Environmental Science & Technology

pubs.acs.org/est
Article

Material Cycles, Environmental Emissions, and Ecological Risks of Bisphenol A (BPA) in China and Implications for Sustainable Plastic Management

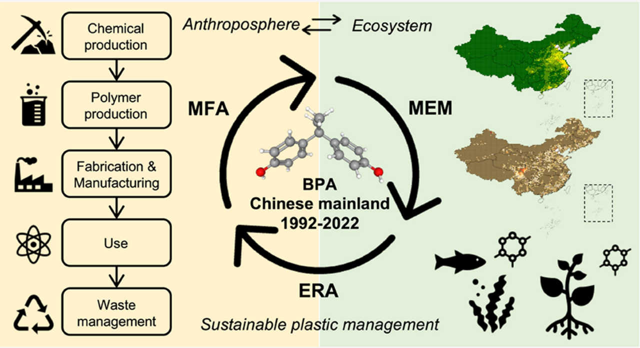
Jiayu Wang, Faith Ka Shun Chan,* Matthew F. Johnson,* Hing Kai Chan,* Yunhan Cui, Jingwen Chen, and Wei-Qiang Chen*

Cite This: *Environ. Sci. Technol.* 2025, 59, 1631−1646

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: Bisphenol A (BPA) is a high-production-volume plastic chemical, with ~98% of its usage in China allocated to producing polycarbonate and epoxy resin, and its fugitive release threatens ecosystems. However, knowledge of its anthropogenic cycles, environmental emissions, and ecological risks remains incomplete, hindering effective plastic lifecycle management. Herein, material flow analysis, multimedia environmental modeling, and ecological risk assessment were integrated to comprehensively map BPA dynamics in China. Results reveal a ~ 90-fold increase in BPA consumption between 1992 and 2022 and major applications shifted from optics and packaging to automotive, construction, and electronics. China held ~34 Mt of in-use BPA stock in 2022 (~24 kg per capita), with no indication of reaching saturation. BPA release occurred throughout its lifecycle, and soil and water were primary sinks. Aquatic BPA concentrations exceeded the limit in national pollutant emission standards in ~8.4% of Chinese mainland areas in 2022, and ~4.5% of areas suffered very high chronic ecological risks to aquatic organisms. Scenario analysis indicates that a 90% reduction in BPA emission factors would be required to avoid BPA contamination in all areas of focus. Our findings contribute as a scientific basis for sustainable plastic management and highlight the need for updated techniques, intensified monitoring, and standardized regulations.



KEYWORDS: *plastic chemical, bisphenol A, material flow analysis, environmental concentration, ecological risk level, plastic management*

1. INTRODUCTION

The exponential growth in plastic production and usage has precipitated global concerns about plastic pollution and management strategies.[1,2] In response, the United Nations Environment Assembly (UNEA) endorsed a landmark resolution in 2022 for a legally binding international agreement to eliminate the plastic crisis by the end of 2024. Chemicals of concern in plastics are a key aspect of the treaty. Over 16,000 types of chemicals have been identified in plastics, with at least 4200 categorized as "major concerns" due to their Persistence, Bioaccumulation, Mobile or/and Toxicity (PBMT) properties.[3−6] These chemicals are inevitably released throughout the lifecycle of plastics, posing severe threats to planetary health.[7−9] Therefore, it is imperative to focus on the lifecycle management of plastic chemicals to develop effective strategies for mitigating plastic pollution.

Bisphenol A (BPA), a high production volume (HPV) plastic chemical,[10] bolsters the strength, durability, resilience, and transparency of plastic materials. Global BPA consumption increased from 2.8 million tonnes (Mt) in 2002 to 6.2 Mt in 2020, outpacing other high-concern plastic chemicals like diethylhexyl phthalate (DEHP)[11] and polybrominated diphenyl ethers (PBDEs).[12] This upward trend is expected to continue, driven by the extensive applications of BPA in electronics, automobiles, buildings, and packaging sectors.[13,14] Given its widespread use, BPA has been detected in diverse media, including soil, sediment, atmosphere, water, municipal waste, food, and biota.[15,16] Identified as an endocrine disruptor and listed as a substance of very high concern (SVHC) under the REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) regulation,[17] BPA is linked to numerous environmental and health issues, notably impacting reproductive, immune, and neuroendocrine systems through dietary, inhalation, and dermal exposure.[18−20] Moreover, BPA substitutes, such as bisphenol S (BPS) and bisphenol F (BPF),

Received: September 17, 2024
Revised: December 16, 2024
Accepted: December 17, 2024
Published: December 26, 2024

https://doi.org/10.1021/acs.est.4c09876

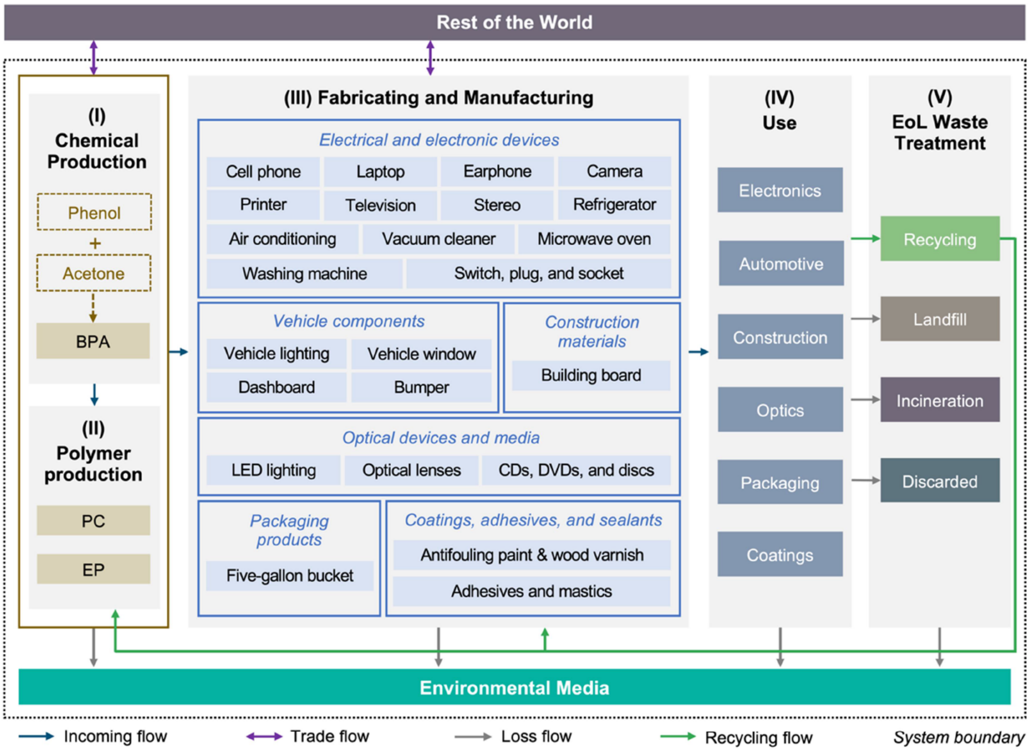


Figure 1. Material flow analysis (MFA) model framework for BPA in the mainland of China.

also exhibit endocrine-disrupting effects due to their analogous molecular structures.[21,22] These problematic properties have positioned BPA at the forefront of the intergovernmental negotiations on plastic pollution. It has been included in the "ban or elimination" list proposed by Norway, Cook Islands, and Rwanda;[23] and featured in Annex A of the European Union's text proposal on chemicals of concern in plastic and plastic products.[24] As the only representative of the bisphenols category in these regulatory proposals, BPA's pervasive use and associated risks highlight the urgency of its inclusion in lifecycle management frameworks to combat the plastic crisis.

China is the world's largest producer, consumer, and importer of BPA, representing approximately a quarter of global consumption, driven by its polycarbonate polymer (PC) and epoxy resin (EP) plastic industries.[25,26] Due to health concerns, the Chinese government has prohibited the import and sale of BPA-containing baby bottles since 2011[27] and imposed limits on BPA content in express packaging (GB 43352-2023) and food contact plastics (GB 4806.7-2023). Chinese industries, including the automotive sector,[28] are evaluating the impacts of BPA restrictions on downstream industries and pursuing green alternatives to meet corporate criteria. However, many BPA-containing products remain exempt from these regulations, and the full scale of the Chinese BPA industrial chain remains unclear due to insufficient information. Given the pressing management requirements for plastic and the lack of relevant knowledge, there is an urgent need to establish a robust scientific basis for BPA management in China, which will also be critical to tackling the global plastic problem.

Developing a systematic macroscopic understanding of the sources and sinks of BPA, alongside tracing the interconnected flows from a life-cycle perspective, are core prerequisites for informing management decisions. Material flow analysis (MFA) is an effective tool for obtaining such information by assessing the flows and stocks of materials within a system defined in space and time.[29−31] Numerous studies have used MFA to understand the anthropogenic cycles of elements,[32,33] products,[34,35] and materials,[36,37] demonstrating its advantages in informing policy decisions for sustainable resource management, waste treatment, and circular economy transition. However, MFA studies focusing on plastic chemicals, particularly BPA, are still in the nascent stage.[38] Few studies have examined the material flows of BPA, confined to specific industries[39] or regions,[25,40] and their applicability to the current BPA landscape in China remains limited due to variations in waste management, phase-out practices, and downstream applications, as well as incomplete consideration of lifecycle stages and flows.

Assessing the environmental exposure concentrations and determining the ecological risk levels of BPA are also core prerequisites for informing management decisions. Multimedia environmental models (MEMs) are widely used as decision-support tools by government agencies to describe the behavior of target chemicals by integrating their emission inventories, intrinsic properties, and ambient attributes of a system.[41,42] Typical MEMs, such as QWASI,[43,44] Globo-POP,[45,46] and BETR,[47,48] have been adopted to predict concentrations, fates, and distributions of chemicals across multiple environmental compartments, providing a rational basis for chemical risk management.[49] However, these models may not fully account for the unique conditions of China due to differences in applicable scales and ambient attribute parameters. Once environmental concentrations are determined, the ecological risk analysis (ERA) method can be applied to evaluate the levels and severity of risks associated with chemical exposure.[50,51] Despite extensive ERA research,[52−54] most studies rely on experiment data for chemical concentrations, restricting the scope and efficiency of the analysis.

https://doi.org/10.1021/acs.est.4c09876
Environ. Sci. Technol. 2025, 59, 1631−1646

Table 1. Parameters Used to Estimate BPA Flows

		parameters		
		market share (*P*)	weight (*W*)	content factor (*C*)
polymers	PC	95%[71]		90 wt %[25,72]
	EP	90%[71]		70 wt %[72]
final products	cell phone	17%[73]		0.4 kg PC per cell phone[56]
	laptop	100%[74]		2 kg PC per laptop[74]
	earphone	21%[73]	In the enclosure: <0.2 kg per unit	2.6 wt %[25]
	camera	15%[73]	In the enclosure: >0.5 kg per unit	2.6 wt %[25]
	printer	10%[73]		25 kg PC per printer[56]
	television	72%[73]		2 kg plastic per television[56]
	stereo	33%[73]	In the enclosure, diaphragm, and bracket: 1 kg per unit	2.6 wt %[25]
	air conditioning	62%[73]	In the electric control box shell, wind deflector, and air outlet grille: 100 kg per unit	2.6 wt %[25]
	refrigerator	21%[73]	In the lampshade, inside shelf, and relay: <50 kg per unit	70 wt %[56]
	washing machine	56%[73]	In the cover plate and display panel: 50 kg per unit	2.6 wt %[25]
	vacuum cleaner	7%[73]	In transparent fittings: <10 kg per unit	2.6 wt %[25]
	microwave oven	6%[73]	In the case material: >20 kg per unit	2.6 wt %[25]
	switch, plug, and socket	90%[56]		0.0032 kg PC per switch, plug, and socket[56]
	vehicle lighting	50%[56]		2.1 kg PC per vehicle lighting[56]
	vehicle window	1%[73]		6 kg PC per m^2 vehicle window[75]
	dashboard	100%		0.84 kg PC per dashboard
	bumper	100%		0.338 kg PC per bumper
	building board	40%		22.5 wt %[25]
	LED lighting	36%[73]		0.1 kg PC per LED lighting[76]
	optical lenses	10%[56]	0.01 kg per unit	0.03202 wt %[77]
	CDs, DVDs, and discs	100%[74]		0.01818 kg PC per optical disc[74]
	five-gallon bucket	12%[78]	0.78 kg per unit	0.76 kg PC per five-gallon bucket[74]
	antifouling paints and wood varnish	70%		40 wt %[79]
	adhesives and mastics	3%[80]		20 wt %[79]

Here we adopted a method combining MFA, MEM, and ERA to bridge the knowledge gaps in China's lifecycle management of BPA amid the plastic crisis. Notably, this approach provides a comprehensive coverage of processes, polymers, products, periods, and the real-world conditions of the Chinese plastic industry and environment. First, we established an MFA framework including all lifecycle stages and flows and traced the three-decade dynamic flows, stocks, and emissions of BPA across six key sectors in the mainland of China. Based on the emission flows, we employed a spatially explicit MEM parametrized for China to quantify BPA exposure concentrations in different environmental media. Combining the predicted concentrations with the hazard properties of BPA, we assessed the probability, magnitude, and acceptability of BPA risks to ecosystems and their components. We additionally explored the potential of phasing out, substituting, and optimizing production technologies to mitigate BPA pollution. The implications of the findings for sustainable plastic management and BPA risk management were finally discussed.

2. MATERIALS AND METHODS

2.1. Spatiotemporal Boundary. Given the dominant role of the mainland of China in the production of BPA and its associated polymers,[55,56] the study confines its spatial boundary to the Chinese mainland. According to the scientific literature[57] and expert consultations, the industrial production of BPA in China commenced in 1992 at the Wuxi Resin Factory (now Bluestar Nantong Star Synthetic Materials Co., Ltd.), the temporal scope of the study therefore spans from 1992 to 2022 to capture the long-period evolution of BPA dynamics.

2.2. Material Flow Analysis Model. *2.2.1. Model Conceptualization.* Figure 1 outlines the model structure for BPA material flows in the mainland of China from 1992 to 2022. The model is characterized by five lifecycle stages of BPA (I–V): from (I) chemical production, where BPA is synthesized from phenol and acetone; into (II) polymer production, where BPA is involved in polymerization reactions to produce plastic polymers; into (III) fabricating and manufacturing (F&M), where these polymers are processed into plastic materials and used in fashioning finished products; followed by (IV) use, where these BPA-containing products enter the market for consumption; and culminating in (V) End-of-Life (EoL) waste treatment, where these products are disposed of and managed within waste and recycling systems upon reaching the end of their service life.

In China, approximately 98% of BPA is consumed by the PC and EP plastic industries.[18,58] This study incorporated flows and stocks of BPA contained in the two industries. These plastic polymers are mostly used as the building blocks for 24 kinds of key end-consumer products (Figure 1) that were identified through consultations with experts from the China Synthetic Resin Association (CSRA) and the leading Chinese polymer manufacturing companies. These products span six downstream sectors, including electronics, automotive, construction, optics, packaging, and coatings. At the end of their service life, these products enter waste streams, contributing to various forms of plastic waste in China, which are commonly subject to recycling, landfilling, incineration, or dispersed into the environment (i.e., improperly discarded).[59] Trade flows across the system boundary, including imports and exports of BPA, plastic polymers, and associated products between China and the rest of the world, were factored into the study scope. However, BPA contained in traded waste was excluded due to insufficient data. Additionally, the life-cycle emissions of BPA into different environmental media, including the atmosphere, soil, and water bodies, were estimated to elucidate its environmental fates and ecological impacts.

2.2.2. Data Compilation and Accounting. Based on the developed analytical model, combined with collected data (detailed below) and identified parameters, the dynamic flows and stocks of BPA in the mainland of China were quantified using the top-down MFA approach.

In stages (I)−(III), the material flows of BPA (F^{BPA}, measured in kilogram, kg) in these stages include domestic production ($F^{\mathrm{BPA}}_{\mathrm{domestic production}}$), consumption ($F^{\mathrm{BPA}}_{\mathrm{consumption}}$), imports ($F^{\mathrm{BPA}}_{\mathrm{import}}$), exports ($F^{\mathrm{BPA}}_{\mathrm{export}}$), and emissions ($F^{\mathrm{BPA}}_{\mathrm{emission}}$). Each type of BPA-containing polymer and product adheres to the following mass conservation principle (eq 1), where the left and right sides denote the inputs and outputs of each process, respectively.

$$F^{\mathrm{BPA}}_{\mathrm{domestic production}} + F^{\mathrm{BPA}}_{\mathrm{import}} = F^{\mathrm{BPA}}_{\mathrm{consumption}} + F^{\mathrm{BPA}}_{\mathrm{export}} + F^{\mathrm{BPA}}_{\mathrm{emission}} \tag{1}$$

Annual domestic production data were retrieved from the China Industry Statistical Yearbooks, China petrochemical economic analysis reports,[60−62] industrial reports, and scientific literature,[25,63] measured in kg or the number of units. Cross-border statistics were mainly obtained from the advanced UN Comtrade database[64−66] using specific Harmonized System (HS) codes: 290723 for BPA, 390740 for PC, and 390730 for EP, all measured in kg. Product-specific HS commodity codes are provided in Table S1. For items lacking registered HS codes, data were collected from industrial reports and scientific literature.[25,63] Emissions were quantified by multiplying production activity data by corresponding emission factors. Emission factors were derived from the Technical Guideline for the Assessment of Environmental and Health Exposures to Chemical Substances of the Ministry of Ecology and Environment (MEE),[67] which is applicable to various emission scenarios (e.g., different sectors, lifecycle stages, operating conditions, and applications), as well as from scientific literature.[15,68−70] Details for the inputs are available in Table S2.

Since the material flows of BPA represent the mass of BPA within BPA-containing products, each type of BPA flow (F^{BPA}) was estimated by multiplying the material flow for BPA-containing product (F^{product}, measured in the number of units) by a series of parameters, as shown in eq 2. These parameters, as shown in Table 1, include (1) P^{product} (in percentage): the market share of PC- or EP-containing products, also referred to as the penetration of these products, reflecting the proportion of product numbers to the total when the content factor is measured in mass per unit and the mass share when measured in weight percentage; (2) W^{product} (in mass per unit): the weight of BPA-containing product; (3) C^{polymer} (in weight percentage or in mass per unit): the content factor of PC or EP in product; (4) P^{polymer} (in percentage): the market share of BPA-containing PC or EP, representing the mass proportion of these polymers; and (5) C^{BPA} (in weight percentage or in mass per unit): the content factor of BPA in PC or EP.

$$F^{\mathrm{BPA}} = F^{\mathrm{product}} \times P^{\mathrm{product}} \times W^{\mathrm{product}} \times C^{\mathrm{polymer}} \times P^{\mathrm{polymer}} \times C^{\mathrm{BPA}} \tag{2}$$

In stage (IV), BPA accumulates in finished consumer products that are currently in active use, forming in-use BPA stocks ($S^{\mathrm{BPA}}_{\mathrm{in-use}}$).[81] These stocks represent the difference between BPA flows entering ($F^{\mathrm{BPA}}_{\mathrm{consumption}}$) and leaving ($F^{\mathrm{BPA}}_{\mathrm{EoL}}$) from the stage. The accumulated BPA in-use stocks for each product in year i were calculated as follows (eq 3). For the initial year, the BPA in-use stocks ($S^{\mathrm{BPA}}_{\mathrm{in-use},1991}$) were assumed to be zero.

$$S^{\mathrm{BPA}}_{\mathrm{in-use},i} = S^{\mathrm{BPA}}_{\mathrm{in-use},i-1} + F^{\mathrm{BPA}}_{\mathrm{consumption},i} - F^{\mathrm{BPA}}_{\mathrm{EoL},i} \tag{3}$$

In stage V, BPA wastes flowing into this stage ($F^{\mathrm{BPA}}_{\mathrm{EoL}}$) were estimated using the lifetime model, assuming that the life expectancy distribution of each BPA-containing consumer product follows a normal distribution, as shown in eqs 4 and 5.

$$F^{\mathrm{BPA},j}_{\mathrm{EoL},t} = \sum_{i=1992}^{i=t} F^{\mathrm{BPA},j}_{\mathrm{consumption},i} \times P_i^{t,j} \tag{4}$$

$$P_i^{t,j} = \int_{t-1}^{t} \frac{1}{\sigma_j \cdot \sqrt{2\pi}} \exp\left(-\frac{\left(t-i-\mu_j\right)^2}{2\sigma_j^2}\right) \cdot \mathrm{d}t \tag{5}$$

where $P^{t}_{i,j}$ represents the probability that product j, produced in year i, reaches its EoL in year t; μ_j and σ_j^2 represent the mean and standard deviation of the lifespan for product j, respectively (Table S3), and were collected from the national standard,[82] plastic industry development blue book,[56] and market surveys. The BPA wastes treated by each EoL method were quantified by multiplying the total EoL BPA waste flows for each year by the proportion allocated to each EoL treatment method (Table S4). These annual proportions were derived from the government report,[83] plastic industry development reports,[84,85] China Plastic Industry Yearbooks, and scientific literature.[63,86−88]

BPA accumulates in wastes within landfills ($F^{\mathrm{BPA}}_{\mathrm{EoL-landfill}}$), forming BPA waste stocks ($S^{\mathrm{BPA}}_{\mathrm{waste}}$), estimated as eq 6. The waste stocks of BPA for the starting year ($S^{\mathrm{BPA}}_{\mathrm{waste},1991}$) were assumed to be zero.

$$S^{\mathrm{BPA}}_{\mathrm{waste},i} = S^{\mathrm{BPA}}_{\mathrm{waste},i-1} + F^{\mathrm{BPA}}_{\mathrm{EoL-landfill},i} - F^{\mathrm{BPA}}_{\mathrm{emission-landfill},i} \tag{6}$$

where $F^{\mathrm{BPA}}_{\mathrm{emission-landfill},i}$ represents BPA emissions in the landfill process in year i.

2.3. Multimedia Environmental Model.

The MFA-derived emission flows were geographically allocated into 5506 interconnected grid cells (0.5° × 0.5°) using surrogate data retrieved from the National Bureau of Statistics, including gross regional production (GRP, for emissions production and F&M stages), population (for emissions from in-use stocks), and delivering quantity of house refuse (for emissions from EoL management stage). These allocations cover the 31 provinces of the Chinese mainland to derivate total BPA emission inventories.

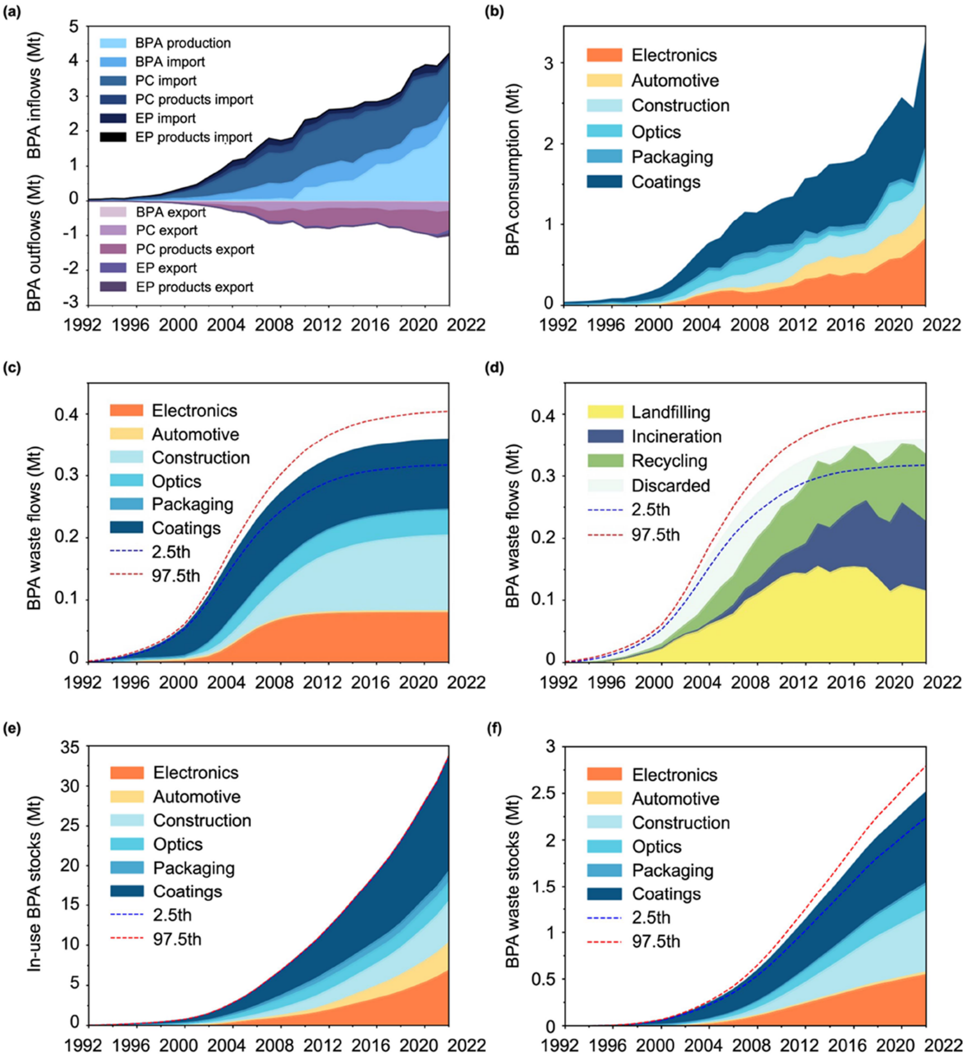


Figure 2. BPA flows through domestic production and cross-border trade (a), BPA flows through consumption by end-use sector (b), BPA waste flows by end-use sector (c), BPA waste flows by EoL treatments (d), BPA in-use stocks by end-use sector (e), and BPA waste stocks by end-use sector (f) from 1992 to 2022 in the mainland of China. The PC (products) import, EP (products) import, PC (products) export, and EP (products) export in (a) represent BPA flows embedded in these polymers or products. The uncertainty range is indicated by the area between the dash lines, suggesting that 95% of simulated values lie in this range.

Based on the developed BPA emission inventories, environmental concentrations of BPA in environmental compartments across China were estimated by the multimedia environmental model (MEM). The Sino Evaluative Simplebox-MAMI Model (SESAMe v3.4 model),[89] specifically parametrized and spatially tailored for the Chinese mainland, was employed. The model inputs include the developed BPA emission inventories, physicochemical parameters of BPA (Table S5) sourced from the PubChem database and scientific literature,[15,90] as well as environmental attribute parameters of the Chinese mainland that are built into the model. The model generates the BPA concentration distributions in air, water, and soil in China with a spatial resolution of 0.5°, serving as outputs.

2.4. Ecological Risk Assessment. Based on the MEM-simulated environmental exposure concentrations, an ecological risk assessment (ERA) was conducted to inform BPA risk management strategies in China. The risk quotient (RQ) approach, widely used and recognized for its simplicity, operational ease, and intuitive interpretation, was adopted to quantitatively characterize the ecological risks associated with BPA.[91] The RQ was calculated by dividing the predicted environmental concentration (PEC, in mol·m^{-3}) by the predicted no-effect concentration (PNEC, in mol·m^{-3}), as represented in eq 7. The PNEC was determined based on the assessment factor (AF) method,[92] as specified in eq 8. This method prioritizes the most sensitive ecotoxicity end-point values—whether acute or chronic—for aquatic, terrestrial, and sediment species and plants (Table S6). An AF of 1000 is applied when acute toxicity data are the most sensitive, while an AF of 10 is used for chronic toxicity data.[92]

$$\mathrm{RQ}_{m,i} = \mathrm{PEC}_{m,i}/\mathrm{PNEC}_{m} \tag{7}$$

$$\mathrm{PNEC}_{m} = L(E)C_{50,m}/\mathrm{AF} \text{ or } \mathrm{NOEC}_{m}/\mathrm{AF} \tag{8}$$

where m refers to a specific environment compartment; i represents a specific year. The half-lethal concentration (LC$_{50}$) and half-effect concentration (EC$_{50}$) serve as acute toxicity indices, while the no observed effect concentration (NOEC) is utilized as a chronic toxicity index, sourced from the US EPA

https://doi.org/10.1021/acs.est.4c09876

Ecotoxicology (ECOTOX) database and European Union Risk Assessment Report.[93] Different RQ values indicate varying levels of ecological risks: RQ < 1 suggests no significant risk, 1 ≤ RQ < 10 suggests low potential risk, 10 ≤ RQ < 100 suggests high risk, and RQ ≥ 100 suggests very high risk.

2.5. Uncertainty Characterization. The results of MFA studies may be subject to uncertainties arising from data sources, data quality, study assumptions, and parameter determination.[94] In the current case, production and trade data on BPA, PC, EP, and their associated products were mainly obtained from Chinese government agencies, Chinese industrial associations, and the United Nations Statistics Division, which are officially registered and thus considered reliable.

To address data limitations before 2000, linear or exponential interpolation methods are applied based on the trend of existing data. In instances of missing data spanning certain years, the average of adjacent years was used to interpolate the gaps to maintain the overall trends of the data in time series and minimize potential biases. Given that BPA consumption before 2000 constituted only ~1.1% of the temporal boundary (1992–2022), uncertainties from this period are believed to have minimal impact on the overall findings.

Parameters, including market shares of BPA-containing polymers and products, content factors of BPA and polymers, emission factors of each life-cycle stage, and life expectancy of each product, were used to determine the BPA flows in finished products and wastes. To examine the sensitivity of model outputs in response to these input parameters, local sensitivity analyses were conducted. Each individual parameter (I) was scaled by 10% above and below its baseline levels (I_0) at a time, and the elasticity of model outputs (E) relative to their present values was measured, as expressed in eq 9.

$$S = \left.\frac{\partial E/E}{\partial I/I}\right|_{I=I_0} = \frac{1}{20\%}\cdot\frac{E_{I=I_0\cdot 110\%} - E_{I=I_0\cdot 90\%}}{E_{I=I_0}} \tag{9}$$

As shown in Figure S1, the absolute value of S ($|S|$) is generally close to zero or moderately sensitive ($|S| < 1$) to changes in most input parameters, indicating robust and reliable results despite input variability. Notably, the average lifetime of BPA-containing products emerges as a highly influential parameter, affecting the outputs of waste flows and stocks, with $|S|$ values reaching 1.7 and 1.3, respectively, in 2022. Despite efforts to compile such information, data on average lifetimes remains uncertain or unavailable for many products, likely due to immense temporal and spatial variability in product life spans.[95] Addressing this gap is crucial for ensuring simulation accuracy, necessitating the acquisition of reliable and comprehensive lifespan data across diverse product categories.

To understand the impact of different choices for the key parameter (i.e., the average lifetime of each product) on the results, a Monte Carlo simulation was further conducted, assuming the key parameter follows a normal distribution.[96] For each data point, random parameter values were generated 10,000 times based on the probability distribution, resulting in a set of simulation outputs. From these outputs, a 95% confidence interval was established, corresponding to the 2.5th and 97.5th percentiles of the probability distribution. This confidence interval provides a data range that allows decision-makers to formulate policies by adopting results with fewer deviations. Results show that key parameters have lower coefficients of variation (with a maximum value of ~10%), suggesting less data volatility and greater certainty of the results.

3. RESULTS

3.1. Evolution of BPA Material Flows and Stocks. Since 1992, the annual flows of BPA into the mainland of China have surged over 40-fold, peaking at about 4.2 million tonnes (Mt) in 2022 (Figure 2a). This increase corresponds with the expansion of production capacities among Chinese enterprises in recent years,[55] leading to a shift in BPA sources from primarily imported primary products (i.e., BPA, PC, and EP) to domestic production. Domestic production and imports of BPA raw material, alongside imports of BPA-containing polymers, collectively constituted ~92% (1.6 Mt) of the total BPA inflows, serving as the primary BPA sources in the mainland of China. In contrast, BPA embedded in imported products accounted for only ~8.0% of the total inflows.

Annually, China's BPA outflows have also seen significant growth (Figure 2a), reaching a maximum of 1.1 Mt in 2021. The largest contributors to BPA outflows were exports of PC (~32% of total outflows) and its finished products (~47% of total outflows), serving as the primary pathways for BPA leaving the Chinese mainland. Given the large inflows relative to the minor outflows, China has become a major BPA net accumulator, holding substantial BPA stocks, with an annual net accumulation averaging around 1.2 Mt.

Figure 3 shows the overview of BPA material flows in 2004, 2013, and 2022, highlighting the development in China's BPA industry over the past two decades. China has achieved self-sufficiency in EP production, with domestic BPA production meeting approximately 60, 89, and 96% of the country's EP demand, respectively. Conversely, the demand for PC heavily relied on BPA imports in 2004 (99%) and 2013 (75%). By 2022, this trend had reversed, with over 68% of PC demand being fulfilled by domestically produced BPA, fueled by the expansions in the Chinese BPA production capacity since 2010.[57,97]

The demand for BPA has surged, fueled by increased usage of PC in the automotive, construction, and electronics sectors, and EP in the coatings sector. BPA consumption grew from 0.77 Mt in 2004 to 1.6 Mt in 2013, and to 3.3 Mt in 2022, reflecting an average annual growth rate of 9.6% (Figure 2b). Notably, a shift in sectoral consumption patterns occurred during this period. In 2004, the optics sector ranked the third largest after coatings and electronics in BPA consumption. However, with the advent of streaming media reducing the need for physical discs, BPA consumption in optics declined. By 2013 and 2022, the construction and automotive sectors had overtaken optics.

The consumption growth has led to a doubling of BPA waste flows, from 1.7 Mt in 2004 to 3.6 Mt in 2022, largely due to the generation of construction waste and e-waste (Figure 2c). Most BPA waste ended up in landfills, although recycling and incineration have become more prevalent (Figure 2d). In 2022, cumulative BPA waste amounted to 6.4 Mt, with nearly 40% landfilled, ~25% recycled, and ~19% incinerated. The proportion of recycled BPA has increased from 20% in 2004 to 30% in 2022.

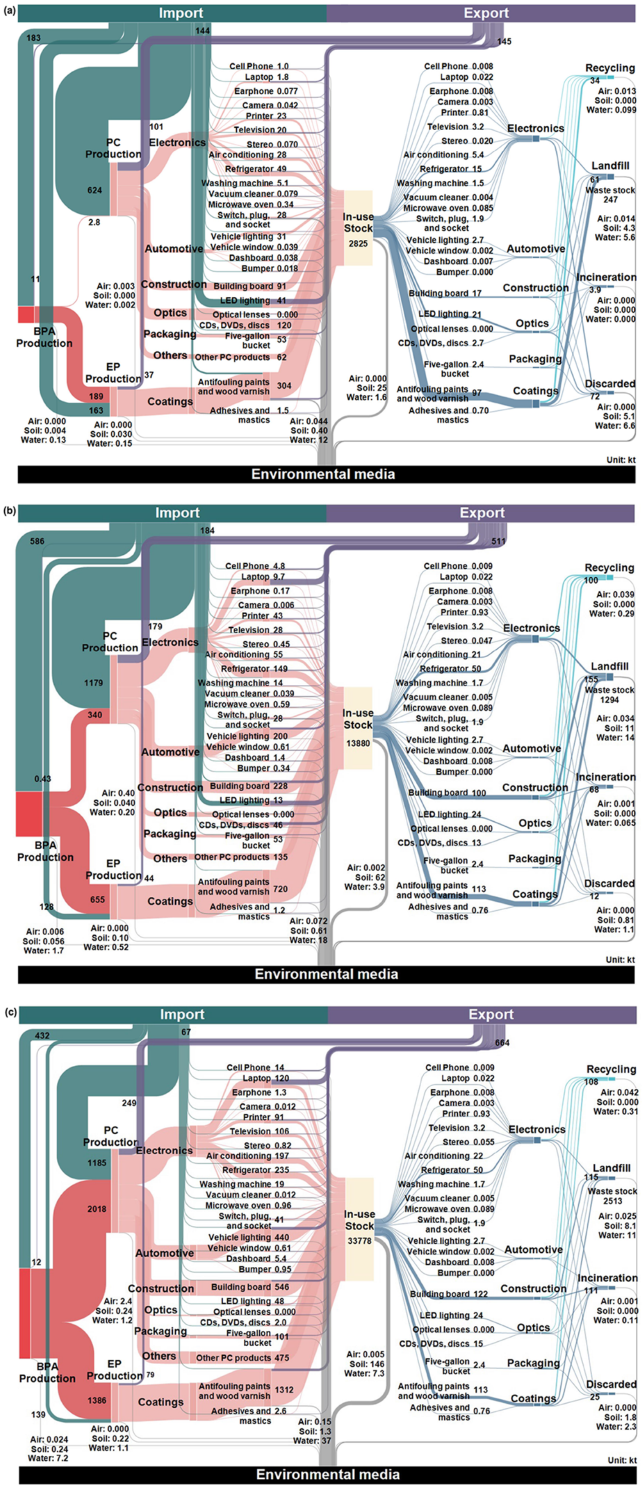


Figure 3. Overview of BPA material flows in the mainland of China in 2004 (a), 2013 (b), and 2022 (c).

The in-use BPA stocks have witnessed a remarkable surge from 1992 to 2022 (Figure 2e). As of 2022, the total in-use stocks of BPA reached ~34 Mt, marking an over 455-fold increase compared to 1992. The coatings (14 Mt, ~43%), electronics (6.9 Mt, ~20%), and construction (5.2 Mt, ~15%) sectors were the primary contributors, with key sources including antifouling paints and wood varnish, PC building boards, and refrigerators (Figure S2). The in-use BPA stock per capita reached an estimated 24 kg in 2022 (Figure S3). The average annual increase in BPA in-use stocks per capita, defined as the difference between annual per capita BPA consumption and annual per capita BPA waste flows, increased from 0.030 kg in 1992 to 2.1 kg in 2022, with the upward trend expected to continue.

Landfilling remains the dominant method of EoL management for BPA, resulting in substantial waste stocks (Figure 2f). BPA waste stocks had accumulated to 2.5 Mt by 2022. Before 2010, the coatings sector dominated BPA waste stocks, responsible for over 50% of the total. However, since 2010 BPA waste stocks from building materials have increased, reaching 0.66 Mt in 2022 and accounting for ~26% of total waste stocks. E-waste stocks have also experienced significant growth, approaching 0.55 Mt (~22%) in 2022. This trend can be attributed to the rapid advancement of urbanization and digitalization in China, along with variations in the service life of different end-consumed products.

Figure 4 shows the BPA emissions by environmental compartment, sector, and life cycle stage. Total BPA emissions in the mainland of China have grown dramatically, from 0.008 Mt in 1992 to 0.23 Mt in 2022. Among these emissions, ~65% seeped into the soil, ~34% infiltrated water bodies, and ~0.58% entered the atmosphere (Figure 4a), indicating the prominent roles of soil and water as recipients of BPA within the Chinese mainland. Soil contamination mainly originated from the use of BPA-containing products, representing ~84% of total BPA soil emissions, whereas water contamination largely arose from F&M (~47%) and waste management practices (~38%), particularly landfilling and inappropriately discarded items. Atmospheric pollution mainly resulted from polymer production, comprising nearly 80% of total BPA air emissions.

From a sectoral perspective (Figure 4b), BPA emissions were highly concentrated in the construction and coatings sectors, collectively contributing ~88% of the cumulative BPA emissions in the mainland of China. This is likely to be attributable to the high BPA consumption in these sectors, alongside the prolonged service life of building PC boards and EP paintings. From a life cycle perspective (Figure 4a), the use stage emerged as the leading contributor of BPA emissions, responsible for nearly 58% of the total, followed by the EoL management stage at ~23%.

3.2. Environmental Fates, Distribution, and Ecological Risk Levels of BPA.

Figure 5 presents the spatially resolved overview of BPA concentrations, which generally increased across all environmental media during the past two decades. In some regions, BPA levels in water bodies exceeded the upper limit (0.1 mg L^{-1}) set by the national pollutant emission standards for the petroleum chemistry industry (GB 31571-2015, revised in 2024) and the synthetic resin industry (GB 31572-2015, revised in 2024). In 2004, 0.65% of areas in the mainland of China had BPA concentrations surpassing the limit, rising to ~3.5% in 2013 and ~8.4% in 2022. The regions with the highest levels of contamination in 2022 were mostly located in Sichuan (accounting for ~20% of the total polluted areas), followed by Shanxi (~9.5%), Shandong (~6.9%), Hebei (~6.7%), and Shaanxi (~6.5%).

Geographically, BPA levels were visibly higher in coastal areas located in eastern, southern, and southwestern inland China. Airborne BPA concentrations were centralized in the Beijing-Tianjin-Hebei province cluster, Yangtze River Delta, and Pearl River Delta, correlating with their significant gross regional production and economic activities. Similarly, high

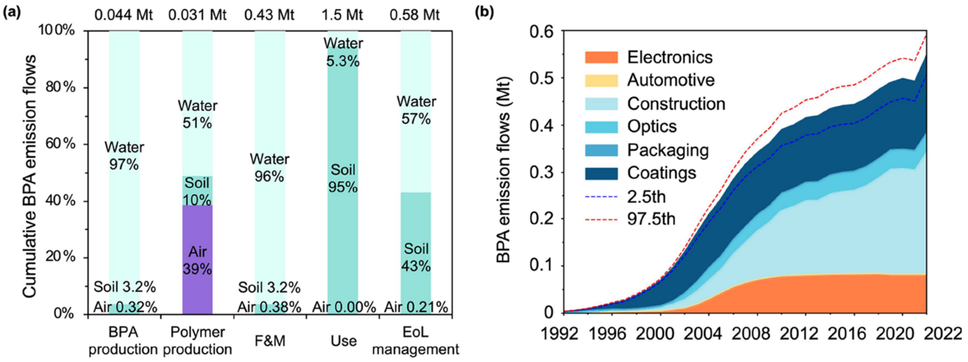


Figure 4. BPA emissions by life cycle stage (a) and by end-use sector (b) from 1992 to 2022 in the mainland of China. The uncertainty range is indicated by the area between the dash lines, suggesting that 95% of simulated values lie in this range.

BPA concentrations were observed in the soil, water, sediments, and vegetation of Sichuan and Beijing. This is likely due to (1) the thriving manufacturing industries and urban household refuse-delivering infrastructures in Beijing responsible for BPA pollution in water bodies;[98] and (2) the extensive urban soil areas, unique basin topography, and meteorological condition, alongside substantial runoff loss from water to the soil in Sichuan,[99] combined with vegetation interception, exacerbating BPA contamination in soil and vegetation. A comparison between modeled concentrations and literature-reported measurements[100−120] reveals that average concentrations deviated by 1−2 orders of magnitude in most environmental compartments (Figure S4). This difference magnitude is consistent with previous studies,[63,121] indicating the need for targeted pollution control measures and more environmental monitoring to better validate modeling approaches and assess accuracy.

Increasing environmental concentrations of BPA have led to increased ecological risks, particularly chronic risks, as shown in Figure 6. Organisms living in aquatic environments, including pelagic and benthic organisms, faced the most severe risks, whereas those that burrowed into soils and terrestrial plants were at a much lower risk of harm (RQs < 1). In 2022, approximately 4.5% of the mainland of China encountered very high chronic risks to pelagic organisms, with an additional ∼27% facing high chronic risks. For sediment-burrowing organisms, ∼0.56% experienced very high acute risks, and ∼10% faced high acute risks.

Spatial analysis indicates that ecological risks were more pronounced in BPA contamination hotspots and their surroundings, including Chongqing, Guizhou, Shanxi, Shaanxi, Henan, Shandong, Fujian, and Zhejiang provinces. Such a dispersive pattern, compared to the centralized pattern of concentrations, reflects a "space-time lag" caused by the persistence, bioaccumulation, and long-range environmental transport of BPA.[90] This results in prolonged exposure, delayed risks, and broader distributions as BPA persists in the environment bioaccumulates in the food chain, and spreads to uncontaminated areas.

3.3. Mitigation Strategies for BPA Contamination.

Our findings reveal that BPA concentrations in ∼8.4% of aquatic environments in the mainland of China in 2022 exceeded the limit specified in the national emission pollutant standards. To further explore the extent to which key parameters, including market share, content factor, and emission factor, can be adjusted to align BPA levels with the national standards, we evaluated three mitigation strategies: PO (i.e., BPA phase-out by the plastic industry), SU (i.e., BPA substituted by toxic-free plastic chemicals), and TO (i.e., optimization of production techniques by the BPA industry). BPA consumption was assumed to reduce accordingly under the PO and SU scenarios but remained unchanged under the TO scenarios. We analyzed the reduction in the percentage of areas in the mainland of China exceeding BPA concentration limits set by the national pollutant emission standards, compared to the baseline (i.e., current conditions), by adjusting key parameters by 10% (PO1, SU1, TO1), 30% (PO2, SU2, TO2), 50% (PO3, SU3, TO3), 70% (PO4, SU4, TO4), and 90% (PO5, SU5, TO5) under each scenario, respectively. The gradient levels were designed to reflect the varying extents of potential interventions that could reduce BPA environmental concentrations in water bodies across the mainland of China, aligning them with national standards. These percentages offer decision-makers a range of plausible intervention scenarios, with higher values indicating more significant reductions in BPA emissions. Details on the scenario description are provided in Table S7.

As shown in Figure 7, at reductions of 10, 30, and 50% conditions, the PO and SU scenarios were more effective, whereas at reductions of 70 and 90% conditions, the TO scenario proved more effective. This suggests that phasing out BPA in the market and replacing it with safer alternatives could be an effective short-term strategy, while target interventions such as advancing production and recycling technologies, offer substantial long-term potential for reducing BPA levels and related ecological risks. The TO5 scenario achieved the largest reduction, with nearly all areas in the mainland of China meeting the national pollution emission standard and escaping from BPA pollution, indicating the greatest potential for emission factors in reducing the environmental concentration of BPA.

4. DISCUSSION

4.1. Theoretical Implications.

Our study is one of the first attempts to map spatially and temporally resolved BPA material cycles, detailing its dynamics within both the anthroposphere and the ecosystem. By integrating MFA, MEM, and ERA, our research presents a novel and reliable methodology for efficiently capturing granular-level knowledge on anthropogenic cycles, emission inventories, and ecological risks associated with BPA in China. This integrated approach advances previous studies[25,63,121,122] by adopting the localized MEM tailored to China's environmental conditions, introducing the "market share" parameter for precise MFA modeling,

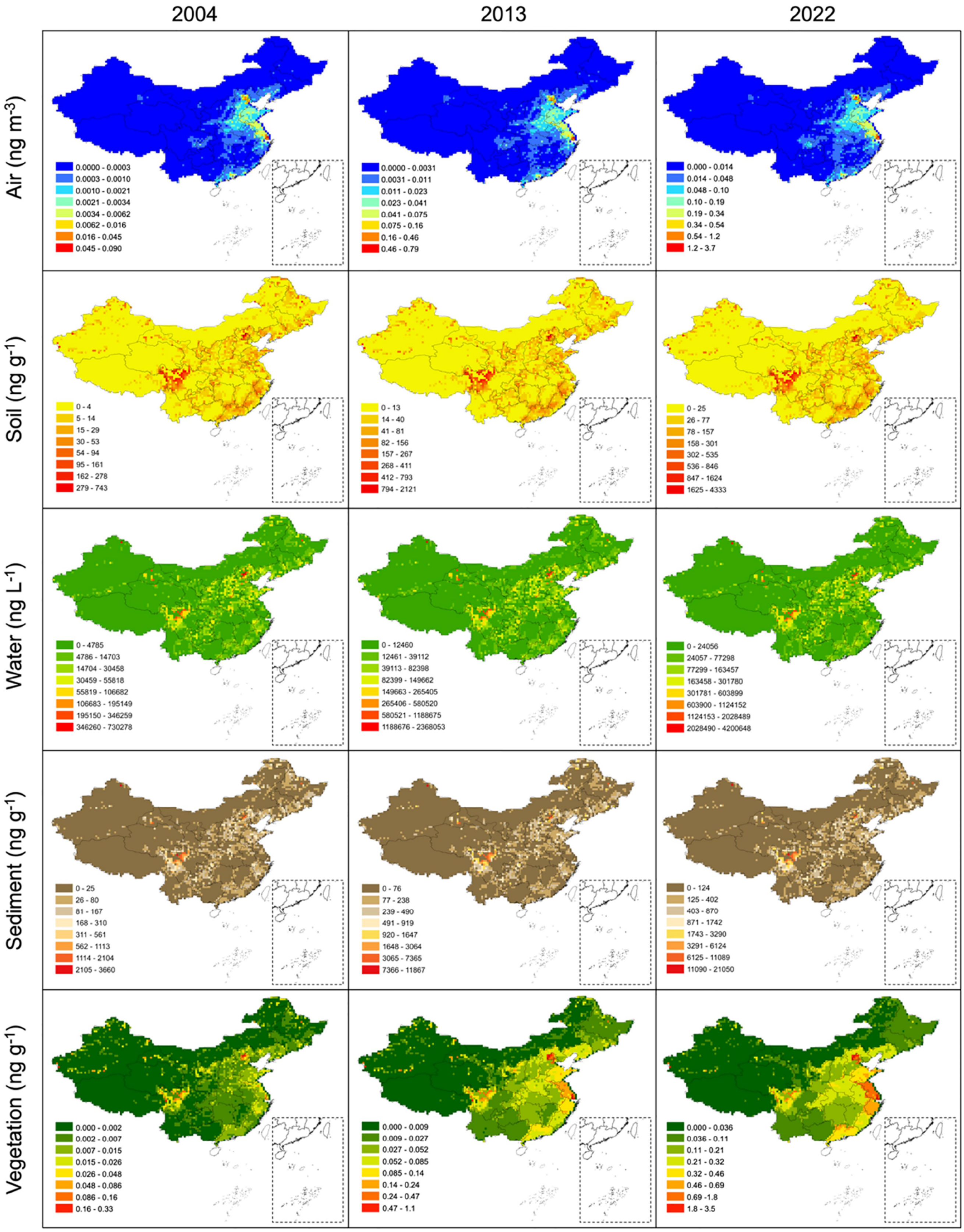


Figure 5. Spatial distribution of BPA concentrations in air, soil, water, sediment, and vegetation across the mainland of China (excluding Hainan province) in 2004, 2013, and 2022. The blank areas indicate data unavailable.

and integrating real-world data from government sources, industry investigations, and expert consultations. These refined data sets and methods provide a robust theoretical basis for government agencies to develop data-driven, tailor-made

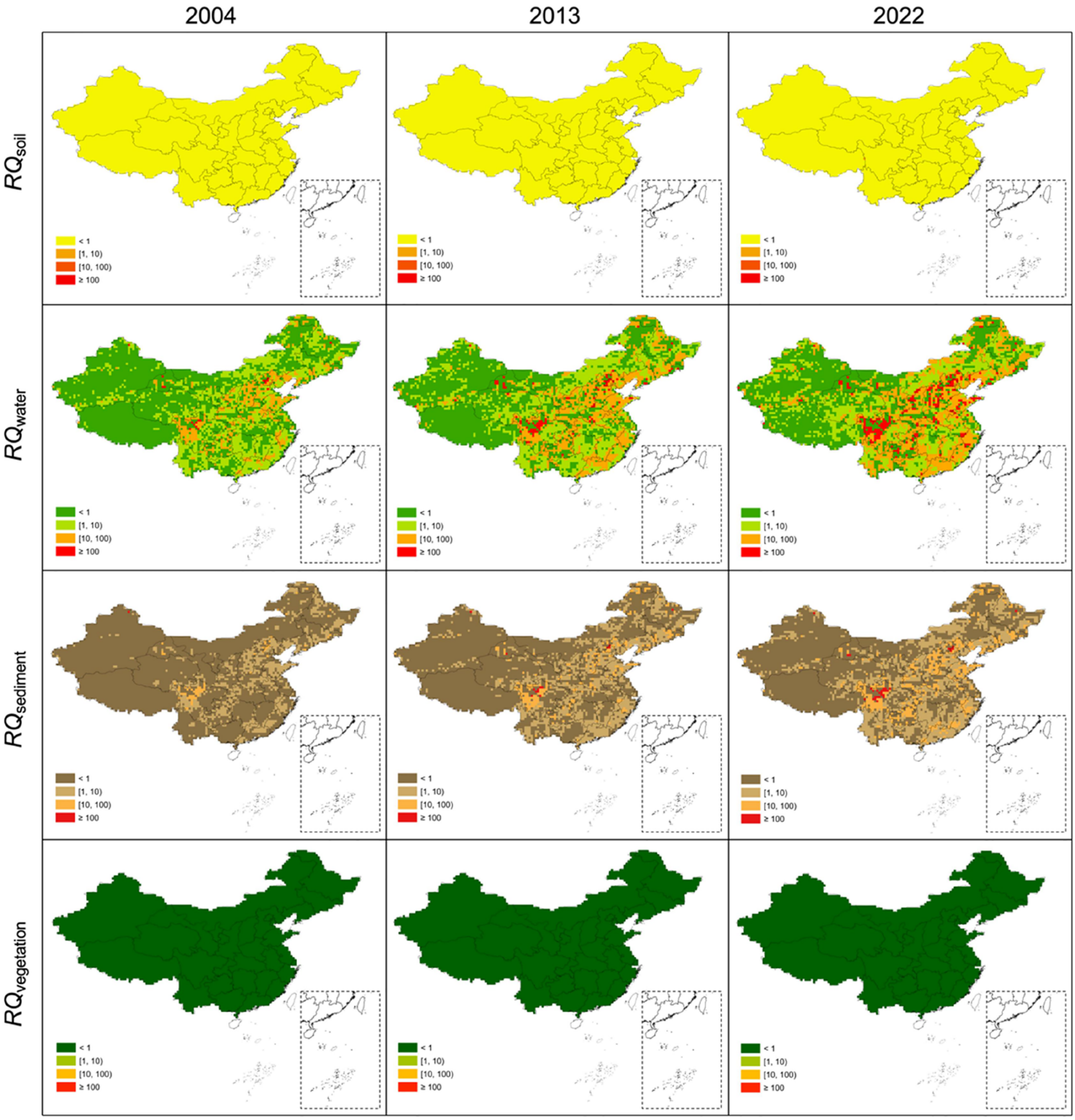


Figure 6. Spatial distribution of BPA ecological risks to aquatic, terrestrial, and sediment organisms across the mainland of China (excluding Hainan province) in 2004, 2013, and 2022. The blank areas indicate data unavailable.

management strategies addressing regional BPA risk and plastic pollution issues. Further, this framework offers a reference for broader research into other plastic chemicals, such as per- and polyfluoroalkyl substances (PFAS) and phthalate esters (PAEs), which are increasingly relevant in the context of the global plastic treaty.[38]

4.2. Practical Implications for Material Management. Material stocks provide critical insights into the sources and scales of future material flows. Our study identifies key sectors and products holding large in-use BPA stocks, notably epoxy coatings, electronic devices, and construction materials (Figures 2e and S2), serving as a warning about the potential for substantial plastic waste generation from these downstream applications. The findings underscore an urgent need for proactive countermeasures within these hotspots to avoid potential environmental burdens induced by BPA. Strategies may include identifying the flow pathways of relevant products and considering recalls of substandard ones.

Waste stocks represent sustained sources of chemical release. In 2021, the Chinese government enacted the "14th Five-Year" Plastic Pollution Control Action Plan, aiming to curtail direct landfilling of plastic waste and enhance recycling by 2025. Our

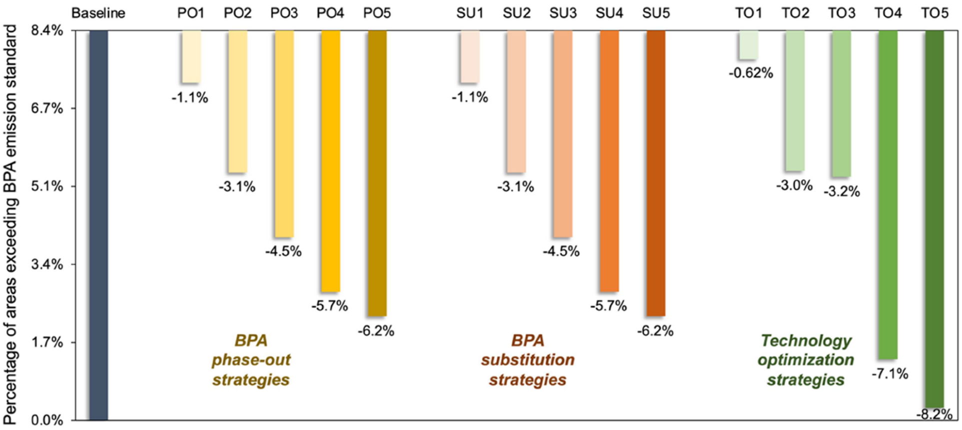


Figure 7. Impact of key strategies on BPA emissions in the mainland of China.

results indicate that there has been a decrease in the average landfilling rate from 35 to 32% and an increase in the recycling rate from 26 to 30% over the past three years, the average growth rate of BPA waste stocks has reduced from 5.7 to 4.8% annually (Figure 2f). This reflects a shift in China's waste management system from being "landfilling-led" to "recycling-driven," although the effect remains modest. Given the large BPA waste stocks in the construction and electronic sectors, prioritization of these areas is needed as part of ongoing plastic waste management reforms in China. Further, real-time tracking of BPA waste flows in these sectors and strengthened oversight of waste management practices among relevant enterprises, may be required.

Material stocks per capita normally have a saturation point, beyond which incoming and EoL flows approximate an equilibrium. While previous studies have revealed saturation points for metals[123−125] and bulk materials,[126−128] less attention has been given to chemicals embedded in products. In terms of BPA, our research suggests that the in-use stock per capita was ∼11 kg in 2014, increasing by ∼0.73 kg annually. This result aligns with Jiang et al.,[25] who reported an estimated 10 kg in 2014, with an annual increase of around 0.80 kg. Our estimates further reveal that by 2022, the in-use BPA stock per capita has risen to approximately 24 kg, with each year adding ∼1.6 kg since 2014, which suggests that stock accumulation per capita for BPA is still ongoing. Thus, it is necessary to continue tracing the saturation point of in-use BPA stock per capita and other plastic chemicals for gaining future insights into plastic management.

Our study reveals large environmental emissions of BPA across its entire life cycle, highlighting the need for a holistic approach to environmental mitigation, targeting all stages. This begins with enhancing source controls by modernizing production techniques and equipment designed to lower emission factors. Considering the large emissions from the use stage (Figure 4a), minimizing or phasing out BPA content in end-use plastic products is critical, which is achievable by seeking alternatives and enacting regulatory bans. Further, it is imperative to provide clear product labels or warning signals to guide consumers toward BPA-free options, thereby decreasing its market prevalence. The EoL stage requires improvements in the waste management system, including enhanced waste classification, collection, and resource recycling processes. In practice, challenges in downstream plastic waste treatment, such as BPA migration from PC to polyethylene terephthalate (PET) due to poor waste classification,[129] degrade the quality of recycled materials and complicate BPA-related waste flows. Further, increasing demand for recycled plastics has prompted manufacturers to add more chemical additives to address viscosity, degradation, color, and aging issues,[130] resulting in higher emissions during recycling. These highlight the necessity of promulgating standardized regulations governing plastic disposal processes and limiting toxic chemical contents in recycled materials. Our scenario analysis serves as an illustration of the potential for reducing BPA emissions through these initiatives, suggesting that addressing BPA consumption would be more effective in the near term, whereas focusing on production and EoL stages would be impactful in the long term.

4.3. Practical Implications for Risk Management.

Our study underscores the urgent need for effective risk management strategies to address the toxicity of BPA in plastics, which has garnered public and policy attention. By linking material flows to environmental consequences, we provide insights into macroscopic strategies for mitigating BPA's ecological risks. Our findings indicate a large magnitude of BPA emissions from construction materials, epoxy coatings, and electronic devices, which create severe ecological risks (Figure 4b), necessitating stringent sectoral-specific regulations. Packaging materials, although contributing less to BPA emissions, are particularly concerning health risks due to their direct contact with food. Several regions, such as the US,[77] France (Law no. 2012-1442), Denmark (Statutory Order No. 822), U.K. (Materials and Articles in Contact with Food (England) Regulations 2012), and China,[27] have banned the certain use of BPA in human-contact products such as baby bottles. These measures emphasize the need for further research on BPA-induced human health risks to evaluate the effectiveness of existing regulations and guide future actions.

Our research identifies key regions and environmental compartments with severe BPA contamination and related ecological risks (Figures 5 and 6), facilitating spatially defined interventions for BPA release control, especially in heavily polluted areas. Soil pollution induced by toxic chemicals like BPA is characterized by its concealment, hysteresis, and accumulation,[131] leading to groundwater pollution. Thus, it is crucial to enhance soil pollution remediation and control technologies. Water pollution, which disperses rapidly,[132] demands advanced monitoring and control technologies. Our findings suggest that aquatic environments in the mainland of China faced the highest chronic ecological risks from BPA, underscoring the need for intensified risk monitoring and control measures in water bodies and sediments. The regions identified with high risks are also closely linked to potential health risks suffered by local communities, such as endocrine, immune, and oncological diseases,[19,133] and thus warrant further evaluation in future studies. Moreover, the large waste stocks call for regular risk assessment for landfills and their surroundings. Advanced monitoring techniques, such as satellite remote sensing and crewless ships, could improve detection accuracy and efficiency in BPA pollution control and risk management.

4.4. Limitations. Due to model restrictions, this study fails to differentiate the life expectancy of BPA itself from that of BPA-containing consumer products when calculating waste flows. Since BPA is gradually released during the product use stage, its residence time is likely shorter than that of the products themselves. This omission could introduce a slight "imbalance" in the modeling.[134] Given the low magnitude of BPA emissions, such imbalance is considered to have limited impacts on the results, though it could be addressed in future research. Moreover, certain parameters, including market shares of polymers and products, BPA emission and content factors, and product lifespans, are treated as fixed values in this work, with appropriate justification. While this approach is supported by uncertainty and sensitivity analyses (Section 2.5), indicating the model's reliability and robustness, future studies could benefit from extending these parameters into a dynamic domain by adopting probabilistic MFA,[135,136] which integrates uncertainties of parameters as probabilistic distributions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.4c09876.

> HS codes, emission factors, life expectancy, and EoL treatment data used in MFA; input parameters of MEM; ecotoxicity end points used in ERA; details on scenario analysis; results of sensitivity analysis; and supplemental figures showing BPA in-use stocks by end-consumed products, BPA in-use stock per capita, and comparison between predictive and literature-reported BPA environmental concentrations (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

Faith Ka Shun Chan − *School of Geographical Sciences, University of Nottingham Ningbo China, Ningbo 315100, China; Water@Leeds and School of Geography, University of Leeds, Leeds LS2 9JT, U.K.;* orcid.org/0000-0001-6091-6596; Email: faith.chan@nottingham.edu.cn

Matthew F. Johnson − *School of Geography, University of Nottingham, Nottingham NG7 2RD, U.K.;* Email: m.johnson@nottingham.ac.uk

Hing Kai Chan − *Nottingham University Business School China, University of Nottingham Ningbo China, Ningbo 315100, China;* Email: hingkai.chan@nottingham.edu.cn

Wei-Qiang Chen − *Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China; University of Chinese Academy of Sciences, Beijing 100049, China;* orcid.org/0000-0002-7686-2331; Email: wqchen@iue.ac.cn

Authors

Jiayu Wang − *Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China; Nottingham University Business School China, University of Nottingham Ningbo China, Ningbo 315100, China*

Yunhan Cui − *Key Laboratory of Industrial Ecology and Environmental Engineering (Ministry of Education), Dalian Key Laboratory on Chemicals Risk Control and Pollution Prevention Technology, School of Environmental Science and Technology, Dalian University of Technology, Dalian 116024, China;* orcid.org/0000-0003-3606-093X

Jingwen Chen − *Key Laboratory of Industrial Ecology and Environmental Engineering (Ministry of Education), Dalian Key Laboratory on Chemicals Risk Control and Pollution Prevention Technology, School of Environmental Science and Technology, Dalian University of Technology, Dalian 116024, China;* orcid.org/0000-0002-5756-3336

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.4c09876

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was financially supported by the National Natural Science Foundation of China (52070178, 22136001, W2432029, and 41850410497) and the National Key R&D Program of China (2022YFC3902100)

■ ABBREVIATIONS

BPA, bisphenol A; UNEA, United Nations Environment Assembly; PBMT, persistence, bioaccumulation, mobile or/and toxicity; HPV, high production volume; REACH, registration, evaluation, authorization, and restriction of chemicals; SVHC, substance of very high concern; BPS, bisphenol S; BPF, bisphenol F; PC, polycarbonate polymer; EP, epoxy resin; MFA, material flow analysis; MEM, multimedia environmental model; ERA, ecological risk analysis; CSRA, China Synthetic Resin Association; F&M, fabricating and manufacturing; EoL, end-of-Life; HS, harmonized system; MEE, Ministry of Ecology and Environment; GRP, gross regional production; RQ, risk quotient; PEC, predicted environmental concentration; PNEC, predicted no-effect concentration; AF, assessment factor; NOEC, no observed effect concentration; LC_{50}, half-lethal concentration; EC_{50}, half-effect concentration; PO, phase-out; SU, substituted; TO, technique optimization; PFAS, polyfluoroalkyl substances; PAEs, phthalate esters; PET, polyethylene terephthalate

■ REFERENCES

(1) OECD. *Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options; Organization for Economic Co-operation and Development*: Paris, 2022.

(2) EEA. *Plastics, the Circular Economy and Europe's Environment-A Priority for Action*; Luxembourg, 2021.

(3) UNEP. *Chemicals in Plastics: A Technical Report*; Geneva, 2023.

(4) Wiesinger, H.; Wang, Z.; Hellweg, S. Deep Dive into Plastic Monomers, Additives, and Processing Aids. *Environ. Sci. Technol.* **2021**, *55* (13), 9339−9351.

(5) Wagner, M.; Monclús, L.; Arp, H. P. H.; Groh, K. J.; Løseth, M. E.; Muncke, J.; Wang, Z.; Wolf, R.; Zimmermann, L. State of the

Science on Plastic Chemicals - Identifying and Addressing Chemicals and polymers of Concern; *Zenodo*, **2024**.

(6) Wang, H.; Wang, Z.; Chen, J.; Liu, W. Graph Attention Network Model with Defined Applicability Domains for Screening PBT Chemicals. *Environ. Sci. Technol.* **2022**, *56* (10), 6774−6785.

(7) Aurisano, N.; Weber, R.; Fantke, P. Enabling a Circular Economy for Chemicals in Plastics. *Curr. Opin Green Sustain Chem.* **2021**, *31*, No. 100513.

(8) Koch, H. M.; Calafat, A. M. Human Body Burdens of Chemicals Used in Plastic Manufacture. *Philos. Trans. R. Soc., B* **2009**, *27*, 2063−2078.

(9) Zimmermann, L.; Dierkes, G.; Ternes, T. A.; Völker, C.; Wagner, M. Benchmarking the in Vitro Toxicity and Chemical Composition of Plastic Consumer Products. *Environ. Sci. Technol.* **2019**, *53* (19), 11467−11477.

(10) OECD. OECD Existing Chemicals Database. https://hpvchemicals.oecd.org/ui/Default.aspx#Tracking_Chemicals (accessed 2024-09-11).

(11) Pritchard, G. Global Demand for Plasticizers Continues to Rise. *Addit. Polym.* **2017**, *10*, 10−11.

(12) Abbasi, G.; Li, L.; Breivik, K. Global Historical Stocks and Emissions of PBDEs. *Environ. Sci. Technol.* **2019**, *53* (11), 6330−6340.

(13) Rybczyńska-Tkaczyk, K.; Skóra, B.; Szychowski, K. A. Toxicity of Bisphenol A (BPA) and Its Derivatives in Divers Biological Models with the Assessment of Molecular Mechanisms of Toxicity. *Environmental Science and Pollution Research* **2023**, *30* (30), 75126−75140.

(14) Bailin, P. D.; Byrne, M.; Lewis, S.; Liroff, R. *Public Awareness Drives Market for Safer Alternatives: Bisphenol A Market Analysis Report*. In Investor Environmental Health. Network, 2008; pp 1−37

(15) Vasiljevic, T.; Harner, T. Bisphenol A and Its Analogues in Outdoor and Indoor Air: Properties, Sources and Global Levels. *Science of The Total Environment* **2021**, *789*, No. 148013.

(16) Im, J.; Löffler, F. E. Fate of Bisphenol A in Terrestrial and Aquatic Environments. *Environ. Sci. Technol.* **2016**, *50* (16), 8403−8416.

(17) ECHA. Candidate List of substances of very high concern for Authorisation. https://echa.europa.eu/candidate-list-table?p_p_id=disslists_WAR_disslistsportlet&p_p_lifecycle=1&p_p_state=normal&p_p_mode=view&_disslists_WAR_disslistsportlet_javax.portlet.action=searchDissLists (accessed 2024-09-11).

(18) Huang, Y. Q.; Wong, C. K. C.; Zheng, J. S.; Bouwman, H.; Barra, R.; Wahlström, B.; Neretin, L.; Wong, M. H. Bisphenol A (BPA) in China: A Review of Sources, Environmental Levels, and Potential Human Health Impacts. *Environ. Int.* **2012**, *42*, 91−99.

(19) Rochester, J. R. Bisphenol A and Human Health: A Review of the Literature. *Reproductive Toxicology* **2013**, *42*, 132−155.

(20) Vandenberg, L. N.; Colborn, T.; Hayes, T. B.; Heindel, J. J.; Jacobs, D. R., Jr.; Lee, D.-H.; Shioda, T.; Soto, A. M.; vom Saal, F. S.; Welshons, W. V.; Zoeller, R. T.; Myers, J. P. Hormones and Endocrine-Disrupting Chemicals: Low-Dose Effects and Nonmonotonic Dose Responses. *Endocr Rev.* **2012**, *33* (3), 378−455.

(21) Zhang, Y.-F.; Ren, X.-M.; Li, Y.-Y.; Yao, X.-F.; Li, C.-H.; Qin, Z.-F.; Guo, L.-H. Bisphenol A Alternatives Bisphenol S and Bisphenol F Interfere with Thyroid Hormone Signaling Pathway in Vitro and in Vivo. *Environ. Pollut.* **2018**, *237*, 1072−1079.

(22) Pivnenko, K.; Laner, D.; Astrup, T. F. Dynamics of Bisphenol A (BPA) and Bisphenol S (BPS) in the European Paper Cycle: Need for Concern? *Resour Conserv Recycl* **2018**, *133*, 278−287.

(23) Chemicals of concern in plastics: Proposal by Norway, Cook Islands and Rwanda for an approach to criteria and lists, including initial lists. https://resolutions.unep.org/incres/uploads/chemicals_of_concern_in_plastics_proposal_by_cook_islands_rwanda_and_norway.pdf (accessed 2024-12-03).

(24) European Union and Its Member States-Text Proposal on Chemicals of Concern in Plastic and Plastic Products Chemicals of Concern in Plastics and Plastic Products; 2024. https://resolutions.unep.org/incres/uploads/european_union_part2_chemicals_of_concern.pdf (accessed 2024-12-03).

(25) Jiang, D.; Chen, W. Q.; Zeng, X.; Tang, L. Dynamic Stocks and Flows Analysis of Bisphenol A (BPA) in China: 2000−2014. *Environ. Sci. Technol.* **2018**, *52* (6), 3706−3715.

(26) Bi, X.; Pang, Y.; Zhong, W. Production, Market Analysis, and Prediction of Bisphenol A. *Chem. Ind.* **2023**, *41* (1), 58−64. (in Chinese)

(27) Chinese Ministry of Health, M. of I. and I. T. M. of C. S. A. for I. and C. G. A. of Q. S. I. and Q. and the S. F. and D. A. The announcement by the Ministry of Health and Six Other Departments on the Ban of Bisphenol A in Infant Bottles. http://www.nhc.gov.cn/sps/s7891/201105/bcfe48fd3da849128e3017251833c9f3.shtml (accessed 2024-05-31).

(28) China Automotive Technology and Research Center Co., Ltd. Interpretation of an International Legally Binding Instrument on Plastic Pollution: The Future Path of Chinese Automotive Plastics. http://www.catarc.info/ (accessed 2024-08-04).

(29) Wolman, A. The Metabolism of Cities. *Sci. Am.* **1965**, *213* (3), 178−193.

(30) Brunner, P. H.; Rechberger, H. Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers, 2nd ed. In *Handbook of Material Flow Analysis*; CRC Press: Taylor & Francis Group: Boca Raton, FL, 2016; pp 207−388.

(31) Graedel, T. E. Material Flow Analysis from Origin to Evolution. *Environ. Sci. Technol.* **2019**, *53* (21), 12188−12196.

(32) Chen, W. Q.; Graedel, T. E.; Nuss, P.; Ohno, H. Building the Material Flow Networks of Aluminum in the 2007 U.S. *Economy. Environ. Sci. Technol.* **2016**, *50* (7), 3905−3912.

(33) Song, L.; Wang, P.; Hao, M.; Dai, M.; Xiang, K.; Li, N.; Chen, W. Q. Mapping Provincial Steel Stocks and Flows in China: 1978−2050. *J. Clean Prod* **2020**, *262*, No. 121393.

(34) Geyer, R.; Jambeck, J. R.; Law, K. L. Production, Use, and Fate of All Plastics Ever Made. *Sci. Adv.* **2017**, *3*, No. 1700782.

(35) Heller, M. C.; Mazor, M. H.; Keoleian, G. A. Plastics in the US: Toward a Material Flow Characterization of Production, Markets and End of Life. *Environmental Research Letters* **2020**, *15* (9), No. 094034.

(36) Gonçalves, M.; Freire, F.; Garcia, R. Material Flow Analysis of Forest Biomass in Portugal to Support a Circular Bioeconomy. *Resour Conserv Recycl* **2021**, *169*, No. 105507.

(37) Lefeuvre, A.; Garnier, S.; Jacquemin, L.; Pillain, B.; Sonnemann, G. Anticipating In-Use Stocks of Carbon Fibre Reinforced Polymers and Related Waste Generated by the Wind Power Sector until 2050. *Resour Conserv Recycl* **2019**, *141*, 30−39.

(38) Wang, J.; Chan, F. K. S.; Johnson, M. F.; Chan, H. K.; Cui, Y.; Chen, J.; Zhu, Y.-G.; Chen, W.-Q. Material Flow Analysis of Chemical Additives in Plastics: A Critical Review. *Crit Rev. Environ. Sci. Technol.* **2024**, *154*, 1692.

(39) Pivnenko, K.; Laner, D.; Astrup, T. F. Material Cycles and Chemicals: Dynamic Material Flow Analysis of Contaminants in Paper Recycling. *Environ. Sci. Technol.* **2016**, *50* (22), 12302−12311.

(40) Jiang, D.; Chen, W. Q.; Liu, W.; Chertow, M. Inter-Sectoral Bisphenol A (BPA) Flows in the 2012 Chinese Economy. *Environ. Sci. Technol.* **2017**, *51* (15), 8654−8662.

(41) MacLeod, M.; Scheringer, M.; McKone, T. E.; Hungerbuhler, K. The State of Multimedia Mass-Balance Modeling in Environmental Science and Decision-Making. *Environ. Sci. Technol.* **2010**, *44* (22), 8360−8364.

(42) Mackay, D. Finding Fugacity Feasible. *Environ. Sci. Technol.* **1979**, *13* (10), 1218−1223.

(43) Mackay, D.; Joy, M.; Paterson, S. A Quantitative Water, Air, Sediment Interaction (QWASI) Fugacity Model for Describing the Fate of Chemicals in Lakes. *Chemosphere* **1983**, *12* (7), 981−997.

(44) Mackay, D.; Paterson, S.; Joy, M. A Quantitative Water, Air, Sediment Interaction (QWASI) Fugacity Model for Describing the Fate of Chemicals in Rivers. *Chemosphere* **1983**, *12*, 1193−1208.

(45) Wania, F.; Mackay, D. A Global Distribution Model for Persistent Organic Chemicals. *Science of The Total Environment* **1995**, *160−161*, 211−232.

(46) Wania, F.; Mackay, D. Modelling the Global Distribution of Toxaphene: A Discussion of Feasibility and Desirability. *Chemosphere* **1993**, *27* (10), 2079−2094.

(47) MacLeod, M.; Woodfine, D. G.; Mackay, D.; McKone, T.; Bennett, D.; Maddalena, R. BETR North America: A Regionally Segmented Multimedia Contaminant Fate Model for North America. *Environ. Sci. Pollut. Res.* **2001**, *8* (3), 156−163.

(48) Song, S.; Su, C.; Lu, Y.; Wang, T.; Zhang, Y.; Liu, S. Urban and Rural Transport of Semivolatile Organic Compounds at Regional Scale: A Multimedia Model Approach. *Journal of Environmental Sciences* **2016**, *39*, 228−241.

(49) Su, C.; Zhang, H.; Cridge, C.; Liang, R. A Review of Multimedia Transport and Fate Models for Chemicals: Principles, Features and Applicability. *Science of The Total Environment* **2019**, *668*, 881−892.

(50) EPA. Technical Overview of Ecological Risk Assessment: Risk Characterization. https://www.epa.gov/pesticide-science-and-assessing-pesticide-risks/technical-overview-ecological-risk-assessment-risk (accessed 2024-08-05).

(51) Backhaus, T.; Faust, M. Predictive Environmental Risk Assessment of Chemical Mixtures: A Conceptual Framework. *Environ. Sci. Technol.* **2012**, *46* (5), 2564−2573.

(52) Zhu, Q.; Xu, L.; Wang, W.; Liu, W.; Liao, C.; Jiang, G. Occurrence, Spatial Distribution and Ecological Risk Assessment of Phthalate Esters in Water, Soil and Sediment from Yangtze River Delta. *China. Science of The Total Environment* **2022**, *806*, No. 150966.

(53) Sah, R.; Baroth, A.; Hussain, S. A. First Account of Spatio-Temporal Analysis, Historical Trends, Source Apportionment and Ecological Risk Assessment of Banned Organochlorine Pesticides along the Ganga River. *Environ. Pollut.* **2020**, *263*, No. 114229.

(54) Nika, M. C.; Ntaiou, K.; Elytis, K.; Thomaidi, V. S.; Gatidou, G.; Kalantzi, O. I.; Thomaidis, N. S.; Stasinakis, A. S. Wide-Scope Target Analysis of Emerging Contaminants in Landfill Leachates and Risk Assessment Using Risk Quotient Methodology. *J. Hazard Mater.* **2020**, *394*, No. 122493.

(55) Cui, X. Supply and Demand Situation and Development Prospect Analysis of Bisphenol A in China. *Technol. Econ. Petrochem.* **2022**, *38*, 13−18. (in Chinese)

(56) China Synthetic Resin Association Polycarbonate Branch. *Blue Book of Polycarbonate Industry Development in China 2021*; Chemical Industry Press: Beijing, 2021 (in Chinese).

(57) Li, H.; Wang, X.; Shi, C.; Jin, X.; Zhang, H. Analysis and Prospect of Bisphenol A Market in China. *Chem. Ind.* **2020**, *38* (2), 58−62. (in Chinese)

(58) Bi, X.; Pang, Y.; Zhong, W. Production, Market Analysis and Prediction of Bisphenol A. *Chem. Ind.* **2023**, *41* (1), 58−64. (in Chinese)

(59) Chen, Y.; Cui, Z.; Cui, X.; Liu, W.; Wang, X.; Li, X.; Li, S. Life Cycle Assessment of End-of-Life Treatments of Waste Plastics in China. *Resour Conserv Recycl* **2019**, *146*, 348−357.

(60) Li, X. Bisphenol A Market Analysis and Prospects. *China Petrochem. Ind. Obs.* **2019**, *8*, 59−61. (in Chinese)

(61) Li, M. Market Analysis and Prospect of Bisphenol A in China in 2015. *China Petrochem. Ind. Obs.* **2016**, *8*, 55−57. (in Chinese)

(62) Li, M. Market Analysis and Prospect of Bisphenol A in China. *China Petrochem. Ind. Obs.* **2017**, *11*, 58−60. (in Chinese)

(63) Cui, Y.; Chen, J.; Wang, Z.; Wang, J.; Allen, D. T. Coupled Dynamic Material Flow, Multimedia Environmental Model, and Ecological Risk Analysis for Chemical Management: A Di(2-Ethylhexyl) Phthalate Case in China. *Environ. Sci. Technol.* **2022**, *56* (15), 11006−11016.

(64) Chen, C.; Jiang, Z.; Li, N.; Wang, H.; Wang, P.; Zhang, Z.; Zhang, C.; Ma, F.; Huang, Y.; Lu, X.; Wei, J.; Qi, J.; Chen, W. Q. Advancing UN Comtrade for Physical Trade Flow Analysis: Review of Data Quality Issues and Solutions. *Resour Conserv Recycl* **2022**, *186*, No. 106526.

(65) Chen, W.-Q.; Wang, H.; Li, N.; Wang, P. Advancing UN Comtrade for Physical Trade Flow Analysis. *Resour Conserv Recycl* **2022**, *186*, No. 106520.

(66) Zhang, Z.; Jiang, Z.; Chen, C.; Zhang, X.; Wang, H.; Li, N.; Wang, P.; Zhang, C.; Ma, F.; Huang, Y.; Qi, J.; Chen, W.-Q. Advancing UN Comtrade for Physical Trade Flow Analysis: Addressing the Issue of Missing Values. *Resour Conserv Recycl* **2022**, *186*, No. 106525.

(67) Ministry of Ecology and Environment of the People's Republic of China. Technical Guidelines for Assessment of Environmental and Health Exposures to Chemical Substances (Trial). https://www.mee.gov.cn/xxgk2018/xxgk/xxgk01/202012/W020201225515745341837.pdf (accessed 2024-06-30).

(68) Rhodes, V. L.; Kriek, G.; Lazear, N.; Kasakevich, J.; Martinko, M.; Heggs, R. P.; Holdren, M. W.; Wisbith, A. S.; Keigley, G. W.; Williams, J. D.; Chuang, J. C.; Satola, J. R. Development of Emission Factors for Polycarbonate Processing. *J. Air Waste Manage Assoc* **2002**, *52* (7), 781−788.

(69) Arp, H. P. H.; Morin, N. A. O.; Hale, S. E.; Okkenhaug, G.; Breivik, K.; Sparrevik, M. The Mass Flow and Proposed Management of Bisphenol A in Selected Norwegian Waste Streams. *Waste Management* **2017**, *60*, 775−785.

(70) Sidhu, S.; Gullett, B.; Striebich, R.; Klosterman, J.; Contreras, J.; DeVito, M. Endocrine Disrupting Chemical Emissions from Combustion Sources: Diesel Particulate Emissions and Domestic Waste Open Burn Emissions. *Atmos. Environ.* **2005**, *39* (5), 801−811.

(71) Zhang, L. New Trend of Polycarbonate Development in China. *Chem. Ind.* **2021**, *39* (1), 35−44. (in Chinese)

(72) Groshart, C. P.; Okkeman, P. C.; Pijnenburg, A. *Chemical Study on Bisphenol A*; Rijkswaterstaat, RIKZ, 2001.

(73) Market Monitor. https://www.globalmarketmonitor.com.cn/ (accessed 2024-07-02).

(74) Analysis of Production Technology and Market Consumption of Polycarbonate at home and abroad. (in Chinese).

(75) Prospects for Polycarbonate Car Windows. Automobile Industry. 2009; pp 48−49 (in Chinese).

(76) Ding, Y. Application of Engineering Plastic Polycarbonate in LED Lamp. *Chem. Eng. Manage.* **2015**, *34*, 222−223. (in Chinese)

(77) Office of Environmental Health Hazard Assessment, C. E. P. A. Proposition 65 Warnings. https://www.p65warnings.ca.gov/fact-sheets/bisphenol-bpa (accessed 2024-07-01).

(78) International Bottled Water Association. Bottled Water Packaging Has the Lowest Environmental Footprint of All Packaged Drinks. https://bottledwater.org/packaging/ (accessed 2024-07-02).

(79) Centre, J. R.; Protection, I. for H. and C.; Pakalin, S.; Aschberger, K.; Munn, S. *Updated European Union Risk Assessment Report 4,4′-Isopropylidenediphenol (Bisphenol-A)−Human Health Addendum of February 2008*; Pakalin, S.; Aschberger, K.; Munn, S., Eds.; Publications Office, 2010.

(80) Wang, L.; Hou, Y. Brief Discussion on the Development Prospect of Epoxy Resin Adhesive. *China Chem. Trade* **2012**, *4* (5), 1.

(81) Chen, W.-Q.; Graedel, T. E. In-Use Product Stocks Link Manufactured Capital to Natural Capital. *Proc. Natl. Acad. Sci. U. S. A.* **2015**, *112* (20), 6265−6270.

(82) General Requirements on Fixed Number of Years of Safety Use and Recycling for Household and Similar Electrical Appliances GB/T 21097.1−2007. https://www.ndrc.gov.cn/xxgk/jianyitianfuwen/qgrddbjyfwgk/202107/t20210708_1289675_ext.html (accessed 2024-07-04).

(83) National Development and Reform Commission. Annual Report on Comprehensive Utilization of Resources in China; Beijing, 2014.

(84) China Plastic Recycling Association of CPRA. Development Report of China Plastic Recycling Industry (2020−2021); 2022 (in Chinese).

(85) China Plastic Recycling Association of CPRA. 2022 Development Report of China Plastic Recycling Industry; 2023 (in Chinese).

(86) Fan, M. Analysis of Resource Utilization of Recyclable Garbage in China. *Urban Rural Dev.* **2018**, *02*, 23−27. (in Chinese)

(87) Xu, H. Comparative Analysis on the Material Recycling of Municipal Solid Waste in China. *Environ. Protect.* **2016**, *44* (19), 39−44. (in Chinese)

(88) Yi, C.; Chen, Q.; Liu, Y. Recovery Technique on Waste Plastic in China. *J. Jingzhou Teachers College (Nat. Sci.)* **2003**, *26* (2), 87−90. (in Chinese)

(89) Zhu, Y.; Price, O. R.; Kilgallon, J.; Rendal, C.; Tao, S.; Jones, K. C.; Sweetman, A. J. A Multimedia Fate Model to Support Chemical Management in China: A Case Study for Selected Trace Organics. *Environ. Sci. Technol.* **2016**, *50* (13), 7001−7009.

(90) Corrales, J.; Kristofco, L. A.; Steele, W. B.; Yates, B. S.; Breed, C. S.; Williams, E. S.; Brooks, B. W. Global Assessment of Bisphenol A in the Environment: Review and Analysis of Its Occurrence and Bioaccumulation. *Dose-Response* **2015**, *13* (3), No. 1559325815598308.

(91) Peterson, R. K. D. Comparing Ecological Risks of Pesticides: The Utility of a Risk Quotient Ranking Approach across Refinements of Exposure. *Pest Manag Sci.* **2006**, *62* (1), 46−56.

(92) European Chemicals Bureau. Technical Guidance Document on Risk Assessment; 2003. https://op.europa.eu/en/publication-detail/-/publication/212940b8-3e55-43f8-8448-ba258d0374bb (accessed 2024-05-31).

(93) European Union. Updated European Union Risk Assessment Report 4,4'-Isopropylidenediphenol (Bisphenol-A); 2010. https://op.europa.eu/en/publication-detail/-/publication/4c398091-dba8-4fbe-9483-69dc4e8f785b (accessed 2024-05-31).

(94) Wang, Y.; Ma, H. Analysis of Uncertainty in Material Flow Analysis. *J. Clean Prod* **2018**, *170*, 1017−1028.

(95) Cooper, T. Slower Consumption Reflections on Product Life Spans and the "Throwaway Society. *J. Ind. Ecol* **2005**, *9* (1−2), 51−67.

(96) Laner, D.; Feketitsch, J.; Rechberger, H.; Fellner, J. A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and Its Application to Plastics Flows in Austria. *J. Ind. Ecol* **2016**, *20* (5), 1050−1063.

(97) Cui, X. Market Analysis of Bisphenol A in China (in Chinese). *Fine Specialty Chem.* **2017**, *25* (7), 14−17.

(98) Liu, T.; Wu, Y.; Tian, X.; Gong, Y. Urban Household Solid Waste Generation and Collection in Beijing. *China. Resour Conserv Recycl* **2015**, *104*, 31−37.

(99) Wang, N.; Du, Y.; Chen, D.; Meng, H.; Chen, X.; Zhou, L.; Shi, G.; Zhan, Y.; Feng, M.; Li, W.; Chen, M.; Li, Z.; Yang, F. Spatial Disparities of Ozone Pollution in the Sichuan Basin Spurred by Extreme. *Hot Weather. Atmos. Chem. Phys.* **2024**, *24* (5), 3029−3042.

(100) Lin, Z.; Wang, L.; Jia, Y.; Zhang, Y.; Dong, Q.; Huang, C. A Study on Environmental Bisphenol A Pollution in Plastics Industry Areas. *Water Air Soil Pollut.* **2017**, *228* (3), 98.

(101) Li, J.; Wang, G. Airborne Particulate Endocrine Disrupting Compounds in China: Compositions, Size Distributions and Seasonal Variations of Phthalate Esters and Bisphenol A. *Atmos Res.* **2015**, *154*, 138−145.

(102) Yamazaki, E.; Yamashita, N.; Taniyasu, S.; Lam, J.; Lam, P. K. S.; Moon, H.-B.; Jeong, Y.; Kannan, P.; Achyuthan, H.; Munuswamy, N.; Kannan, K. Bisphenol A and Other Bisphenol Analogues Including BPS and BPF in Surface Water Samples from Japan, China. *Korea and India. Ecotoxicol Environ. Saf* **2015**, *122*, 565−572.

(103) Kang, J. H.; Aasi, D.; Katayama, Y. Bisphenol A in the Aquatic Environment and Its Endocrine-Disruptive Effects on Aquatic Organisms. *Critical Reviews in Toxicology.* **2007**, *37*, 607−625.

(104) Huang, D.-Y.; Zhao, H.-Q.; Liu, C.-P.; Sun, C.-X. Characteristics, Sources, and Transport of Tetrabromobisphenol A and Bisphenol A in Soils from a Typical e-Waste Recycling Area in South China. *Environmental Science and Pollution Research* **2014**, *21* (9), 5818−5826.

(105) Xu, Y.; Hu, A.; Li, Y.; He, Y.; Xu, J.; Lu, Z. Determination and Occurrence of Bisphenol A and Thirteen Structural Analogs in Soil. *Chemosphere* **2021**, *277*, No. 130232.

(106) Fan, D.; Liang, M.; Guo, M.; Gu, W.; Gu, J.; Liu, M.; Shi, L.; Ji, G. Exposure of Preschool-Aged Children to Highly-Concerned Bisphenol Analogues in Nanjing. *East China. Ecotoxicol Environ. Saf* **2022**, *234*, No. 113397.

(107) Qin, Y.; Liu, J.; Han, L.; Ren, J.; Jing, C.; Lu, G.; Yang, X. Medium Distribution, Source Characteristics and Ecological Risk of Bisphenol Compounds in Agricultural Environment. *Emerg Contam* **2024**, *10* (2), No. 100292.

(108) Gao, Y.; Xiao, S. K.; Wu, Q.; Pan, C. G. Bisphenol Analogues in Water and Sediment from the Beibu Gulf, South China Sea: Occurrence, Partitioning and Risk Assessment. *Sci. Total Environ.* **2023**, *857*, No. 159445.

(109) Wang, Q.; Zhang, Y.; Feng, Q.; Hu, G.; Gao, Z.; Meng, Q.; Zhu, X. Occurrence, Distribution, and Risk Assessment of Bisphenol Analogues in Luoma Lake and Its Inflow Rivers in Jiangsu Province, China. *Environmental Science and Pollution Research* **2022**, *29* (1), 1430−1445.

(110) Zhang, H.; Zhang, Y.; Li, J.; Yang, M. Occurrence and Exposure Assessment of Bisphenol Analogues in Source Water and Drinking Water in China. *Science of The Total Environment* **2019**, *655*, 607−613.

(111) Wei, D.; Yuan, K.; Ai, F.; Li, M.; Zhu, N.; Wang, Y.; Zeng, K.; Yin, D.; Bu, Y.; Zhang, Z. Occurrence, Spatial Distributions, and Temporal Trends of Bisphenol Analogues in an E-Waste Dismantling Area: Implications for Risk Assessment. *Science of The Total Environment* **2023**, *867*, No. 161498.

(112) Jin, H.; Zhu, L. Occurrence and Partitioning of Bisphenol Analogues in Water and Sediment from Liaohe River Basin and Taihu Lake. *China. Water Res.* **2016**, *103*, 343−351.

(113) Liu, J.; Zhang, L.; Lu, G.; Jiang, R.; Yan, Z.; Li, Y. Occurrence, Toxicity and Ecological Risk of Bisphenol A Analogues in Aquatic Environment−A Review. *Ecotoxicol Environ. Saf* **2021**, *208*, No. 111481.

(114) Diao, P.; Chen, Q.; Wang, R.; Sun, D.; Cai, Z.; Wu, H.; Duan, S. Phenolic Endocrine-Disrupting Compounds in the Pearl River Estuary: Occurrence, Bioaccumulation and Risk Assessment. *Science of The Total Environment* **2017**, *584−585*, 1100−1107.

(115) Wu, M.; Wang, L.; Xu, G.; Liu, N.; Tang, L.; Zheng, J.; Bu, T.; Lei, B. Seasonal and Spatial Distribution of 4-Tert-Octylphenol, 4-Nonylphenol and Bisphenol A in the Huangpu River and Its Tributaries, Shanghai. *China. Environ. Monit Assess* **2013**, *185* (4), 3149−3161.

(116) Peng, X.; Wang, Z.; Yang, C.; Chen, F.; Mai, B. Simultaneous Determination of Endocrine-Disrupting Phenols and Steroid Estrogens in Sediment by Gas Chromatography−Mass Spectrometry. *J. Chromatogr A* **2006**, *1116* (1), 51−56.

(117) Jin, X.; Huang, G.; Jiang, G.; Zhou, Q.; Liu, J. Simultaneous Determination of 4-Tert-Octylphenol, 4-Nonylphenol and Bisphenol A in Guanting Reservoir Using Gas Chromatography Mass Spectrometry with Selected Ion Monitoring. *J. Environ. Sci.* **2004**, *16* (5), 825−828. (in Chinese)

(118) Zhao, X.; Zhang, H.; Chen, Z.; Wang, X.; Shen, J. Spatial and Temporal Distributions of Bisphenol Analogues in Water and Sediment from the Lanzhou Section of the Yellow River, China. *Arabian J. Geosci.* **2020**, *13* (21), 1115.

(119) Liao, M.; Gan, Z.; Sun, W.; Su, S.; Li, Z.; Zhang, Y. Spatial Distribution, Source Identification, and Potential Risks of 14 Bisphenol Analogues in Soil under Different Land Uses in the Megacity of Chengdu. *China. Environmental Pollution* **2024**, *352*, No. 124064.

(120) Fu, P.; Kawamura, K. Ubiquity of Bisphenol A in the Atmosphere. *Environ. Pollut.* **2010**, *158* (10), 3138−3143.

(121) Chen, Z.; Ma, T.; Liu, W.; Yuan, G.; Pan, X.; Zhang, M.; Luan, X.; Cui, Z.; Xin, J. Brominated Flame Retardants (BFRs) in China Over the Past Half-Century: Stocks, Flows, Fates, and Ecological Risks. *Environ. Sci. Technol.* **2024**, *58* (31), 13613−13623.

(122) Bi, M.; Liu, W.; Luan, X.; Li, M.; Liu, M.; Liu, W.; Cui, Z. Production, Use, and Fate of Phthalic Acid Esters for Polyvinyl Chloride Products in China. *Environ. Sci. Technol.* **2021**, *55* (20), 13980−13989.

(123) Graedel, T. E.; Cao, J. Metal Spectra as Indicators of Development. *Proc. Natl. Acad. Sci. U. S. A.* **2010**, *107* (49), 20905−20910.

(124) Pauliuk, S.; Wang, T.; Müller, D. B. Steel All over the World: Estimating in-Use Stocks of Iron for 200 Countries. *Resour Conserv Recycl* **2013**, *71*, 22−30.

(125) Pauliuk, S.; Wang, T.; Müller, D. B. Moving Toward the Circular Economy: The Role of Stocks in the Chinese Steel Cycle. *Environ. Sci. Technol.* **2012**, *46* (1), 148−154.

(126) Wiedenhofer, D.; Fishman, T.; Plank, B.; Miatto, A.; Lauk, C.; Haas, W.; Haberl, H.; Krausmann, F. Prospects for a Saturation of Humanity's Resource Use? An Analysis of Material Stocks and Flows in Nine World Regions from 1900 to 2035. *Global Environmental Change* **2021**, *71*, No. 102410.

(127) Ciacci, L.; Passarini, F.; Vassura, I. The European PVC Cycle: In-Use Stock and Flows. *Resour Conserv Recycl* **2017**, *123*, 108−116.

(128) Fishman, T.; Schandl, H.; Tanikawa, H.; Walker, P.; Krausmann, F. Accounting for the Material Stock of Nations. *J. Ind. Ecol* **2014**, *18* (3), 407−420.

(129) Yun, W. M.; Ho, Y. Bin; Tan, E. S. S.; How, V. Release of Bisphenol A from Polycarbonate and Polyethylene Terephthalate Drinking Water Bottles under Different Storage Conditions and Its Associated Health Risk. *Malays. J. Med. Health Sci.* **2018**, *14*, 18.

(130) BASF. BASF's IrgaCycle^{TM} stabilizes recycled plastics used to protect pineapples from sunburn in Malaysia. https://www.basf.com/global/en/media/news-releases/2022/07/p-22-298.

(131) Sun, Y.; Zhou, Q.; Xie, X.; Liu, R. Spatial, Sources and Risk Assessment of Heavy Metal Contamination of Urban Soils in Typical Regions of Shenyang. *China. J. Hazard Mater.* **2010**, *174* (1), 455−462.

(132) Barthlott, W.; Neinhuis, C. Purity of the Sacred Lotus, or Escape from Contamination in Biological Surfaces. *Planta* **1997**, *202* (1), 1−8.

(133) Hengstler, J. G.; Foth, H.; Gebel, T.; Kramer, P.-J.; Lilienblum, W.; Schweinfurth, H.; Völkel, W.; Wollin, K.-M.; Gundert-Remy, U. Critical Evaluation of Key Evidence on the Human Health Hazards of Exposure to Bisphenol A. *Crit Rev. Toxicol* **2011**, *41* (4), 263−291.

(134) Li, L.; Wania, F. Tracking Chemicals in Products around the World: Introduction of a Dynamic Substance Flow Analysis Model and Application to PCBs. *Environ. Int.* **2016**, *94*, 674−686.

(135) Chen, L.; Liu, W.; Yang, T.; Nowack, B. Probabilistic Material Flow Analysis of Eight Commodity Plastics in China: Comparison between 2017 and 2020. *Resour Conserv Recycl* **2023**, *191*, No. 106880.

(136) Kawecki, D.; Scheeder, P. R. W.; Nowack, B. Probabilistic Material Flow Analysis of Seven Commodity Plastics in Europe. *Environ. Sci. Technol.* **2018**, *52* (17), 9874−9888.