**Material Flow Analysis of Chemical Additives in Plastics: A Critical Review**

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**ABSTRACT:**

The exponential growth in plastic production and usage has escalated global concerns about plastic pollution, particularly regarding harmful chemical additives. Understanding the anthropogenic cycles of these additives is the prerequisite to developing effective strategies for plastic pollution control and a toxics-free circular economy. Here we analyze 269 anthropogenic cycles of plastic additives by reviewing 42 extant academic articles to identify research gaps and needs. Based on their characteristics and the available knowledge, we classify these plastic additives into five research priority levels, with 3,116 designated as “urgent level”, further subgrouped into 17, 14, and 20 additive categories considering their functions, polymer types, and application sectors, respectively, to inform future investigations. Four key research gaps are highlighted: limited research coverage for hazardous chemical additives, lack of specificity to plastic products, incomplete consideration of life cycle stages and relevant flows, and insufficient attention to policy implications. To close these gaps, we recommend expanding the scope of plastic additives with a specific focus on urgent-level cases, exploring all chemical flows tailored to various plastic types, enhancing the quality and accessibility of relevant data, and fostering a mechanism for strong science-policy-society inter-actions on the management of plastic additives. This review offers a roadmap for advancing research on material flow analysis of plastic additives and sustainable plastic management.

KEYWORDS: Anthropogenic cycle, Material flow analysis, Plastic additives, Plastic pollution control, Sustainable plastic management.

## Introduction

Plastics contribute positively to our livelihoods and industrial development, including telecom-munications, transportation, and infrastructure. Since the 1950s, annual production of plastics has exponentially increased, reaching 460 million tonnes in 2019, and its demand has surpassed all conventional bulk materials such as steel and cement (EEA, 2021; IEA, 2018; OECD, 2022a). Fueled by economic growth, population expansion, and digitalization, projections indicate a doubling of global plastic production and usage by 2050 (OECD, 2022b; Stegmann et al., 2022). The escalating demand for plastics brings challenges to human and planetary health, with growing concerns including the accumulation of plastic marine litter (Law & Thompson, 2014; Ostle et al., 2019), generation of secondary micro- and nano plastics (Borrelle et al., 2020; Wei et al., 2022), over-use of single-use plastics (Truelove et al., 2022; Walker et al., 2021), exposure to toxic plastic chemicals (Aurisano et al., 2021; Dey et al., 2022), as well as carbon footprints and related climate impacts of plastic industry (Bachmann et al., 2023; Cabernard et al., 2021). While it is impractical for humans to entirely cease using plastics, not least because alternatives can also have serious ecotoxicological, waste management, and carbon impacts (O'Connor et al., 2018; Tan et al., 2023; Wu et al., 2017), it should prioritize the development of effective management strategies to ensure the safe and sustainable utilization of plastics, thereby addressing plastic pollution and its associated ramifications.

Plastic chemicals are a key aspect of plastic management. Plastics contain diverse chemical substances, including organic polymers (e.g., polyethylene (PE) and polypropylene (PP)) serving as the plastic backbone, processing aids (e.g., catalyst and lubricant) facilitating the manufacturing processes, non-intentionally added substances (NIAS) (e.g., byproducts and contaminants), and notably, chemical additives (e.g., plasticizers, antioxidants, and flame retardants) enhancing the functionality of plastic materials and products (Amos, 2009; Groh et al., 2019). Currently, over 16,000 types of plastic chemicals have been identified, with at least 4,200 classified as "major concern" due to fulfilling one or more of the Persistence, Bioaccumulation, Mobile or/and Toxicity (PBMT) criteria (UNEP, 2023a; Wagner et al., 2024; Wang et al., 2022; Wiesinger et al., 2021). The annual production volume of chemical additives is expected to escalate, with projections suggesting a five-fold increase by 2060, mirroring the overall growth in plastic production (Wagner et al., 2024). These additives, being non-chemically bound to the polymer matrix, are inevitably released throughout the lifecycle of plastics, posing severe risks to ecosystems and human health (Aurisano et al., 2021; Hermabessiere et al., 2017; Koch & Calafat, 2009; Meeker et al., 2009; Tang et al., 2015, 2016; Zimmermann et al., 2019). Furthermore, they can pose technical challenges for plastic recycling by corroding machinery and contaminating secondary end-products, impeding the transition to a sustainable circular economy (Aurisano et al., 2021; Leslie et al., 2016). Therefore, in the pursuit of effective management strategies for zero plastic pollution, it is necessary to focus on the lifecycle management of chemical additives in plastics.

Understanding the anthropogenic cycles of chemical additives in plastics, including identifying their initial sources and eventual sinks, and tracing the flows linking them from a life-cycle perspective, is a prerequisite for making lifecycle management decisions to tackle the plastic crisis. However, scientific knowledge in this domain remains limited, fragmented, or frequently undisclosed even when available. As a result, only ~6% of chemical additives in plastics, mostly well-known ones, are currently regulated globally (Simon et al., 2021; Wagner et al., 2024). The regulation gap would be larger due to the higher number of additives being produced in high volumes, presenting formidable obstacles to the lifecycle management of plastic chemicals. Hence, there is an urgent need for consolidated information on the anthropogenic cycles of chemical additives in plastics, which will help targeted and efficient measures for plastic pollution control. Material flow analysis (MFA) serves as an effective tool for obtaining such information (Fischer-Kowalski, 1998; Wolman, 1965). MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time (Brunner & Rechberger, 2016; Graedel, 2019). To date, a growing number of studies have used MFA to better understand the anthropogenic cycles of elements (Chen et al., 2016; Song et al., 2020; Tang et al., 2020), products (Geyer et al., 2017; Heller et al., 2020; Jian et al., 2022), and materials (Gonçalves et al., 2021; Lefeuvre et al., 2019). These studies have demonstrated the advantages of MFA in informing policy decisions related to sustainable resource and environmental management, waste treatment, and circular economy transition. In recent years, there have been emerging MFA studies on plastic additives, including phthalate esters (PAEs) (Cui et al., 2022; Muchangos et al., 2019), polybrominated diphenyl ethers (PBDEs) (Abbasi et al., 2015, 2019), and bisphenol A (BPA) (Jiang et al., 2018). However, relevant research remains sparse and scattered when considering the diversity and problematic properties of chemical additives in plastics, the limited analytical scope of these studies, and the pressing need for global plastic management.

The knowledge gap motivated a review of existing MFA studies on mapping the anthropogenic cycles of chemical additives in plastics to inform future studies on plastic additives and guide decision-making on reducing plastic pollution. We seek to answer four key research questions: (1) what are the primary research dimensions and focal points of current MFA studies on plastic additives; (2) what knowledge gaps exist in these studies; (3) which plastic additives matter most for future exploration of their anthropogenic cycles; and (4) what are the potential ways to improve MFA studies on plastic additives and promote efforts in plastic management?

To address these questions, we first systematically analyze key features of selected publications and the chemical additive cycles identified in these studies. Then, we propose an MFA research framework intended to characterize the anthropogenic cycles of plastic additives. Based on the PlastChem database (Wagner et al., 2024), we further identify plastic additives lacking information on their anthropogenic cycles and classify them into five levels and several groups for prioritizing future academic research and policy actions. Finally, we generalize four major knowledge gaps and corresponding needs in this field.

## 2. Methods

### 2.1. Selection of articles

A bibliographic search was conducted to collate relevant publications on the anthropogenic material cycles of chemical additives in plastics. The references were screened on the online databases Web of Science and Google Scholar by using the keywords related to MFA – “material flow analysis”, “mass flow analysis”, “substance flow analysis”, “flows and stocks analysis”, “anthropogenic cycles”, “industrial metabolism", "urban metabolism", "social metabolism", or "material metabolism", combined with "chemical additive in plastic", "chemical additive", or "plastic additive". We excluded biogeochemical cycles that are primarily or exclusively specific to the material metabolism in the natural system. Our selection principle is that at least one life-cycle stage of plastic additives in the anthroposphere should be addressed. As for the objects concerned, we excluded plastics, metal and nonmetal elements, engineering materials, and nanomaterials, although they are automatically classified as plastic additives under our retrieval. We only included research articles available in English and excluded literature published before the year 2000.

## 2.2. Identification of chemical additive cycles

Chemical additive cycles, based on their temporal boundary, can be categorized into static cycles, representing a snapshot of flows at a specific point in time, and dynamic cycles, characterizing material flows of a chemical additive over a time interval and permitting a determination of its in-use and "hibernating" stocks (Chen & Graedel, 2015; Graedel, 2019). For each kind of cycle, the identification process of chemical additive cycles remains consistent, primarily upon the additive types and spatial boundaries of the reviewed studies. One chemical additive cycle corresponds to one specific type of additive within one defined geographical region or spatial unit. For example, in a study examining global dynamic material flows of three distinct types of chemical additives across seven sub-regions worldwide, the total number of chemical cycles would be calculated by multiplying three (the number of additive types) by eight (including seven sub-regions and the globe) resulting in 24 cycles. If a chemical additive type contains individual congeners and they have been clearly indicated in the reviewed study, both the main chemical additive mixture and its congeners' cycles will be identified. For example, in a study analyzing the material flow of PBDEs, considering their six congeners combined into PBDEs, the number of additive types would be seven.

## 2.3. Identification of research gaps, priorities, and groups

Figure 1 shows the workflow used to identify plastic additives lacking material cycle information and their research priorities. The chemical additive inventory was retrieved from the PlastChem database (Wagner et al., 2024), which consolidates and updates publicly available information from various databases (e.g., PlasticMAP (Wiesinger et al., 2021), CPPdbv1 (Groh et al., 2019), FCCdbv5 (Groh et al., 2021), and FCCmigex (Geueke et al., 2023)), scientific literature, and regulatory sources, providing a synthesis of state-of-the-art knowledge on plastic chemicals. The database contains 16,325 distinct chemical substances present in plastics with unique Chemical Abstract Service Registry Numbers (CASRNs) and their characteristic information. These chemical substances include starting substances (e.g., monomers and initiators), intentionally added substances (e.g., processing aids and multiple chemical additives), and NIAS (e.g., intermediates). Based on the regulatory status and hazard properties, these chemical substances are categorized into six lists for prioritizing regulatory actions. The red list comprises plastic chemicals of concern not currently regulated internationally but deemed necessary for regulation due to their hazard properties. The orange list contains plastic chemicals classified as less hazardous currently but may become chemicals of concern pending additional hazard trait identification. The watch list includes plastic chemicals undergoing hazard evaluation, with the potential to become chemicals of concern pending comprehensive assessment. The white list consists of plastic chemicals deemed non-hazardous. The MEA (Multilateral Environmental Agreement) list contains plastic chemicals currently regulated under existing MEAs, including the Basel, Stockholm, and Minamata Conventions, as well as the Montreal Protocol. The grey list consists of plastic chemicals lacking hazard information and no regulatory action is possible at present.

We first removed 1,791 kinds of plastic chemicals used exclusively as starting substances, processing aids, and NIAS from the PlastChem database. This update leads to a plastic additive inventory consisting of 5,785 identified chemical additives and 8,749 chemicals potentially used as additives due to their empty table entries in the database (Fig. 1). We then categorized these plastic additives into the six regulatory prioritization lists. Plastic additives appearing in the watch and grey lists were designated as TBD (To-Be-Decided)-level research priority, reflecting their uncertain nature and potential to become concerning chemicals. Plastic additives in the white list were assigned a low-level research priority due to their identified non-hazardous properties. For plastic additives in other lists, we conducted a comparative analysis with findings from the reviewed MFA studies to determine research gaps and priority levels. This evaluation includes determining whether the information on selected additives had been explored in existing MFA research; and for additives in the red and orange lists, assessing the comprehensiveness of available knowledge. Based on the screening process, plastic additives in the inventory were classified into five priority levels: urgent, high, medium, low, and TBD, reflecting their standing in terms of research requirements on anthropogenic material cycles. Finally, we consolidated all the information to establish a database on the anthropogenic material cycles of plastic additives.

To expand the range of potential future research directions, we additionally used the hierarchical clustering algorithm to create several categories for the urgent-level cases based on their key characteristics within the dataset, including functions, polymer types applied, and industrial sectors involved. Hierarchical clustering, a widely-utilized technique in data mining and analysis, enables the systematic organization of data points into hierarchical structures, thus helping reveal the underlying complex relationships of the data (Murtagh & Contreras, 2012, 2017). The algorithm allows for the determination of an optimized number of clusters by assessing the intrinsic structure of the data, ensuring robust categorizations. Chemical additives grouped within the same cluster exhibit similar attributes across their specific characteristics.

# 3. Results

## 3.1. Number and spatio-temporal characteristics of chemical additive cycles

In total, 269 anthropogenic cycles of plastic additives are identified. These cycles are drawn from 42 publications, distributed across four research domains, including environmental sciences, environmental engineering, multidisciplinary sciences, and environmental studies. Regarding the temporal dimension, most of these cycles are dynamic and thereby contain several sub-cycles within them, but a few are static (Table S1). All chemical additive cycles are mapped for a calendar year, with the prevailing year being 2000 or later. As for the spatial dimension, as shown in Table 1, ~52% of chemical additive cycles are characterized on a regional scale, fol-lowed by the global (~28%) and country scale (~16%). Some global-level cycles are aggregates of cycles for regions, whereas others characterize the global cycle directly. Chemical additive cycles at the city and river basin or plant levels are rarely mapped, representing less than 5% of the total. Hot-spot spatial boundaries selected in these MFA studies focus on the European continent and China and also extend to countries such as Nigeria, the USA, Canada, Switzerland, and Korea (see Supplementary Information (SI) for details).

Research in mapping the anthropogenic cycles of plastic additives originated in 2002 when scholars sought to map the global historical anthropogenic emission flows of polychlorinated biphenyls (PCBs) based on a dynamic mass balance model, as a direct result of their widespread application in a series of products (Breivik et al., 2002). Since the year 2013, the total number of publications has increased rapidly (Fig. 2a), reflecting a growing interest in plastic chemicals. These publications are mainly from European countries (n = 14), China (n = 11), and the USA (n = 5), with a focus on a group of scholars from few research affiliations, including Peking University (n = 18), University of Toronto Scarborough (n = 12), and Lancaster University (n = 10). Most of the articles are sourced from the Science Citation Index (SCI) journals in the field of environment, particularly the journals of Environmental Science & Technology (n = 15) and Science of the Total Environment (n = 8) (see SI for details).

For chemical additives to plastics, current publications are mostly available for PBDEs and their congeners, such as decabromodiphenyl ether (DecaBDE), pentabromodiphenyl ether (PentaBDE), and octabromodiphenyl ether (OctaBDE)), collectively representing over 50% of the reported chemical additive cycles (Table 1). This is probably due to their unique and extensive applications in plastic materials and the greater availability of reliable basic data. PCBs and chlorinated paraffins (CPs) with varying chain lengths, are also of particular concern, contrib-uting ∼21% and ∼13% of the total number of chemical additive cycles, respectively. Anthropogenic cycles for per- and polyfluoroalkyl substances (PFASs), especially perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), as well as PAEs, have received increasing attention in recent years, despite still relatively limited research on their material flows. Additionally, some emerging alternatives to PBDEs (e.g., hexabromocyclododecane (HBCDD) and decabromodiphenyl ethane (DBDPE)), along with BPA and hydrofluoric acid (HF), have been subject to scant investigation, likely due to data accessibility challenges.

3.2. Existing research dimensions of chemical additive cycles

Some of the anthropogenic chemical additive cycles in the studies, either static or dynamic, treat the whole life-cycle stages of plastic additives. Figure S1 summarizes a general framework for mapping anthropogenic cycles of plastic additives. The entire life cycle stage normally follows chemical additives from their synthesis (i.e., where they are produced directly or indirectly from fossil fuels including coal, petroleum, and natural gas) into plastic polymer production (i.e., where the chemical additives are involved in chemical reactions to produce plastic polymers), to plastic material production (i.e., where the plastic polymers are processed into primary plastic products like pellets and films), to plastic product fabrication and manufacturing (i.e., F&M, where the plastic materials are used in fashioning utilitarian finished plastic products), to plastic product consumption, and eventually discarded into the waste management and recycling system. In the recycling system, some chemical additives are reclaimed alongside plastic products after initial use (i.e., Post-Consumer Recycling, PCR). This includes physical recycling, where plastic wastes are reprocessed into plastic materials; and chemical recycling, which involves the conversion of plastic wastes into plastic polymers through chemical reactions. Additionally, some chemical additives may undergo recycling alongside plastics before reaching the final consumer (i.e., Post-Industrial Recycling, PIR). These plastic additives are from waste generated during the F&M of plastic products and are reused in plastic materials production. Apart from recycling, most plastic waste is treated by landfilling, incinerating, or sinking into centralized sewage treatment plants (STPs). Releases of chemical additives into the environment occur at each phase, generally categorized into chemical leakage (i.e., dissipative loss) during the production process and unintended chemical leaching during the use and End-of-Life (EoL) stage. Once released, they can find their way into environmental media, including the hydrosphere, soil, and atmosphere. Transfers across system boundaries, such as trade flows of chemical additives and associated plastic materials, products, and wastes, may occur unless the cycle is performed for the entire planet.

It was common to find that one stage or several sub-stages of the life cycle, or some relevant flows, were ignored or inadequately characterized (Fig. 2b). Particularly, trade flows of plastic additives themselves and associated plastic materials, products, and wastes were totally or partly omitted in most of the documented cycles, with only ~7% of the reviewed publications fully estimating the trade flows. Loss flows (i.e., leakage flows and leaching flows) of plastic additives, despite normally being considered in the studied system boundary, were seldom captured completely unless the research explicitly targeted emission inventory. Fewer than 60% of the current studies addressed the environmental release flows of plastic additives across their life cycle (see SI for details). This is partly due to the difficulties in obtaining related information, notably, emission factors or emission scenarios associated with these additives. Recycling flows were disregarded or roughly calculated in many studies (nearly 40%), probably due to the small recycling amount or unavailable data on the recycling ratios of different plastic wastes.

A prominent example of a country-level dynamic cycle (Cui et al., 2022) is shown in Fig. 3. The results are displayed for the lifecycle flows and stocks of di(2-ethylhexyl) phthalate (DEHP) in mainland China. Substantial information is contained in the cycle, for example, (1) flows of DEHP from chemical production to the product use stage were large; (2) losses of DEHP were largest in the use phase when compared to other lifecycle phases; (3) the DEHP flow exiting the use stage was smaller than that entering, indicating an accumulative in-use stock of DEHP; (4) high consumption of DEHP-containing products was highly centralized in the synthetic rubbers, flooring materials, as well as wires and cables, with substantial use-stocks in the end-use sectors; (5) most DEHP-containing wastes were treated by incineration and landfill, whilst only <10% can be recycled for second use; and (6) soil and water were the major sinks of DEHP (estimated to be 94% of DEHP), with <5% ending up in the air.

Key features of a dynamic cycle can be seen by focusing on specific flows and stocks over a period of time, for example, as shown for DEHP in Fig. 3b and 3c. The overall input and output flows of DEHP have increased since the 1960s, which is mostly contributed by the pro-duction and trade of DEHP, as well as the consumption of synthetic rubbers. The increase of in-use stocks of DEHP originated in 1956 but slightly declined during the period 2012-2015 due to the series of restrictions on the production and use of DEHP imposed by local governments, and then regrew afterwards. For EoL management, improper discard was the dominant practice in China until 2012. However, advancements in municipal solid waste management have led to a recent shift toward incineration and landfills (Zheng et al. 2014). The recycling flows of DEHP-containing products remained at a relatively low level throughout the period.

### 3.3. Research gaps, priorities, and groups

Overall, 14,224 types of plastic additives, representing about 98% of the total, are identified as lacking information regarding their anthropogenic cycles. Another 294 types (~2%) possess incomplete information, while less than 1% have relatively detailed information available. The majority of these chemical additives fall into the TBD priority level for academic research, due to uncertainty on their roles in plastics or ongoing hazard assessments. Among additives with confirmed roles, approximately 60% (~3,116 types) are categorized as urgent-level research priorities, followed by high- and medium-level research priorities at around 20% and 16%, respectively (Fig. 1). Only a minor fraction, about 4%, falls under the low-level research.

For each research priority level, there is a significant portion of plastic additives that remain unidentified in terms of their functions, associated polymers, and sectors of application (Fig. 4), indicating an urgent need for further exploration to facilitate risk assessment and management. Plastic additives warranting urgent research are mostly associated with dying (~41%), stabilization (~25%), filling (~25%), and biocidal (~16%) functions (Fig. 4a). These urgent research needs are primarily observed in polyethylene (PE) (~17%), including high-density polyethylene (HDPE) and low-density polyethylene (LDPE), as well as polyvinyl chloride (PVC) (~11%), polyethylene terephthalate (PET) (~9%), and polyurethane (PUR) (~9%) (Fig. 4b). Sectors including textiles, building & construction, automotive, and packaging, electrical and electronic equipment, and food-contact plastics, are the focal points for the plastic additives, collectively accounting for ~85% of downstream application areas (Fig. 4c). These indicate that additives associated with these hot-spot functions, polymers, and industrial sectors demand priority research attention and subsequent stringent regulations in the future.

Chemical additives categorized as the high-level research priority are primarily employed as colorants and fillers in polymers such as PE, PET, PVC, Polyamide (PA), and other thermoplatics. These additives find extensive utilization in sectors such as textiles (~25%), packaging (~23%), and food-contact plastics (~21%), highlighting the necessity for focused research endeavors. Additionally, plastic additives falling under the TBD priority level of research are dominated by colorants (~16%), fillers (~8%), plasticizers (~5%), and biocides (~5%), applied in PA (~5%) and PE (~5%), in sectors like packaging (~8%), textiles (~7%), and food-contact plastics (~7%), suggesting the need for particular scrutiny in these aspects due to potential concerns of these additives.

Based on the key characteristics, we further classified the urgent-level cases using a hierarchical clustering algorithm. As shown in the Excel sheets of SI, our findings delineate a nuanced classification of the urgent-level research needs, grouping them into 17 clusters based on their respective functions, 14 clusters based on associated polymers, and 20 clusters based on industrial sectors. Within each cluster, plastic additives exhibit similarities in their functions, applications in polymers, and industrial uses, indicating cohesive patterns and potential relationships among them. Detailed information on the plastic additives in each group can be accessed in the SI using the corresponding number of clusters

## 4. Discussion

Four major research gaps are identified based on the review. Firstly, there is a lack of coverage: the overall scope of the extant MFA research articles represents only limited and fragmentary comprehension of plastic additives. This gap is particularly concerning given the ever-increased number of hazardous chemical additives present in plastics and the expanding plastic industry (Wang et al., 2020; Wiesinger et al., 2021). The lifecycle management of plastic additives necessitates sound information on all harmful chemical additives in plastics, including their sources, flow pathways, sinks, geographical emissions, and distributions (Kogg & Thidell, 2010; SAICM, 2015; Wang et al., 2022). However, this sort of knowledge is currently inadequate and, in some cases, not readily accessible for academic research, posing challenges to environmental and health exposure assessments of plastic chemicals and the subsequent risk management efforts. Our results indicate that there are currently only ~2% (302 types) of plastic additives that have pertinent knowledge available, and even in these cases knowledge remains incomplete (see SI for details). Notably, widely used plastic additives known for their endocrine-disrupting properties, such as BPA, HBCDD, and DBDPE (with potential endocrine-disrupting properties), have not received sufficient research attention despite their well-documented severe risks to human well-being and wildlife (Adeyi & Babalola, 2019; Bajard et al., 2021; Naveira et al., 2021).

Secondly, there is a lack of specificity: most of the current studies focus on mapping the material flows of chemical additives across various products, but few specifically target plastic products. Products serve as essential “carriers” of chemicals, directly influencing their socioeconomic metabolism. Different from metal elements and other materials, MFA studies for chemical additives often cover a series of products containing these additives. For example, Abbasi et al. (2015) traced the time-variant stocks and flows of PBDEs in the USA and Canada in 11 kinds of PBDE-containing products from six sectors. They further evaluated the global historical stocks and emissions of PBDEs in association with various products from five main sectors (Abbasi et al., 2019). From the perspective of exposure, however, it is specific product types, such as rubber, textile, and plastic products, that directly encounter ecosystems and humans, rather than the chemical additives themselves. Hence, through a focused analysis of material flows and related risks tied to particular product types, it becomes feasible to address latent chemical pollution issues within these products and guide targeted regulatory actions.

Plastic pollution, a pressing topic on the international agenda, is claimed to be closely related to problematic chemical additives (Dey et al., 2022; UNEP, 2020). Scientists and governments have highlighted the necessity of integrating and understanding chemical issues in plastic management to effectively address the ecological, health, and environmental justice concerns of plastic. As a response, most studies have screened chemical additives of concern in plastics and assessed their impacts on environmental media, food, and the human body (Aurisano et al., 2021; Darbre, 2020; Hahladakis et al., 2018; Tan et al., 2023; Tuuri & Leterme, 2023). However, our work reveals that less than 15% of the reviewed studies focus on addressing the anthropo-genic cycles of chemical additives specific to plastic products, while these studies still lack discussions on the management implications of mapping such cycles for plastic pollution control.

Thirdly, there is a lack of comprehensiveness: few studies have fully quantified all flow pathways of plastic additives in the anthroposphere. Sound management of chemical additives is based on life cycle thinking (UNDESA, 2009), a holistic approach to understanding their environmental and health impacts throughout plastic life cycles. However, our findings suggest that certain stages or sub-stages within the life cycle, as well as pertinent flows (e.g., trade flows, emission flows, and recycling flows), are frequently overlooked or insufficiently characterized (Fig. 2b).

Only a limited number of studies (n = 3) have extensively explored the global trade of plastic additives (see SI for details). International trade serves as a significant pathway for toxic chemicals to circulate globally by connecting countries with enhanced flows of goods, services, resources, and technologies, promoting the global economy and welfare. However, it complicates chemical risk management by geographically separating consumption, production, and disposal, leading to the shift of chemical-related burdens (e.g., resource consumption, environmental degradation, and health threats) via global supply chains (D'Odorico et al., 2014; MacDonald et al., 2015; Wiedmann & Lenzen, 2018). One example is that some developed countries seek to achieve their chemical pollution control targets by offshoring domestic plastic wastes to developing countries with less stringent regulations. Such trade patterns have left some regions as "chemical pollution havens" (Cole, 2004; Gill et al., 2018; Tang, 2015) that have to sustain environmental and health ramifications induced by the product demand elsewhere (i.e., "embodied" burdens in global trade). Moreover, global product trade provides an efficient and direct pathway for the distribution of chemical additives "embedded" in consumer products (Huang et al., 2020), redistributing the location of chemical emissions and associated ramifications. However, most reviewed studies focus solely on the gross trade flows of individual countries, neglecting the transboundary movements of additives embodied and embedded in plastics among different countries.

Furthermore, existing research often provides only rough estimates of recycling flows, failing to consider critical factors such as recycling patterns (e.g., PCR and PIR) and methods (e.g., physical recycling and chemical recycling). Precise quantification of these aspects is crucial for setting appropriate thresholds of chemical additives content to incentivize technical innovation of plastic recycling and promote the establishment of assessment certification systems for recycled plastic chemicals.

As for emission flows, while some current studies have offered estimates, they heavily rely on emission factors derived directly from official documents. These data, typically being non-localized, fail to accurately reflect the real emission backgrounds, thus impeding effective regional management of chemical risks. Once released into the environment, chemical additives transform into emerging contaminants, characterized by diverse structures and forms (e.g., polymers and aggregates), persistence, and insidious hazardous effects (e.g., carcinogenicity and mutagenicity) (Wang et al., 2022). Existing explorations, grounded in established data for quantifying emission flows, may inadequately address the intricate complexities associated with emerging contaminants.

Fourthly, there is a lack of relevance: only a fraction of studies have engaged deeply with the practical implications of tracing the material cycles of plastic additives. Understanding the material metabolism characteristics of plastic additives can furnish policymakers with a robust scientific basis for formulating effective strategies to combat plastic pollution. However, our analysis indicates that nearly 65% of the reviewed studies solely focus on mapping the historical evolution of the plastic additive cycles (see SI for details), without translating the historical data into actionable policy insights, posing challenges for policymakers in making well-informed decisions to address the plastic crisis.

A prerequisite for effective translation lies in the identification of key factors influencing the characteristics of plastic additive cycles. For example, extant research has highlighted various factors affecting the demands for energy and minerals, including population size, economic aggregates, industrial structures, social wealth, infrastructure improvement, urbanization, industrialization, technology advancement, as well as national and social policies (Jones, 1991; Li & Lin, 2015; Zheng & Walsh, 2019). These factors have paved the way for forecasting future resource demands under different scenarios, facilitating decision-making on resource and environmental management. However, none of the existing studies have quantitatively examined the factors driving the usage and emissions of plastic additives. Without such analysis, the academic findings are not optimally leveraged for informing policy options on plastic pollution control.

Against the backdrop of these four knowledge gaps, we encourage researchers to refocus on addressing the latent chemical concerns hidden within the plastic industry. It is imperative to further investigate the anthropogenic cycles of hazardous plastic additives and related risk problems (refer to gap 1) to gather sound information essential for the effective lifecycle management of these additives. Our study proposes a systematic evaluation of the research priority levels of current plastic additives, which may serve as a foundational guideline for future research efforts. Plastic additives identified as urgent-level research needs, as shown in SI, should be prioritized in the near-term agenda of plastic pollution control. The clusters of plastic additives (see SI for details), categorized by their key characteristics, may offer an opportunity to advance MFA studies on additive groups, given that items within each cluster share common functions or are always used together due to compatibility with specific polymer types or industrial applications. This approach transitions from isolated investigations of individual additives to exploring additive categories in certain areas, tailored to specific research aims or managing requirements, enabling the development of precisely targeted policies to address various management needs.

The material cycles of chemical additives specific to plastic products should be explored (refer to gap 2), with a particular focus on distinguishing between different plastic categories such as PE, PET, PVC, etc. Given variations in toxicity levels and environmental behaviors, different types of plastics make disproportionate contributions to environmental plastic levels. Therefore, conducting such research is imperative to enable risk assessments of specific plastic products and address chemical challenges concealed in plastic pollution through targeted governance of specific plastic types. The research framework for the anthropogenic cycle of plastic additives (Fig. S1) present herein can serve as a reference for broadly exploring such information with detailed resolution.

Furthermore, all lifecycle stages and relevant flows of plastic additives should be assessed, considering multifaceted dimensions (refer to gap 3). Notably, in the context of globalization, a pressing need emerges to explore the chemical additive flows “embedded” and “embodied” in the global plastic trade and their associated environmental and health risks. Enhancing the quality and accessibility of pertinent data is crucial to facilitate this endeavor. While various potential data sources exist, including the United Nations Comtrade database, World Trade Organization statistics, industry reports, and peer-reviewed literature, they often provide low-resolution statistics limited in scope or dispersed. We propose the development of a state-of-the-art integrated and exportable database on global plastic additives, covering both macro-level (e.g., production and trade, flows and stocks) and micro-level data (e.g., environ-mental concentrations). Stakeholders including researchers, local governments, industry associations, civil society organizations, and enterprises, are encouraged to participate as data providers, lending their expertise and knowledge. Moreover, it is imperative to achieve a more accurate understanding of recycling scenarios and emission factors of plastic additives. This necessitates experimental and field investigations, alongside enterprise consultations and expert interviews, to gather and localize data and gain real-world insights. Such efforts will help not only advance plastic recycling but assess the complicated impacts of emerging contaminants (Jian et al., 2022; Wang et al., 2021).

We also encourage the establishment of an overarching intergovernmental panel to foster the interactions among science, policy, and society on plastic additive management. Plastic pollution presents a global challenge that extends beyond environmental and human health concerns, with broader implications for socio-economics, intergenerational justice, and human rights. At the international level, various MEAs like the Basel, Rotterdam, and Stockholm Conventions, have addressed specific facets of global plastic governance and associated chemical issues, each with its mechanisms for disseminating knowledge on reducing plastic pollution. The proposed panel would serve as a centralized platform to prevent duplication and fragmentation of these agreements while encouraging collaborations on plastic additive management, facilitating a robust science-policy-society interface. Within the panel, scientists would further explore policy-oriented research on the driving factors, mechanisms, and scenario analysis of plastic additive cycles to shape future policies on plastic pollution control (refer to gap 4). Policymakers and society, in turn, would interpret the scientific evidence to craft plastic additive management strategies and promptly inform the scientific community on strategy-relevant scientific questions, potentially through participation in scientific conferences and communicating with research funding organizations (Wang et al., 2021).

Similar organizations, such as the Intergovernmental Panel on Climate Change (IPCC) focusing on climate change (Beck et al., 2017) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) focusing on biodiversity (Ruckelshaus et al., 2020), have been established. In the domain of chemical management, the International Panel on Chemical Pollution (IPCP) collects scientific knowledge about chemical pollution issues, including those related to plastics, and provides summaries and interpretations of the knowledge for policymakers and the public (International Panel on Chemical Pollution, 2008). The Science-Policy Panel (SPP) on chemicals, waste, and pollution prevention (UNEP, 2023b), aiming to contribute to the sound management of chemicals, is also under development.

Despite these efforts, there remains a lack of an independent intergovernmental organization with robust global influence specifically focusing on plastic additives. The establishment of an overarching intergovernmental panel on plastic additives management would be crucial to bridging existing gaps and strengthening the dialogue of science, policy, and society, thereby paving the way for developing a legally binding international treaty to address the plastic crisis

## TABLES AND FIGURES

**Table 1** Number of chemical additive cycles at different levels

| **Chemical additive** | **Global** | **Regional** | **Country** | **City** | **River basin or plant** | **Total** |
|---|---|---|---|---|---|---|
| PBDEs | 14 | 108 | 15 | 2 | 3 | 142 |
| HBCDD | 0 | 0 | 3 | 0 | 1 | 4 |
| DBDPE | 0 | 0 | 1 | 0 | 0 | 1 |
| PAEs | 0 | 3 | 7 | 0 | 0 | 10 |
| BPA | 0 | 0 | 3 | 0 | 1 | 4 |
| CPs | 4 | 28 | 4 | 0 | 0 | 36 |
| PFASs | 2 | 1 | 7 | 4 | 0 | 14 |
| PCBs | 54 | 0 | 0 | 0 | 2 | 56 |
| HF | 0 | 0 | 1 | 0 | 0 | 1 |
| No type specified | 0 | 0 | 1 | 0 | 0 | 1 |
| **Total** | 74 | 140 | 42 | 6 | 7 | 269 |

*Notes for the abbreviation of chemical additives: polybrominated diphenyl ethers (PBDEs); hexabromocyclododecane (HBCDD); decabromodiphenyl ethane (DBDPE); phthalate esters (PAEs); Bisphenol A (BPA); chlorinated paraffins (CPs); per- and polyfluoroalkyl substances (PFASs); polychlorinated biphenyls (PCBs); hydrofluoric acid (HF). More detailed information is available in the SI.

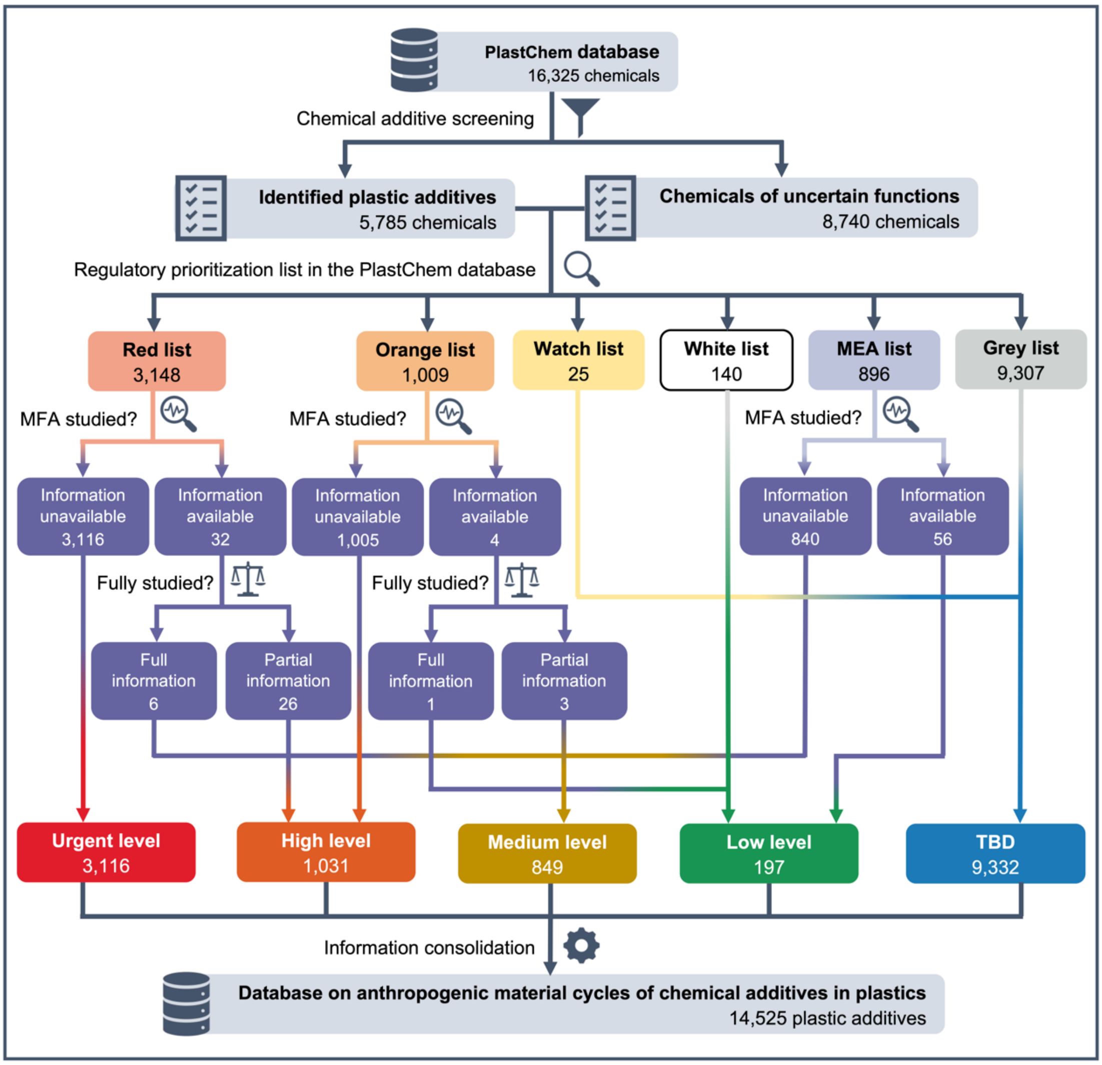


**Figure 1** Schematic overview of the workflow identifying research needs and priorities

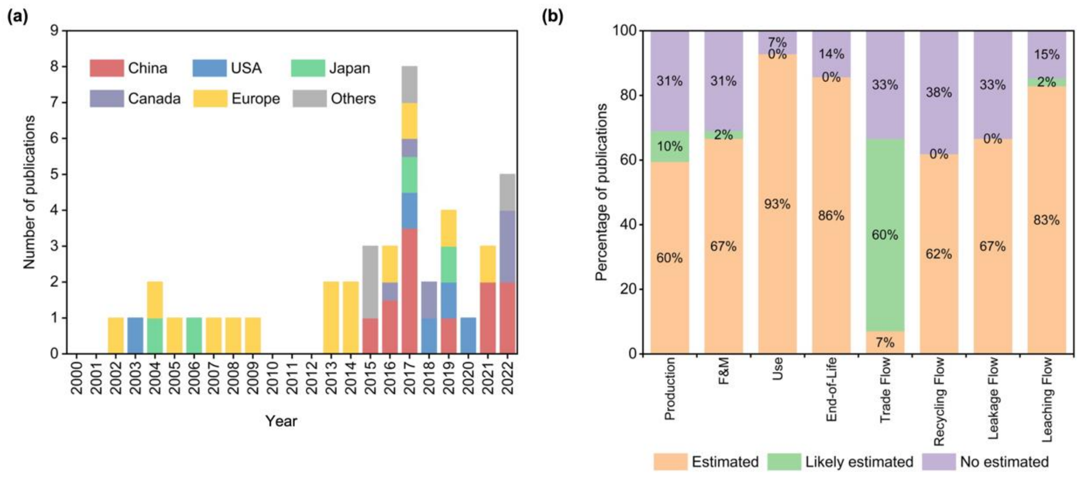


**Figure 2** Basic features of the reviewed publications. (a) Number of publications by region as a function of time. (b) Proportion of publications for different life-cycle stages and relevant flows. More detailed information is available in the SI.

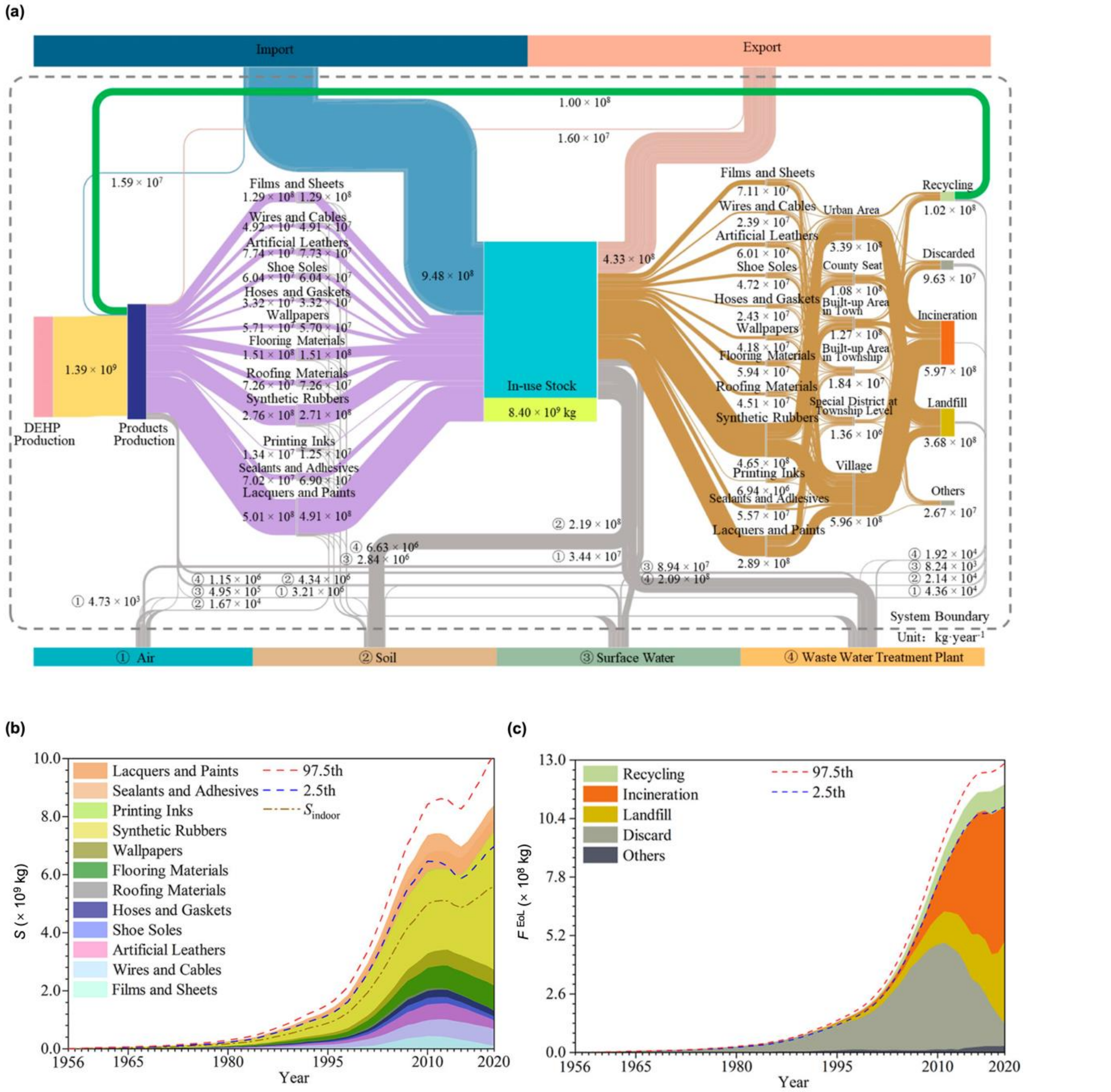

**Figure 3** An example of the chemical additive cycle (modified from Cui et al. (2022)): (a) anthropogenic cycle of DEHP for mainland China, 2020; the widths of the arrows roughly correspond to the relative magnitudes of the flows; (b) in-use stocks of DEHP by sector; (c) annual waste flows of DEHP by EoL treatment ways.

**(a)**

| Function | Urgent | High | Medium | Low | TBD |
|---|---|---|---|---|---|
| Colorant | 1283 | 472 | 386 | 83 | 1450 |
| Filler | 776 | 233 | 30 | 57 | 740 |
| Biocide | 494 | 124 | 175 | 33 | 426 |
| Stabilizer | 412 | 73 | 135 | 19 | 223 |
| Light stabilizer | 382 | 67 | 110 | 17 | 188 |
| Plasticizer | 312 | 92 | 17 | 29 | 433 |
| Odor agent | 336 | 110 | 6 | 35 | 356 |
| Antioxidant | 315 | 62 | 22 | 10 | 186 |
| Flame retardant | 122 | 39 | 30 | 19 | 179 |
| Heat stabilizer | 95 | 16 | 40 | 4 | 60 |
| Antistatic agent | 106 | 23 | 0 | 10 | 66 |
| Impact modifier | 5 | 6 | 0 | 2 | 18 |
| Adhesive | 1 | 0 | 0 | 0 | 5 |
| Anti-fog additive | 0 | 0 | 0 | 0 | 3 |
| Pigment | 0 | 0 | 1 | 0 | 1 |
| Ultraviolent-absorbing agent | 0 | 0 | 0 | 0 | 2 |
| Unspecified additive | 6 | 1 | 0 | 0 | 67 |
| Not available | 1120 | 359 | 375 | 81 | 6805 |

**(b)**

| Polymer | Urgent | High | Medium | Low | TBD |
|---|---|---|---|---|---|
| PET | 283 | 85 | 79 | 19 | 376 |
| HDPE | 254 | 83 | 209 | 27 | 239 |
| LDPE | 287 | 94 | 241 | 29 | 249 |
| PP | 215 | 70 | 82 | 17 | 217 |
| PVC | 327 | 85 | 100 | 22 | 285 |
| PS | 164 | 67 | 74 | 18 | 170 |
| EPS | 22 | 5 | 54 | 6 | 15 |
| ABS | 174 | 56 | 64 | 14 | 130 |
| HIPS | 48 | 11 | 58 | 7 | 20 |
| PC | 110 | 45 | 59 | 7 | 99 |
| PA | 269 | 85 | 67 | 23 | 492 |
| PUR | 273 | 61 | 73 | 18 | 137 |
| Other - Thermoplastic | 251 | 84 | 175 | 51 | 267 |
| Other - Bioplastic | 135 | 28 | 75 | 11 | 48 |
| Not available | 2169 | 811 | 490 | 110 | 8221 |

**(c)**

| Industrial sector | Urgent | High | Medium | Low | TBD |
|---|---|---|---|---|---|
| Packaging | 906 | 236 | 82 | 75 | 778 |
| Building & Construction | 995 | 203 | 96 | 67 | 486 |
| Automotive | 942 | 178 | 387 | 93 | 455 |
| Electrical and electronic equipment | 883 | 158 | 318 | 62 | 353 |
| Agriculture | 381 | 78 | 12 | 36 | 143 |
| Household items | 631 | 132 | 30 | 55 | 273 |
| Textiles | 1048 | 256 | 208 | 74 | 670 |
| Food-contact plastics | 804 | 212 | 20 | 64 | 653 |
| Not available | 1646 | 646 | 409 | 81 | 7987 |

**Figure 4** Number and distribution of plastic additives in different research priority levels. (a) by function. (b) by polymer. (c) by industrial sector. Detailed information for certain plastic additives is available in the SI.

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