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RESEARCH AND ANALYSIS

Critical review of global plastics stock and flow data

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Abstract

The production, consumption, and waste of plastics have been rapidly growing worldwide in the last decades. A variety of data are needed to characterize plastics stocks and flows across space, time, and life cycle to derive insights for developing strategies to address various sustainability challenges from plastics and plastics waste. Here we review data sources on plastics stocks and flows to identify data gaps and research needs. We categorize the reviewed data sources by life cycle stages of plastics including material production, semi-manufacturing, manufacturing, additives, consumption, in-use stock, end-of-life, waste treatment, and trade. We identify four data gaps in these existing data for characterizing plastics stocks and flows, including inconsistent classification, missing data, conflicting data, and inexplicit data for plastics products and waste. These data gaps represent critical research needs including common platform for data sharing, standard methods for data reconciliation and estimation, consistent data collection and reporting, and new approaches for data collection and curation. This review establishes the state-of-the-art of plastics stock and flow data and develops a roadmap for a high-quality, comprehensive characterization of plastics stocks and flows to develop management strategies to address the sustainability challenges of plastics production, consumption, waste, and pollution.

KEYWORDS
data, industrial ecology, plastics, plastics waste, societal metabolism, stock and flow

1 | INTRODUCTION

Plastics (also known as polymers) first appeared in the early 20th century. Owing to the outstanding advantages of its light weight, durability, and the versatility in color, touch, and shape, plastics started to flourish in the 1950s (ACC, 2020a; Andrady & Neal, 2009; Thompson et al., 2009b). Ever since then, plastics have surpassed most other human-made materials (UNEP, 2018) with rapid production growth of nearly 200-fold from 2 million tons (Mt) in 1950 (Geyer et al., 2017) to 359 Mt in 2018 (PlasticsEurope, 2019). As a result, plastics waste has emerged as a global sustainability challenge. Overall, nearly 60% of plastics that has ever been made are estimated to be landfilled or discarded in the environment without proper treatment, which will persist for centuries with very slow degradation (Chamas et al., 2020; Moore, 2008; UNEP, 2019). Such a substantial amount of long-lived plastics waste causes a variety of critical environmental, ecological, and health issues (Khoo et al., 2010; Law et al., 2010; Peng et al., 2018; Perkins, 2015; Thompson et al., 2009a). With more than 8 Mt of plastics waste estimated to enter the ocean each year, at least 267 different animal species have suffered from entanglement and ingestion of plastics debris (Greenpeace, 2006), leading to the death of approximately 1 million sea birds and 100,000 sea mammals, among others (United Nations, 2020a).

In response to the pressing challenges of plastics waste, more than 88 countries and regions have introduced regulatory or economic policies to improve waste management, promote recycling, and reduce the use of certain plastics products, such as levying taxes and bans on single-use plastics bags and plastics waste imports (Brooks et al., 2018; Crawford & Quinn, 2016; European Commission, 2019; UNEP, 2018; Xanthos & Walker, 2017). Thanks to these efforts, the global average rate of plastics waste discard declined from 100% in the 1980s to 55% in 2015 (Geyer et al., 2017). However, up to 80% of plastics waste is still not properly managed and discharged into the environment in many countries, especially in emerging and developing economies such as China, Sri Lanka, the Philippines, and Vietnam (Jambeck et al., 2015).

The plastics supply chain involves multiple stakeholders spanning many sectors and industries across the globe. Addressing the complex issue of plastics waste requires a systematic solution integrating technical, economic, social, and political approaches and considering national and regional heterogeneities. Nevertheless, any solution addressing plastic waste needs to first establish a baseline of the amounts of produced, consumed, and end-of-life plastics to measure the progress in reducing plastics waste and particularly mismanaged plastics waste. Such a baseline is also known as stock and flow accounting which characterizes the amount of materials (plastics in this case) in key stages of the material life cycle in a society. With the material stock and flow accounting, one can identify patterns of material consumption, predict the generation of waste, and evaluate the potential of recycling. Specifically, material flow analysis (MFA) is the primary method for stock and flow accounting and has been applied widely to examine anthropogenic stocks and flows of various materials (Allen et al., 2009; Bringezu & Moriguchi, 2015; Brunner & Rechberger, 2016).

There is a growing interest in the literature to characterize plastics stocks and flows at the global, regional, national, and urban scales. However, considering that plastics and plastics waste are so ubiquitous in our daily life and the environment, existing studies on plastics stocks and flows are actually scattered. Our literature search only found 28 case studies on plastics stocks and flows, 21 of which were published after 2010. These studies predominately focus on specific types of plastics and bulk plastics aggregating multiple types of polymers or plastics products. Detailed studies covering the whole spectrum of plastics family and plastics life cycle are rare.

Common challenges identified by existing studies on plastics stocks and flows mostly relate to data. These challenges include the complexity of required data due to complex plastics supply chain with numerous processes, hundreds of types of polymers, and thousands of plastics products spanning across various industries and countries, lack of primary data especially for developing countries where plastics pollution is most challenging, conflicting data from different sources, and inconsistent data structure, among others. Given the ever increasing global challenge of plastics waste, developing comprehensive plastics stock and flow accounts also becomes increasingly important for establishing baseline, developing mitigation strategies, and monitoring progress. Therefore, it is necessary to have a basic understanding of data required for developing plastics stock and flow accounts.

Here we present a critical review of existing primary data sources for plastics stock and flow accounting. Specifically, we aim to answer the following questions: What data are needed? What data are available? What data gaps exist? And what solutions do we have? We first provide an overview of the plastics life cycle and identify data needed for plastics stock and flow accounting. Next we review existing studies on plastics stock and flow analysis to synthesize the state-of-the-art. We then review existing primary sources of data for all stages of the plastics supply chain for major plastics producing and consuming countries and regions. Also reviewed are data for key parameters in characterizing plastics stocks and flows, such as the lifespan of various plastics products and the amount of additives used in the production of plastics materials and products. Finally, we identify critical data gaps and provide recommendations for future research to fill these gaps.

2 | LIFE CYCLE OF PLASTICS

We focus on plastics that are produced through synthesis from fossil fuel-based primary chemicals (ACC, 2020b) given its vast amount of production and variety of environmental impacts, excluding other alternatives such as bioplastics (Plastics Industry Association, 2020).

Plastics can be broadly categorized into thermoplastics and thermosets based on their behavior when heated. The former can be remelted into a liquid, while the latter cannot. Thermoplastics account for about 85% of all plastics production (ACC, 2019). Popular thermoplastics include polyethene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and expanded polystyrene (EPS). In addition, polyurethane (PUR) is the most produced thermosets (PlasticsEurope, 2019; Forsdyke & Starr, 2002). Table 1 shows the market shares and main applications of these major types of plastic.

Figure 1 shows the life cycle of plastics excluding the extraction of fossil fuels as raw materials. First, polymers (or virgin plastics or resin) are produced from fossil fuels in material processing. Additives, such as plasticizers and ultraviolet (UV) stabilizers, are added in polymers to provide additional features for broad applications. Second, polymers are further processed into various semi-finished products (e.g., tubes, sheets, pipes). Next, semi-products are manufactured into finished products for consumption in various sectors such as packaging, transportation, food, and industrial machinery (Geyer et al., 2017; Sevigné-Itoiz et al., 2015; Kawecki et al., 2018). These finished products can be entirely made of plastics (e.g., plastic bags), partially consist of plastic, or use plastics as packaging. Additives may be needed during semi-manufacturing or manufacturing stages if necessary. The finished product may stay in stock for various lifespans. At the end of the lifespan, plastics enter into the waste stream as post-consumer

TABLE 1 Global and European market share and applications of major types of plastic

Plastics type	Market share (Geyer et al., 2017; PlasticsEurope, 2019)[a]	Main applications (PlasticsEurope 2019)
PE	31% (30%)	Building and construction, consumer goods, fibers and textiles, packaging
PP	18% (19%)	Automotive parts, building and construction, consumer goods, fibers and textiles, medical products, packaging
PVC	10% (10%)	Automotive parts, building and construction, consumer goods, fibers and textiles, medical products, packaging
PET	9% (8%)	Packaging
PUR	7% (8%)	Automotive parts, building and construction, consumer goods
PS/EPS	6% (6%)	Automotive parts, building and construction, consumer goods, packaging
Other[b]	19% (19%)	—

[a]Market share in Europe in brackets.
[b]Other refer to polyester, polyamide, and acrylic (PP&A) and other undefined polymer types for global market share (Geyer et al., 2017) or acrylonitrile butadiene styrene/styrene acrylonitrile (ABS/SAN), polyamides (PA), polycarbonate (PC), polymethyl methacrylate (PMMA), other engineering thermoplastics (ETP), and other plastics (PlasticsEurope, 2019).

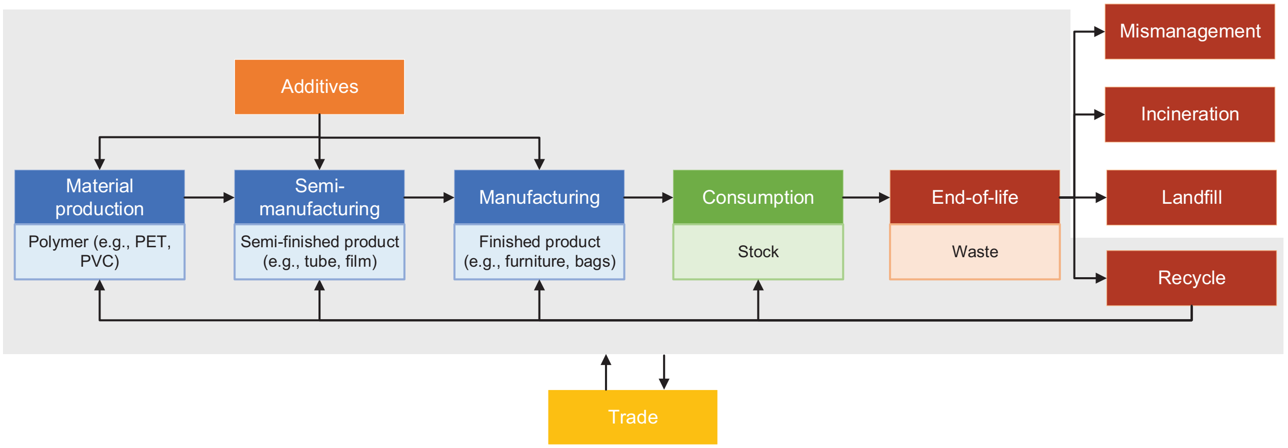

FIGURE 1 Life cycle of plastics

plastics waste, often as part of the municipal solid waste (MSW) stream. The plastics wastes are landfilled, incinerated, recycled, or inappropriately managed (mismanaged) and directly discarded into the environment (Dauvergne, 2018).

3 | STATE-OF-THE-ART ON PLASTICS STOCK AND FLOW ANALYSIS

To identify studies on plastics stocks and flows, we search in Web of Science using the keywords "plastic/plastics/a particular plastic-type (e.g., PVC or plastic packaging)" and "flow or stock" or at least one of the plastic flow stages (e.g., manufacturing, consumption, waste collection) from titles of peer-reviewed journal articles in English as of November 21, 2020. The results are further refined by the research area "environmental science" and "environmental studies." We then review the titles and abstracts of the resulting publications to identify studies on plastics stocks and flows.

Our search found 28 peer-reviewed studies on plastics stocks and flows (Table 2 and Supporting Information S1). While the earliest study was published in 1997, 21 of these 28 studies were published after 2010, corresponding to the increasing public attention on plastics waste after 2010. These studies focus on plastics stocks and flows at multiple spatial scales, from global, regional (mostly Europe), national (mostly European and Asian countries), to urban scales.

At the global scale, Geyer et al. (2017) examined the production, use, and fate of eight types of plastics from 1950 to 2015, providing the first-ever estimation of plastics stocks and flows at the global level.

At the regional or national scale, plastics industry associations, such as PlasticsEurope (2019) and American Chemistry Council (ACC, 2019), regularly release reports including key statistics of plastics production and consumption for specific countries/regions as well as the global total. Largely based on the PlasticsEurope data, Ciacci et al. (2017) examined the stocks and flows of PVC in Europe and estimated the in-use stock to be 11.2 kg per person on average. As a comparison, Nakamura et al. (2009) estimated the average PVC in-use stock in Japan was 11.7 kg per person. Specifically, a series of studies examined plastics stocks and flows in Austria, and estimated the average Austrian consumer used 35 kg plastics for packaging (Van Eygen et al., 2018) and 156 kg plastics in products (Van Eygen et al., 2017) in 2004, and generated 120 kg plastics waste in 2004 (Bogucka et al., 2008) and 62–91 kg (Van Eygen et al., 2017; Laner et al., 2016) in 2010.

At the urban scale, plastics are predominately studied as part of MSW (Tang et al., 2018; Banar & Özkan, 2008; Tunesi et al., 2016; Rochat et al., 2013). For example, Banar and Özkan (2008) estimated the amount of plastics waste in Eskisehir, Turkey, and found 5.6% of its MSW is plastics waste. Tang et al. (2018) found that 0.46 Mt of plastics waste in Guangzhou, China can be recycled or recovered, accounting for 63% of recyclable MSW in the city. Rochat et al. (2013) examined the material flows of post-consumer PET waste in Tunja, Colombia.

Besides these studies examining the flows of plastic, other studies have focused on plastics waste at various scales. Jambeck et al. (2015) estimated that 275 Mt of mismanaged plastics waste was generated in 2010 worldwide, equivalent to 87.9% of the total plastics production in the same year, 1.7-4.6% (4.8-12.7 Mt) of which finally entered into the ocean due to coastal population littering or inadequate management. Lebreton et al. (2017) estimated 1.2-2.4 Mt of global plastics waste generated from inland enters into the ocean annually via rivers. Efforts toward reducing plastics waste are also examined at global and country level, such as Lau et al. (2020) and Borrelle et al. (2020). Many studies estimate the amount of plastics components in MSW at city or regional level, such as in China (Tang et al., 2018), Turkey (Banar & Özkan, 2008), Italy (Tunesi et al., 2016), India (Nandy et al., 2015). Additional studies have specifically focused on plastics waste at city or regional scale (Chaerul et al., 2014; Dahlbo et al., 2018; Brouwer et al., 2018). For example, Chaerul et al. (2014) found around 58.4 tons of plastics packaging waste is generated daily in Bandung City, Indonesia and 64.6% is recycled through informal channels.

TABLE 2 Peer-reviewed studies on plastics stocks and flows reviewed in this paper

Study	Type of plastics[a]	Region/ country/city	Year of study	Scope[b]
Tukker et al. (1997)	PVC	Sweden	1994	P&M, consumption, waste, and trade
Duchin and Lange (1998)	Plastic, general	United States	1987	Consumption, waste
Patel et al. (1998)	Thermosets and thermoplastics (PE/PP, PVC, PS, polyacrylates, other)	Germany	1976–2050	P&M, consumption, waste, trade, and stock
Joosten et al. (2000)	Plastic, general	The Netherlands	1990	P&M, consumption, waste, and trade
Mutha et al. (2006)	Plastic, general	India	2000/2001	P&M, consumption, waste, trade, and stock
Bogucka et al. (2008)	Plastic, general	Austria and Poland	1994/2004	P&M, consumption, waste, and trade
Nakamura et al. (2009)	PVC	Japan	2000	P&M, consumption, and trade
Kuczenski and Geyer (2010)	PET	United States	1996–2007	P&M, consumption, waste, and trade
Zhou et al. (2013)	PVC	China	1957–2008	P&M, consumption, waste, trade, and stock
Rochat et al. (2013)	PET	Tunja, Colombia	2003	Consumption and waste
Lee et al. (2014a)	General plastic, DEHP, DBP, and BBP	EU27 + Norway + Switzerland	2012	P&M, consumption, waste, and trade
Lee et al. (2014b)	DEHP, DBP, and BBP	EU27 + Norway + Switzerland	2012	P&M, consumption, waste, and trade
Lee et al. (2015)	PBDEs	Korea	2011	P&M, consumption, and waste
Sevigné-Itoiz et al. (2015)	Plastic, general	Spain	1999–2011	P&M, consumption, waste, and trade
Van Eygen et al. (2015)	Plastic, general	Austria	2010	P&M, consumption, waste, and trade
Nandy et al. (2015)	Plastics waste, general	India	2012	P&M, consumption, waste, and trade
Laner et al. (2016)	Plastic, general	Austria	2010	Consumption, waste, and trade
Van Eygen et al. (2017)	Plastic, general	Austria	2010	P&M, consumption, waste, and trade
Ciacci et al. (2017)	PVC	EU27	1960–2012	P&M, consumption, waste, and trade
Geyer et al. (2017)	LDPE, LLDPE, HDPE, PP, PS, PVC, PET, PUR, PP&A fibers[c]	Global	1950–2050	P&M, consumption, waste, and stock
Singkran (2018)	Plastic, general	Thailand	2014	P&M, consumption, waste, and trade
Bureecam et al. (2018)	Plastic, general	Thailand	2013/2020	P&M, consumption, waste, and trade
Kawecki et al. (2018)	LDPE, HDPE, PP, PS, EPS, PVC, and PET	EU28 + Norway + Switzerland	2014	P&M, consumption, waste, and trade
Van Eygen et al. (2018)	LDPE, LLDPE, HDPE, PP, PS, EPS, PET, and PVC	Austria	2013	Consumption and waste
Liu et al. (2020)	PVC	China	1980–2050	P&M, consumption, waste, trade, and stock
Jiang et al. (2020)	PE, PP, PVC, PS, and ABS	China	1978–2017	P&M, consumption, waste, trade, and stock

(Continues)

TABLE 2 (Continued)

Study	Type of plastics[a]	Region/ country/city	Year of study	Scope[b]
Heller et al. (2020)	LDPE, LLDPE, HDPE, PP, PS, EPS, PVC, PET, polyester fiber, ABS, polycarbonates, other thermoplastics, and styrene butadiene rubber	United States	2017	P&M, consumption, waste, and trade
Eriksen et al. (2020)	PET, PE, and PP	Europe	2016–2066	P&M, consumption, waste, trade, and stock

[a]Additives used in plastics production: bis(2-ethylhexyl) phthalate (DEHP), dibutyl phthalate (DBP), benzyl butyl phthalate (BBP), and polybrominated diphenyl ethers (PBDEs).
[b]P&M refers to production and manufacturing.
[c]LDPE, low-density polyethylene; LLDPE, linear low-density polyethylene; HDPE, high-density polyethylene.

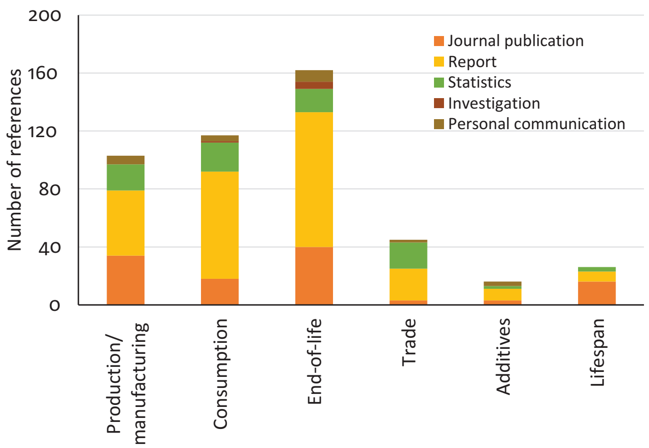

FIGURE 2 Number of references as data sources in reviewed studies on plastics stocks and flows by reference types and plastics life cycle stages. The data for Figure 2 is provided in Supporting Information S2

There are 469 references cited in these studies as data sources. As shown in Figure 2, these data sources can broadly be categorized into five groups: peer-reviewed journal publications, reports published by various organizations (e.g., trade associations, research institutes, and international organizations), government statistics, onsite investigations, and personal communications with industrial professionals. In general, reports are the dominant source of data, contributing up to 61% of the total number of references. About 19% and 27% of these references are government statistics and peer-reviewed journal publications, respectively. Among these data sources, reports and government statistics are the primary data and publicly available. We focus on these data sources in our review.

4 | DATA SOURCES BY LIFE CYCLE STAGES

In addition to the publicly available primary data sources identified from the reviewed studies on plastics stocks and flows (reports and government statistics), we further explore other primary data that are publicly available. We identify a total of 51 primary data sources for 43 individual countries and regions and 7 for cities, countries, or regions at the global scale. Below we review these data sources by key stages of the plastics life cycle. We also review the choices of key parameters in the literature used for estimation when primary data are not available, such as the amount of additives added in the production of plastics materials and products and the lifespan of various plastics products.

4.1 | Material production

The production of plastics materials was first centered in Europe and North America, then gradually shifted to Asia, notably in China and Japan (Polymer Properties Database, 2019). In 2016, China, Europe, the NAFTA (North American Free Trade Agreement, including the United States, Canada, and Mexico) region, Japan, and the rest of Asia account for around 86% (27.8%, 18.5%, 18.5%, 4.3%, and 16.7%, respectively) of global production of plastics materials (PlasticsEurope, 2019).

Available data for plastics material production are largely recorded by polymer types. Table S1 in Supporting Information S1 lists major data sources and specifics of the data they provide. In general, these data are from government statistics agencies (e.g., in China (National Bureau of Statistics of China, 2019) and Europe (European Commission, 2020)), industry trade groups (e.g., in Japan (JPIF, 2020) and the United States (ACC, 2019)), or international organizations (e.g., UN (United Nations, 2018)). Note that data sources for individual EU member states are not listed in Table S1 in Supporting Information S1 as they are already included in Eurostat (European Commission, 2020). However, most EU member states also provide plastics material production data through their own statistics agencies (e.g., Statistik Austria (2020)).

Among major polymer producing countries, Egypt has the least detailed data, with only the production volume of PE available (Ministry of Planning (Egypt), 2019). Japan Plastics Industry Federation (JPIF) (2020) has statistics on polymer production in Japan. The Ministry of Economy Trade and Industry (2020) also compiles polymer production data in Japan, with nine more types of polymer and a longer period (1989-2018) covered than the JPIF data. In Europe, Eurostat compiles production data for 46 types of polymers for each EU member country from 1995 to 2017 (European Commission, 2020). In addition, PlasticsEurope offers the same data for each of the EU member countries as well as for Norway and Switzerland every year since 2002 (PlasticsEurope, 2019). The data for plastics production in the United States can be purchased from ACC, including detailed production information of 13 types of polymer from 1970 to 2018 (ACC, 2019). However, for some polymers (e.g., LDPE), the ACC data include the aggregate production in the United States, Canada, and Mexico without country-specific data. The UN curates data for the production of 11 major types of polymer for 61 countries or regions in both mass and value (United Nations, 2018).

Four main issues exist for the polymer production data listed in Table S1 in Supporting Information S1. First, classifications of polymer types are inconsistent across various data sources. For instance, the production of PS and ABS is merged as one entry by Statistics Canada (Statistics Canada, 2020), while others have separate entries for these two polymers. Second, data for some countries are aggregated in some sources. For example, polymer production data for Belgium and Luxembourg are reported as one entry by PlasticsEurope (2019), and North America (the United States, Canada, and Mexico) are considered as one region without country-specific data in ACC's Resin Review (ACC, 2019). Third, most of these datasets are incomplete, with a significant amount of data missing for either particular types of polymer or specific periods of time. Only Eurostat (European Commission, 2020) and Instituto Brasileiro de Geografia e Estatística (IBGE) (2020) provide full records of the production of the seven major types of polymer. Data for PUR and EPS production are the least available across all sources. Lastly, the UN offers a common data platform for 61 countries or regions which cover the majority of the polymer production worldwide. However, data for some of these countries or regions are different from the data reported by, respectively, national or regional sources for the same polymer in the same year. For example, the HDPE production in Brazil in 2015 is reported to be 1.5 and 1.0 Mt by UN (United Nations, 2018) and IBGE (2020), respectively.

4.2 | Semi-manufacturing and manufacturing

Plastics materials are used to produce a variety of semi-finished products, such as films, sheets, and fittings. Additives, which will be discussed separately in the next section, are added in semi-manufacturing to give various features to semi-finished plastics products (Kawecki et al., 2018; Mutha et al., 2006). Semi-finished plastics products are further manufactured for finished products. These finished products are generally classified into different commodity sectors. Here we focus on data for semi-finished plastics products, and will discuss data for finished products in the next section for the consumption stage.

As shown in Table S2 in Supporting Information S1, semi-finished plastics products are classified differently across countries and regions. The most detailed classification is from Eurostat (European Commission, 2020) (PRODCOM list) which is used for EU member states and Norway (Statistics Norway, 2020). There are 107 categories of semi-finished plastics products in the PRODCOM list. For other countries or regions, the classification of semi-finished plastics products is much less detailed. For example, Japan's statistics only classify semi-finished plastics products into 30 micro-types and 11 meso-types (JPIF, 2020).

In addition to inconsistent product classifications quantities, another key challenge for data on semi-finished plastics products is the inconsistency of units. Some sources provide data in quantities while others are in monetary units. For those with quantities, a variety of units are used in weight, volume, area, or the number of items.

To trace the stocks and flows of plastic, one needs to match semi-finished plastics products with various types of polymers in the material production stage (Geyer et al., 2017). The data sources listed in Table S2 in Supporting Information S1 do not have information on how much and what types of polymers are used for producing specific semi-finished products, except for the US data provided by ACC (2019). As a result, the types and amounts of polymers used in various semi-finished plastics products are often estimated. For example, Mutha et al. (2006) estimated the growth of various polymers used in 15 popular semi-finished plastics products during 1991–2000. Also, there are governmental guidelines that specify the polymer contents in particular industrial commodities, such as the Commodity Guide by the Swedish Chemicals Agency (2019). Nevertheless, it remains as a challenging task to estimate polymer types and quantities in various semi-finished plastics products for a variety of countries or regions with statistics that are difficult to converge.

4.3 | Additives

Additives are commonly used in plastics manufacturing for enhancing polymers' basic mechanical, physical, or chemical properties and prolonging their life by protecting the polymer from the degrading effects of light, heat, or bacteria (Hahladakis et al., 2018; ACC, 2019). However, information on the types and amounts of additives is largely confidential and proprietary (Van Eygen et al., 2017). As a result, public data sources, such as statistics from government agencies or industry trade groups, normally do not have well-documented data on additives.

Estimations of the mass of additives used in plastics have often been done based on chemical principles (Pritchard, 1998; Murphy, 2001; Mutha et al., 2006; Tukker & Kleijn, 1996). On average, the share of additives used in plastics is estimated to range from 6.4% to 10% by weight (Geyer et al., 2017; Patel et al., 1998; Nandy et al., 2015). However, a wider range of estimates is available for specific types of polymer (Kawecki et al., 2018) and plastics products (Mutha et al., 2006). For example, the mass shares of additives used in LDPE, HDPE, PP, PET, PS, and PVC are estimated to be 25%, 25%, 15%, 25%, 6%, and 30%, respectively (Kawecki et al., 2018), while the shares in plastics films, injection-molded goods, extrusion coating, and plastics sheets are approximately 4–5%, 6–10%, 7%, and 15% (Mutha et al., 2006), respectively. Great uncertainties also exist for such estimation across countries and regions. For instance, the estimated mass share of additives used in PVC stocks in Sweden is 16% (Kleijn et al., 2000), while for Europe it is 30% (Kawecki et al., 2018).

4.4 | Consumption

Finished products containing plastics are mainly in several key commodity sectors, including agriculture, building and construction, electrical and electronic equipment, furniture, household and consumer products, medical devices, packaging, and transport (Mutha et al., 2006; Geyer et al., 2017; Ciacci et al., 2017; Zhou et al., 2013; Kawecki et al., 2018).

There are only a few data sources that provide data directly on the consumption of finished plastics products, as shown in Table S3 in Supporting Information S1. For instance, PlasticsEurope (2019) has data on the share of finished plastics products among seven sectors (i.e., agriculture; automotive; building and construction; electrical and electronics; household, leisure, and sports; packaging; and others) for European countries (EU27, Norway, and Switzerland).

To address the data gaps on stocks and flows of plastics in finished products, many studies have estimated plastics products' quantities in or shares among relevant commodity sectors. For example, Kawecki et al. (2018) estimated the material flows of seven major polymers through nine commodity sectors and four waste treatment approaches in EU28 and Switzerland in 2014. Zhou et al. (2013) summarized data for sector-level PVC consumption from peer-reviewed studies. Van Eygen et al. (2017) compiled plastics consumption data for Austria from multiple sources. Table 3 lists estimates of shares of plastics products among relevant sectors by weight in the literature. Across all studies, building and construction and packaging sectors consistently have the largest shares of plastics products among all sectors. In some cases, the shares of plastics products in household and furniture sectors can be high as well, for example,, 24% in India in 2000 (Mutha et al., 2006) and 25% in the Netherlands in 1990 (Joosten et al., 2000). Great discrepancies exist in these estimates. For example, estimations can be very different for the shares of plastics products among sectors in the same country in the same year (Austria in 2010) (Van Eygen et al., 2015; Laner et al., 2016; Van Eygen et al., 2017).

4.5 | Stock and lifespan

Various plastics products have different lifespans (or service life) which determines how long plastics remain in use as stocks and when the stocks become plastics waste (Murakami et al., 2010; Oguchi et al., 2010). The value of lifespan for plastics products thus is critical for estimating the type, amount, and time of plastics waste generation. Tables 4 and 5 summarize lifespan values used in various studies for plastics products in different sectors and different types of plastics products, respectively.

As shown in Table 4, plastics used in packaging is generally considered to be in use for 1 year or less (Geyer et al., 2017; Patel et al., 1998; Ciacci et al., 2017). By contrast, plastics products in the building and construction sector are long lived with the average lifespan ranging from 30 to 50 years. Similarly, a wide range of lifespan values for various types of plastics products are reported in the literature, from 1 year for some plastics films to 50 years for plastics pipes (Table 5). Normal distributions are usually adopted to characterize the uncertainty of the lifespan of various plastics products (Ciacci et al., 2017; Geyer et al., 2017).

4.6 | End-of-life

Plastics waste broadly from two sources: industrial plastics waste (pre-consumer) and municipal plastics waste (post-consumer). The former is generated from industrial processes in material production and manufacturing stages, while the latter comes from end-of-life products and are often part of the MSW stream.

TABLE 3 Shares of plastics products among relevant sectors estimated in the literature. Shares in each column are from the same study for a specific country in a year or during a period, which do not add up to 100% due to rounding errors

<table>
<tr><th></th><th>Germany (1989) (Patel et al., 1998)</th><th>The Netherlands (1990) (Joosten et al., 2000)</th><th>India (2000) (Mutha et al., 2006)</th><th>Austria (2010) (Van Eygen et al., 2017)[a]</th><th>Switzerland (2014) (Kawecki et al., 2018)</th><th>China (2011-2015) (Liu et al., 2020)[b]</th><th>EU28+ Norway+ Switzerland (2017) (PlasticsEurope, 2019)[c]</th><th>Global (2002-2014) (Geyer et al., 2017)</th><th>Australia (2017-2018) (Australian Bureau of Statistics (2020)[d]</th></tr>
<tr><td>Agriculture</td><td>5%</td><td>1%</td><td>-</td><td>4%</td><td>-</td><td>5%</td><td>3%</td><td>-</td><td>3%</td></tr>
<tr><td>Building and construction</td><td>28%</td><td>20%</td><td>14%</td><td>20%</td><td>-</td><td>60%</td><td>20%</td><td>19%</td><td>17%</td></tr>
<tr><td>Clothing</td><td>-</td><td>-</td><td>-</td><td>6%</td><td>7%</td><td rowspan="3">11%[f]</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Furniture</td><td>6%</td><td>-</td><td rowspan="2">24%[e]</td><td>5%</td><td rowspan="2">7%</td><td>-</td><td rowspan="2">12%[g]</td><td>-</td></tr>
<tr><td>Household</td><td>7%</td><td>25%</td><td>4%</td><td>4%</td><td>-</td></tr>
<tr><td>Electrical/ electronic</td><td>8%</td><td>-</td><td>-</td><td>7%</td><td>4%</td><td>9%</td><td>6%</td><td>4%</td><td>6%</td></tr>
<tr><td>Industrial goods/ machinery</td><td>-</td><td>23%</td><td>13%</td><td>-</td><td>9%</td><td>-</td><td>-</td><td>1%</td><td>-</td></tr>
<tr><td>Investment</td><td>-</td><td>16%</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Medical</td><td>4%</td><td>-</td><td>-</td><td>1%</td><td>-</td><td>2%</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Packaging</td><td>22%</td><td>-</td><td>42%</td><td>25%</td><td>61%</td><td>11%</td><td>40%</td><td>45%</td><td>32%</td></tr>
<tr><td>Transportation</td><td>15%</td><td>-</td><td>-</td><td>14%</td><td>11%</td><td>2%</td><td>10%</td><td>7%</td><td>6%</td></tr>
<tr><td>Others</td><td>3%</td><td>15%</td><td>7%</td><td>14%</td><td>-</td><td>-</td><td>17%</td><td>13%</td><td>36%</td></tr>
</table>

[a] Shares of plastics products among relevant sectors in Austria for 2010 are also available in Van Eygen et al. (2015) and Laner et al. (2016).

[b] PVC only. Shares of plastics products among relevant sectors in China for the year from 1980–2010 are also available in Liu et al. (2020).

[c] Shares of plastics products among relevant sectors in EU27 + Norway + Switzerland for 2012 are also available in Lee et al. (2014b); Shares of plastics products among relevant sectors in EU28 for 2014 are also available in Kawecki et al. (2018)

[d] Detailed sector shares for different polymer types are provided in the original data source.

[e] Consumer products.

[f] Consumer goods and others.

[g] Consumer and institutional products.

TABLE 4 Lifespan (years) of plastics products used in different sectors

Sector	Global (1950-2050) (Geyer et al., 2017)	EU 27 (2014) (Ciacci et al., 2017)	Germany (1989) (Patel et al., 1998)	China (1980-2015) (Liu et al., 2020)
Agriculture	-	-	2	1
Building and construction	35	50	50 (pipes for buildings)[a] 30 (other building compounds)	35
Clothing	5 (textiles)	-	3	-
Furniture	3 (consumer and institutional products)	10 (home and leisure)	10	3 (consumer and other)
Household			7 (households)	
Electrical/ electronic	8	10 (electrical engineering)	10 (electrical appliances and precision engineering)	8 (electronic)
Investment	-	-	-	-
Industrial goods/ machinery	20	-	11 (vehicles and machinery)	-
Medical	-	1	-	1
Packaging	0.5	1	1	1
Transportation	13	20	11 (vehicles and machinery)	13
Others	5	-	8	-

[a]Description used in the original study, same hereafter.

Data on plastics waste, either industrial or municipal, are not well documented around the world. Previous studies have mainly used two approaches to estimate the amount of plastics waste, largely focusing on plastics waste in the MSW stream.

The first approach is to estimate the amount of plastics waste based on the total amount of industrial or MSW and shares of plastics waste. Table S4 in Supporting Information S1 lists the main data sources of industrial or MSW for countries and regions. The majority of these data are for MSW; data on industrial solid waste as well as industrial plastics waste are largely lacking.

Among these data sources, OECD (2020) and United Nations (2020b) have the most comprehensive and detailed MSW data for many countries. Specifically, the OECD compiles data reported from member countries with necessary adjustments based on other relevant data. The UN data are provided by government agencies and complemented by data from Eurostat (European Commission, 2020) and OECD (2020). In addition, the World Bank offers data on the amount of MSW for each of the 217 countries or regions, but only for the most recent available year which varies for each country (World Bank, 2019).

Statistics on the portion of plastics in industrial or MSW are rare. Plastics waste is estimated to be around 9–15% of the MSW stream by weight in the United States (EPA, 2019), Japan (Statistics Bureau of Japan, 2020), and Taiwan, China (Department of Statistics (Taiwan), 2020) in recent decades, and less than 7% in Japan before 1985 (Statistics Bureau of Japan, 2020). Similar to the World Bank MSW data, the data on shares of plastics waste in MSW are also only available for the most recent year for each country which may be different from the year when the MSW data are available (World Bank, 2019). For example, the World Bank data for Monaco include the total amount of MSW in 2013 and the share of plastics waste in MSW in 2012, while for Palau the data are for 2016 and 2014, respectively. In addition, field surveys or on-site investigations have been conducted to examine plastics waste in MSW (Dahlbo et al., 2018; Banar & Özkan, 2008; Sha'Ato et al., 2007; Nandy et al., 2015; Chen et al., 2018).

The second approach is to estimate plastics waste based on the lifespan of plastics products and the amount of in-use stocks (Geyer et al., 2017; Liu et al., 2020; Patel et al., 1998; Kuczenski & Geyer, 2010; Mutha et al., 2006; Zhou et al., 2013; Ciacci et al., 2017), known as dynamic MFA.

TABLE 5 Lifespan (years) of different types of plastics products

India (2000) (Mutha et al., 2006)		Germany (1989) (Patel et al., 1998)		China (1957–2008) (Zhou et al., 2013)	
Product	**Lifespan**	**Product**	**Lifespan**	**PVC product**	**Lifespan**
Appliances	20	Films/sheets	10	Bottle	1
Blow-molding products	8	Films for agriculture, vehicles, machinery	4	Cable material	15
Extrusion coating	1	Films for building	30	Film	1
Films/flexible packaging	1	Films for packaging	1	Footwear	3
Footwear	2	Foamed plastic	20	Leather	5
Hoses and tubes	5	Large containers	8	Pipe	30
Injection-molded goods	5-15	Molded compounds	20	Planking	10
Monofilaments	3	Molded compounds for investment and consumer goods	10	Profile	15
Pipes and conduits	35	Molded packaging material	3	Others hard products	5
Profiles	30	Other molded compounds for buildings	30	Other soft products	3
Rotomolded products	10	Packaging material, medium life	2	Others products	3
Sheets (thick)	10	Packaging material, short life	1		
Wire and cable	30	Pipes for buildings	50		
Woven sacks	3	Plastics sheets	30		
Others	1–3	Synthetic fibers	9		
		Vessels/containers, medium life	8		
		Other plastics products	14		
		Average of all plastics products	14		

Specifically, the amount of plastics waste generated from the end-of-life of the specific product (*i*) in a particular year (*j*), $\text{Waste}_{\text{gen}(i,j)}$, is estimated as:

$$\text{Waste}_{\text{gen}(i,j)} = \sum_{x}^{k} \text{Consumption}_{(i,j-x)} \times \text{Lifespan}_{(i,\,x)},$$

where k donates the lifespan of product i, x is the in-use duration (years) of product i; $\text{Consumption}_{(i,j-x)}$ stands for the consumption of product i in year j-x; $\text{Lifespan}_{(i,x)}$ represents the probability of entering into the waste stream of product i after in-use for x years.

In this approach of dynamic MFA, the variation of the service period of a product is reflected by adopting a lifespan distribution function (Müller et al., 2014). This probabilistic method has been widely used to study stocks and flows of metals (Müller et al., 2014; Chen & Graedel, 2012), timber (Müller et al., 2004), and cement (Kapur et al., 2008), among others. This approach has also been applied to study plastics waste by assuming a normal distribution for the lifespan of plastics products (Geyer et al., 2017; Patel et al., 1998; Liu et al., 2020). The standard deviation (SD) is estimated to address the variation of the lifespan of various plastics products. For example, Patel et al. (1998) assumed identical SD, ranging from 10% to 30% of the mean, for a specific plastics product. Geyer et al. (2017) set the SD of the lifespan distributions for seven sectors of plastics products from 0.1 year for packaging to 7 years for construction and building.

4.7 | Waste treatment

Plastics waste generally has four pathways after product end-of-life: recycling, incineration (with or without energy recovery), landfilling, and mismanagement (discard without any treatment). Data on the amount of plastics waste entering each of the four pathways are missing for many countries. For those available data sources (Table S5 in Supporting Information S1), OECD (2020), United Nations (2020b), and the World Bank (2019) curate datasets with relatively comprehensive details for large countries and regions. These data include the amounts of recycled, landfilled, and incinerated MSW covering from 1990 to 2016 for 48 countries (OECD, 2020), and the share of different pathways in each country for a specific year (the latest year available) for 143 countries or regions in the OECD (2020) or 216 in the World Bank (2019). In addition, Waste Atlas provides data with visualizations on MSW generation, collection rate, and recycling rate for 164 countries or regions and 1799 cities by compiling data from various sources (Waste Atlas, 2019). Despite these available data, most of the previous studies involving plastics waste use MSW treatment data as proxies or are based on field surveys (Putri et al., 2018; Bureecam et al., 2018).

The destination of the recycled plastics waste depends on the recycling technologies and the local recycling scheme (Ragaert et al., 2017). Whether it is closed-loop recycling (i.e., the recycled plastics are used to produce the same product they were originally recovered from) or open-loop recycling (i.e., the recycled plastics are used to produce a different product) has an impact on the plastics flows accounting. Yet, the destination of recycled plastics is barely documented in the reviewed data sources. The only exception is the Australian Bureau of Statistics (2020) which provides surveyed results of the application areas of recyclate by polymer types.

Mismanaged plastics waste is of particular importance as the main source of plastics pollution in terrestrial and aquatic environments. However, primary data on mismanaged plastics waste are scarce. Previous studies have thus estimated the amount of mismanaged plastics waste primarily using the World Bank (2019) data on MSW generation and treatment (e.g., Jambeck et al., 2015; Lebreton et al., 2017; Law et al., 2020). Specifically, certain MSW disposal methods are considered as mismanagement such as dumps and landfills, the latter of which only applies to low-income countries given their inadequately managed practice of landfills. The portion of MSW in the mismanagement categories is then used as a proxy to estimate mismanaged plastics waste for each country or region. For countries without such information, regression models are used to estimate the percentage of mismanaged MSW based on disposal methods, economic classification, and geographic region of countries.

4.8 | Trade

International trade happens in all stages of the plastics life cycle. The UN Comtrade database (2019a) compiles detailed trade data from government customs agencies on a wide range of traded commodities, including polymers, semi-finished and finished plastics products, and plastics waste. For each traded product, the database (United Nations, 2019) provides the annual or monthly value of traded products among over 170 countries and regions around the world. Traded products are classified in Harmonized System (HS), Standard International Trade Classification (SITC), or Broad Economic Categories (BEC). The temporal coverage varies for each country in the database, with data from as early as in 1962 to the most recent year.

For some traded products with a more detailed level of classifications (e.g., 6-digit level in HS), there are quantity data available in addition to values, with various units. For those without quantity data, UN Comtrade provides standard unit values (SUV) as a global average to estimate quantities of traded goods based on their values (United Nations, 2019). Uncertainties also exist in the values of traded products in UN Comtrade. For example, each trade flow is reported by both the export country and import country, and in general imports are reported on a cost, insurance, and freight (CIF) basis while exports are reported on a free on board (FOB) basis. Additional uncertainties come from re-exports and re-imports, which refer to the exports of foreign goods in the same country or region as previously imported or the goods imported in the same country or region as previously exported. These uncertainties may lead to significant discrepancies in estimating quantities of traded products. We estimate the net export (export–import) of seven major polymers for all countries using the quantity data from UN Comtrade and estimated using SUVs if not available. In theory, the global net export should be zero because any export is an import for another country or region. However, as Figure 3a shows, the estimated net exports range between −2 Mt and 4 Mt from 1988 to 2017. Those discrepancies can be as high as 7% of the global polymer production (Figure 3b) (Geyer et al., 2017), leading to great uncertainties in the estimation of plastics stocks and flows with substantial international trade involved.

Notably, the traded plastics waste is a growing global concern for plastics pollution and waste management. Currently, UN Comtrade provides data on PET, PS, PVC, and other plastics waste or scrap ("plastics waste or scrap nes"). Challenges exist in allocating the other plastics waste or scrap into different polymer types, estimating plastics waste contained in other documented and undocumented traded products (e.g., waste computers), and illegal or mislabeled waste trade (Cotta, 2020). In addition, the reusability of traded low-quality plastics remains uncertain. These challenges lead to the lack of transparency and accountability of plastics waste trade data.

5 | DATA GAP AND RESEARCH NEED

Based on our review of the data sources for plastics stock and flow accounting, we evaluate the quality of these data by each of the plastics life cycle stages except for the stock stage because material stocks are generally estimated based on consumption and lifespan of products. Specifically, we qualitatively compare the data sources from five dimensions:

1. Completeness: How comprehensive are the data?
2. Conformity: Do data comply with each other in terms of definition, units, format, etc.?

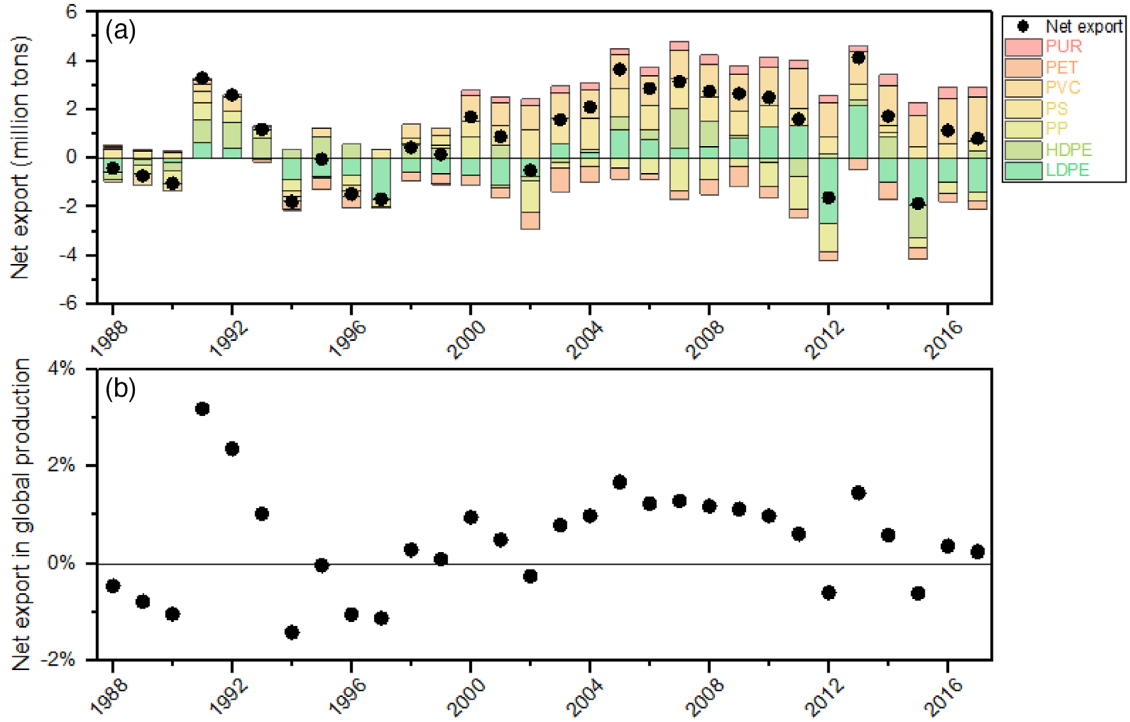

FIGURE 3 Estimated global net export of eight polymers using UN Comtrade data (HS 1996) (United Nations, 2019). (a) Net export value for each polymer type (bars) and the total net export of the seven types of polymers (dots). (b) Estimated net export as a percentage of the global production of these seven types of polymers in the same year (Geyer et al., 2017). The data for Figure 3 is provided in Supporting Information S2

TABLE 6 Comparison of data quality by stages of plastics life cycle

Life cycle stage	Completeness	Conformity	Consistency	Granularity	Timeliness
Material	M	G	M	M	M
Manufacturing	P	P	M	M	M
Additives	P	P	P	P	P
Consumption	P	M	P	P	P
End-of-life	P	G	M	P	P
Waste treatment	P	M	M	P	G
Trade	M	M	M	G	G

G, Good; M, Moderate; P, Poor.

3. Consistency: How much do data from different sources contradict each other and other trusted resources?
4. Granularity: How detailed are the data?
5. Timeliness: How up to date are the data? Are they updated regularly in time?

Table 6 shows our qualitative rating of data quality for each stage of the plastics life cycle except the stock stage. Generally, "Good" means data are ready to use with minimal processing, "Moderate" indicates data can only be useful after some major processing, and "Poor" means data are difficult to use without making substantial assumptions and estimations.

Data for polymer production are moderately complete as the amounts of key polymers for major producers are generally available (e.g., EU countries, NAFTA countries, China, Japan, Norway, Turkey, and Brazil). Although polymer production in other countries is likely marginal or even nonexistent, these data are still valuable when studying the plastics system in a local context. Polymer production data from various sources are recorded in mass values (pound, ton, kg, etc.), which could be easily converted for conformity. Most of the data from national statistics agencies are detailed enough for individual polymer types and are consistent with data from other sources (e.g., UN). In a few cases data are aggregated without polymer-specific information. For example, there are only data for PE without breaking down to LDPE, HDPE, etc. in China (China Petroleum and Chemical Industry Federation (2005), China Plastics Processing Industry Association (2019)). Also, data from difference sources can contradict each other. For instance, PP production in Japan in 2014 from Japan Plastics Industry Federation (JPIF) (2020) is 19% lower than that from United Nations (2018) for the same year. Lastly, most of the data are updated yearly with the exception of data for India and Egypt which are currently updated for only 2011 and 2013, respectively.

Data for plastics products are generally poorly documented, especially for semi-finished plastics products. Only data for major economies are available. The classifications of semi-finished and finished plastics products vary greatly across countries and regions, some with handful of product categories and others with over hundred distinct types. Weights of plastics products are generally recorded and can be easily converted for consistency. Some data sources provide very detailed information on plastics products (e.g., 107 product categories for EU countries), while others only cover limited number of categories (e.g., 4 types for India). Similar to polymer production data, data for plastics products are generally updated yearly and up to date with the exception of India, Egypt, and South Africa updated until 2010, 2012, and 2003, respectively.

Additives have the least available data among all plastics life cycle stages. They are barely recorded in government or industry statistics. Scattered data points reported in journal publications are often used to estimate the amount and types of additives added in plastics products (e.g., Geyer et al., 2017).

Data for the consumption of plastics products are only available in four data sources for Australia, the United States, South Africa, and the aggregate total of European countries (EU27 + Norway + Switzerland). Among these four available data sources, classification of plastics products is inconsistent and incomparable. Three of the four data sources are updated regularly and timely, while data for South Africa are only available until 2003. A variety of estimation methods are used to estimate the amount and type of plastics products consumed in existing studies.

Time-series data specifically on the amount of end-of-life plastics are available for Australia, Japan, South Africa, Taiwan (China), the United States, and EU28. Some of these are updated regularly and up to date, while others are not regularly updated and out of date (e.g., most recent data for Japan is for 2003). For other countries or regions, only time-series data on MSW are available and various methods are used to estimate the portion of plastics in MSW. Notably, United Nations (2020b), World Bank (2019), and Waste Atlas (2019) provide data on plastics waste for most countries and regions as weight percentage of MSW, but only available for the most recent year which varies for individual countries and regions ranging from 1993 to 2017. Generally these data sources only include aggregate plastics waste without information on specific types of plastics waste.

Similar to data on plastics waste generation, data on plastics waste treatment are generally poorly recorded and vary greatly across data sources in multiple dimensions leading to the lack of conformity and consistency. Most data sources only provide information on plastics waste pathways in different, broad categories (e.g., recycled, landfilled, incineration). Similarly, United Nations (2020b), World Bank (2019), and Waste Atlas (2019) have data for most countries and regions around the world, but available only for the most recent year which varies for individual countries and regions.

Detailed and up-to-date plastics trade data are available from the UN Comtrade database (United Nations, 2019). However, polymer-specific data on traded plastics waste are only available for PET, PS, and PVC, while trade data for other types of polymer waste are aggregated. In addition, trade data for specific polymers, plastics products, or plastics waste for some countries or regions are not available in weight, rather in other physical units. For example, “the sheet etc, cellular of polymers of vinyl chloride” are recorded in “area in square meters” in some cases, which requires estimation of weight per unit. Another challenge for the UN Comtrade data is that some historical data are only available in specific classification systems but not in others. The conversion between classification systems, for example, between the SITC and Harmonized System (HS), may cause inconsistent coverage of products in the same category, thus abnormal time-series trade flows which sometimes can grow or decline annually by orders of magnitude.

Based on our review of the literature and data sources on plastics stock and flow analysis, we identify the following four data gaps:

1. **Inconsistent classification**. The classifications of plastics materials, products, and waste are greatly inconsistent across various data sources. As a result, existing studies on plastics stocks and flows are highly aggregated focusing on plastics in general. To provide insights for managing plastics and plastics waste which is a global challenge, in-depth analyses of global and regional plastics stocks and flows are still in urgent need. Such analysis requires a consistent classification of plastics materials, products, and waste with sufficient details.
2. **Missing data**. Many of the existing databases miss data for specific countries or regions, certain periods of time, or particular types of plastics materials, products, or waste. For material production, even the six most popular thermoplastics (i.e., PE, PP, PS, PVC, PET, and EPS) and the most produced thermosets (i.e., PUR) are not all recorded for the major plastics production countries and regions. Data on additives almost do not exist. Production of semi-finished products are rarely documented for non-EU countries. Consumption data and waste mismanagement data are also rarely accounted in the current statistics. China, the top plastics producer and consumer, does not provide detailed information for plastics flows and stock accounting. Those missing data need to be estimated to fill the gaps.
3. **Conflicting data**. Conflicts exist across multiple data sources and need to be reconciled. Data from government statistics agencies are often different from those from industry trade groups or international organizations such as OECD, UN, and World Bank. For example, polymer production data from the UN Industrial Commodity Statistics Yearbook can be orders of magnitude different from those of government statistics agencies.

4. **Inexplicit data for plastics products and waste**. Data for plastics stocks and flows are currently compiled with different purposes for different life cycle stages. At the material production stage, data are collected by types of polymers. At the semi-manufacturing, manufacturing, and consumption stages, data are collected mainly by products that contain plastics, rather than by types of plastics. At the end-of-life stage, plastics waste is not specifically tracked, but generally considered as part of industrial waste or MSW. Often, the waste treatment pathways are not completely recorded, especially for the mismanaged waste. Also, the use of recycled plastics waste is rarely documented. To track plastics across the various life cycle stages, we need to estimate the amount and type of plastics in a variety of semi-finished products, finished products, industrial waste, and MSW.

These data gaps represent critical research needs to develop high-quality, comprehensive data characterizing the physical aspect of the plastics life cycle to assist in combating a variety of sustainability challenges associated with plastics production, consumption, waste, and pollution. We identify four such research needs:

1. **Common platform for data sharing**. Given the various data sources hosted by different providers, a common platform is needed to curate and share these data. Such a platform will greatly enhance our ability to map and track plastics across life cycle stages, countries and regions, and time. An institutional infrastructure needs to be in place for such an endeavor.
2. **Standard methods for data reconciliation and estimation**. Developing plastics stock and flow accounting involves significant efforts to reconcile data from multiple sources and estimate missing data. Previous studies have used various methods for data reconciliation and estimation. Standard methods or "best practices" should be identified and recommended for future studies to ensure comparability and reproducibility.
3. **Consistent data collection and reporting**. In the long term, it is necessary to transform the current data collection and reporting systems in various countries and regions that vary greatly with each other in multiple dimensions to a consistent one. To develop such a consistent system, we need to engage all stakeholders including those who are currently curating plastics-related databases.
4. **New approaches for data collection and curation**. We currently rely predominately on government agencies, industry trade groups, and international organizations such as OECD, UN, and the World Bank on plastics data. Innovative approaches should be explored to bring new capacity in data collection and curation. For example, the Internet of Things (IoT) applications such as radio-frequency identification (RFID) could enable accurate tracking of materials and components across the supply chain (Tu et al., 2018). Crowdsourcing information from consumers might provide additional data on plastics stocks, such as My Little Plastic Footprint (2020). In addition, the rapidly developing field of data science may offer new ways to effectively and efficiently estimate missing data (Xu et al., 2015; Zhu et al., 2019).

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CONFLICT OF INTEREST

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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