date, however, few reports have focused on these technologies, and information on various technological developments is scattered. This leaves policymakers, innovators, and researchers without a central, comprehensive, and reliable source of information on the status of available technology to target this global problem. The goal of this study was to address this gap by creating a comprehensive inventory of technologies currently used or in development to prevent the leakage of plastic pollution or collect existing plastic pollution. Our Plastic Pollution Prevention and Collection Technology Inventory (https://nicholasinstitute.duke.edu/plastics-technology-inventory) can be used as a roadmap for researchers and governments to 1) facilitate comparisons between the scope of solutions and the breadth and severity of the plastic pollution problem and 2) assist in identifying strengths and weaknesses of current technological approaches. We created this inventory from a systematic search and review of resources that identified technologies. Technologies were organized by the type of technology and target plastics (*i.e.,* macroplastics, microplastic, or both). We identified 52 technologies that fall into the two categories of prevention or collection of plastic pollution. Of these, 59% focus specifically on collecting macroplastic waste already in waterways. While these efforts to collect plastic pollution are laudable, their current capacity and widespread implementation are limited in comparison to their potential and the vast extent of the plastic pollution problem. Similarly, few technologies attempt to prevent plastic pollution leakage, and those that do are limited in scope. A comprehensive approach is needed that combines technology, policymaking, and advocacy to prevent further plastic pollution and the subsequent damage to aquatic ecosystems and human health.

1. Introduction

Since its popularization in the 1950s, plastic use has skyrocketed due to its benefits to societal health, safety, and energy (Andrady & Neal, 2009). However, due to plastics' longevity and resistance to decomposition (Andrady, 2015), their widespread use has led to an epidemic of mismanaged waste. Over 7,800 million metric tons (MMT) of plastic resin and fibers have been produced since 1950, with over half of that plastic being produced from 2004 to 2017 (Geyer et al., 2017). By 2015, annual plastic production had approached the combined weight of the human population (Worm et al., 2017), and it is estimated that 150 MMT of plastic were circulating in the marine environment as of 2016 (World Economic Forum, 2016). Furthermore, experts estimate that up to 10% of plastic debris produced will enter the sea (Thompson, 2006) and that plastics will outweigh fish in the ocean by 2050 (World Economic Forum, 2016).

Plastics have deleterious effects on the environment by destroying habitat (Sheavly & Register, 2007), entangling marine animals (Gall & Thompson, 2015; Kühn et al., 2015; Lusher et al., 2018), facilitating the transport of invasive species across habitats (Kiessling et al., 2015), and depositing in sediments, leading to potential impacts on the animals that live and forage in the benthos (Brandon et al., 2019). When

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consumed by marine animals, plastic can have both physical and chemical impacts. In addition to entanglement, physical impacts include blockages in the digestive tract when plastic is consumed by marine animals (de Stephanis et al., 2013; Laist, 1987; Ryan et al., 2016), which can lead to false satiation. A review of 340 original publications found that at least 690 different species have been impacted by marine debris (92% of which is plastic) (Gall & Thompson, 2015).

The chemical impacts of ingested microplastics and macroplastics are also a growing concern (Brennecke et al., 2016; Karbalaei et al., 2018, 2019, 2020; Luo et al., 2020; Teuten et al., 2009; Turner, 2018). Plastics may serve as efficient delivery systems of toxic pollutants, like plastic additives from the manufacturing process (*e.g.*, heavy metals, plasticizers) or chemicals that have adsorbed to plastic from the surrounding environment (*e.g.*, heavy metals) (Gallo et al., 2018; Turner, 2016, 2018). For example, some microplastics have been shown to contain additives that are known reproductive toxins, carcinogens, and mutagens (Wright & Kelly, 2017). These chemicals may bioaccumulate up the food chain through ingestion at multiple trophic levels, and the implications for food webs are not yet fully understood (Carbery et al., 2018; Farrell & Nelson, 2013; Lusher et al., 2018). Plastic additive leaching has been shown in studies on barnacles, anemones, and Japanese medaka, along with an avian physiologically-based model (Diana et al., 2020; Li et al., 2016a; Turner, 2018; Zhu et al., 2020). This is a potential human health hazard, because humans consume an estimated 39,000 to 52,000 microplastic particles per year from food and beverages alone (Cox et al., 2019). As plastics enter the human food chain, they carry additives from the manufacturing process, chemicals adsorbed to the plastics, and pathogens or parasites that may be on the plastics (Barboza et al., 2018; Vethaak & Leslie, 2016; Wu, 2017). However, despite this, most countries continue to classify plastics as harmless solid waste (Lechner & Ramler, 2015; Rochman et al., 2013).

In light of the growing concern about the negative impacts of plastics on environmental and human health, some governments are increasingly responding to this problem at the local, national, and international levels (Adam et al., 2020; Karasik et al., 2020; Schnurr et al., 2018; Xanthos & Walker, 2017). Between the years 2000 and 2019, at least 28 international policies were established to reduce plastic pollution, three of which are binding to member states: the Antarctic Treaty, London Convention and Protocol amendments, and the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex V (Karasik et al., 2020). The United Nations Environment Assembly (UNEA) has enacted multiple resolutions that aim to reduce marine plastic pollution (*e.g.*, Resolutions 1/6, 2/11, 3/7, 4/6, 4/7, 4/9) (Carlini & Kleine, 2018; Karasik et al., 2020; Resolution 1/6 Marine Plastic Debris and Microplastics, 2016; Resolution 2/11 Marine Plastic Litter and Microplastics, 2016; Resolution 3/7 Marine Litter and Microplastics, 2018; Resolution 4/6 Marine Plastic Litter and Microplastics, 2019; Resolution 4/7 Environmentally Sound Management of Waste, 2019; ten Brink et al., 2018; Resolution 4/9 Addressing Single-use Plastic Products Pollution). Similarly, the Group of Seven Summit acknowledged in 2015 that marine pollution is a global challenge affecting marine and coastal ecosystems and human health and ultimately passed an Ocean Plastics Charter in 2018 that committed to taking specific actions to reduce plastics in the marine environment (Niaounakis, 2017). Similarly, the Group of Twenty agreed to an Action Plan on Marine Litter in 2017 (G20 Action Plan on Marine Litter, 2017).

In addition to these international efforts, regional groups of governments (in various geographic locations) have started to respond to the marine plastic pollution issue. As of 2019, at least 39 regional policy documents have been adopted, primarily in Europe (Karasik et al., 2020). Regional policies facilitated by the United Nations Environment Programme (UNEP) and the Regional Seas Programme make up over half of these policies and the remaining policies were adopted by the European Union (EU), Antarctic Treaty signatories, Nordic countries, and East African member states (Karasik et al., 2020). Regional governments including the EU, Baltic Marine Environment Protection Commission (Helsinki Commission), Nordic Council of Ministers, Convention for the Protection of the Marine Environment of the North-East Atlantic, and Secretariat of the Pacific Regional Environment Programme have agreed to phase out plastic microbeads through statements of support and regional action plans (UNEP, 2018).

In addition to these international and regional efforts, national and subnational government responses have increased over the last decade, focusing primarily on bans, levies/taxes/fees, and voluntary efforts (*e.g.*, "reduce and reuse campaigns") in order to address plastic bags and, to a lesser extent, single-use plastics more broadly (Lam et al., 2018; Schnurr et al., 2018; Xanthos & Walker, 2017). At the national level, governments worldwide are increasingly adopting policies to target single-use plastic bags and other macroplastics, primarily through the adoption of regulatory bans (Karasik et al., 2020; Schnurr et al., 2018; Xanthos & Walker, 2017). A number of national single-use plastic bag bans, taxes, or levies have been adopted in countries in sub-Saharan Africa (Jambeck et al., 2018; Karasik et al., 2020). Twelve of the 16 countries in West Africa have instituted single-use plastic reduction policies, which include 11 bans and one market-based approach in Ghana (the Environmental Excise Tax Act 863) (Adam et al., 2020). Nationwide bans on the use of microbeads in cosmetic products have been adopted in the United States, Canada, United Kingdom, New Zealand, Finland, France, Iceland, Ireland, Italy, Luxemburg, Norway, and Sweden (Dauvergne, 2018a). Local legislation to reduce plastic pollution has also increased worldwide (Karasik et al., 2020; Schnurr et al., 2018; Xanthos & Walker, 2017). In cities in the United States, for example, plastic bag bans have become the most common form of local ordinance used to address plastic pollution (Wagner, 2017).

Despite these policy efforts, the rate of plastic pollution continues to grow (Dauvergne, 2018b; Jambeck et al., 2015). With governance fragmented across a number of national and local jurisdictions, business and political interests have often taken precedence over the capacity of marine systems, and international institutions have struggled to fill the gaps (Dauvergne, 2018b). These governance challenges are further complicated by the durability and dispersal of plastics, the scientific uncertainty in the amount of pollution making its way into the oceans, and the difficulty in determining who is responsible for that pollution (Dauvergne, 2018b). Meanwhile, the growing plastics industry has exerted considerable influence, dispersing plastic through opaque trading structures and sending waste to jurisdictions with poor waste management practices (Dauvergne, 2018b).

Existing international governance mechanisms, such as Annex V of MARPOL and the 2011 Honolulu Strategy, have proved insufficient to address the plastic marine litter crisis (Dauvergne, 2018b; Gold et al., 2013). Current international rules, state policies, nonstate rules, and consumer behaviors are not strong or comprehensive enough to protect the environment at a global level (DeSombre, 2018). This is primarily due to the fact that governance is fragmented across national and local jurisdictions, allowing for regulatory gaps in global environmental governance that make it easy to evade responsibility and deflect the costs of plastic pollution (Dauvergne, 2018b).

While governments have an important role to play, these efforts are more effective when coupled with private industry action and technological innovation, especially given the global nature of the problem and the extent of stakeholders involved. Indeed, Gold and colleagues (2013) called for investment in emerging technologies to increase the efficiency of marine litter clean-up efforts. To that end, both for-profit and non-governmental organizations (NGOs) are trying to reduce the negative impacts of plastic pollution by developing new technologies designed to remediate plastic pollution in the environment. For example, new technologies and strategies to remediate plastic pollution have been compiled by Ubuntoo, a for-profit company that shares innovative solutions developed by private entities, NGOs, governments, and academics in a web-based database ("About Us," n.d.). Additionally, the for-profit entities of Systems, Applications, and Products

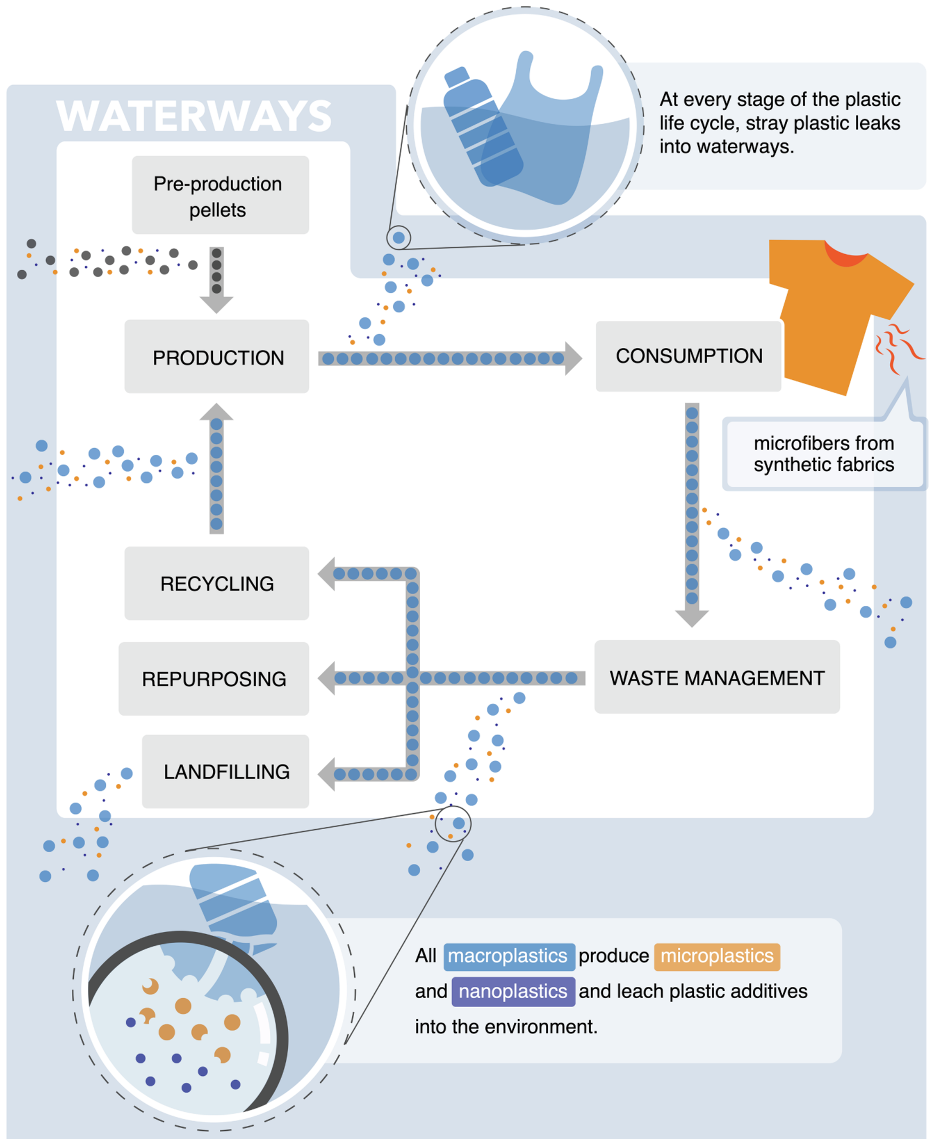

Fig. 1. Sources of marine pollution throughout the plastic lifecycle. Plastic pollution prevention and collection technologies can capture plastic leakage from any stage of the plastic lifecycle.

in Data Processing (SAP), Modis, Cermaq, and Wilhelmsen supported the United Nations (UN) Reboot the Ocean Challenge, in which innovators worldwide submitted technological solutions to reduce marine plastic pollution in the "End Waste Entering the Ocean" session ("Reboot the Ocean," n.d.).

These innovative techniques to reduce the amount of global plastic pollution focus on different life cycle stages of plastic, including production, consumption, and waste management, which can involve landfilling, recycling, or repurposing (*e.g.*, waste-to-energy) (Nielsen et al., 2020; Prata et al., 2019). Approximately 80% of marine plastic pollution arrives in the ocean from land-based sources (Li et al., 2016b; Ritchie and Roser, 2018) and it is common for plastic to leak out of waste management channels into the environment as mismanaged waste throughout the production, consumption, and waste management stages of the plastic life cycle (Fig. 1) (Nielsen et al., 2020; Prata et al., 2019). For example, plastic can be lost to the surrounding environment and transported to the oceans via waterways, winds, and tides due to littering and improper waste management in open or uncontrolled landfills (Law, 2017; Ritchie & Roser, 2018). Microplastics can enter the environment through wastewater, storms, and catastrophic events, which can carry materials of all kinds, including plastics, into the oceans (Law, 2017). Technologies addressing these issues are geared toward either 1) directly preventing plastic leakage into waterways or 2) collecting existing plastic pollution. During the recycling phase, innovative recycling solutions, such as plastic-to-fuel and bioremediation, are being explored (Mohanraj et al., 2017; Sheth et al., 2019; Tournier et al., 2020; Yoshida et al., 2016).

These technologies serve as promising complements that can work in tandem with policy efforts to combat marine plastic pollution (Cordier & Uehara, 2019; Gold et al., 2013; Worm et al., 2017). The UNEA Resolution 2/11 notes that member states should "cooperate regionally and internationally on clean-up actions of such hotspots where appropriate and develop environmentally sound systems and methods for such removal and sound disposal of marine litter" (Resolution 2/11 Marine Plastic Litter and Microplastics, 2016; ten Brink et al., 2018). This study seeks to identify these technologies through creation of the Plastic Pollution Prevention and Collection Technology Inventory (https://nicholasinstitute.duke.edu/plastics-technology-inventory), which can serve as a tool for stakeholders who are undergoing cleanup efforts of marine plastic hotspots, as suggested by the UNEA in Resolution 2/11 (Resolution 2/11 Marine Plastic Litter and Microplastics, 2016). The Inventory focuses on technologies that 1)

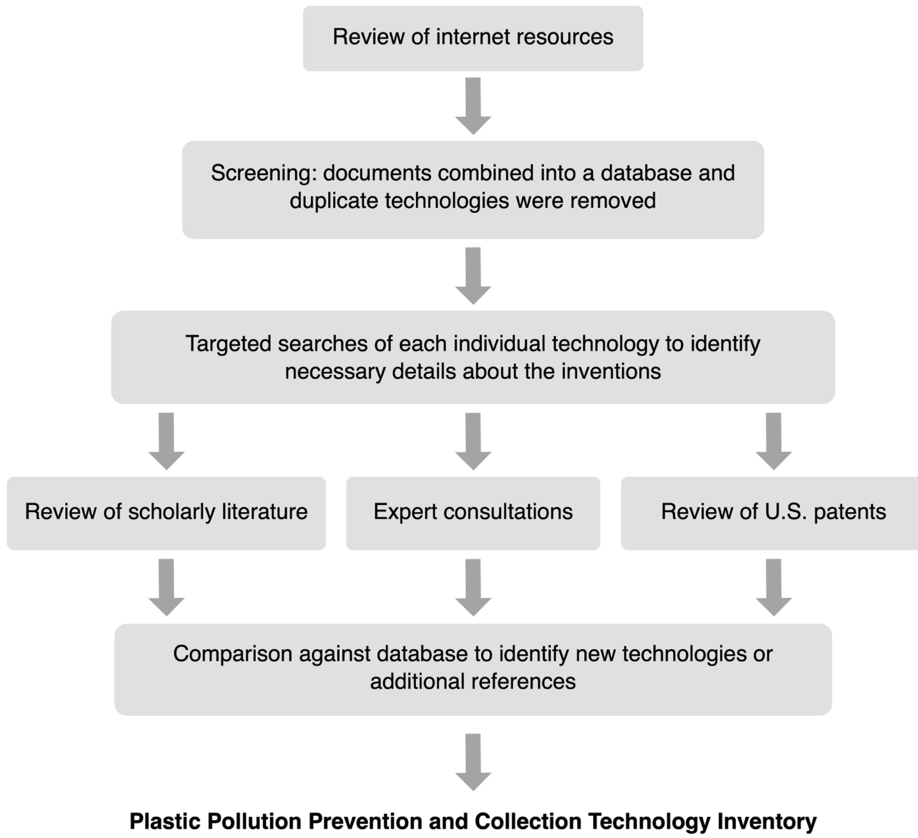

Fig. 2. Overview of methods used to assemble the Plastic Pollution Prevention and Collection Technology Inventory.

prevent plastic leakage into riverine and marine environments or 2) collect existing pollution that leaked during other plastic lifecycle stages including production, consumption, and waste management. We focused on these technologies because they are specific to plastic pollution already in waterways and the marine environment, or they focus on plastic pollution in systems that immediately feed into those environments, such as sewage systems and wastewater. To our knowledge, these technologies have not been systematically reviewed.

The Inventory created from this review can serve as a streamlined tool that researchers, industry, NGOs, and governments can use to learn about the options available for plastic pollution remediation. A white paper published by the Benioff Ocean Initiative surveyed the broad types of technologies used to reduce river plastic pollution (The Benioff Ocean Initiative, 2019); we hope that this study builds upon their work by encompassing marine ecosystems and including a searchable inventory of specific technologies that allows for faster learning. Moreover, the Inventory enables comparisons between the scope of solutions and the breadth and severity of the plastic pollution problem, and it identifies the strengths and weaknesses of current technological approaches and implementation. We hope that innovators and policymakers will use the Inventory to determine how best to target future innovation efforts and incorporate technological solutions to complement existing policy efforts.

2. Methods

For this review, we conducted a systematic search of internet resources, scholarly literature, and patents to identify technologies that either reduce the amount of plastic pollution entering the ocean and rivers or extract existing plastic pollution from waterways. We also included technologies that aim to prevent plastic pollution from entering waters upstream of oceans and rivers (*e.g.*, industrial or residential wastewater). Because most information regarding plastic pollution prevention and collection technologies is located in internet resources, we focused on this literature, including news media, press releases, and other non-peer reviewed literature. We then supplemented that search by analyzing scholarly literature, reviewing United States Patent and Trademark Office patent databases, and carrying out expert consultations with Ubuntoo and the UN Reboot the Ocean Challenge (Fig. 2).

2.1. Review of internet resources and assembly of the Inventory

We first conducted a systematic search to identify announcements in press releases, key events, or other media that discussed technologies to either prevent plastic leakage into waterways or remove existing plastic pollution from riverine and marine environments. To perform this search, we developed a series of Boolean search strings by reviewing news articles and press releases on plastic remediation technology. Search terms were either synonyms or types of plastic pollution (*e.g.*, "marine debris," "shopping bag," "Styrofoam") paired using “AND” with synonyms for technology (*e.g.*, "invention"). Where search terms led to predominantly irrelevant results, we added the terms “collect” and “remove” with the Boolean connecter “AND.” We performed a Google search using the resulting search terms (Table 1). After conducting pilot searches on several terms, we determined that after approximately 100 news articles, the searches returned results that were either irrelevant or duplicative of prior results. Therefore, we focused the review on the first 100 news articles for each of the 40 search terms (n = 3,910 articles total). We considered news articles published prior to October 1, 2019 for this study.

From these search results, we included all discrete technologies in the Inventory that were designed to either prevent the leakage of plastic pollution into waterways or collect existing plastic pollution. We excluded technologies that did not fall into these two categories – such as plastic-to-fuel, bioremediation, or new materials to replace plastic – due

Table 1
Boolean strings of search terms used to identify plastic pollution remediation technology.

Search terms
"cigarette waste" AND "invent*"
"marine debris" AND "tech"
"marine debris" AND "invent*"
"marine litter" AND "invent*"
"microplastic" AND "invent*"
"microfiber" AND "invent*"
"nurdle*" AND "invent*"
"nylon" AND "invent*"
"marine plastic" AND "invent*"
"ocean plastic" AND "invent*"
"polyethylene" AND "invent*"
"polymethyl methacrylate" AND "invent*"
"polypropylene" AND "invent*"
"polystyrene" AND "invent*"
"polyvinyl chloride" AND "invent*"
"shopping bag" AND "invent*"
"Styrofoam" AND "invent*"
"synthetic disposable" AND "invent*"
"tire" AND "invent*"
"tyre" AND "invent*"
"marine waste" AND "collect" AND "tech"
"marine debris" AND "collect" AND "tech"
"marine litter" AND "collect" AND "tech"
"marine waste" AND "collect" AND "invent*"
"marine debris" AND "collect" AND "invent*"
"marine litter" AND "collect" AND "invent*"
"marine waste" AND "cleanup" AND "invent*"
"marine debris" AND "cleanup" AND "invent*"
"marine litter" AND "cleanup" AND "invent*"
"marine waste" AND "remove" AND "invent*"
"marine debris" AND "remove" AND "invent*"
"marine litter" AND "remove" AND "invent*"
"plastic" AND "remove" AND "waterway"
"plastic" AND "collect" AND "waterway"
"plastic" AND "remove" AND "ocean"
"plastic" AND "collect" AND "ocean"
"litter" AND "trap" –cat[2]
"trash" AND "marine" AND "technology"
"ocean" AND "booms"
"river" AND "booms"

[2]The search of "litter" AND "trap" yielded mostly results about cat litter, therefore "-cat" was added in order to remove results that were irrelevant to the search.

to our focus on prevention and collection technology.

When determining whether two sources described discrete technologies, we first assessed whether the two technologies appeared similar in purpose, mechanism, and construction. Even for those technologies that appeared similar, we considered inventions discrete if they were differently branded or if they were manufactured, sold, or marketed by different entities. When inventions were not branded, but were labeled with descriptive names, we grouped together inventions that appeared identical. This included, for example, generic river booms that are often described in a merely descriptive way and are frequently cited in localized collection efforts.

We then assembled the list of discrete technologies, assigned each technology a unique identification number, and categorized them as either prevention or collection technologies. When a technology could be used for either prevention or collection, we categorized it as the former since prevention is further upstream in the plastic lifecycle than collection.

To determine if an invention targets macroplastic, microplastic, or both, we relied on the reporting and categorizations in the literature itself. In rare cases where the targeted plastics were not described but a size of targeted plastics was provided, we defined microplastics as plastics smaller than 5 mm and macroplastics as anything larger (Arthur et al., 2009). We also identified the year that the technology was invented (if available), use status (*i.e.,* in use, not in use, pilot testing, or unknown), and geographic location where the technology was invented (if available). If the source did not clearly identify the year that the technology was invented, we used the year that the earliest source article was published as a proxy.

After assembling the Inventory, we performed a targeted, in-depth search in Google on each technology to gather any information that was not provided in the initial reference articles. Search terms included the name of the technology or inventor/manufacturer and the piece of missing data (*e.g.*, plastic type targeted).

2.2. Review of scholarly literature

After assembling the Inventory, we applied the same search terms (Table 1) in Google Scholar and the Duke University Library system to cross-check the peer-reviewed literature (published prior to October 1, 2019) with technologies previously identified. We filtered search results by relevance and reviewed them to identify new technologies not already in the Inventory or extract information on technologies already in the Inventory.

2.3. Review of patents

We next searched the United States Patent and Trademark Office patent database for relevant technologies patented prior to October 1, 2019. Our patent search was limited in scope and is discussed in more detail in the Supplementary Material. Future patent research by experts trained in the technical and engineering aspects of these issues could allow for a more detailed analysis of the scope of the patent literature and enhance the Inventory.[2]

2.4. Expert consultations

In addition to these searches, we consulted with experts to add additional technologies to the database that we did not identify through our review of internet sources, scholarly literature, or patents. These expert consultations included meeting with the co-founder of Ubuntoo, a company that compiles a variety of novel solutions to plastic pollution, and then carrying out searches for technology on Ubuntoo (see Supplementary Material). One author (Z. Diana) served as a judge and mentor for innovators who submitted plastic prevention and collection technologies to the UN Reboot the Ocean Challenge "End Waste Entering the Ocean" session (see Supplementary Material). Additional technologies from Ubuntoo and the UN Reboot the Ocean Challenge were added to the Inventory for analysis.

3. Results

The Boolean search strings in Table 1 resulted in 3,910 Google news articles for screening, from which 39 discrete technologies were identified that were designed to either 1) prevent plastic from entering waterways or 2) collect existing marine and riverine plastic pollution. The search of scholarly literature revealed no additional technologies, although it did result in one additional reference. The patent search resulted in one additional technology. Expert consultations resulted in 12 additional technologies. Among the 52 total technologies, 14 were categorized as technologies focusing on plastic pollution prevention and 38 were categorized as collection technologies (Table 2). Of the 52 total technologies, 39 targeted macroplastics, nine targeted

[2] Michael Niaounakis extensively reviews patents of this nature from around the world in his volume Management of Marine Plastic Debris (Niaounakis, 2017). A complete review of that collection is beyond the scope of our technical expertise but could be useful in supplementing the Inventory.

Table 2
The Plastic Pollution Prevention and Collection Technology Inventory.

		Name	Year[3]	Description	Used?	Location invented	References
Prevention: macroplastics	*Stormwater and wastewater filters*	In-line Litter Separator (ILLS)	1999	Trap attached to the drainage system downstream of shopping areas removes litter from passing stormwater	Yes	Australia	Phillips, 1999
		StormTrap TrashTrap	2018	Mesh net system uses water flow to capture and remove trash, floatables, and solids from stormwater and wastewater	Yes	United States	"TrashTrap: Capture floatables with innovative netting systems," n.d.; "TrashTrap Floatables Collection System Guide Specification," 2018
		PumpGuard	2016	Mesh nets remove debris from stormwater and wastewater	Yes	United States	"Pump protection solutions for wastewater, stormwater and combined sewer overflow (CSO) discharges," n.d.; "Pumpguard," n.d.
		Watergoat Trash Trap	2006[4]	Floating boom and net attached to embankments, stormwater outfalls, canals, or creeks collects floating debris	Yes	United States	"Mark Maksimowicz," n.d.; "'Watergoat' trash traps helping curb litter in Augusta," 2018; Parsons, 2017; tfarrell, 2019
		Netting TrashTrap System	1999	Mesh nets capture and remove trash from stormwater and discharge	Yes	United States	Fresh Creek Technologies, Inc., n.d.; "Fresh Creek Technologies Installs 200th TrashTrap Systems," 2010; Turner et al., 2005a, 2005b; United States Environmental Protection Agency, 1999
Prevention: macroplastics	*Stormwater and wastewater filters*	StormX Netting Trash Trap	1995	Commercial grade reusable nets provide full capture of gross pollutants as small as 5 mm in stormwater runoff, including organic materials (such as leaves) that could reduce the levels of phosphorous and nitrogen in water	Yes	Australia	"City of Carrollton, Texas installs StormX netting trash trap," 2012; "StormX Netting Trash Trap," n.d.; Wodalski, 2010
	Miscellaneous leakage prevention	Stow it, Don't Throw It	2012	Tennis ball containers repurposed into fishing line recycling bins for anglers	Yes	United States	"Home: The Stow It-Don't Throw It Project," n.d.; "Stow It Don't Throw It Project," n.d.; Savedge, 2014
		CLEVER-Volume	2019	Sensors allow port authorities to certify the amount of ship waste reported, in comparison to the volume reported to MARPOL inspectors	No	Portugal	"CLEVER-Volume – 3DModelling PT," n.d.; Solana, 2019
Prevention: microplastics	*Miscellaneous removal from wastewater*	Unnamed Invention by Students at Gering High School	2017	Gravity-fed, three-stage attachable filter catches microplastics (*e.g.*, microfibers shed from laundry) before they enter the wastewater	No	United States	Fielder, 2017; "These students found a way to keep microplastics out of your drinking water," 2018
		GoJelly Project	2018	Jellyfish mucus (secreted when they reproduce or become stressed) captures and binds to nano-sized particles, removing microplastics from wastewater	No	Unknown (Funded by European Union)	Diaz, 2019; "GoJelly," n.d.; Javidpour, 2018
Prevention: microplastics	*Laundry balls*	Cora Ball	2019	Balls placed in the laundry machine capture microfibers shed when washing synthetic fibers	Yes	United States	"Cora Ball," n.d.; Kart, n.d.
		Fibre Free	2017	Balls placed in the laundry machine or dryer capture microfibers shed when washing or drying synthetic fibers	No	United States	Chou, 2018; Dunbar, 2017
	Residential wastewater treatment	Lint LUV-R	2016	Water filter on laundry machines captures microfibers when water is drained through the machine	Yes	Canada	Kart, n.d.; Krieger, 2016; "Lint LUV-R washing machine discharge filter," n.d.

(*continued on next page*)

Table 2 (*continued*)

		Name	Year[3]	Description	Used?	Location invented	References
		Showerloop	2012	Filter removes microplastics while primarily filtering water for reuse	Unknown	Finland	"How it works," n.d.; "Make it," n.d.; Young, 2018
Collection: macroplastics	*Large-scale booms*	Ocean Cleanup System	2013	C-shaped boom and screens use currents to corral trash	Yes[5]	Netherlands	BeauHD, 2018; Carr, 2017; Cross, 2019; Edwards, 2016; Gertz, 2014; Hill, 2016; Howard et al., 2019; Knapton, 2017; Leatherman, 2015; Lim, 2018; Miller, 2018; Onorevole, 2016; Papadopoulos, 2019; Ryall, 2015; Shah, 2017; Spary, 2018; "The Ocean Cleanup," n.d.; "Will the Great Pacific Garbage Patch meet its match?", 2018; Wamsley, 2018; Wright, 2018
		Holy Turtle	2018	1,000-foot-long floating unit is towed by two marine vessels and captures floating waste; large vent hole protects marine life	Yes	United States	Kotecki, 2018; SodaStream International Ltd., 2018
Collection: macroplastics	*Drones and robots*	FRED (Floating Robot for Eliminating Debris)	2019	Solar-powered vessel with conveyor belts collects floating debris	Yes[5]	United States	"About – Clear Blue Sea," n.d.; "Meet Fred – Clear Blue Sea," n.d.; Thomson, 2019
		WasteShark	2016	Drone modeled after a whale shark skims the water and collects floating debris	Yes	Netherlands	"Chomping down on trash: WasteShark collects marine debris," 2018; Cook, 2019; Dormehl, 2016; Morjaria, 2019
		Jellyfishbot	2018	Remote-controlled robot collects garbage from waterways	Yes	France	"A jellyfish robot arrives in the Old Port to collect waste," 2019; "Jellyfishbot," n.d.; Franklin, 2018
		Seabin	2013	Automated bucket uses a pump to capture floating debris, including plastic	Yes	Australia	Edwards, 2016; "Seabin, a new kind of floating bin," 2019; "Seabin project—Cleaner oceans for a brighter future," n.d.
		BluePhin	2017	Battery-powered, zero carbon emissions robot uses artificial intelligence to collect floating waste	Unknown	United Arab Emirates	BluePhin Technologies, n.d.
	Boats and wheels	SeaVax	2015	Solar- and wind-powered ship collects plastic and other debris; sensors detect waste and sonar protects fish and other animals from being collected	Yes	United Kingdom	Chow, 2016; Edwards, 2016; "SeaVax Robotic Vacuum Ship," n.d.
		Mighty Tidy	2003	Trash skimming boat scoops plastic from the surface, and a conveyor belt moves waste to a bin	Yes	United States	Babineck, 2003; "News," 2003
		Inner Harbor Water Wheel	2014	Wheel collects trash in the river before it can flow into the harbor	Yes	United States	Hamers, 2019; Krieger, 2016; "Trash wheel project," n.d.
		Versi-Cat Trash Skimmer Boat	2009	Skimmer collects floating and semi-submerged debris in a removable basket for later disposal	Yes	United Kingdom	"Versi-Cat, n.d.; "Water Witch: World Leaders in Waterway Cleanup," n.d.
Collection: macroplastics	*Boats and wheels*	ERVIS	2016	Ship with saucers uses centripetal force to capture and separate waste into five size classes for later disposal	No	India	"Pune: 12-Year-old designs ship to remove plastic from ocean, save marine life," 2019; Think Change India, 2018
		One Earth-One Ocean SeeHamster	2012	Small catamarans (4 × 12 m), equipped with fold-down nets or fishing gear collect debris from inland waters	Yes	Germany	"One Earth One Ocean," n.d.
		One Earth-One Ocean SeeKuh	2016	Nets with 2.5 cm mesh are suspended from catamarans (12 x10 m) and collect plastic waste up to 4 m deep from bays, estuaries, and coastal regions	Yes	Germany	"One Earth One Ocean," n.d.

(*continued on next page*)

Table 2 (*continued*)

		Name	Year[3]	Description	Used?	Location invented	References
		Manta	2016	Ship brings waste onboard for manual sorting and mechanical compacting before being carried to land for processing	No	France	"The Manta, a revolutionary vessel," n.d.
		The Interceptor	2019	Solar-powered catamaran autonomously extracts floating plastics from rivers, using barriers and a conveyor belt	Yes	Netherlands	"How it works: The interceptor," n.d.
		MariClean	2020	Catamaran fitted with a conveyor belt collects debris from seas, straits and bays	No	Canada	Echavez, 2020
Collection: macroplastics	*Detection aids*	Malolo I	2017	Unmanned aerial robot detects marine debris (especially fishing gear) in the open ocean for later collection or satellite tagging	Yes	United States	Mayer, n.d.
		Unnamed GPS Device on Ghost Nets	2019	Vessels place GPS units on ghost nets to mark them for collection	Yes	United States	"Ocean Voyages Institute," n.d.; SMART, 2019
		NetTag	2019	Low-cost transponders allow fishers to locate and recover lost nets	Yes[5]	England	E&T Editorial Staff, 2019
		Wikilimo	2019	Uses satellite imagery to detect major garbage patches in oceans; uses numerical models and machine learning to identify optimum routes for cleaning up garbage patches	No	United States	"Machine learning and satellite imagery based oceanography," n.d.
	Waterway litter traps	Bandalong Litter Trap	2009	Floating device uses waterway currents to capture and guide litter into the trap before it flows downstream	Yes	Australia	"Bandalong Litter Trap," n.d.-a; "Bandalong Litter Trap," n.d.-b; "Storm Water Systems installs first U.S. Bandalong Litter Trap," 2009
		Clear River Litter Trap	2014	Floating device uses waterway currents to capture and guide litter into the trap before it flows downstream	Yes	Netherlands	"Litter Traps," n.d.; "Timeline," n.d.
		SCG Litter Trap	2019	Floating litter trap uses a bypass flap to leverage water flow and pressure to capture and trap floating litter	Yes[5]	Thailand	"'Litter trap' a success blocking trash from the sea," 2019; "SCG's Floating Litter Trap to Prevent Marine Debris Entering Oceans at Rayong Estuaries and Samut Sakhon Canals," 2019
Collection: macroplastics	*River booms*	Clean River Project River Boom	2005	Floating beams create a barrier that collects surface debris along rivers	Yes	United States	Blessing, 2018; "Clean River Project," n.d.
		Bandalong Boom	2015	Floating boom couplings span waterways to capture waste and prevent it from traveling further downstream	Yes	Australia	"Bandalong Boom System," n.d.; "Bandalong Boom System tested by University of Kentucky," 2015; "Bandalong Boom Systems," n.d.
		The Litterboom Project	2017	Large pipes anchored across rivers catch surface-level debris	Yes	South Africa	"About the project," n.d.
		AlphaMERS Floating Barrier	2015	Floating barricade carries debris to the riverbank for manual or mechanical collection	Yes	India	"AlphaMERS Ltd," n.d.
		Plastic Fischer Trash Boom	2019	Boom made of PVC pipe floaters and galvanized steel catching nets collects surface plastics up to 60 cm deep	Yes	Germany	"Our solutions," n.d.

(*continued on next page*)

Table 2 (*continued*)

		Name	Year[3]	Description	Used?	Location invented	References
	Sand filters	Barber Surf Rake	Unknown	Tractor-towed machine removes waste on beaches	Yes	United States	"Surf Rake—Tractor-towed beach cleaner machines," n.d.
		Barber Sand Man	Unknown	Walk-behind sand sifting machine uses a vibrating screen to sift debris from sand and soil on beaches	Yes	United States	"Walk behind sand cleaner: The Barber SAND MAN 850," n.d.
Collection: microplastics	*Miscellaneous capture*	Unnamed Invention by Anna Du	2018	Remotely operated vehicle uses infrared light to detect, photograph, and help remove microplastics from waterways	No	United States	"Anna's World," n.d.; Williams, 2019
		Unnamed Invention by Fionn Ferreira	2019	Combination of oil and magnetite powder binds microplastics for extraction with a magnet	No	Ireland	Bendix, 2019; Nace, n.d.; "What is Fionn About," n.d.
Collection: microplastics	*Sand filter*	Marine Microplastic Removal Tool	2013	Sand is piled on a sheet of fine mesh stretched between two long poles, and the mesh catches plastic and other foreign material while allowing the sand to fall through	Yes	United States	Fisher, 2018; Ward, 2015
Collection: all	*Boat*	OC-Tech	2013	Boat collects oil, microplastics, and other debris using a system of nets and baskets; clean water then flows back into ocean	Unknown	Spain	"OC-Tech: Innovative vessel for cleaning-up activities in marine and fluvial environments.," n.d.; "Products—Ocean Cleaner Technology," n.d.
	Skimmer	Marina Trash Skimmer	2016	Pump in a partially submerged plastic box draws in and catches surface trash	Yes	United States	Faulkner, 2019; Kraimer et al., n.d.; "Marina Trash Skimmers," n.d.
	Vacuum	Hoola One	2019	Vacuums approximately three gallons of sand and debris per minute into a tank that separates particles by buoyancy, allowing for plastic separation and removal	Yes	Canada	"Hoola One – We hand the beaches back to nature," n.d.; "Hoola One microplastic removal machine arrives on Hawaii," 2019; KITV Web Staff, 2019; Mendoza, n.d.; Peters, 2019
	Air barrier	The Great Bubble Barrier	2019	Tubes placed diagonally across the bottom of the waterway create a bubble barrier by pumping air, creating a current that brings debris to the surface and guides it to a catchment system	Yes	Netherlands	"Bubble Barrier," n.d.; "Bubble barrier catches micro-plastics from effluent sewage treatment," n.d.; Thomson, 2019

[3]Year designates the year invented; if the year invented was unavailable, the earliest year that an article about the technology was published was used.
[4]This date was found on the personal website of the inventor.
[5]In testing phase.

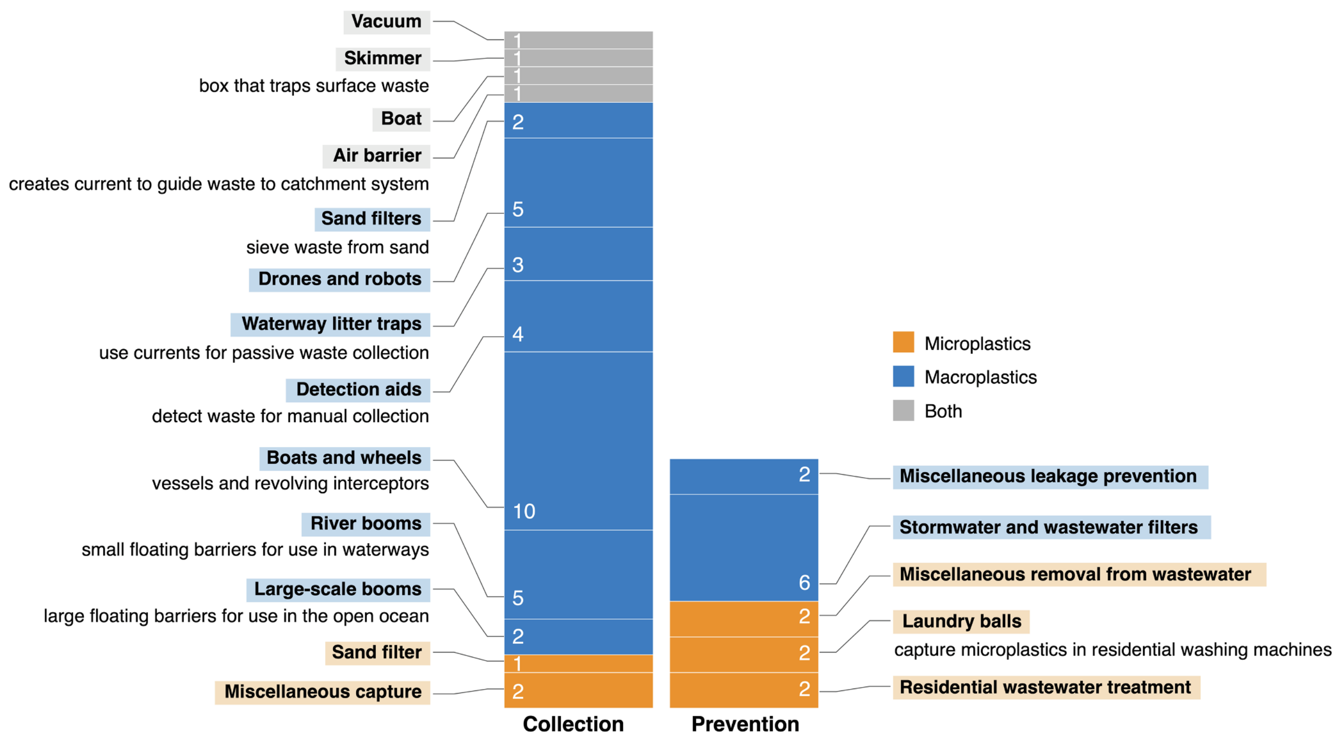

Fig. 3. The number and type of technologies directed toward leakage prevention versus collection and the type of plastic targeted (microplastics, microplastics, or both). In total, three plastic pollution collection technologies target microplastics, 31 target macroplastics, and four target both. Six plastic pollution prevention technologies target microplastics, and eight target macroplastics. Technology definitions were created based on descriptions of the technologies in the Inventory.

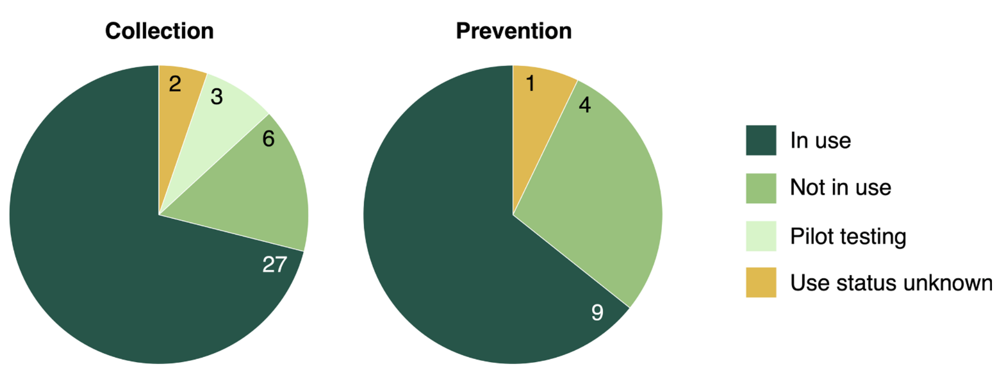

Fig. 4. The number of prevention and collection technologies that have been used, not used, pilot tested, or unknown.

microplastics, and four targeted both categories of plastic.

Fewer technologies are aimed at preventing plastic leakage than collecting it from marine and riverine environments (Fig. 3). Additionally, while prevention technologies focused on macroplastics and microplastics almost equally, collection technologies overwhelmingly addressed macroplastics. The category of "boats and wheels" had the highest number of technologies focused on plastic pollution collection, and the category of "storm and wastewater filters" included the most technologies targeting plastic pollution prevention (Fig. 3). The Inventory highlighted that not all of the inventions are commercialized, and some inventions are in initial testing phases (Fig. 4).

4. Discussion

The 52 technologies in the Plastic Pollution Prevention and Collection Technology Inventory represent important efforts in the fight against plastic pollution (Nicholas Institute for Environmental Policy Solutions, 2020). Fourteen technologies in the Inventory focus on plastic pollution leakage prevention and 38 focus on plastic pollution collection, with technologies ranging from household wastewater filters and laundry balls to large-scale skimmers and booms. The Inventory includes "Mr. Trash Wheel" in Baltimore, Maryland, the United States, which collected approximately one million pounds of waste over the course of around 2.5 years (Campbell, 2016). This is a massive step in cleaning up Baltimore's waterways, and similar technologies have been used in other municipalities, such as the "Watergoat Trash Traps" in Augusta, Georgia, the United States ("'Watergoat' trash traps helping curb litter in Augusta," 2018), the "In-line Litter Separator" in Melbourne, Victoria, Australia (Phillips, 1999), and the "Holy Turtle" in Roatán, Honduras (Kotecki, 2018).

However, these technologies cannot tackle the plastic pollution problem alone. The Inventory allows us to reflect on challenges in scale, the plastic lifecycle stage targeted, the ubiquity of microplastics, costs associated with technology implementation, and deployment location for these technologies. These challenges highlight the need for collaborative efforts across multiple scales and implementation in key hotspots to combat plastic pollution.

4.1. Scaling up localized solutions for global pollution

The enormity of the plastic pollution epidemic requires a large-scale, global response that effectively implements and expands on current technological solutions. For example, a simulation model by Cordier and Uehara (2019) provides quantitative estimates of the amount of marine plastic that could be collected based on the number of technologies deployed, along with cost estimates to meet various goals for stabilizing and reducing marine plastic pollution. Simulation modeling suggests that collecting plastic from the ocean alone, without other potential solutions (*e.g.*, improving waste management), would require the annual removal of about 15% of ocean plastic accumulating between the years 2020 and 2030 (over 135 MMT removed in total) to reduce the 2010 levels of marine plastic pollution (79.24 MMT) by 25%, for a goal of 59.43 MMT remaining (Cordier & Uehara, 2019). Cordier and Uehara (2019) estimated that 1,924 technologies similar to the Ocean Cleanup Project (Slat, 2014) would need to be deployed in the open ocean to achieve the aforementioned reduction.

The Ocean Cleanup Project has been refining its design since 2012 and has recently developed "System 002," which improves upon the previous design ("Cleaning Up the Garbage Patches," n.d.). Implementation of this technology, which is noted to be "the first full-scale, fully operational cleanup system" is expected in 2021 ("Cleaning Up the Garbage Patches," n.d.), suggesting that this new, refined design will be in operation soon. Our Inventory provides a sample of technologies that could be used in future feasibility studies and simulation models to determine the number of technologies that would need to be deployed to reach various plastic cleanup goals.

4.2. The lifecycle stages of collected plastic: A focus on leakage prevention is needed

Given the large quantities of marine debris entering the ocean, it is imperative to slow the release of plastic to the marine environment=. The Inventory reveals that the leakage prevention technologies can make important contributions toward addressing this problem; however, the majority of available technologies are collection technologies (38 inventions), with fewer technologies focused on preventing plastic leakage (14 inventions).

Most of the technologies that prevent plastic leakage are geared toward removing plastic from wastewater discharge. For example, "PumpGuard" uses mesh nets to remove debris from wastewater and stormwater systems and removes 97% of debris present ("Pumpguard," n.d.). While "PumpGuard" represents a substantial step forward in preventing the release of plastic through wastewater, this is only one of many potential inputs into the marine environment. Technology has rarely addressed the other potential inputs, including the loss of industrial pre-production pellets during shipping, loss during use (*e.g.*, catastrophic events, fishing/aquaculture, shipping, ocean science, and other platforms), and improper waste management (Jambeck et al., 2015; Law, 2017).

The only technology aimed specifically at preventing the leakage of industrial waste is the "CLEVER-Volume" system, which is a monitoring tool that measures the amount of waste on ships to identify improper disposal ("CLEVER-Volume – 3DModelling PT," n.d.). Because marine sources of plastic pollution make up approximately one fifth of the total plastic waste entering the ocean (Ritchie & Roser, 2018), the "CLEVER-Volume" system represents a major step forward in preventing industrial waste leakage from marine sources.

Plastic lines, ropes, and fishing nets comprise more than half of the plastic in the Great Pacific Garbage Patch (Ritchie & Roser, 2018). The only invention that specifically targets the prevention of fishing gear pollution is the "Stow It Don't Throw It" – an invention aimed at changing fishers' behavior at a small scale by collecting fishing lines used by recreational fishers before they enter the marine environment as waste ("Home: The Stow It-Don't Throw It Project," n.d.). The "Stow It Don't Throw It" campaign is led by youths in local communities across the United States, and thus has the added benefit of training future leaders in marine conservation ("The Project," n.d.).

4.3. Microplastic prevention technologies: All macroplastics end up as microplastics

Macroplastics in the environment constantly break down into microplastics (Cole et al., 2011; Jahnke et al., 2017). Six technologies in the Inventory are focused on preventing microplastic pollution, and all but one of these are directed toward preventing microplastics from entering the water system through residential water. These inventions, such as laundry balls and filtration systems, collect microplastics generated from laundering synthetic fabrics in the household. For example, the "Cora Ball" is a ball that is placed in a laundry machine and captures microfibers that are generated when washing synthetic clothing items ("Cora Ball," n.d.). The "Lint LUV-R" is a filter that is installed outside of the washing machine that captures synthetic microfibers in wastewater discharge ("Lint LUV-R washing machine discharge filter," n.d.). A study on the effectiveness of the "Cora Ball" and "Lint LUV-R" found that these technologies significantly reduced the number of microfibers in washing machine effluent after washing a fleece blanket, by 26% and 87% respectively (McIlwraith et al., 2019). Each of these technologies resulted in a significant decrease in microfibers in wastewater, which is promising; however, these technologies require consumers to purchase the systems so usage may not be widespread. Scholars have noted that market-friendly solutions overestimate the value of consumer responsibility and cannot keep pace with the rising environmental costs of the plastic pollution problem (Dauvergne, 2018b).

Importantly, residential solutions cannot combat the microplastic problem alone; industrial leakage from processing plants is an important source of microplastic pollution (Lechner & Ramler, 2015). For example, while water treatment systems that remove microplastics are currently marketed toward consumers for residential use (*e.g.*, the "Showerloop," which filters water for reuse and removes microplastics simultaneously; How it works. (n.d.), government institutions could enact policies to encourage their adoption in an industrial setting. In addition, governments may consider evaluating wastewater emissions standards to determine the legal plastic wastewater discharge amounts permitted (Lechner & Ramler, 2015). For example, in Austria, the equivalent of approximately 2.7 million PET bottles by weight were discharged annually into aquatic environments through industrial microplastics in wastewater emissions (Lechner & Ramler, 2015). Garcia et al. (2019) note that governments could provide subsidies or tax incentives to companies that institute new technology or practices to reduce plastic consumption. These financial incentives could be used to promote the installation and adoption of these technologies or to scale-up these efforts into larger systems that could be adopted for industrial use.

Given the constant generation of microplastics from macroplastics in the environment (Cole et al., 2011; Jahnke et al., 2017), microplastic prevention and collection technologies need to be paired with macroplastic prevention and collection technologies in the environment and in industrial wastewater systems. Ten Brink and colleagues (2018) have specifically noted that plastic clean-up and collection efforts are limited by the generation and dispersal of microplastics.

4.4. Capital is required for successful implementation and support of technology

Widespread implementation of technology to combat plastic pollution may face financial barriers (Gold et al., 2013). It is apparent from Fig. 4 that many inventions (approximately 36% of prevention technologies and 29% of collection technologies) are still in the pilot phase, not currently in use, or their use status is unknown. Governments and other stakeholders implementing plastic prevention and collection technologies may face cost barriers, especially for technologies that capture river pollution (The Benioff Ocean Initiative, 2019). Although examining the financial feasibility and costs was beyond the scope of this study, such a massive global problem cannot adequately be addressed without viable, consistent sources of funding (Gold et al., 2013).

Cleanup efforts, such as beach clean-ups, have been criticized for their high costs relative to their effectiveness, due to the widespread dispersal of marine litter and microplastics generated (ten Brink et al., 2018). However, technologies like those listed in the Inventory can help to increase the efficiency of beach clean-up efforts by groups of people or individuals (*e.g.*, litter surveys), suggesting that investment into these technologies may be worthwhile for program managers tasked with combating marine litter (Gold et al., 2013). For example, the robot "Malolo I" aids in the manual collection of macroplastics through detection of plastic for later collection (Mayer, n.d.). Global positioning system (GPS) devices track ghost nets for later collection and have helped the Oceans Voyages Institute collect 40 tons of plastic from the Great Pacific Garbage Patch ("Ocean Voyages Institute," n.d.; SMART, 2019). Furthermore, a feasibility study and detailed financial analysis of the Ocean Cleanup Project indicated that its technology is between seven to 33 times cheaper than conventional methods (*i.e.*, net collection from a ship) and similar in cost to beach cleanups by people, based on the costs per kilogram of plastic collected (Slat, 2014). These technologies may help to immediately remedy marine plastic pollution, especially in areas where it does social and economic harm (*e.g.*, tourist beaches) (ten Brink et al., 2018).

Costs will likely vary for each technology in the Inventory. The costs to implement the Ocean Cleanup Project include capital expenditure, operating costs, equipment replacements, and decommissioning costs (Cordier & Uehara, 2019; Slat, 2014). At a global scale, Cordier and Uehara (2019) found that the cost to reduce marine plastic pollution by 25% (as compared to 2010 levels) in one decade and using only technology (*i.e.*, the Ocean Cleanup Project) is between 0.7 and 1.0% of the global Gross Domestic Product in 2017 (492–708 billion Euros). Options for potential funding sources to further the implementation and deployment of these technologies may include fees and taxes on plastic products (Gold et al., 2013) or research and development investments by industry (Garcia et al., 2019). For example, the Coca-Cola Foundation and Benioff Ocean Initiative have pledged $11 million to create a network of individuals targeting river plastic pollution (Benioff Ocean Initiative, n.d.). Feasibility studies on the technologies in this Inventory could help to provide cost estimates that may allow governments and investors to evaluate the financial viability of implementing and investing in technologies.

Of the top 20 countries with the greatest amounts of mismanaged waste, 12 countries are classified as low or lower-middle income (Jambeck et al., 2015) and may be less likely to have the resources for public investments to deploy these technologies on a large scale. Seven other countries with the greatest amounts of mismanaged waste are upper-middle income countries (Jambeck et al., 2015), where resources may still be relatively limited. One of the top 20 countries with the greatest amounts of mismanaged waste is a high-income country, the United States (Jambeck et al., 2015), where the government may be the most likely, as compared to others on the list, to have the resources to deploy these technologies. The infrastructure costs associated with implementing microplastic collection technologies are rarely economically feasible, even in wealthier countries (Lau et al., 2020). Global trade patterns have indicated that a large amount of plastic pollution generated in high-income countries (70% of worldwide plastic imports in 2016) is shipped to lower-income countries in East Asia and the Pacific for disposal (Brooks et al., 2018). Thus, limited resources in lower-income countries may hinder the investment in plastic prevention and collection technologies.

4.5. Location, location, location

Plastic pollution distribution is not uniform. Different countries have disproportionate inputs into the ocean (Jambeck et al., 2015) and once plastic enters the ocean, it is transported by waves and currents to various depths and ocean ecosystems. The top five countries in mismanaged plastic waste are China, Indonesia, the Philippines, Vietnam, and Sri Lanka (Jambeck et al., 2015). Additionally, Asian rivers have been estimated to represent 86% of the total plastic releases into rivers globally, making China, India, Bangladesh, and Indonesia locations of particular concern (Lebreton et al., 2017).

Given the scope and cross-boundary nature of the problem, these solutions will need to involve international actors acting across multiple scales. Nations will need to work together to address the problems of plastic in areas beyond national jurisdiction. The utility of technologies in the Inventory could be enhanced if policymakers and other stakeholders work together across jurisdictions to ensure technologies are deployed in areas where they could do the most good (Rochman, 2016; Sherman & van Sebille, 2016). For example, modeling by Sherman and van Sebille (2016) found that microplastic cleanup efforts should target coastal surface waters (before the plastic is ingested by marine animals), specifically in China and Indonesia, due to high amounts of plastic leakage into the ocean in these locations (Jambeck et al., 2015; Rochman, 2016; Sherman & van Sebille, 2016).

The Inventory identifies several exemplary technologies that may aid in targeting microplastic pollution. One of the three technologies specifically targeting microplastic collection is currently in use – the "Marine Microplastic Removal Tool" (Fisher, 2018; Ward, 2015). This tool is a sand filter that can directly collect microplastics (Fisher, 2018; Ward, 2015). In addition, the "Hoola One" is currently in use and can collect microplastics by vacuuming about three gallons of sand per minute and separating out macroplastics and microplastics by buoyancy (Peters, 2019). StormTrap's "TrashTrap" may be helpful for collecting macroplastics (which ultimately generate microplastics; Cole et al., 2011; Jahnke et al., 2017) because it has a 97% debris removal efficiency ("TrashTrap: Capture floatables with innovative netting systems," n.d.). However, as discussed in Section 4.4, costs may be a limiting factor for local governments because 12 of the top 20 countries with the greatest amounts of mismanaged waste are considered low and lower-middle income countries (Jambeck et al., 2015). Global resources could be wisely used by targeting the potential "hotspots" of marine plastic pollution to amplify potential impact (Rochman, 2016; Sherman & van Sebille, 2016).

Finally, while large-scale implementation of these technologies can aid in plastic cleanup efforts in the environment, the widespread dispersal of marine plastic pollution, especially microplastics, creates challenges for collection technologies, which often target the surface of the ocean (ten Brink et al., 2018). For example, none of the inventions are geared toward removing plastics from benthic habitats or deep seabeds where microplastic hotspots have been recently discovered (Brandon et al., 2019; Fischer et al., 2015; Kane et al., 2020; Van Cauwenberghe et al., 2015). This is particularly problematic in light of the fact that plastic is highly persistent on the seafloor because of the slow kinetics of biodegradation and the limited oxygen supply (Andrady, 2015). Thus, analysis of the Inventory highlights the need for stakeholders in various sectors to identify both policies and technologies that can reduce plastic pollution in these geographic and oceanic locations.

4.6. The solution: Collaboration

With an ever-expanding toolkit of policy responses that aim to reduce plastic pollution (Karasik et al., 2020), technologies in this Inventory can help to provide immediate cleanup responses, especially in areas where plastic pollution can cause social and economic harm (ten Brink et al., 2018). Technology is an important facet in decreasing our reliance on any one solution to marine plastic pollution (Cordier & Uehara, 2019; Worm et al., 2017), and it can serve as one piece of an "all hands on deck" response (Garcia et al., 2019), in which multiple levels of governments and stakeholders (including industry) target multiple types and lifecycle stages of plastic pollution (Garcia et al., 2019; Worm et al., 2017). By designing plastic waste out of the system in a circular economy, we may eventually be able to decrease our reliance on these technologies (Gallo et al., 2018; ten Brink et al., 2018). However, given that the amount of plastic pollution entering the ocean is expected to increase by an order of magnitude, as compared to the baseline in year 2010 (Jambeck et al., 2015), both cleanup technologies and upstream responses have an important role to play in helping to clean up the oceans (Gallo et al., 2018; Rochman, 2016; Sherman & van Sebille, 2016; ten Brink et al., 2018; Worm et al., 2017).

Importantly, plastic cleanup technologies should be used in tandem with other preventative solutions, such as sustainable, biodegradable material to replace plastic or improved waste management systems. Cordier and Uehara (2019) modeled the use of plastic collection technologies in tandem with improvements in waste management. These models found that in countries with high levels of mismanaged waste, improvements in waste management could help to decrease the amount of plastic that cleanup technologies would need to capture to meet marine plastic pollution reduction goals. Case studies in Indonesia and China have found that municipalities can engage in more creative government responses to plastic pollution at the local level than at the national level, especially through public–private partnerships (Garcia et al., 2019). Local municipalities may partner with private entities to implement plastic pollution leakage prevention or collection technologies in hotspots of marine plastic pollution, while policy responses can help to prevent this scenario from occurring in the future. Multipronged efforts that incorporate both technology and policy responses, such as improved waste management, would help to take the pressure off of any one entity in reducing plastic pollution (Cordier & Uehara, 2019; Worm et al., 2017), potentially increasing the feasibility of various solutions. Further research is needed on the feasibility, costs, and effectiveness of deploying various cleanup and prevention technologies with improvements in waste management and other plastics policies (e.g., Karasik et al., 2020; Worm et al., 2017; Xanthos & Walker, 2017). This would help stakeholders identify the most cost-effective solutions to help guide both public and private investment in efforts to scale up promising technologies. In addition, future research is needed to examine existing plastic pollution policies (*e.g.*, in the Plastics Pollution Policy Inventory; Karasik et al., 2020) to determine if governments are enacting policies that incentivize or disincentivize the research, development, and use of prevention and collection technologies.

As an example of where technology and policy could serve as useful complements, Gold and colleagues (2013) suggest scaling up fees and taxes on plastic products (*e.g.*, carrier bags, cutlery, packaging), which have been successfully used to fund localized cleanup efforts in some cities in the United States (*e.g.*, Oakland, California and Washington, District of Columbia). New microplastic prevention technologies may also work in concert with policy efforts to establish inventories detailing microplastic release into the environment and efforts to decrease the use of harmful chemicals in microplastics, especially microfibers from synthetic clothing items (Browne, 2015). Microplastic prevention technologies include general wastewater removal technologies like the "GoJelly Project," which uses jellyfish mucus to capture microplastics ("GoJelly," n.d.), laundry balls that capture synthetic fibers in the washing machine like the "Cora Ball" and "Fibre Free" ("Cora Ball," n.d.; Chou, 2018), or residential water systems that filter out microplastics or microfibers like the "Lint LUV-R" and "Showerloop" ("Lint LUV-R washing machine discharge filter," n.d.; "How it works," n.d.).

Upstream solutions that help to reduce plastic waste at the source (*e.g.*, Gallo et al., 2018; Rochman, 2016; Sherman & van Sebille, 2016; ten Brink et al., 2018) and thus microplastic generation (*e.g.*, Cole et al., 2011; Jahnke et al., 2017) will be particularly helpful in long-term microplastic solutions. In combination with efforts to reduce the source of plastic waste and subsequent microplastic generation (Rochman, 2016), policymakers could create incentives for expanding and implementing these technologies in areas that are hotspots of marine plastic pollution. Incentives and regulations could be implemented to increase the number of systems put in place, and certain technologies could be adapted to other contexts (*e.g.*, scaling up microplastic filters for use in preventing industrial leakage).

Marine plastic pollution is a complex and extensive problem, and there are no simple solutions. Technological developments cannot be separated from policy, which likewise cannot be separated from individual and industry efforts. Only through continued combined efforts to find creative solutions across technology, policy, and advocacy can we stop plastic leakage into the oceans and mitigate its effects. Until then, we hope that this Inventory serves as a tool that stakeholders can use to learn about the options available to prevent plastic leakage into waterways and clean up plastic pollution.

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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.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A. Supplementary data

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