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The evolving global plastics policy landscape: An inventory and effectiveness review

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ABSTRACT

Governments worldwide are increasingly adopting public policies, laws, and ordinances to reduce plastic pollution. To date, studies have not analyzed the content of, and trends in, these policies. Employing a content analysis and literature search, we set out to better understand: (i) governments responses to this problem over time, and (ii) the state of the available evidence on the effectiveness of policy responses. Our motivations were to: (i) expand evidence-based policy-making to reduce plastic pollution by identifying and classifying the policy instruments used by governments; (ii) compile evidence regarding policy effectiveness; and (iii) provide a global database in the form of a Plastics Policy Inventory (https://nicholasinstitute.duke.edu/plastics-policy-inventory) to track government responses, as requested by the United Nations Environment Assembly in Resolution 4/6. Policies that fell within our scope aimed to reduce plastic pollution beyond business-as-usual solid waste management schema. This Inventory and study have an English-language bias. International and national policies are fairly representative of plastic pollution policies and the subnational (*e.g.,* states, cities) policies are examples. International governments most frequently used plans and commitments for future action. National and subnational governments most frequently used bans. Ten policies targeted only microplastics and one policy targeted tire wear particles, lagging reported pollution. The peer-reviewed literature reported plastic bag consumption reductions between 27% and 100% after policy adoption. This work lays a foundation for future evidence-based policymaking to reduce plastic pollution and provides a useful tool to track policies, analyze existing policies from new angles, and target gaps in the global plastics policy landscape.

1. Introduction

Since commercialization, plastics are playing an ever increasing role in our daily lives (Andrady and Neal, 2009) and are the most widely used human-made substances on the planet (Worm et al., 2017). The ubiquity of plastic and its waste mismanagement resulted in pervasive plastic pollution in soil (Fuller and Gautam, 2016), ocean surface waters (Eriksen et al., 2014), the deep sea (Fischer et al., 2015), Arctic sea ice (Obbard et al., 2014), and even in rain (Brahney et al., 2020). Marine vertebrates including fish, turtles (review, López-Martínez et al., 2021), other megafauna including birds and mammals (review, Puskic et al., 2020) and humans (review, Galloway, 2015) have been documented ingesting plastics, resulting in potential harm. Estimates suggest that even with immediate and ambitious efforts from stakeholders, plastic pollution in all environments is projected to grow by an additional 710 million metric tons (MMT) between 2016 and 2040 (Lau et al., 2020).

As plastic pollution grows, government responses to reduce plastic pollution have also grown (Schnurr et al., 2018; UNEP and WRI, 2018; Xanthos and Walker, 2017). Responses are often driven by local context, and are fragmented compared to the global scale of the problem (Dauvergne, 2018a; Schnurr et al., 2018; UNEP and WRI, 2018; Xanthos and Walker, 2017).

Addressing ocean plastic pollution is complicated by the transboundary movement of plastic waste through trade of plastic waste/

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scrap, and natural and physical processes. Estimates indicate that the top-ranked countries generating the highest amount of mismanaged plastic waste were concentrated among middle and low-income countries with only one of the top 20 countries classified as high-income, the United States (Jambeck et al., 2015). However, since 1988 high-income countries have been exporting plastic waste to lower-income countries in East Asia and the Pacific (Brooks et al., 2018). When plastic waste exports are accounted for, a different picture emerges — six of the top-20 polluters (United States, Japan, Kuwait, Oman, Argentina, and Italy) are high-income countries (Law et al., 2020). Meijer et al. (2021) found that riverine input of plastic waste into the ocean is more globally distributed than previous analyses (Lebreton et al., 2017). These studies suggest that both an international and national policy approach to the plastic pollution problem is needed.

A global landscape of government policies to address plastic pollution across the plastic value chain is lacking, both in terms of inventorying what has been adopted and understanding policy design and effectiveness (though some European and North American plastic bag fees/bans have been studied). Vince and Stoett (2018) recommended "better science and policy inventories, including databases of extant and evolving legislative, regulatory and communication-oriented efforts" as tools to advance evidence-based policymaking to address plastic pollution. The United Nations Environment Assembly (UNEA) Resolution 4/6 requests a stocktaking "of existing activities and actions by governments, regional and global instruments, international organizations, the private sector, non-governmental organizations and other relevant contributors to reduce marine plastic litter and microplastics…" (UNEA, 2019).

We conducted a review of public policies adopted to reduce plastic pollution from international, national, and select subnational governments to construct a global policy inventory, identify gaps, and characterize policy design. The policies reviewed are published in an open-access, database — the "Plastics Policy Inventory" (the "Inventory"). Although we captured certain policies in French and Spanish, the Inventory and accompanying qualitative analysis have an English-language bias. We hope to expand the Inventory to include additional policies in French, Spanish, and other languages in the future to be more representative of the global policy landscape. We also synthesized peer-reviewed evidence of public policy effectiveness in reducing plastic pollution. Our study builds upon reviews by Schnurr et al. (2018); Xanthos and Walker (2017); and UNEP and WRI (2018) and aims to identify gaps and share best practices to facilitate and accelerate government responses to reduce plastic pollution. The Inventory can serve as a baseline for monitoring government responses to reduce plastic pollution, lay the groundwork for evidence-based plastic pollution policy-making, and contribute to the stocktaking called for under UNEA Resolution 4/6.

2. Methods

2.1. Conceptual basis

We define public policy as a particular course of action or inaction pursued by governments, individually or collectively (Heidenheimer et al., 1990). Generally, the public policy cycle begins with problem identification and definition[1] followed by policy design, delivery, evaluation and adaptation (Gupta, 2011a; Weiss, 1989). We synthesized the design and delivery of government responses to plastic pollution by collecting and analyzing primary policy documents with the *explicit intention* of reducing plastic pollution.

[1] Weiss (1989) defines problem definition in the policy cycle as the "package of ideas that includes at least implicitly an account of the causes and consequences of some circumstances that are deemed undesirable, and a theory about how a problem may be alleviated."

We define plastic pollution policies as government responses that explicitly aim to reduce plastic leakage. The total government response to this problem includes general waste management policies and public policies aiming to reduce plastic pollution (Supplementary Fig. S1). Due to great amounts of plastic leakage into the environment (Borrelle et al., 2020; Jambeck et al., 2015; Geyer et al., 2017; Law et al., 2020; Lau et al., 2020), we considered policies that aim to reduce plastic at all lifecycle stages to be policies that reduce plastic leakage and subsequent pollution. We also included marine debris as within our definition of "plastic pollution" due to consistent reports that plastic items are the most frequently found (by count) material in marine debris (Gall and Thompson, 2015), and the historical use of the term "marine debris" in international agreements. We did not consider policies that manage plastics (without an intention of addressing plastic pollution) in our scope, such as general waste management policies targeting litter or waste broadly and those public policies governing the use of additives in plastics.

We compiled two decades of original public policy documents (*e.g.*, statutes, management and strategic plans, executive orders) and qualitatively analyzed policy design, focusing on the specific public policy instruments used to reduce plastic pollution. Based on Bemelmans-Videc et al. (1998), we defined public policy instruments to address plastic pollution as the set of techniques by which governments exercise power in attempting to reduce plastic pollution and grouped these instruments into three mutually exclusive categories of rules: 1) regulatory (rules which mandate actions), 2) economic (rules which hand out or take away resources), and 3) information instruments (rules for transfer of knowledge, communication and persuasion). We included choice architecture (Thaler et al., 2010) as an aspect of the policy instruments in our typology. For instance, we included economic instruments such as a plastic bag levy in our typology, which when applied at the point of use, aims to change consumer behavior through a nudge rather than by internalizing the social cost of plastic (Mogomotsi et al., 2019).

To understand policy effectiveness, we synthesized peer-reviewed evidence on plastic consumption reductions resulting from adopted plastic pollution policies. We compiled metadata including policy instruments and geographic jurisdiction to determine the coverage of effectiveness studies and identify gaps. We synthesized experts' attributions and the extent to which causal inference methods were used.

2.2. Plastic pollution policy search process

We compiled original public policy documents, defined here as official (and occasionally unofficial translations of) documents that include public-facing laws and amendments, statutes, ordinances, management plans, executive orders, agreements, treaties, and memorandums of understanding written and adopted by government entities, demonstrating an intent to reduce plastic pollution at various plastics life-cycle stages. We did not include other government documents such as internal policies, monitoring reports, or research papers. Because no comprehensive library or list of policies addressing plastic pollution was available, we created a Plastics Policy Inventory ("the Inventory") of original public policy documents as defined above – referred to hereafter as plastic pollution policies. The Inventory is provided online as a free, open-access resource at https://bit.ly/PlasticsPolicyInventory.

Original policy documents adopted between January 1, 2000-June 30, 2019 were identified for inclusion in the Inventory by reviewing legal databases (*i.e.*, ECOLEX, 2020; InforMEA, 2020, UN reports and websites [OECD, 2018; UNEP, 2018a, 2018b, 2018c, 2016, 2009, 2008; UNEP and WRI, 2018; United Nations, 2015; UNEA, 2018], and Foreign Law Guide [Reynolds and Flores, 2000] as a cross-check), scientific search engines (*i.e.*, Web of Science, 2020; HeinOnline, 2020; Google Scholar, 2020), grey literature (*i.e.*, Blepp and Mehlhart, 2012; Common Seas, 2019; Dalberg Advisors and WWF, 2019; Diez et al., 2019), and Google News (Fig. 1).

After scoping the grey literature and conducting test searches in legal

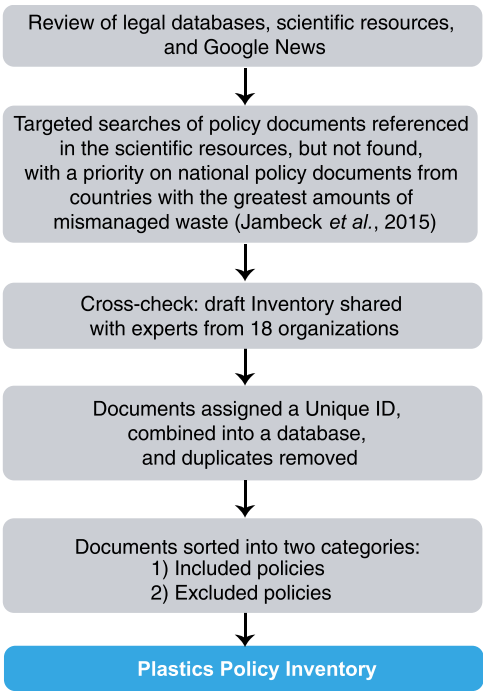

Fig. 1. Flow diagram of the assembly of a Plastics Policy Inventory.

databases, scientific search engines, and Google News, we identified over 200 English keywords that could yield relevant policies. Keywords were iteratively simplified and tested by identifying the minimum number of words that could capture multiple concepts. For example, the search term "plastic* " would capture "plastic waste" and "microplastics" among others. We started with a base set of keywords for legal databases and added keywords for scientific search engines, and Google News (Supplementary Materials).

Searches in the legal databases returned original policy documents, including those that were not in English, but whose title, brief description in English, or context in English articles indicated that plastic pollution was a target. As such, policy documents in languages that the researchers do not speak were included into an initial inventory. Prior to coding, we translated policy documents in Spanish and French into English using Google Translate and then reviewed and corrected by researchers with language proficiency. However, we could only screen and qualitatively analyze English, Spanish, and French policies, which is a bias in the inventory and a gap in the review process, whereby policies from certain parts of the world are underrepresented. Details regarding searches in scientific search engines and Google News are in the Supplementary Materials.

We screened the initially assembled policies to see if any had been adopted by the top twenty countries estimated to have the greatest annual mass of mismanaged plastic waste according to Jambeck et al. (2015) and conducted additional targeted searches for these countries to identify policy documents using the aforementioned criteria. In light of the recent study by Law et al. (2020), we recognize that this screening criterion could create a bias towards countries that receive plastic waste imports but do not necessarily have the domestic capacity to manage the plastic waste received.

2.3. Assembling the Plastics Policy Inventory

After the assembled policies were reviewed for duplicates, one member of the research team screened policy text to sort each policy into one of the following buckets:

- Included policies: Policy documents where the *intent* of the government is the reduction of plastic leakage into the environment at any point in the plastic life cycle;
- Excluded policies: Policy documents with an *impact* on the quantity or quality of plastic pollution, but where the *intent* of these policies as it relates to plastic waste cannot be inferred from the document; and policy documents where the specific *intent* and direct *impact* on plastic pollution is unclear.

The Inventory has three main caveats: 1) English-language bias, since searches were conducted in English; 2) subnational policies are underrepresented in global policy databases used in the Inventory assembly; and 3) more extensive searches in other databases or resources would be required to identify additional plastics policies. Our units of analysis (included policies) is not a random sample so we cannot generalize our findings at the national or subnational levels. We do not assume that we have a representative sample of policies in Spanish or French.

To evaluate completeness, we calculated ratios of international (*i.e.*, geographic jurisdiction covering multiple countries), national, and subnational policies in the Inventory to a proxy for known policies, those in the literature between January 1, 2000-March 31, 2019 (Table 1). The ratio was calculated by dividing the number of policy documents in the Inventory by the total number of policies found plus references in scientific search engines or Google News results, but ultimately not found using our search methods (Appendix A).

Based on the completeness ratio, international policies in the Inventory are considered representative of those adopted in the study period. National policies had a completeness ratio between 39% and 48% (depending on the likelihood that the policy referenced in the literature was adopted). Within the limitations of our methodology (*i.e.*, language access), national policies are considered indicative of national government responses, but not representative. Many national policies were referenced in the literature that appeared to have not yet been adopted. Subnational policies with a completeness ratio of 21% may serve as examples. However, for both national and subnational policies, the completeness and representativeness of policies in the Inventory are likely overestimated due to language barriers that likely missed many non-English/Spanish/French policies and references in the literature.

The initial Inventory was shared with 18 organizations with expertise in plastic pollution policy (Supplementary Table S2), nine of whom responded with policies to add to the Inventory. One researcher from the team screened the suggested policies and added to the Inventory if they met our criteria. If the researcher was unsure if a policy qualified for inclusion, it was shared with other team members and a decision was made on whether the policy exhibited intent to reduce plastic pollution. Included policies were screened during coding with the same criterion.

2.4. Content analysis of plastic pollution policies

We created the summary of codes, which form a typology of policy instruments to reduce plastic pollution (Table 2). This typology was derived from 217 policy instruments that was difficult to consistently use across diverse policies. The codebook was modified iteratively by coding sample policies from the Inventory. After initial sampling, we applied a more simplified typology that was consistent with included policies.

Table 1
Completeness ratios of policies in the Inventory.

Level of jurisdiction	Number of policies in the Inventory	Number of total policies referenced	Completeness ratio
International	67	69	97%
National	147	309–377	39–48%
Subnational	77	362	21%

Table 2
Codebook used for the content analysis of plastic pollution policies. Definitions are from "Merriam-Webster, " (2018) unless otherwise noted.

Variable	Dimension	Code	Sub-code (if any)	Definition
Policy instrument	Type of instrument	Regulatory - affirmative	Develop new, or improve existing process or product	Fundamentally new or enhanced stewardship practices or products
			Plan/commitment	Agreement or pledge to act, a detailed formulation of a program of action
			Post-leakage capture	Technology and mechanical interventions to capture litter (Worm et al., 2017)
			Responsible handling	Waste stewardship practices to minimize plastic leakage
		Regulatory - prohibitive	Ban	To fully or partially prohibit a specific type of plastic
			Irresponsible handling	To prohibit poor waste stewardship practices
			Limitations	To prescribe a maximum amount, quantity or number of plastic items allowed
		Economic	Disincentive (fee, tax, levy, duty)	The taking away of material resources, which is in some cases used as a "nudge" to change the choice architecture of a consumer, when applied at the point of use, in a way visible to the consumer
			Cash for return	To give back used plastic in exchange for money
			Subsidy	A grant by a government to a private entity to assist an enterprise deemed advantageous to the public
			Tax break	A lower tax rate for responsible plastic stewardship
		Information	Education or outreach	The act or process of informing the public about plastic, including awareness campaigns to change consumer behavior
			Label or placard	To display information to people using labels or placards
			Research, data collection, data reporting or record keeping	The assemblage, analysis, maintenance, management, or dissemination of information related to plastic
	Type of plastic pollutants targeted	Macroplastics from land-based activities, excluding plastic bags		Large visible plastic debris that originated from a source on land
		Plastic bags		Flexible container that may be closed for holding, storing, or carrying something
		Microplastics from land-based activities, excluding tire abrasion		A very small fragment or piece of plastic
		Microplastics from tire abrasion		Small plastics generated from the rubber cushion that fits around a wheel (as of an automobile) and usually contains compressed air
		Plastic pollutants from maritime activities		Plastics that enter the marine environment from non-terrestrial sources activities
		All plastics		General plastic or unspecified
	Lifecycle stage of the plastic targeted	Production		To compose or create plastic
		Import		To bring plastic from a foreign or external source
		Selling		The transfer of ownership of plastic from one entity to another for a price
		Use		To utilize plastic towards a particular service or end
		Disposal		Discarding, removing, dumping, or isolating plastic after use
		Collection		Gathering or extracting plastic from a number of persons or sources
		Recycling		To process plastic in order to regain material
		Reuse		To use again for the same purpose that it was originally made for
		All		The production, import, selling, use, disposal, collection, recycling and reuse lifecycles

Plastic pollution policy documents (n = 291) were qualitatively coded in NVivo (2018) to describe the policy instrument(s) used, plastic (s) type targeted, and plastic lifecycle stage targeted using the codebook. In this context, "coding" refers to the consistent application of codes characterizing the suite of policy design options for any given instrument, allowing us to distill policy instruments into discrete categories and summarize overarching trends (Elo and Kyngäs, 2008). We only coded portions of the policy relevant to reducing plastic pollution.

We finalized the codebook once coding by all three researchers indicated moderate to good inter-rater reliability, based on an average Cohen's Kappa of ≥ 0.58 and percentage agreement of $\geq 99\%$ (Cohen, 1960; NVivo, 2020; Stemler, 2000) (Supplementary Table S3). "Agreement" referred to the researcher's consistent selection and coding of as short as one line of text, though often longer, within policy documents (NVivo, 2020; Stemler, 2000).

2.5. Data analysis

The number of total policies adopted annually (non-cumulative) and national policies adopted annually (according to income classifications by the World Bank, (2019)) were fitted to regression lines and the slopes of regression lines were compared to zero using an F-Test. R^2 values were calculated to determine the relationship between the year and the number of policies adopted.

Qualitative coding results and Inventory metadata were analyzed to determine the policy instrument(s) used, plastic type(s) targeted, and plastic lifecycle stage(s) targeted. We used country income classifications by the World Bank (2019) to determine trends among national policy instruments used and plastic types targeted.

2.6. Literature review

A meta-analysis was conducted on the peer-reviewed and grey literature to synthesize plastic pollution policy effectiveness, recommendations for improving policies, and unintended consequences of policy adoption. Searches in legal and scientific search engines were the basis for a review of legal literature, peer-reviewed articles, and grey literature, published between January 1, 2000-March 31, 2019. Peer-reviewed articles and white papers (n = 149, Appendix B) were reviewed with guidelines consistent with Haddaway et al. (2015) to extract qualitative and quantitative measures of outcomes attributed to policy adoption, use of causal inference approaches, and unintended outcomes of policy implementation. If articles referenced an original peer-reviewed study or government report measuring policy effectiveness, we located the original study where possible, and reviewed it to determine if causal inference approaches were used (n = 13). Where possible, we linked information on effectiveness or unintended consequences to policies in the Inventory. Recommendations to improve current or new plastic pollution policies were compiled from peer-reviewed articles on policy effectiveness (n = 244).

3. Results

3.1. Trends in the introduction of plastic pollution policies

Searches in legal databases, scientific search engines, and Google

News yielded 291 included policies at the international (67), national (147) and subnational (77) levels (Supplementary Materials). The number of total policies adopted annually increased from 2 in 2000 to 32 in 2018 (Fig. 2). Based on World Bank (2019) income categories, high- and upper-middle-income countries drove growth in the number national policies adopted (Supplementary Fig. S3).

3.2. Trends in the policy instruments used

3.2.1. International policies

We found no international policy with a global, binding, specific and measurable target for reducing plastic pollution. Recently two non-binding targets have been set: 1) The Convention on Biological Diversity Aichi target (CBD, 2012); and 2) the United Nations Sustainable Development Goal 14 (UN, 2015). We identified 23 legally binding international policies (Supplementary Table S4); all lack a specific and measurable target.

Almost three quarters of the policy instruments used were for planning, education/outreach, or research/record-keeping (Fig. 3).

International policy instruments most commonly targeted plastic at all lifecycle stages (n = 52), followed by disposal (n = 23), recycling (n = 14), use (n = 12), production (n = 10), collection (n = 9), reuse (n = 6), selling (n = 2), and import (n = 1). One policy document or instrument may target more than one lifecycle stage.

International policy instruments targeted all six plastic types in the codebook and most frequently targeted all (*i.e.*, general) plastics (Supplementary Fig. S2). Tire particles were targeted by one policy instrument (*i.e.,* a plan, commitment): the Secretariat of the Pacific Regional Environment Programme's "Cleaner Pacific 2025: Pacific Regional Waste and Pollution Management Strategy," agreed in 2016.

In the first decade of the study period (2000–2009), four policies targeted multiple types of plastic. From 2010 onwards, 25 policies targeted multiple types of plastic. Governments increasingly defined the problem in terms of more than one plastic type (*i.e.,* multiple plastics), as opposed to general plastic pollution (Fig. 4).

3.2.2. National policies

National governments used regulatory instruments 3.5 and 3 times more frequently than economic instruments and information instruments, respectively (Fig. 5). Of the 48 national policies adopting a ban, tax or levy on plastic bags, 18 include information instruments. About 6% (n = 21 of the 326 total policy instruments) called for education and outreach. Neither post-leakage plastic capture (*e.g.*, beach clean ups) nor subsidies were used as national policy instruments.

National policy instruments targeted five of six plastic types (all but tires/tire wear particles) in the codebook, primarily targeting macroplastics (44%) and plastic bags (34%) (Supplementary Fig. S4). Three national policies targeted microplastics solely, all of which were adopted within the last five years. Plastic types targeted and policy instruments used by country income classification is in the Supplementary Materials.

From 2000–2009, multiple types of plastics were targeted by four policies, three of which included plastic bags as one of the types. In the second decade of the study period, multiple plastic types were targeted in 37 policies (33 of which included bags as one of the types) (Fig. 6). This indicates a shift in problem definition and greater complexity of responses as is seen with international policy responses, even as bags remained a key focus.

National policy instruments most commonly targeted the purchasing lifecycle stage (n = 76), followed by production (n = 68), import (n = 58), use (n = 50), disposal (n = 37), recycling (n = 33), all (n = 28), collection (n = 21), and reuse (n = 10). One policy document or instrument may target more than one lifecycle stage.

Content analysis of subnational policies is in the Supplementary

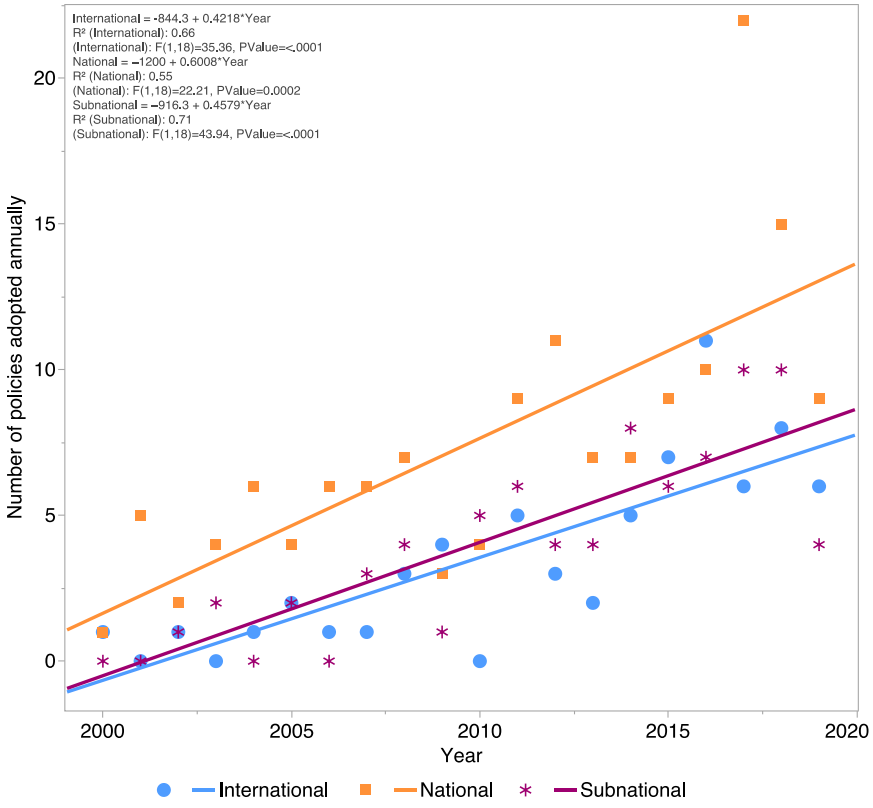

Fig. 2. Number of international, national, and subnational policies adopted annually. Points show the number of policies adopted annually (not cumulative). Text in the figure shows the linear regression lines equations, R^2 values, and F-test results. Slopes of the regression lines are all different from zero ($p < 0.0005$, F-Test). The R^2 values indicate the relationships between the year and the number of policies adopted.

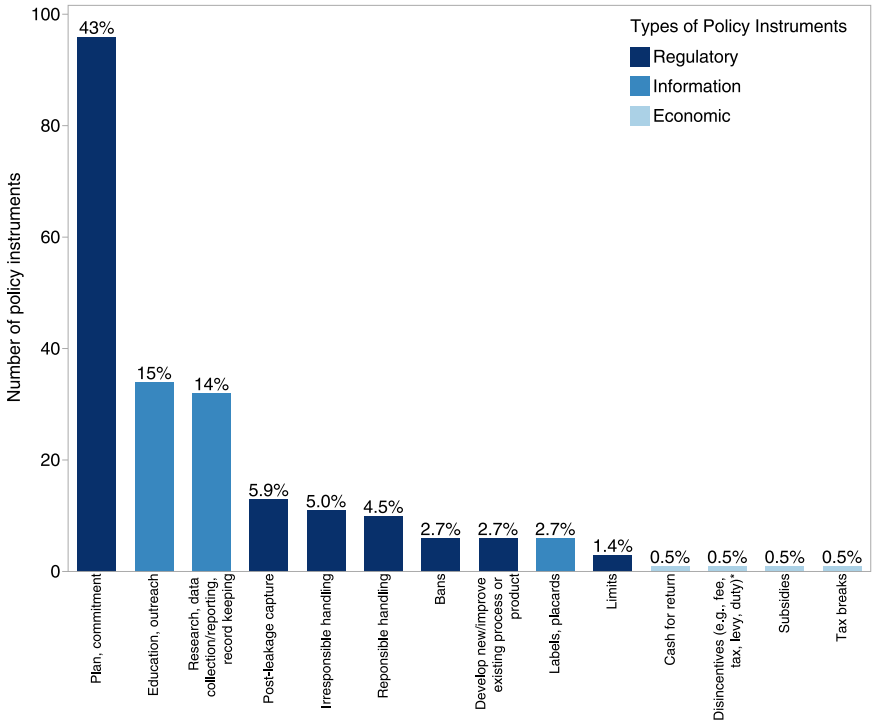

Fig. 3. Types of international policy instruments most frequently used. *includes "nudges" to change consumers' choice architecture.

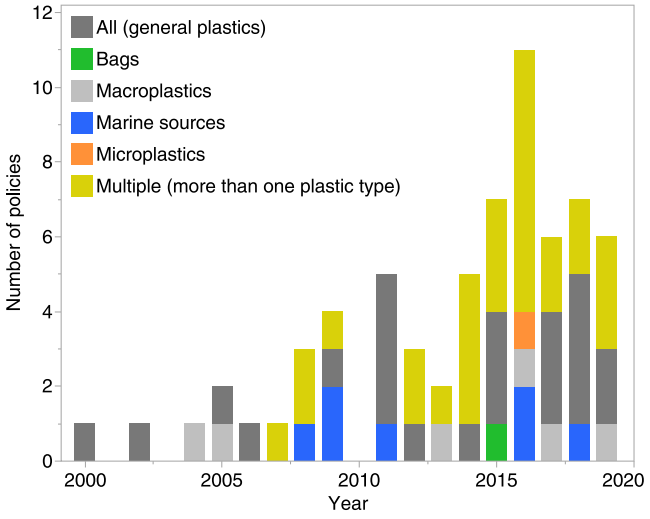

Fig. 4. Plastic type targeted by international policies over time.

Materials.

3.3. Literature review of the effectiveness of policies to reduce plastic pollution

Of the peer-reviewed articles on the effectiveness of policies aiming to reduce plastic pollution (n = 136 total), 40 provide quantitative or qualitative measures of outcomes attributed to 59 policies: two regional policies from the European Union, 23 national policies and 34 subnational policies. For studies with quantitative measures of efficacy, the average time lag between policy adoption and peer-reviewed study publication was 6.5 years (Supplementary Fig. S8). Most policy instruments studied targeted plastic bags (n = 31 of the 40 studies). Unintended consequences of policy adoption noted in peer-reviewed articles can be found in the Supplementary Materials.

3.3.1. Effectiveness measures

In most cases, significant short-term (within one to two years) plastic bag consumption reductions were noted across policies using regulatory (*e.g.*, ban) and economic (*e.g.*, tax or fee) instruments. On average, regulatory and economic instruments reduced plastic bag consumption by 66% following policy introduction (Fig. 7). Heidbreder et al. (2019) noted plastic bag use reductions between 40% and 90% in high-income and low-income countries after adopting a fee.

3.3.2. Causal inference in the study of plastic pollution policies

We found 13 additional studies that were cited within the 136 studies in the peer-reviewed literature to provide additional clarification regarding the methods used (n = 149 total studies). Five of the 149 studies reviewed used causal inference methods to attribute a direct *causal linkage* between policy adoption and an observed outcome (Ferraro et al., 2019; Ferraro and Hanauer, 2014). Outcomes from policy adoption included a decrease in plastic bag use (Homonoff et al., 2018; Homonoff, 2018; Taylor and Villas-Boas, 2016) and plastic bottle consumption (Berck et al., 2016), and an increase in reusable bag use (Rivers et al., 2017).

Most plastic bag effectiveness studies used a "simple difference" (Rivers et al., 2017) approach that measures an outcome (*e.g.,* plastic bag consumption) before and after policy adoption only in the geographic jurisdiction of policy adoption. Without a counterfactual or untreated group (Ferraro and Hanauer, 2014), confounding factors not measured or observed in the treated group might contribute to observed outcomes (Ferraro et al., 2019; Ferraro and Hanauer, 2014; Vincent, 2016). Thus, in those studies *causal* changes in plastic bag use/consumption cannot be attributed solely to the policy instrument evaluated (Jakovcevic et al., 2014; Rivers et al., 2017).

3.3.3. Policy recommendations from the literature

Including and expanding upon the literature reviewed for the effectiveness of policies to reduce plastic pollution, peer-reviewed articles (n = 244) were reviewed to determine general recommendations consistently made by experts to policy-makers (Table 3). Multiple policy recommendations support an integrated "all of the above" approach at

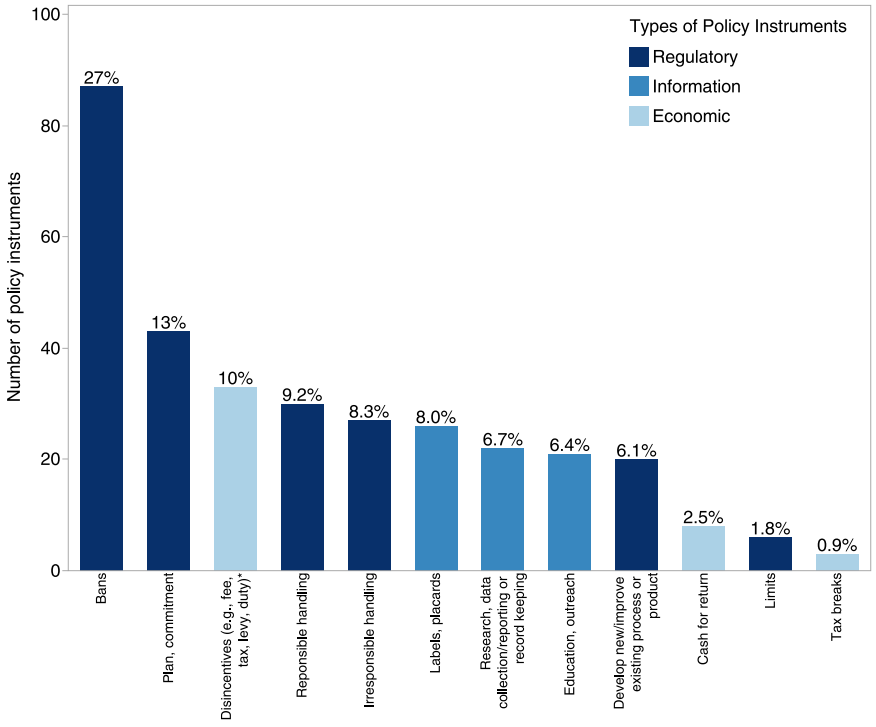

Fig. 5. Types of national policy instruments most frequently used. *includes "nudges" to change consumers' choice architecture.

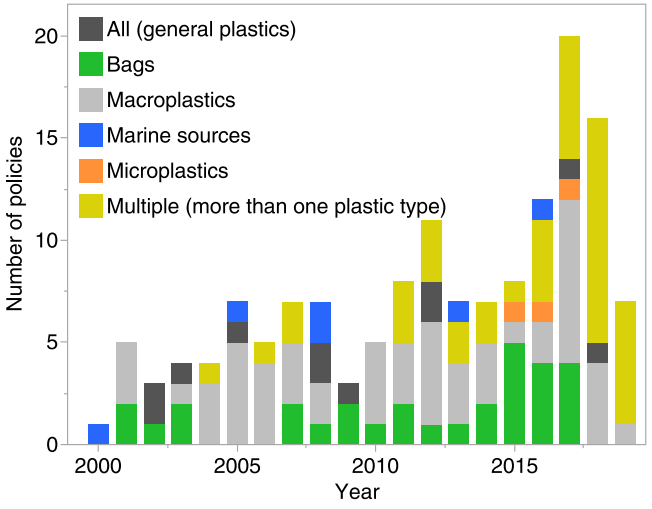

Fig. 6. Plastic type targeted by national policies over time.

multiple government levels (*e.g.,* national, subnational) and plastic lifecycle stages (Brink et al., 2018; Gallo et al., 2018; Garcia et al., 2019; Vince and Hardesty, 2018). Others consistently recommend an international, globally binding treaty with specific and measurable targets (*e.g.,* Coulter, 2010; Dauvergne, 2018a; Gold et al., 2013; Haward, 2018; Raubenheimer and McIlgorm, 2018, 2017; VanderZwaag and Powers, 2008; Worm et al., 2017).

4. Discussion

4.1. The number of national plastic pollution policies is increasing, most commonly targeting more than one plastic type using bans

In our sample, high-income and upper-middle-income countries drive growth in the number of national plastic pollution policies adopted annually (Supplementary Fig. S3). National policies primarily used regulatory bans (n = 87 of 326 total national policy instruments), which suggests that governments may prioritize focused approaches with low economic enforcement costs though geographic trends also play a role.

Our results indicate a growth in national policies targeting multiple plastic types over the study period (Fig. 6), one of which was plastic bags in 89% of those policies (n = 33 of 37 multiple plastic types targeted/policy). Macroplastics were the most common plastic type targeted in policy instruments (n = 215 of 490 total plastic types targeted) followed by bags (n = 167 of 490).

Only three of the 147 total national policies solely target microplastics, (plastics less than 5 mm in size (Arthur, 2009)), and all were adopted in the last five years of the study period. This latency likely reflects recent problem identification, definition, and policy adoption. However, researchers are optimistic that the global community can reduce marine microplastics pollution by 1–2% by 2025 by targeting one type of microplastics: microbeads (Dauvergne, 2018b). Anti-microbead norms, voluntary industry phaseouts, affordable natural substitutes, and government responses lend to the expected reductions in microbead pollution (Dauvergne, 2018a, 2018b). Other microplastics (*i.e.*, plastic pellets, microfibers, tire wear particles) are larger sources than microbeads (Lau et al., 2020) and all macroplastics produce secondary microplastics (Jahnke et al., 2017), so further coordinated government responses are needed to address microplastics beyond microbeads and other primary microplastics (Dauvergne, 2018a). Due to gaps in the plastic life cycle and plastic types targeted, an "all of the above" approach may be needed in which governments at multiple levels (*e.g.,* national, subnational) address pollution of multiple plastic types at multiple life cycle stages (Brink et al., 2018; Gallo et al., 2018; Garcia et al., 2019; Vince and Hardesty, 2018).

4.2. Lessons learned from studies on policy effectiveness to reduce plastic pollution

After the introduction of an economic instrument like a plastic bag tax or fee, consumers may internalize higher bag prices and increase bag consumption, which accordingly diminishes policy effectiveness. This

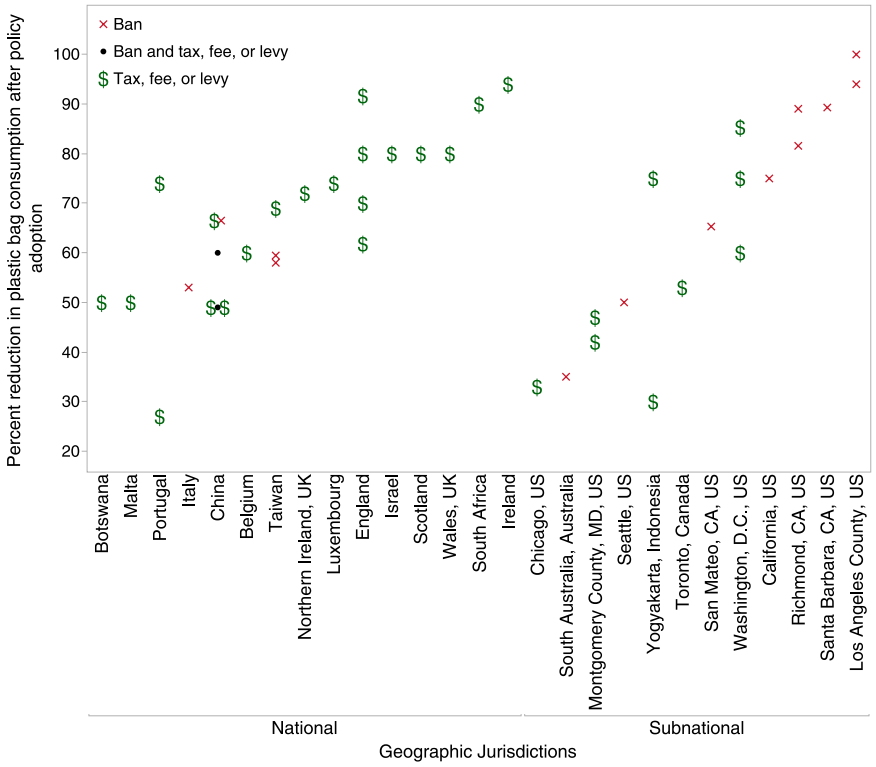

Fig. 7. Percent reduction in plastic bag consumption after national and subnational policy adoption as compared to prior to policy introduction. The following are abbreviated: United States (US), California (CA), Maryland (MD), United Kingdom (UK), and District of Columbia (D.C.).
Sources are in Supplementary Table S7.

Table 3
Policy recommendations for improving policy to reduce plastic pollution, from the literature. Additional context and sources can be found in Supplementary Table S8.

Plastic type	Recommendation
Land-based sources	Implement a binding global treaty that has a specific and measurable target(s) Increase use of information instruments (*e.g.*, education and outreach) Improve solid waste management systems, especially in low and middle-income countries Extend producer responsibility
Plastic bags	Use a combination of instruments, especially education and outreach paired with economic instruments Do not ignore consumer behavior shift (*i.e.,* leakage) to use disposable alternatives to plastic bags (*e.g.,* paper bags) Set plastic bag fees high enough to decrease consumption
Single-use macroplastics (excluding bags)	Apply regulatory bans, typically used on plastic carrier bags, to other single-use plastics (SUPs), at least in the short-term Apply instruments that give consumers cash for returning used SUPs for recycling
Microplastics	Ban microbeads in all cosmetic and personal care products at all levels of government

rebound effect (Dikgang et al., 2012) has been reported in Ireland (Frater and Lee, 2012; Xanthos and Walker, 2017), South Africa (Dikgang et al., 2012), and China (You, 2017). Few studies evaluated policy effectiveness in the long-term (*i.e.*, 2 years after policy adoption) (n = 10 of 41 total studies reviewed). In these ten cases, reduction in consumption of ≥ 50% were reported in Toronto (Rivers et al., 2017); Wales (Schnurr et al., 2018); Malta (Martinho et al., 2017); Washington, D.C., U.S. (Rivers et al., 2017), Taiwan (Liu et al., 2013); Seattle, US (Wagner, 2017), England (Schnurr et al., 2018), Italy (Schnurr et al., 2018), China (Dauvergne, 2018a), and Ireland (Xanthos and Walker, 2017).

The fee amount (which may need to increase over the policy delivery phase), availability of inexpensive reusable alternatives, public awareness to enhance compliance, and enforcement mechanisms all impact the effectiveness of taxes, fees, levies or bans targeting plastic bags. The choice between bans and economic instruments targeting plastic bags does not appear to be a determinant, as both kinds of instruments can be effective in reducing plastic bag consumption, as determined in one study by Taylor and Villas-Boas (2016).

The levy or tax does not reflect the social cost of plastic, but rather serves as a disincentive that can help to change consumer behavior and reduce plastic bag consumption (Mogomotsi et al., 2019). Instrument effectiveness is closely tied to the amount charged for each bag (Dikgang et al., 2012) and was too low in multiple instances (Dikgang et al., 2012; Sobaya et al., 2018) or high enough to only change the behavior of consumers who already occasionally use reusable bags (Rivers et al., 2017). Governments may need to increase the fee amount over time to offset the rebound effect (Dikgang et al., 2012).

Plastic bags follow the economic theory of relatively low price elasticity of cheap goods (Dikgang et al., 2012). The widespread availability of using plastic bags in comparison to less available alternatives is a perceived advantage of plastic bags (Heidbreder et al., 2019). As such, the availability of inexpensive, reusable alternatives to plastic bags has been linked to plastic bag policy effectiveness and potential demand for paper bags (O'Brien and Thondhlana, 2019; Taylor and Villas-Boas, 2016).

Education and outreach campaigns enhance compliance by strengthening consumer support for bans or economic incentives (Convery et al., 2007; Martinho et al., 2017; Zen et al., 2013). For example, using funds from a plastic bag tax to fund education and outreach can enhance compliance (Convery et al., 2007; Heidbreder et al., 2019). However, education and outreach alone are unlikely to change behavior (Sharp et al., 2010). Only eighteen of the 48 national

policies adopting a ban, tax or levy on plastic bags in the Inventory also include an information instrument (*e.g.*, education and outreach). Additionally, weak enforcement has decreased policy effectiveness in multiple locations (UNEP, 2018), such as China (He, 2012; O'Loughlin, 2010) and India (Gupta, 2011b).

4.3. National policy responses vary across geographies

Plastic waste production and mismanagement from coastal countries into the ocean and rivers varies across geographies (Jambeck et al., 2015; Lebreton et al., 2017; Law et al., 2020; Meijer et al., 2021). We found national plastic pollution policies for all but four (Thailand, Egypt, Russian Federation, and Mexico) of the top 20 countries with the highest amounts of mismanaged waste generated by coastal populations in 2016 (Law et al., 2020) and found references to national plastic pollution policy documents in the literature for Thailand and Russia, but not Egypt or Mexico. This may be due to the limitations of the search methodology, which had an English-language bias, or it may indeed be due to the fact the countries had not yet formulated a national level response to plastic pollution.

The 18 organizations contacted for expert input are not headquartered in Thailand, Egypt, Russian Federation, or Mexico, though one organization, Break Free From Plastic (2021) notes global members in these countries. Research or input by experts in the countries noted by Law et al. (2020) will add to our understanding.

The updated list of countries generating the highest mismanaged plastic waste by Law et al. (2020) accounts for U.S. plastic waste exports and uses updated World Bank waste data. As a result, six of the top 20 countries generating mismanaged waste in 2016 were high-income countries compared with only one in the earlier study by Jambeck et al. (2015). This difference could in part be due to the export of waste from high-income countries to middle and low-income countries (Brooks et al., 2018; Law et al., 2020). Future plastic pollution policies should account for the international movement of plastic waste and consider reducing the offloading of plastic waste from high-income countries to low-income countries.

Similarly, policies should consider addressing companies that produce single-use plastics. A recent report found that in 2019, just 20 companies produced over half of single-use plastic waste generated worldwide (Charles et al., 2021). Resources towards improving plastic pollution policies may be used to focus on the largest corporate producers of single-use plastics. The Inventory provides clear evidence that some countries in the Inventory have adopted multiple national policies; however, there are still significant gaps in geography of policy adoption and plastic waste producers targeted.

4.4. There is a need to expand the evidence-base for policy-making to address plastic pollution

Only 5% (n = 7 of 147) of national policies in the Inventory have effectiveness studies in the peer-reviewed literature, where quantitative or qualitative outcomes have been observed and attributed to policy adoption. Only 12% (n = 9 of 77) of subnational policies and 1% of international policies (n = 1 of 67) in the Inventory had an effectiveness study in the literature. Schnurr et al. (2018) and Xanthos and Walker (2017) also noted a research gap in studies of policy effectiveness to reduce plastic pollution though the number of these studies appears to be increasing annually (Supplementary Fig. S8).

Of the 59 policies with measures of outcomes (within 1–2 years of policy adoption) attributed to a policy, studies primarily evaluate policies adopted by wealthier countries in North America (37%, n = 22) and Europe (25%, n = 15), with the remainder in East Asia and the Pacific (29%, n = 17), Africa (5%, n = 3), Middle East (2%, n = 1), and Latin America and the Caribbean (2%, n = 1). We identified only one report from Latin America (Buenos Aires, Argentina) in the peer-reviewed literature (Jakovcevic et al., 2014) and no reported policy outcomes in South Asia. Effectiveness research in these localities is greatly needed to help support evidence-based policy-making to reduce plastic pollution.

In addition to financial resources enabling effectiveness studies, a major impediment to evaluating policy effectiveness are the proprietary nature and scale of single-use plastic production and sales. If science were to inform policy, companies would need to disclose the amounts of plastics sold at the scale of the policy being evaluated. Perhaps policies that require some form of acceptable corporate reporting to databases that are available to researchers and practitioners should be considered.

More studies utilizing causal inference methods in evaluating plastics policy effectiveness are also needed to build the evidence-base for plastic pollution policies. To reduce biases and allow for causal attribution in policy effectiveness studies, a number of methodologies could be used in future studies. For example, authors can incorporate a counterfactual site that did not adopt a policy to reduce plastic pollution to determine what may have happened in the absence of policy adoption (Rivers et al., 2017).

Ferraro et al. (2019) outlines methodologies for attributing causal changes in coupled human and natural systems (CHANS), using literature on marine protected areas. To incorporate causal inference in CHANS (*e.g.,* a community adopting a single-use plastic bag fee), authors could incorporate approaches suggested by Ferraro et al. (2019), such as addressing policy interventions, providing clear descriptions why an area is assigned a policy mechanism or conducting repeated observations of outcomes before and after policy adoption to attempt to limit bias from other sources (Ferraro and Miranda, 2017).

4.5. International policies lack a global, binding treaty with specific and measurable targets

As previously noted by Coulter (2010); Dauvergne (2018a); Haward (2018); Raubenheimer and McIlgorm (2017); Vince and Hardesty (2017); Worm et al. (2017) and Borrelle et al., (2017), our study confirmed that up to 2019, there are no binding, global policy instruments with specific and measurable target(s) for reducing plastic pollution. Although recent legally-binding amendments to the Basel Convention and associated technical guidelines have facilitated the classification of more types of plastic waste as hazardous waste and encouraged signatories to establish time-bound targets for reusing and recycling plastic packaging, these amendments do not include measurable targets for plastic pollution, including packaging. Recent momentum towards such a treaty is evidenced by the publication of the report "The business case for a UN treaty on plastic pollution" and accompanying call to action for a binding, global response with specific and measurable targets by the nongovernmental organization the World Wildlife Fund, companies, and governments (WWF et al., 2020). A global, binding treaty with specific and measurable targets may help to provide a cohesive global response to fragmented national and subnational responses. Such a global response would need to have flexibility to account for geographic and cultural differences.

4.6. The Plastics Policy Inventory is a tool for monitoring and increasing government responses to reduce plastic pollution

An increasing number of governments worldwide are adopting policies to reduce plastic pollution (Schnurr et al., 2018; UNEP and WRI, 2018; Xanthos and Walker, 2017). The Inventory and methods used in its assembly serve as baseline tools that can be easily updated to stay abreast of government responses to plastic pollution. This resource is non-comprehensive and underrepresents policies published in languages other than English. Future efforts should be collaborative and open in nature. Entities who are interested in explicitly searching for and assessing policy documents in areas that are underrepresented in this analysis and inventory will be most successful if led or supported by experts in those areas.

The results of the content analysis provided in this study allow governments to target gaps in the current plastics policy landscape. For example, microplastics generated from tire wear were only targeted by one policy in the Inventory (less than 1% of total policies) though are estimated to comprise 93% of global microplastic pollution (by mass) between 2016 and 2040 (Lau et al., 2020). The content analysis of plastic pollution policies sets the stage for governments to target gaps in the policy landscape or find example model legislation that builds on existing toolkits (*e.g.,* Alpizar et al., 2020; Ocean Conservancy, 2019).

The utility of the Inventory and synthesis could be enhanced through collaboration with governmental bodies and other research institutions. UNEA and UNEP provide a coordinated platform where national-level government responses could be communicated to international governmental bodies and across member states for global coordination. This study provides a baseline of two decades of original policy documents. Coordinated international monitoring could allow for the identification of policy and data gaps, along with potential barriers that limit policy implementation and effectiveness.

5. Conclusions

Our study advances a replicable understanding of government responses to plastic pollution by assembling a global body of public policy into the Plastics Policy Inventory (https://nicholasinstitute.duke.edu/plastics-policy-inventory). This classification system (the Inventory and qualitative coding analysis) represents a detailed analysis of a large subset of policies adopted in the last two decades to reduce plastic pollution. By qualitatively coding policies, we identified patterns and trends among government responses to a complex global problem. The number of policies adopted and how they are designed will evolve over time, as evidenced for example by Canada's listing of plastic as a toxin under the Canada Environmental Protection Act (Government of Canada, 2021). The Inventory allows governments to query and learn from existing policies, as well as identify areas that need more attention or focus. We developed a comprehensive foundation to expand the evidence-base for policymaking to reduce plastic pollution, and to assist in global efforts to monitor government responses to plastic pollution worldwide.

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CRediT authorship contribution statement

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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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Appendix A. Supporting information

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