

塑料可持续生产和消费的关键途径：基于绿色和可持续化学的视角

刘建国，陈嘉喆，章志淳，刘俊宙

北京大学环境科学与工程学院

北京大学碳中和研究院

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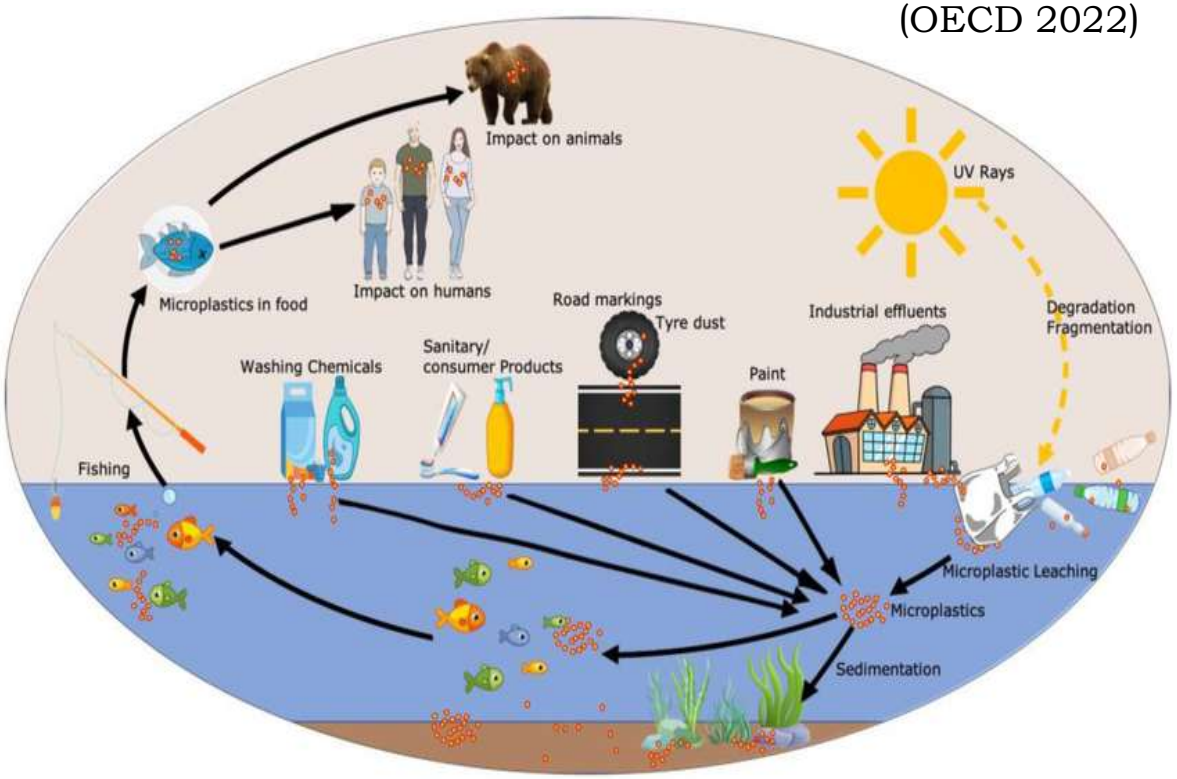
全球塑料污染：超越地球行星边界

全球塑料：~4.6亿吨/年生产，仅~9% 被回收，~0.22亿吨/年泄漏入环境，~170万吨/年流入海洋

(OECD 2022)



（*Image: Timur Matahari/AFP/Getty Images*）



微塑料来源及影响 (Ghosh et al., 2023)

全球塑料公约：旨在全面解决塑料污染，促进塑料可持续生产和消费

艰难进行中的全球塑料公约的政府间谈判：

原计划达成协议时间，但一再推迟

2022.03	2022.12	2023.05	2023.11	2024.04	2024.11-12	2025.08	2026.02	2027
肯尼亚	乌拉圭	法国	肯尼亚	加拿大	韩国	瑞士	瑞士	…?
UNEP-5.2	INC-1	INC-2	INC-3	INC-4	INC-5.1	INC-5.2	INC-5.3	INC-5.4

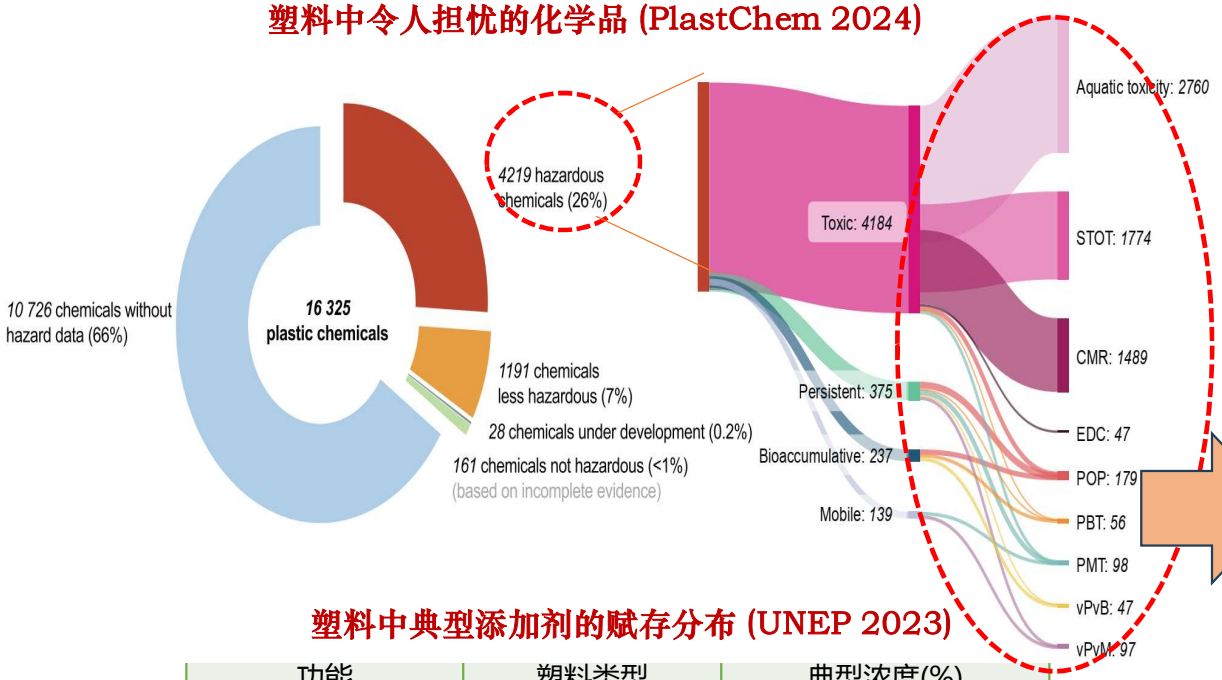


重要焦点：

- ✓ 塑料全产业链/生命周期的环境无害化管理
- ✓ 塑料中有害化学品（塑料添加剂）的风险管理

塑料添加剂：数以千计的有害化学品

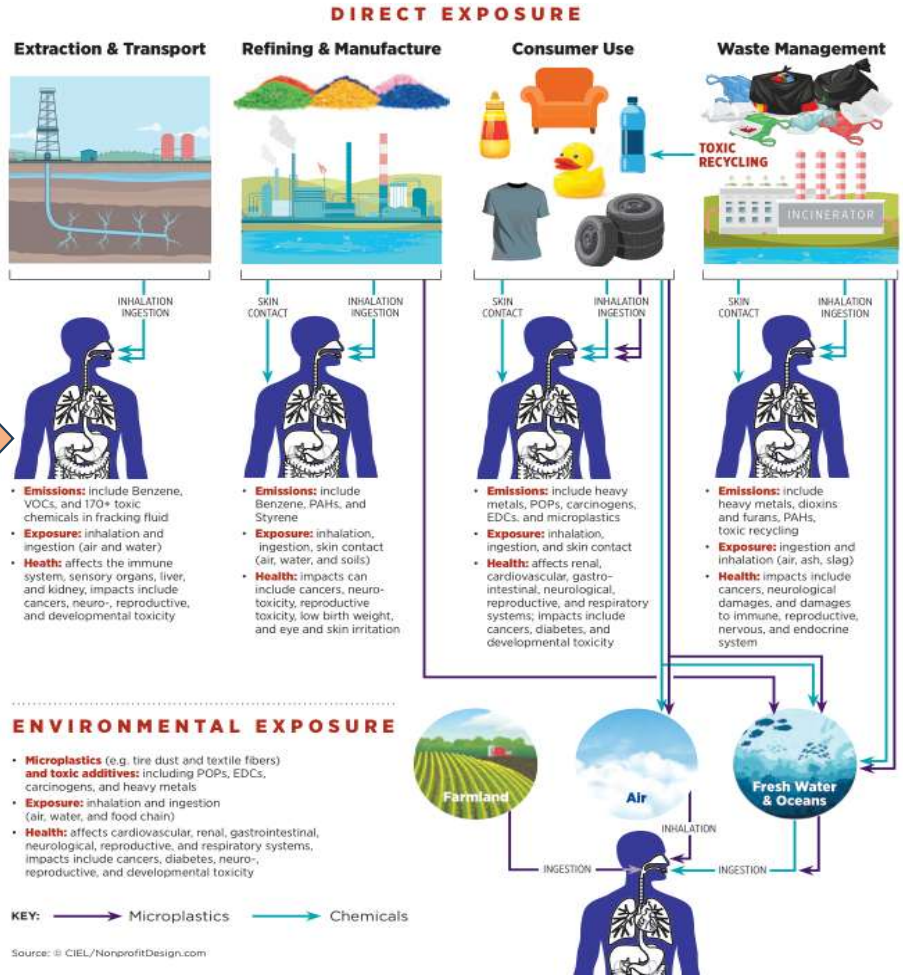
塑料中令人担忧的化学品 (PlastChem 2024)



塑料中典型添加剂的赋存分布 (UNEP 2023)

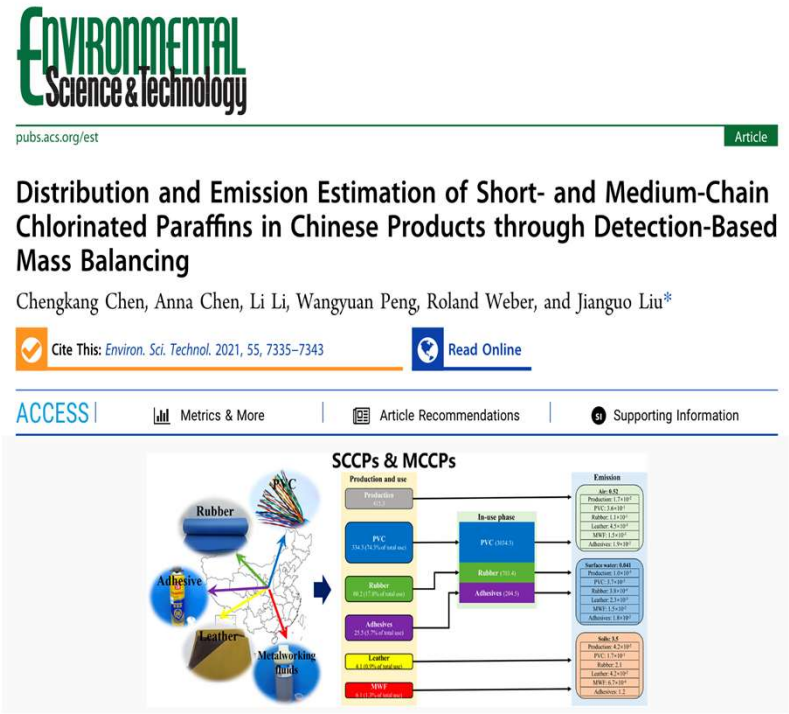
功能	塑料类型	典型浓度(%)
光稳定剂	PE、PP、PVC	0.1-10
热稳定剂	PVC	0.1-3
抗静电剂	PE、PP、PVC	0-1
抗氧化剂	PE、ABS	0.05-3
阻燃剂	All	2-28
增塑剂	PVC	10-70
…		

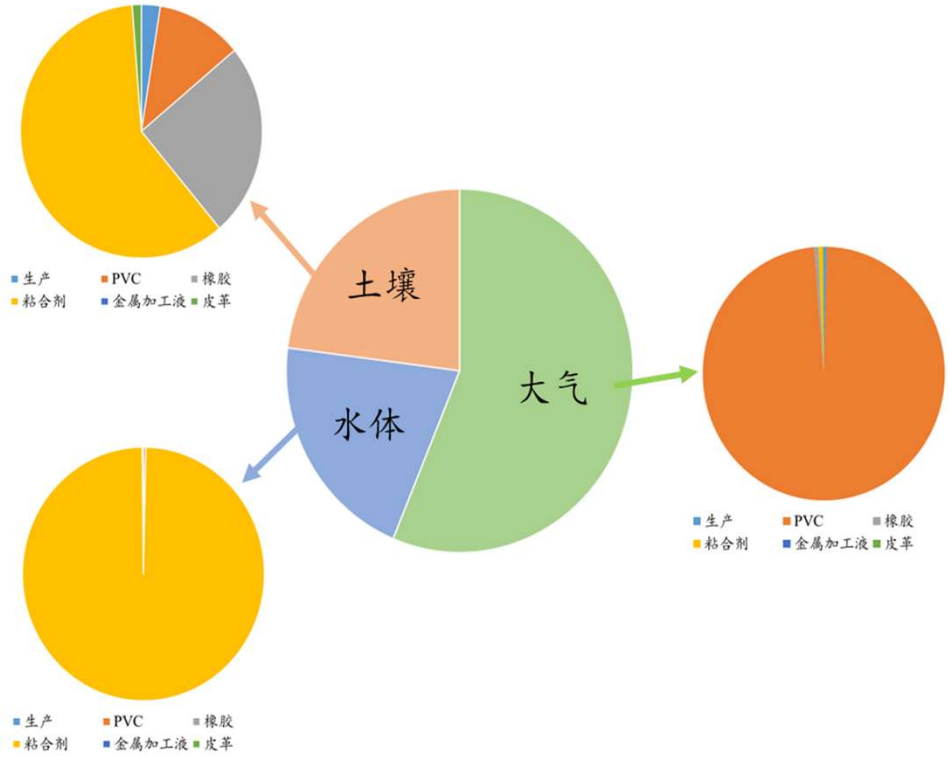
塑料中有害添加剂的人体暴露和健康风险 (CIEL 2019)



典型案例: 短链和中链氯化石蜡 (SCCPs&MCCPs)

- SCCPs & MCCPs——持久性有机污染物（POPs），对肝、肾、甲状腺、内分泌系统、神经系统及免疫系统具有一系列潜在毒性效应



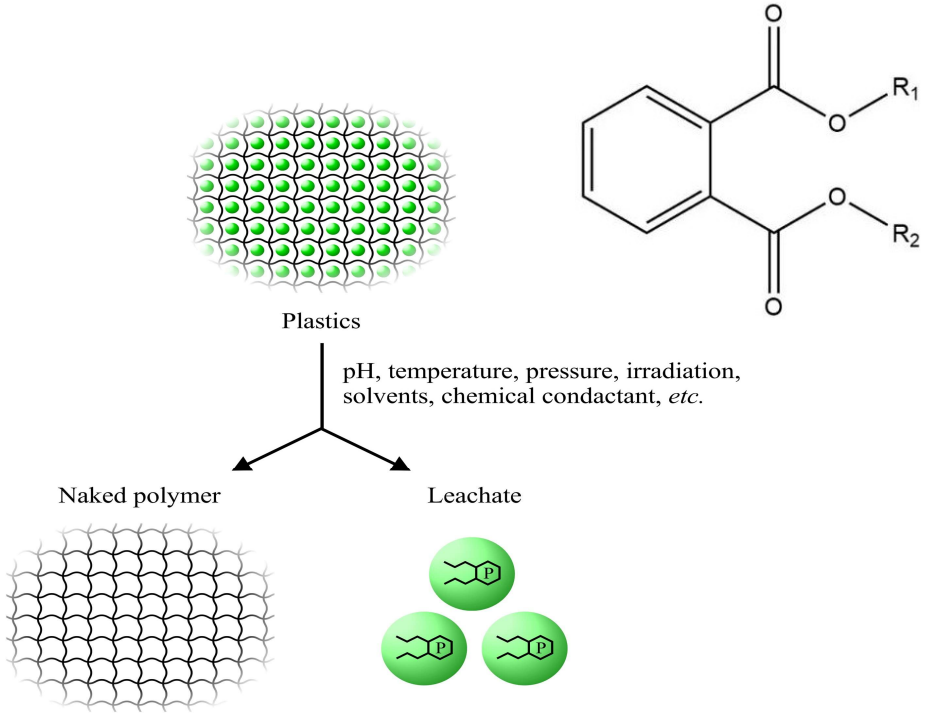


- PVC塑料为主的产品中SCCPs &MCCPs的环境释放：高达~8000 吨/年

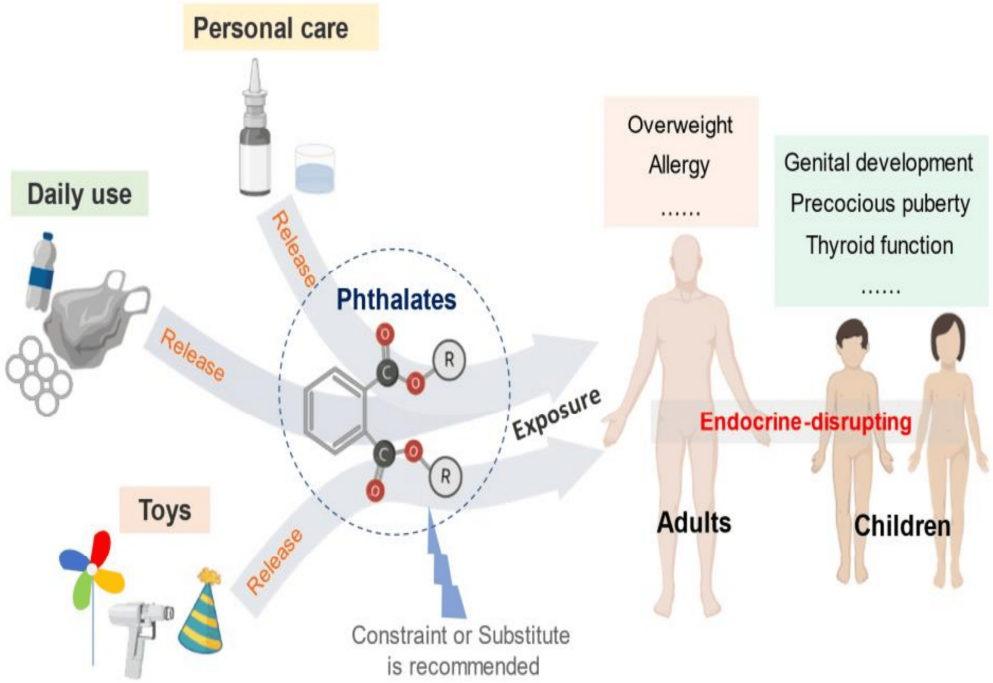
(C Chen, J Liu** et al., ES&T, 2021)

典型案例:邻苯二甲酸酯 (Phthalates, PAEs)

- PAEs——内分泌干扰物质（EDCs），占全球增塑剂市场份额的75%，90%用于塑料中，具有肥胖、糖尿病、性早熟、男性不育等一系列内分泌干扰效应…

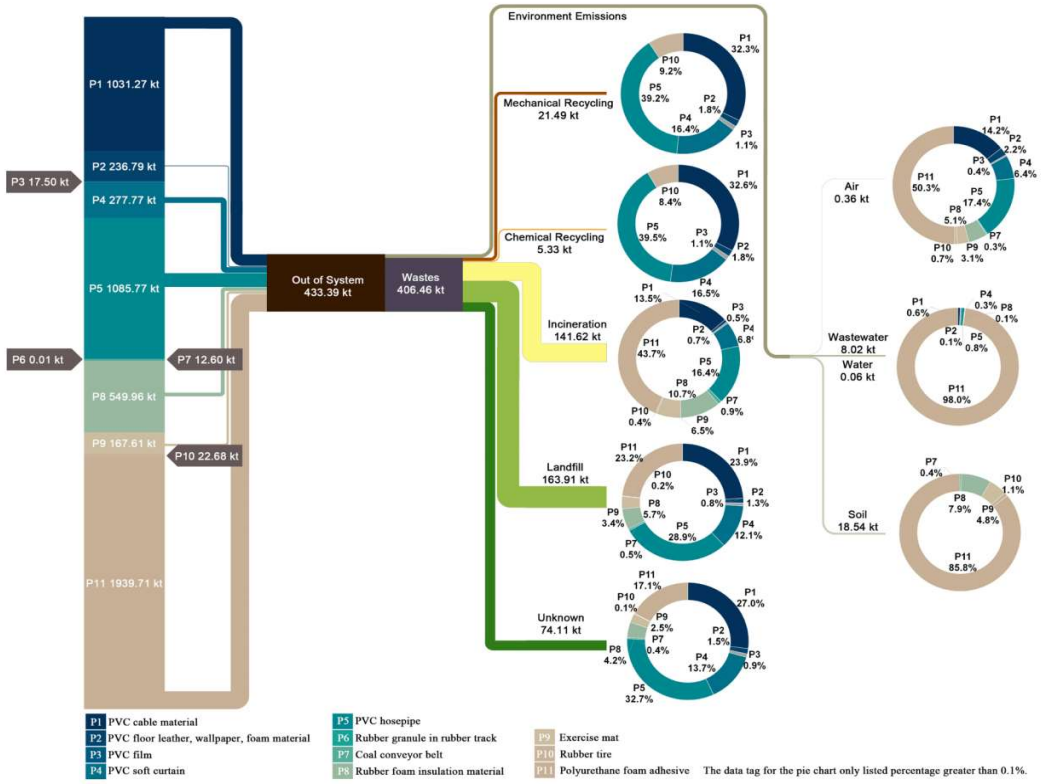


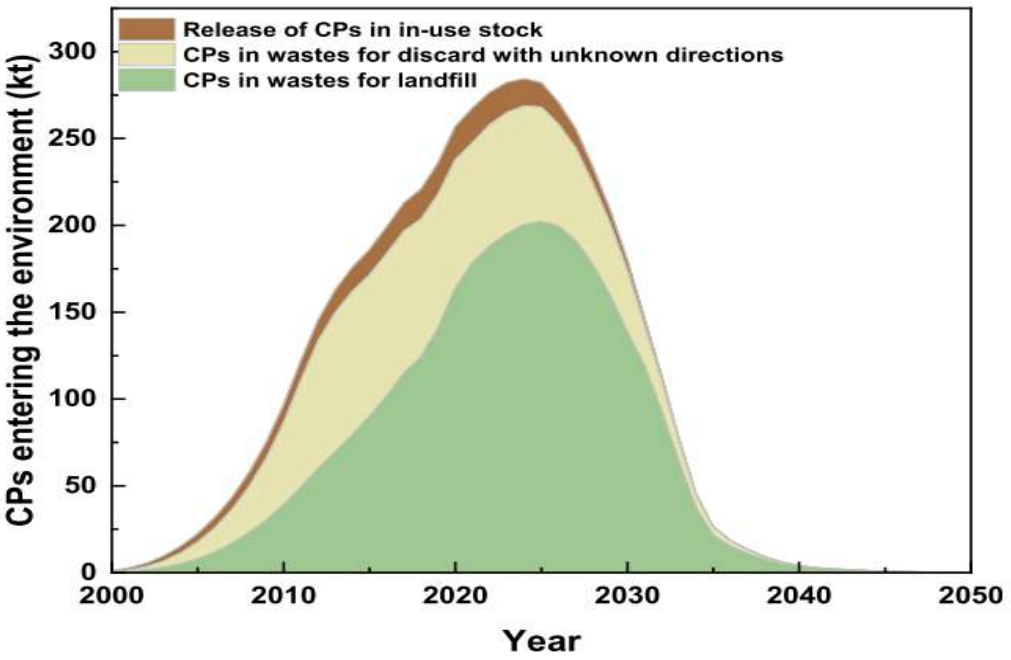
PAEs的环境释放 (Benjamin et al., 2017)



PAEs的人体健康风险 (Wang et al., 2021)

塑料添加剂>90%流入塑料废物,并长期持续释放入环境





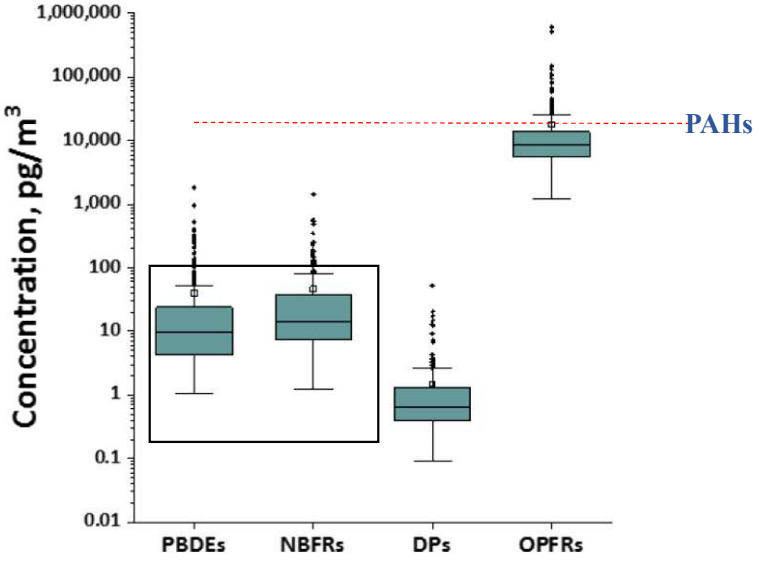
➢ PVC塑料等产品中氯化石蜡（SCCPs &MCCPs）~95%进入废物，~58%将长期持续排放入环境

(J Chen, J Liu* et al., Environment International, 2024)

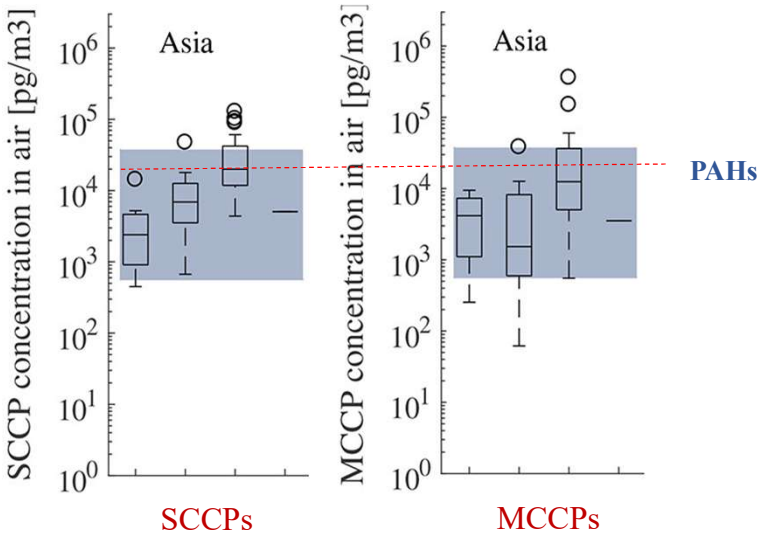
大气中典型塑料有害添加剂污染水平逐渐升高

➢ 塑料有害添加剂的大气浓度已与常规有机污染物多环芳烃（PAHs）相当甚至更高

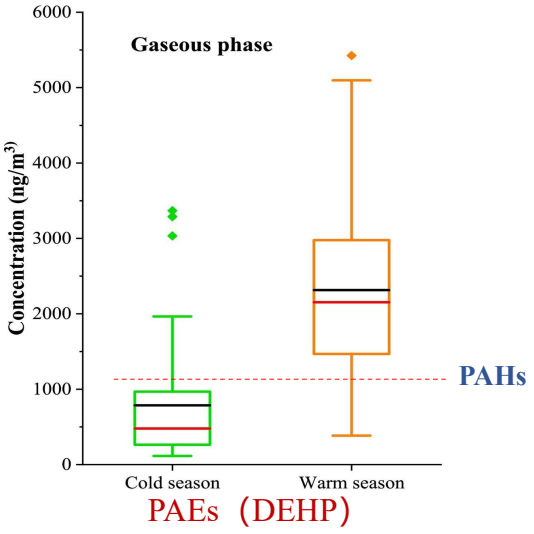
PAHs：10^4 pg·m^{-3} domain　OPFRs：10^4 pg ·m^{-3} domain　CPs：10^3~10^4 pg ·m^{-3} domain　DEHP：10^3 pg ·m^{-3} domain



(Zhao et al., 2021)



(Juliane et al., 2018)



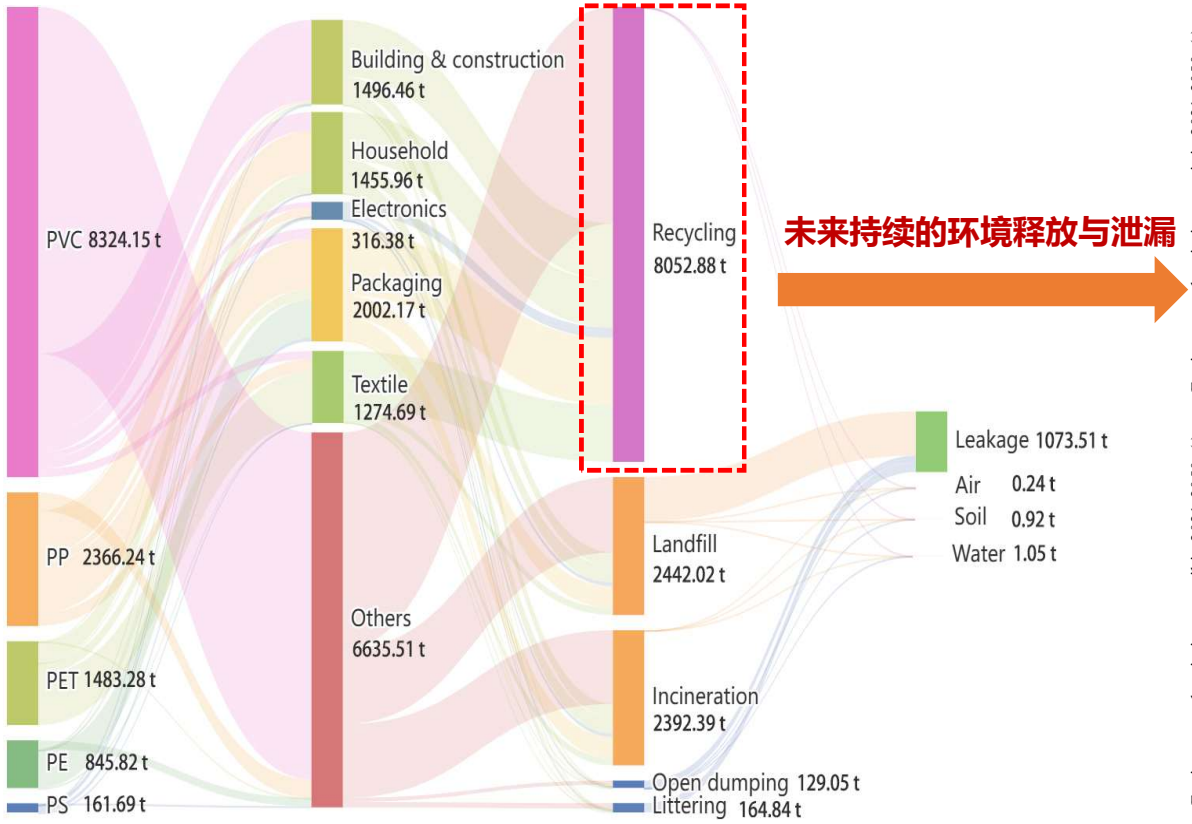
(Lu et al., 2023)

塑料循环中有害添加剂的长期环境和健康影响



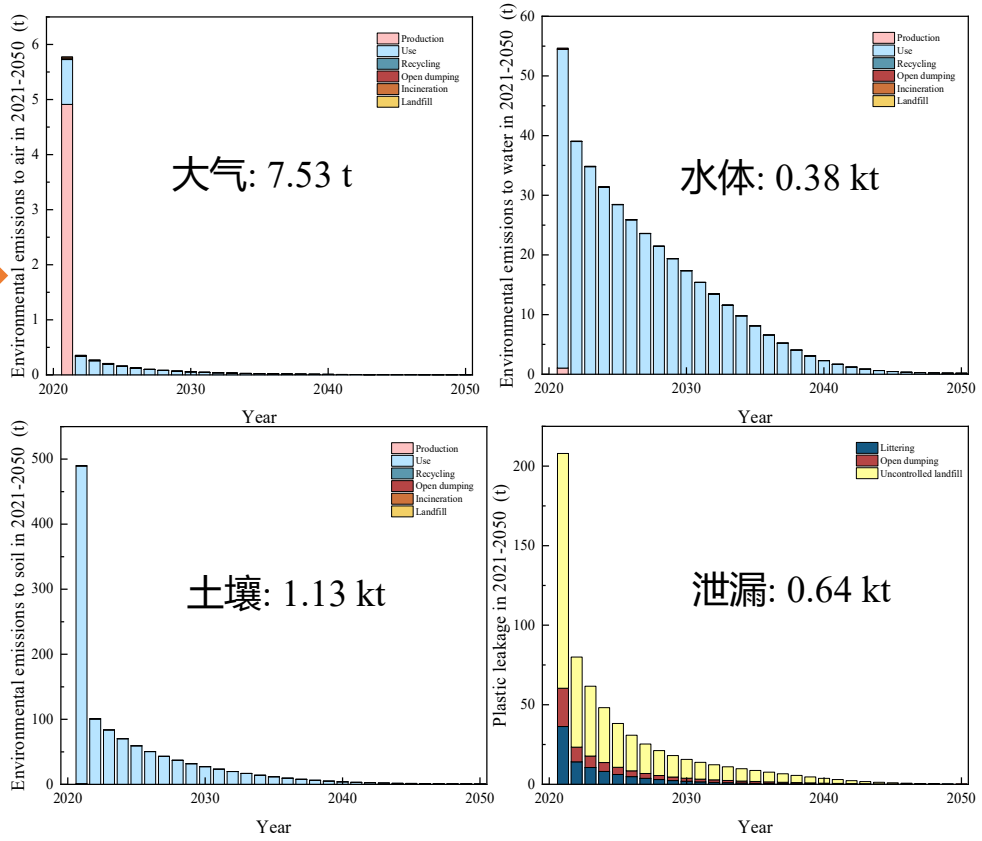
(IPEN, 2024)

塑料循环中有害添加剂的长期环境影响：PAEs研究案例



2020年中国塑料中的PAEs物质流分析（未发表数据）

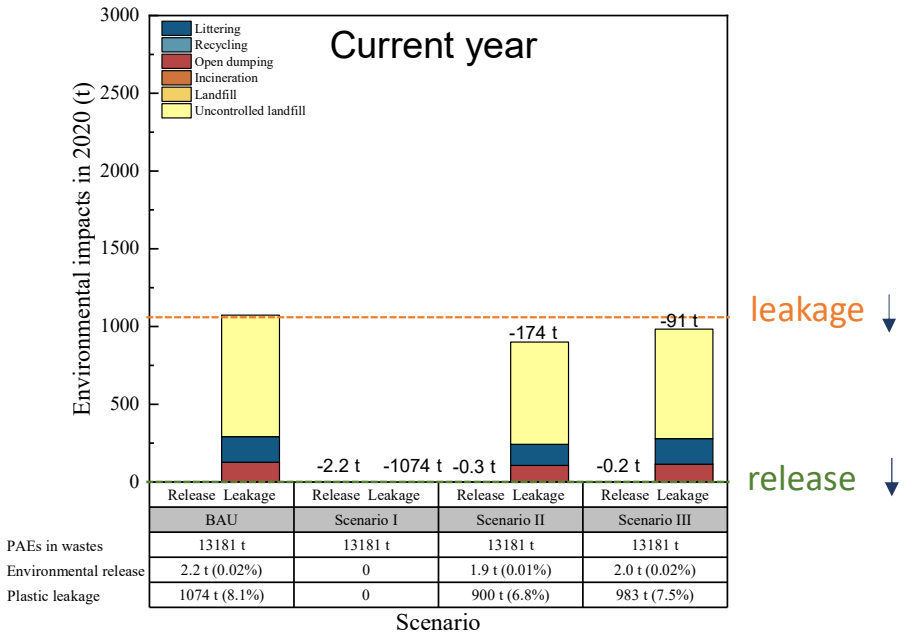
未来持续的环境释放与泄漏

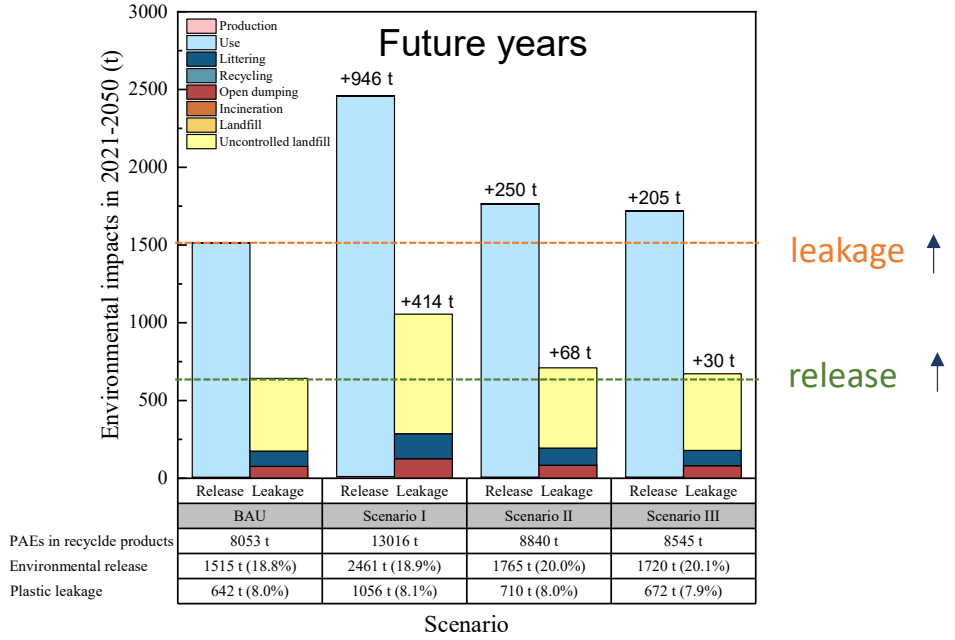


2021-2050年再生塑料中PAEs的环境释放与泄漏（未发表数据）

- **塑料循环中PAEs将产生持续数十年的环境影响：再生塑料中的持续环境释放和泄露**

塑料循环中有害添加剂的长期环境影响: PAEs研究案例





塑料循环中PAEs的环境释放与泄漏（2020–2050， 未发表数据）

- **塑料回收虽可降低PAEs当年环境释放，但塑料循环将造成PEAs持续累积，导致未来PAEs的环境影响持续增加**

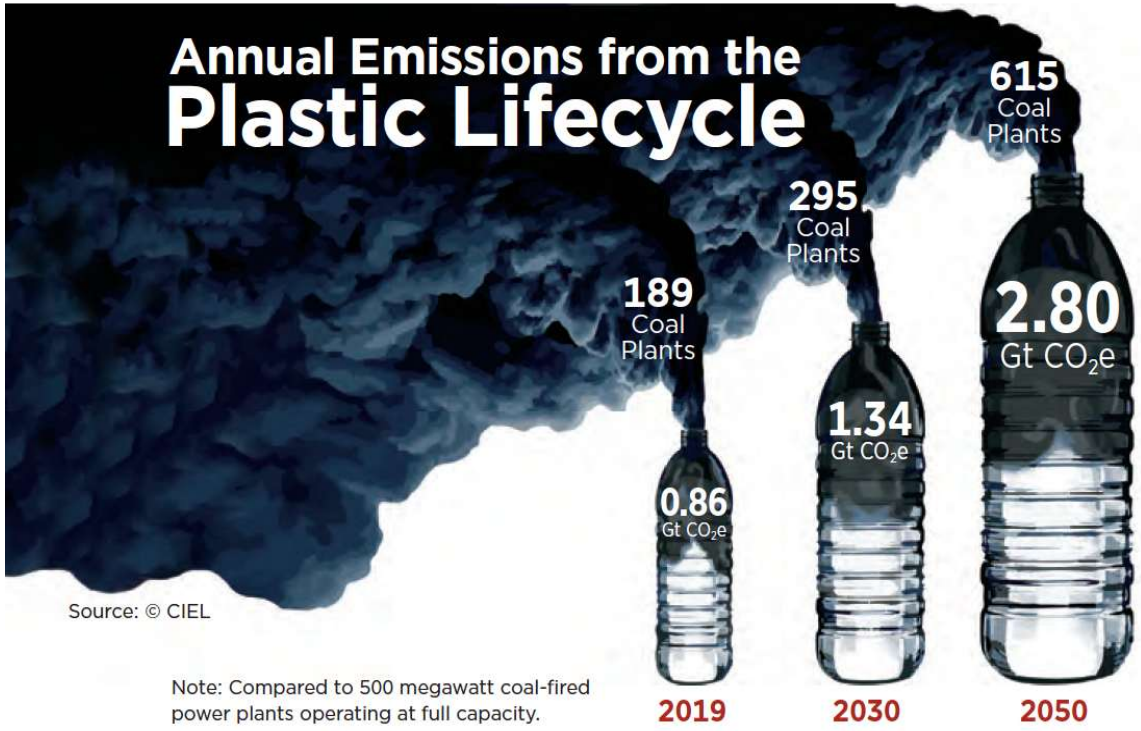
塑料行业的气候影响

➢到2050年，塑料行业温室气体累积排放将>56 $GtCO_2$当量，约占全球剩余碳预算总额的10-13%

(CIEL 2019)

FIGURE 1

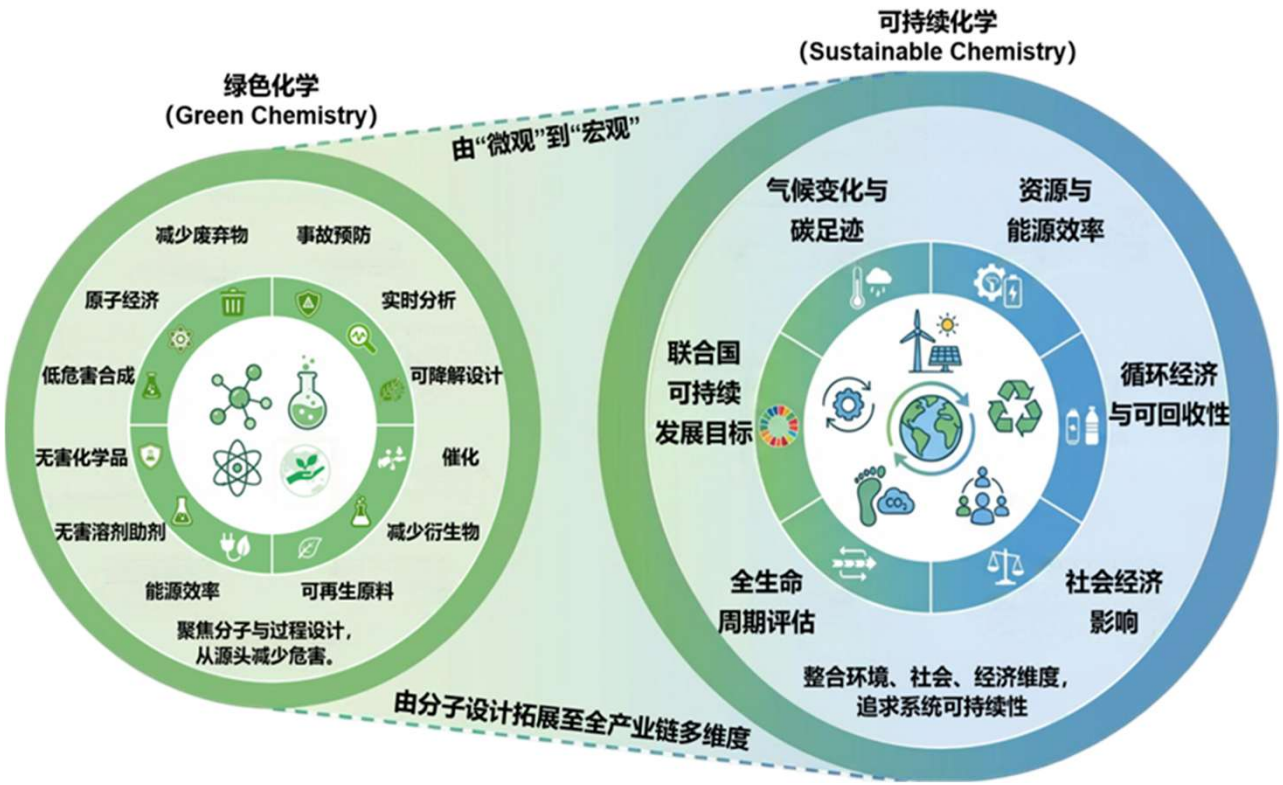
Emissions from the Plastic Lifecycle



温室气体排放来源

- 石油开采与运输：甲烷泄漏、火炬燃烧等
- 塑料炼制与生产：烷烃裂解、聚合等
- 塑料废物处置：焚烧、填埋等
- 环境中的塑料：降解、干扰海洋碳封存等

绿色和可持续化学 (GSC)



（章志淳，刘建国*等，*科学通报*，2026）

绿色和可持续化学的十大目标

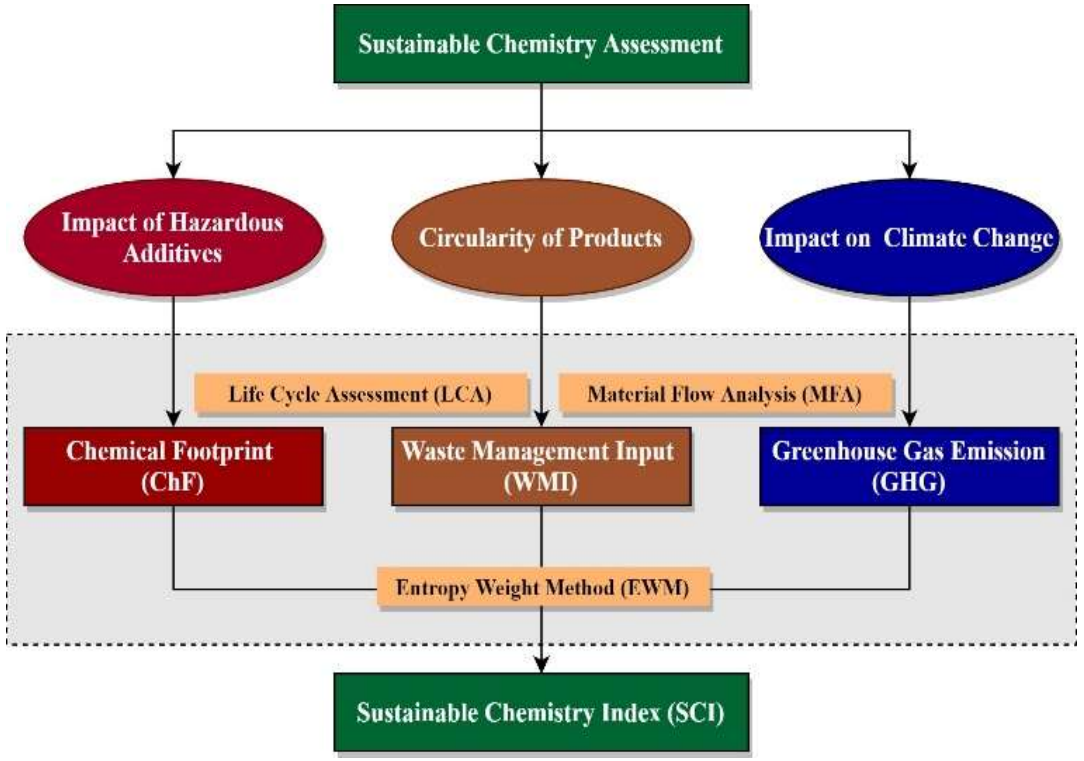
(UNEP, 2021)

- ✓ 最大程度减少化学品危害
- ✓ 避免令人遗憾的替代
- ✓ 可持续的资源和原料采购
- ✓ 推动生产过程的可持续性
- ✓ 推动产品的可持续性
- ✓ 减少化学品释放和污染
- ✓ 实现无毒循环
- ✓ ……

塑料行业可持续化学评估

- 融合化学品足迹、塑料循环性、温室气体排放等指标，构建“可持续化学指数”





Chen J, Liu J*, et al. Towards Sustainable Plastics: A Sustainable Chemistry Assessment. ***Green Chemistry***. 2025 **(Front Cover)**

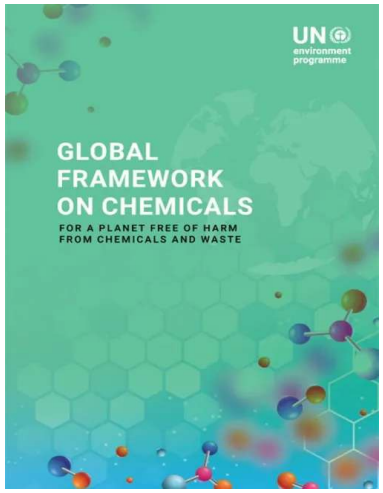
化学品足迹：未来塑料行业可持续性的新指标



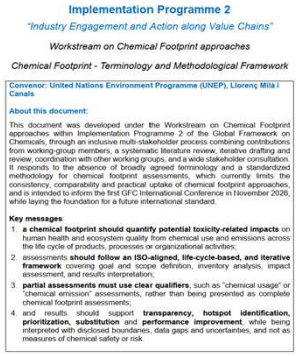
安全替代与可持续化学方案（5 项）

Safer Alternatives and Sustainable Solutions — Including Safety and Sustainability by Design (SSbD)

- **D1** 到 2030：企业投入开发并采用更安全的化学品与材料替代方案
  By 2030: Industry investment in development and adoption of safer alternatives
- **D2** 到 2030：推广安全与可持续设计（SSbD），从源头降低化学品风险
  By 2030: Promoting Safety and Sustainability by Design (SSbD) to reduce risks at source
- **D3** 到 2030：产品价值链减少危险化学品使用，促进循环经济与减量
  By 2030: Reducing hazardous chemicals in value chains; promoting circularity and minimization
- **D4** 到 2030：市场增加安全可持续化学品与材料的供给
  By 2030: Increased availability of safe and sustainable chemicals
- **D5** 到 2030：推广化学品全生命周期足迹评估方法
  By 2030: Methods for life-cycle footprint assessment







Implementation Programme 2

"Industry Engagement and Action along Value Chains"

Workstream on Chemical Footprint approaches

Chemical Footprint - Terminology and Methodological Framework

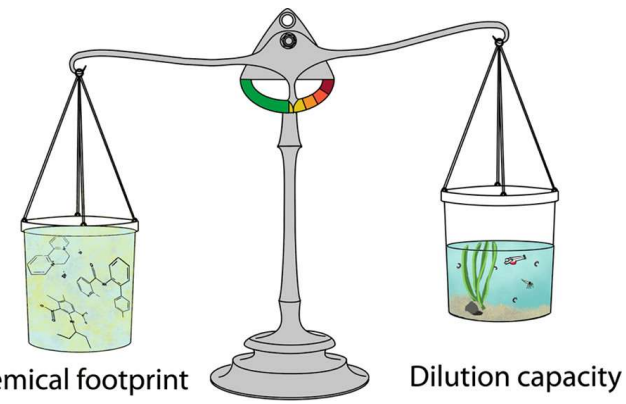
Convenor: United Nations Environment Programme (UNEP), Llorenç Milà i Canals

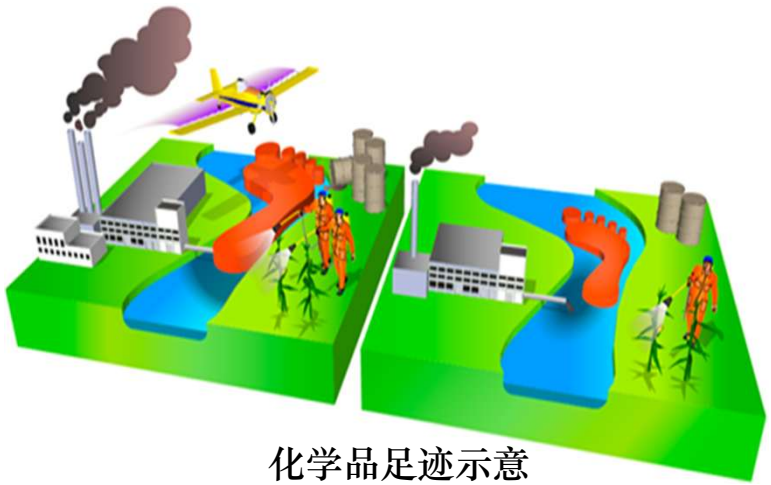
About this document:

This document was developed under the Workstream on Chemical Footprint approaches within Implementation Programme 2 of the Global Framework on Chemicals, through an inclusive multi-stakeholder process combining contributions from working-group members, a systematic literature review, iterative drafting and review, coordination with other working groups, and a wide stakeholder consultation. It responds to the absence of broadly agreed terminology and a standardized methodology for chemical footprint assessments, which currently limits the consistency, comparability and practical uptake of chemical footprint approaches, and is intended to inform the first GFC International Conference in November 2026, while laying the foundation for a future international standard.

Key messages:

1. **a chemical footprint should quantify potential toxicity-related impacts** on human health and ecosystem quality from chemical use and emissions across the life cycle of products, processes or organizational activities;
2. assessments **should follow an ISO-aligned, life-cycle-based, and iterative framework** covering goal and scope definition, inventory analysis, impact assessment, and results interpretation;
3. **partial assessments must use clear qualifiers**, such as "chemical usage" or "chemical emission" assessments, rather than being presented as complete chemical footprint assessments;
4. and results should support **transparency, hotspot identification, prioritization, substitution** and **performance improvement**, while being interpreted with disclosed boundaries, data gaps and uncertainties, and not as measures of chemical safety or risk.



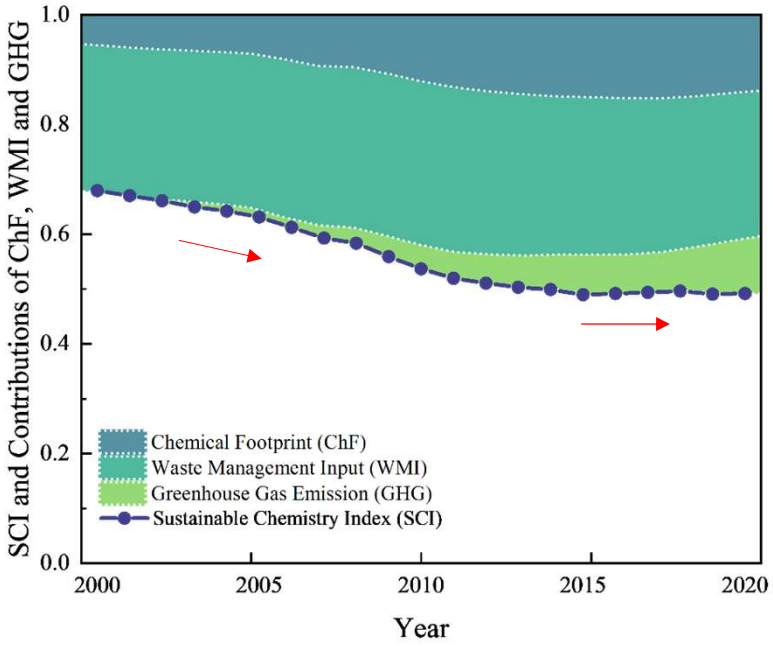


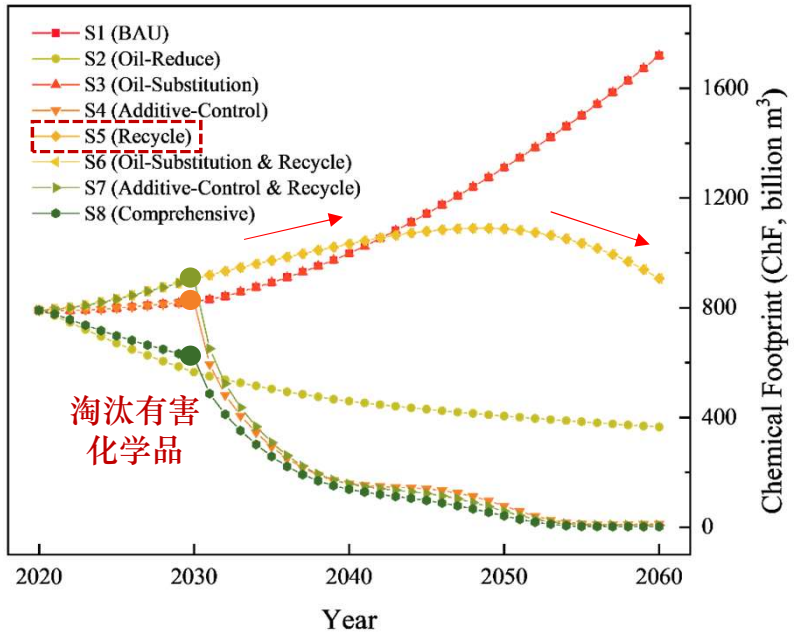
化学品足迹示意

(Bjørn et al., 2014. Zijp et al., 2014)

塑料行业可持续化学评估

- 化学品足迹与可持续化学发展水平同步变化且负相关
- 仅加强回收对减小化学品足迹存在“跷跷板效应”





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➢ **塑料中的化学品构成塑料行业可持续转型的关键因素**

欢迎批评指正！

北京大学化学品环境风险评估、风险管理与全球治理研究组
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