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Confronting the interconnection of chemical pollution and climate change

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ABSTRACT

Climate change and chemical pollution are interdependent planetary threats, but climate change mitigation efforts typically do not consider chemicals and materials. This may exacerbate chemical pollution and associated harm to human and environmental health. Because most chemicals and materials are currently derived from petrochemicals, the extraction of fossil fuels cannot be limited without transitioning chemical manufacturing to different carbon sources. However, simply changing the carbon source is insufficient and could exacerbate the biodiversity crisis. We propose a comprehensive strategy to address the interconnections between chemical pollution, climate change, and biodiversity loss. This includes incentives for key actors to reduce the global production and consumption of chemicals and materials, to transition to chemicals and products that are safe and sustainable by design, to develop metrics and targets to assess progress, and to continuously evaluate and modify strategies based on performance metrics.

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1. Introduction

The 2030 Agenda for Sustainable Development adopted by all United Nations Member States aims to "*protect the planet from degradation (…) so that it can support the needs of the present and future generations*" (United Nations, 2015). Despite this agenda, environmental impacts of societies are exceeding the "safe operating space" defined by Rockström et al. (2009) resulting in climate change, biodiversity loss, chemical pollution, plastics waste, food insecurity, and other global crises that threaten entire societies and ecosystems. In addition, the burden of these crises typically disproportionately falls on those who are most vulnerable and who have contributed least to their causes (Boyd and Orellana, 2022; Woodruff et al., 2023).[1]

Rockström et al. (2009) also warned that "*Planetary boundaries are interdependent, because transgressing one may both shift the position of other boundaries or cause them to be transgressed*." This environmental interconnectivity has also been described as a complex system, where risks can propagate from one system to another (Hope, 2006; Renn et al., 2022). For example, replacing fossil fuels with biobased resources, both for energy and chemicals, will put pressure on land and shift impacts from climate change to biodiversity loss. Similarly, Persson et al. (2022) highlighted connections between plastics and climate change and biosphere integrity.

A holistic approach to addressing environmental issues has been called for in several policy documents, including the *EU Chemicals Strategy for Sustainability* (CSS) (European Commission, 2020b) and the *Strategic Approach to International Chemicals Management* (SAICM), now the Global Framework on Chemicals (GFC) (Friege et al., 2024). This was also addressed by the United Nations in 2021, by acknowledging that chemical pollution is a global environmental crisis that must be tackled with the climate emergency and decline in biodiversity (Boyd and Orellana, 2022; United Nations Environment Programme, 2021). Unfortunately, perhaps because of the complexity of the problem and lack of data, the impact of chemicals on planetary health is rarely considered holistically. The complexity covers aspects such as the diversity of chemicals, their varied uses in materials and products, their potential transformation to other chemicals, their environmental transport and fate, the multiple exposure routes that may exist, and the different toxicities that a substance may have alone or in combination with other chemicals (mixture toxicity) or with other stressors (Posthuma et al., 2019).

Despite the limited research and awareness, chemicals, including plastics, affect all aspects of the environment, including climate change. Since impacts are caused by the sum of chemicals affecting a biological or earth system, this also implies that chemical production and consumption must be considered in their totality and across the chemical life cycles. As a consequence, it is necessary to assess both historic, accumulated pollution, as well as current emissions in order to assess the absolute impacts of chemical uses and the size of the safe operating space for future activities (Kosnik et al., 2022). Rockström et al. (2023) warned that, while their impacts could not be quantified due to a lack of data, novel entities and other pollutants "*raise clear intragenerational and intergenerational justice concerns*." Therefore, policies that only address one environmental issue in isolation may shift the burden to other environmental issues, and thereby fail to protect healthy living conditions for humans and wildlife.

Tackling decarbonization and, more broadly, environmental degradation requires addressing the core drivers. In particular, efforts to decarbonize the energy economy or move toward a post-extractivist model will fall short without recognizing that most of the chemicals and materials used in the global economy are currently derived from fossil fuels. This in turn calls for a broader policy mix, aimed at enabling innovation, experimentation, diffusion and networking, as well as facilitating structural economic change (European Environment Agency, 2019a). To achieve sustainability transitions, radical innovations need to move beyond experimentation and diffuse more widely (European Environment Agency, 2019a). As Tickner et al. (2022) phrased it, "*Achieving an industry transition of the magnitude required necessitates an urgent "wartime effort" akin to the postwar effort that launched the petrochemical industry's rapid growth during the 1940s*."

In this paper we highlight the connection between impacts of chemicals and climate change, and why climate change mitigation efforts that fail to address their externalities may increase chemical pollution and biodiversity loss. We thus propose a comprehensive strategy for producing, using, and managing chemicals and materials in close connection with climate mitigation efforts to remain within planetary boundaries.

2. Key challenges

2.1. Chemical pollution is a planetary threat

Chemical pollution is one of the nine planetary threats (Rockström et al., 2009; Steffen, Richardson, et al., 2015), but few attempts have been made to define characteristics of chemicals that constitute planetary boundary threats (Diamond et al., 2015; MacLeod et al., 2014). An international goal to minimize adverse impacts of chemicals and wastes by 2020 was not met (United Nations Environment Programme, 2019). Meanwhile, global use of chemicals is rising and is predicted to continue to do so. Chemical production is expected to triple by 2050 (Boyd and Orellana, 2022; United Nations Environment Programme, 2019). The increasing use of chemicals has led to increasing pollution, thereby exacerbating exposures and risks to health and the environment (European Environment Agency, 2019b; United Nations Environment Programme, 2019). Many chemicals and materials currently in use have well-documented impacts on human and environmental health that arise throughout chemical and product life cycles, from fossil fuel extraction through manufacturing, product use, and disposal (Boyd and Orellana, 2022; Trowbridge et al., 2023; United Nations Environment Programme, 2019). By chemicals we also mean plastics, i.e., polymers in combination with non-polymeric additives.

[1] DALY: Disability adjusted life years; HFC: Hydrofluorocarbons; HCFC: Hydrochlorofluorocarbons; PFASs: Per- and polyfluoroalkyl substances.

The World Health Organization estimated that two million lives and 53 million disability-adjusted life-years (DALYs) were lost in 2019 due to exposure to only a few well-studied chemicals (World Health Organization, 2021). A recently-published analysis of 2018 data for the U.S. found that certain chemicals used in plastics contribute significantly to the disease burden, with an estimated cost of $249 billion, or 1.22 % of the U.S. gross domestic product (Trasande et al., 2024). Previous studies estimated the economic burden due to the health impacts of endocrine-disrupting chemicals to be $340 billion (or 2.33 % of the gross domestic product) in the U.S. (Attina et al., 2016) and €163 billion (or 1.28 % of the gross domestic product) in the European Union (Trasande et al., 2016).

Additionally, chemical pollution is a known driver of biodiversity loss by negatively affecting and ultimately extinguishing a wide range of species (Groh et al., 2022). The sensitivity of biota to pesticides and other chemicals may be intensified when organisms are affected by multiple environmental stressors, such as heat or water scarcity (Liess et al., 2016). Moreover, the disease burden and environmental hazards attributable to chemical pollution are underestimated because most chemicals in commerce lack safety and toxicity data (Wang et al. 2020; Fuller et al., 2022; Kristiansson et al., 2021). Given the lack of information, precautionary measures are needed in chemicals management (Table 1) (European Environment Agency, 2013).

2.2. Chemicals and materials are typically not addressed in climate change mitigation efforts

Climate change mitigation efforts aimed at reducing oil and gas consumption and greenhouse gas emissions tend to focus on the energy and transportation sectors, ignoring the fact that the majority of chemicals and materials are sourced from fossil fuels and that this also contributes substantially to greenhouse gas emissions. Oil and natural gas comprise the main sources of the building blocks used to make most chemicals and materials (Boyd and Orellana, 2022; International Energy Agency, 2018; Kähler et al., 2021; Trowbridge et al., 2023). Petrochemical feedstocks account for 14 % of global oil demand and 9 % of global gas demand (International Energy Agency, 2020), yet their use and contributions to climate change have remained unaddressed in climate change mitigation efforts (Minovi and Huang, 2021). By 2030, petrochemicals are projected to account for more than one-third of growth in global oil demand (International Energy Agency, 2018). Thus, the extraction and refining of fossil fuels will continue to increase for as long as the chemicals and materials economy is intrinsically tied to fossil fuels. Even with a worldwide transition to alternative energy sources, there will be ongoing extraction of fossil fuels unless the carbon source for chemical manufacturing is changed.

Additionally, the chemicals sector uses more energy than any other manufacturing sector in the world (European Environment Agency, 2021a; International Energy Agency, 2018; United Nations Environment Programme, 2019). The chemical and plastics manufacturing industries generally are based on a resource-extractive model, in which hydrocarbons as well as other resources are used to create a wide range of chemicals and materials through energy-intensive processes. For instance, in 2019, bulk chemicals accounted for approximately 35 % of total U.S. industrial energy consumption (EIA, 2020). Globally, the chemicals sector is the third largest industrial source of greenhouse gas emissions (International Energy Agency, 2018), emitting an estimated 3.3 billion tonnes of greenhouse gases each year (Boyd and Orellana, 2022). All chemicals require energy use during extraction, production, transport, disposal, or incineration. To the extent that energy to make chemicals is generated from fossil fuels, chemical manufacturing also produces greenhouse gases.

Lastly, some industrial chemicals are potent greenhouse gases themselves, while others lead to greenhouse gas emissions during their manufacturing or at end-of-life. For instance, in 2015, the global plastics industry emitted an estimated 1.7 gigatonnes of carbon dioxide equivalents (Zheng and Suh, 2019). In 2019, manufacturing of certain fluorinated polymers in the U.S. led to emissions of over 100 tonnes of a feedstock chemical, chlorodifluoromethane (HCFC-22), a highly potent greenhouse gas and ozone-depleting substance (Schreder and Kemler, 2021). In addition, the potent greenhouse gas trifluoromethane (HFC-23, global warming potential of 12,400) is formed as a synthesis by-product of HCFC-22 and may be released during production. Fluorinated gases with high global warming potential are also likely to be formed in the thermal degradation of fluorinated polymers and other per- and polyfluoroalkyl substances (PFASs) below temperatures that mineralize the materials to inorganic constituents, such as during the uncontrolled smoldering of electronics and lithium-ion batteries (Mossali et al., 2020).

Table 1
Intrinsic chemical properties and other attributes that indicate a need for precautionary measures (adapted from European Environment Agency (2013)).

Property/attribute
Toxicity/ecotoxicity
Novelty (i.e., where there is a low ‘knowledge/ignorance ratio’)
Environmental persistence and difficulty of removal
Potential for accumulation in biota, including humans, or in the environment
Ability to undergo long-range environmental transport
Seriousness of potential hazard, including to vulnerable groups or ecosystems
Multiple sources and repeated exposures
Irreversibility of potential effects, including inter-generational effects
Evidence of hazards from structurally similar chemicals
Inequitable distribution of hazardous impacts across time and space, or on specific regions, people, and generations

2.3. Climate change mitigation efforts that fail to address their externalities may exacerbate chemical pollution

Not only is current materials consumption intricately tied to fossil fuel uses (Tickner et al., 2021), but also some part of chemical pollution is often an invisible externality of climate change mitigation. By 2050, it is expected that chemicals and material manufacturing will use 1000 million tonnes of carbon per year, up from 450 million tonnes in a 2021 estimate (Kähler et al., 2021). This increase is driven by market forces pushing for an expansion of petrochemical and plastic production as an alternate market for companies selling fossil fuel products (Bauer et al., 2022; Tickner et al., 2021). It is no coincidence that many of today's largest chemical companies are also oil and gas giants (Tickner et al., 2021). The fraction of crude oil converted into petrochemicals at typical refineries could grow from the current 5–20 % to 60–80 % (Yadav et al., 2020). Plastic manufacturing is also expected to grow, and with it, the plastic pollution, which is often irreversible, ubiquitous, and harmful, representing a planetary-scale threat (Arp et al., 2021). Currently, plastic production increases at a rate of 4 % per year (Brahney et al., 2021). With the expected expansion in manufacturing, plastic is estimated to emit a total of over 56 gigatonnes of carbon dioxide-equivalent greenhouse gases between 2015 and 2050, which is 10–13 % of the entire remaining carbon budget (Hamilton et al., 2019).

Moreover, several known hazardous substances are frequently used in renewable-energy technologies, such as solar panels, wind turbines, advanced batteries, and electric vehicles. These chemicals of concern include a variety of metals, whose extraction and processing are energy-intensive, harm surrounding ecosystems and communities, and contaminate drinking water and food webs (Watari et al., 2020). The International Energy Agency (2021) estimated that the clean energy transition will require four to six times more mineral inputs by 2040. For example, onshore wind plants require nine times more minerals than gas-fired plants, and typical electric vehicles use six times more minerals than conventional vehicles (International Energy Agency, 2021). Electric vehicles, according to the American Chemistry Council (2023), "rely on chemistry," including PFASs, lithium (for lithium ion-batteries), and various plastics such as polyethylene, polypropylene, and fluoropolymers. Some photovoltaic modules are considered hazardous in the U.S. due to their high content of metals such as silver, copper, lead, arsenic, cadmium, and selenium (Department of Toxic Substances Control, 2024; U.S. EPA, 2021). Another example is spray polyurethane foam insulation, used to help meet climate mitigation targets by reducing energy needs for heating and cooling buildings, which often contains hazardous compounds such as halogenated organophosphate flame retardants (Estill et al., 2019) and unreacted methylene diphenyl diisocianate (U.S. EPA, 2015).

This does not mean that climate change mitigation efforts should be abandoned, but they must be done in a way that avoids shifting the burden of harm from one planetary-scale issue to another one such as chemical pollution. Safer alternatives to chemicals of concern in alternative energy technologies often do exist or can be developed (Ateia and Scheringer, 2024). Thus, it is critical to continue to innovate safer chemistries and experiment to demonstrate their feasibility, to avoid lock-in of toxic chemicals in the renewable energy sector.

2.4. Simply changing the carbon source is insufficient to address chemical pollution and its interactions with climate change

Fossil fuels have allowed for the production of chemicals at volumes that are not possible with renewable bio-based sources. The current global materials economy is inherently unsustainable (Bjørn et al., 2015; Hauschild et al., 2020; Ryberg et al., 2018). As we discuss below, a significant downsizing is required in order to transition the chemicals industry away from fossil fuels. But even with such a transition, it is important to keep two things in mind: First, all resource extractive feedstocks are finite and therefore unsustainable in the long term. Second, simply shifting to carbon-neutral feedstocks will perpetuate the issues of chemical toxicity and related adverse impacts, including on vulnerable communities (Tickner et al., 2022).

Similar to crops used as feedstock for energy, which compete for space with agriculture and with natural ecosystems, resulting in biodiversity loss, crops used as feedstock for chemicals will compete for space with natural ecosystems and with various human activities, including housing, transportation, and recreation. Using bio-based chemical feedstocks that are products of industrial agriculture also would have detrimental consequences, including agrochemical pollution, ecosystem damage, biodiversity loss, soil degradation, and nutrient depletion, potentially resulting in a global food crisis. Industrial agriculture has been the major driver of transgressing planetary boundaries of biosphere integrity and biogeochemical flows, and has contributed to adverse impacts on all other planetary boundaries (Campbell et al., 2017). Thus, merely replacing fossil fuels as the carbon source with bio-based feedstocks will perpetuate, or even exacerbate, the problem.

3. Ways forward

To minimize the tradeoffs of current mainstream climate change mitigation strategies and chemical pollution, we propose a comprehensive strategy aimed at transforming how chemicals and materials are produced, used, and managed.

3.1. Acknowledge chemical pollution as a planetary-scale threat and address it together with climate change

To effectively address the climate crisis, not only the energy economy needs to be substantially modified, but also the materials economy. The transition away from fossil fuels to address climate change also requires expeditiously transforming and downsizing the materials economy and internalizing the economic costs of its human health and environmental impacts. Improving *efficiency* alone and making incremental changes will not suffice to address the total impact of chemicals (Steffen, Broadgate, et al., 2015; Tickner et al., 2021). A shift from a linear "take-make-waste" model to more circular economies built on material feedstocks that reduce ecosystem exploitation and damage will be necessary (Yang et al., 2023). This requires ensuring material feedstocks are safer.

The shift to sustainable materials use will involve interactions among multiple societal actors. Scientists, entrepreneurs, and companies large and small will have to engage in reinventing how chemicals and materials are manufactured and used to provide needed services. The design of new processes and products will need to center on minimizing the absolute impacts on planetary health (Fantke and Illner, 2019) rather than on maximizing economic returns. This transformation will also require the financial industry to desist from seeking short-term gains such as financing the oil and gas sector's expansion, and instead to aim for economic returns from long-term investments compatible with a sustainable future. The insurance industry is already concerned about the cost of increasing liability for pollution from PFASs and other chemicals, and is exploring ways to require companies to shift to more sustainable business models as a precondition for securing adequate insurance coverage.

Appropriate incentives for this shift will need to be designed by policymakers and regulators, including measures to prevent or, rather, break up lock-ins of unsustainable technologies. These could involve the use of various policy levers (Meadows, 1999), such as financial instruments (e.g., taxes and subsidies, green public procurement, sustainable finance schemes (European Commission, 2021)) and extended producer responsibility (De Schoenmakere and Gillabel, 2017). For example, industries could be required to deposit sufficient funding or insurance ("anticipatory insurance bonds" (Bharadwaj and Mitchell, 2022)) prior to extraction or production to cover the costs of both foreseen and unforeseen pollution mitigation.

Transitions of this scale involve normative choices between alternative visions of the future and how to get there, which requires not only tools, but a transformation of values (European Environment Agency, 2019a). However, as with climate change mitigation efforts, building public support for transforming the material economy still has far to go. The types of innovations required run the risk of being blocked by incumbent industries (and some government policies) seeking to protect the status quo, while smaller companies

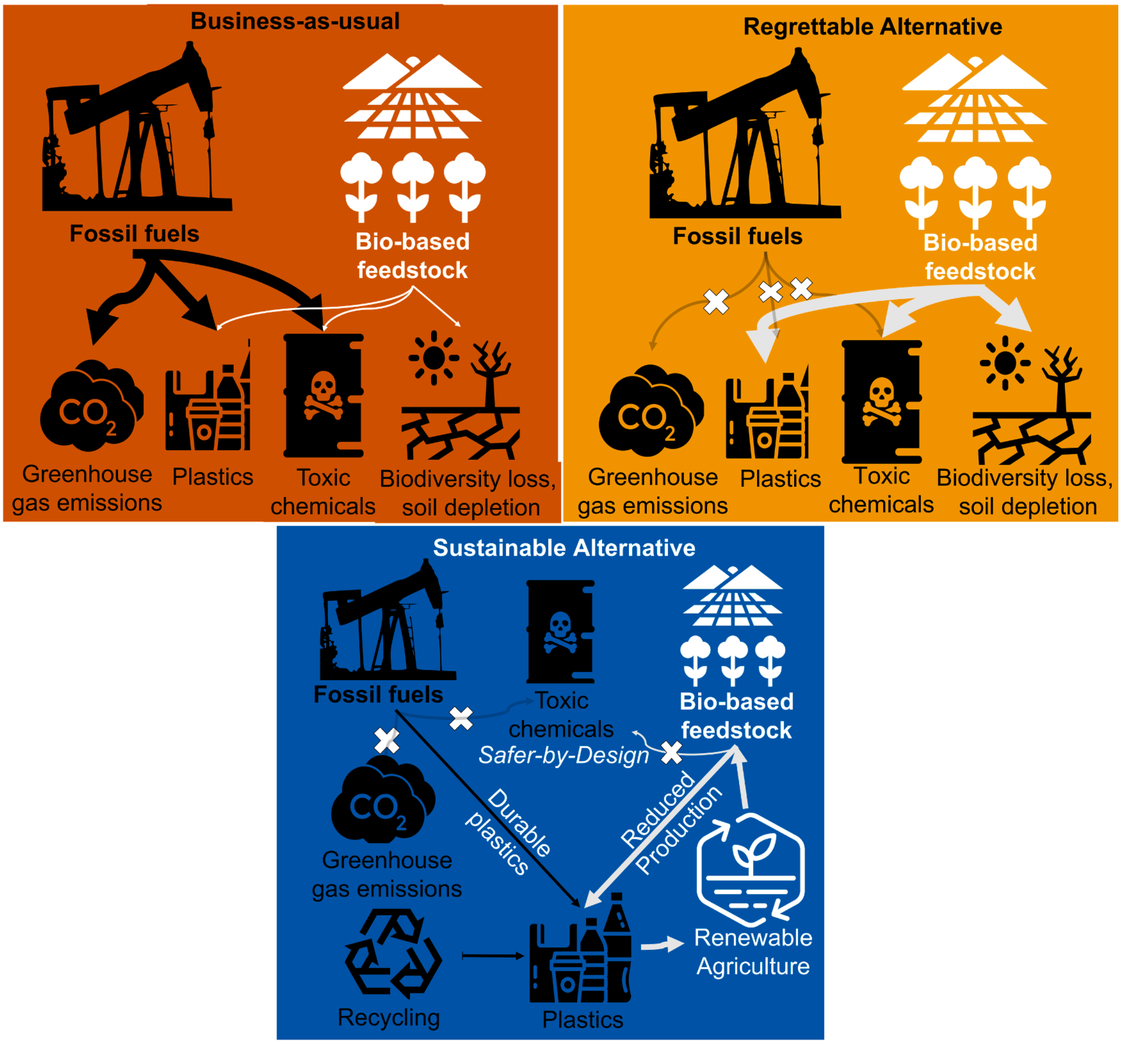

Fig. 1. Transitioning to bio-based feedstocks without reducing overall chemical production is unsustainable since it simply transfers the risks to different systems. The sustainable alternative is to reduce overall chemical production in a circular bio-based economy using renewable agricultural practices and transition to chemicals, materials, and products that are safe and sustainable by design.

willing to experiment may have difficulties finding markets and scaling up.

It remains critical for scientists and policymakers tracking impacts from chemical pollution to address the interconnections with climate change, and for the media to amplify these messages to ensure that they reach the general public and help build momentum for this shift.

3.2. Reduce production and consumption of chemicals and materials

Ensuring a safe environment for current and future generations will require a significant decrease in material consumption (Persson et al., 2022; Wiedmann et al., 2020). For the chemicals and plastics manufacturing industries, that means significantly reducing the annual production and consumption of chemicals sourced from virgin resources. Simply replacing one source of carbon with another, or one chemical with another, will only displace the problem. Both the hazards and absolute volume of industrial chemicals must be reduced.

A path forward could be for chemicals and materials derived from fossil fuels or other virgin resources to only be used for high-value materials essential for society. However, substitution of bio-based feedstocks without reducing consumption runs a great risk of taking limited space from natural ecosystems and food crops, which potentially requires more than half of the world's sustainable biomass supply (Bauer et al., 2022; International Energy Agency, 2018). Additionally, a circular bio-based economy would significantly limit the volumes and types of chemicals that can be made, thus forcing reduced consumption. Instead of merely shifting the source of carbon, a new economic model is needed (Fig. 1), one that can provide services essential to well-being while reducing the diversity and volumes of chemicals and materials produced and used (Fenner and Scheringer, 2021).

3.3. Transition to chemicals, materials, and products that are safe and sustainable by design

In the assessment of chemicals, all externalities along the multiple life cycles need to be considered, including current and future impacts on planetary boundaries. Stronger efforts to identify and eliminate chemicals of concern and remediate (or at least limit the spread of pollution from) contaminated areas are needed, with a focus on vulnerable groups and ecosystems (Alcántar et al., 2017). For example, the EU *Chemicals Strategy for Sustainability – Towards a Toxic-free Environment* aims for an industrial transition to chemicals and materials that are *safe and sustainable by design*, with the goal of enabling society to thrive within planetary boundaries (European Commission, Joint Research Centre, 2022; European Environment Agency, 2021b). We propose the following considerations to help define this concept:

- The function (or service) provided by the chemical or material should be essential to society. The first question to ask of any chemical or material is "Is it necessary?" (Balan et al., 2023; Roy et al., 2022; Tickner et al., 2015). Are there other ways of achieving the function or service provided, perhaps by redesigning the entire system?
- Chemicals and materials, including the intermediates used to make them and their transformation products, (1) should not persist in the environment and should not bioaccumulate; (2) should possess low or no hazard according to a comprehensive assessment that considers a variety of effect endpoints across different species, including low-dose and cumulative effects; (3) should not have a global warming potential greater than that of carbon dioxide; and (4) should not destroy the ozone layer.
- The chemical feedstocks should be either (1) renewable and obtained in ways that do not deplete soil health and local biodiversity, or (2) recycled from waste metals, petrochemicals, or bio-based materials and can in turn be efficiently recycled, with the required recycling infrastructure properly in place, at the appropriate scale, and properly funded, without significant pollution.
- Chemicals and materials are designed with their end-of-life in mind, as well as to increase the life-span of the products, and to enable repair (European Parliament, 2024). After their use phase, chemicals and materials should degrade into non-hazardous compounds in the environment or be efficiently and safely recycled, with proper end-of-life infrastructures in place.
- All manufacturing processes should follow the principles of green, sustainable, and circular chemistry; they should be adaptable, and lean; not lead to severe harm in the case of accidents; and minimize depletion of finite resources.

Many of these points were set forth years ago in the 12 Principles of Green Chemistry (Anastas and Warner, 1998). They have since been augmented by discussions on circularity and a sustainable materials economy. Scientists now point out the need for extra emphasis on the design of chemicals, materials, and products, as well as on their durability, reparability, reusability, and recyclability, since each new process or cycle leads to resource loss and pollution (Kümmerer et al., 2020).

3.4. Set targets, measure progress, and re-evaluate strategies

Approximately 350,000 synthetic chemicals are on the market globally (Wang et al., 2020). The number of chemicals continues to grow, as does the associated pollution of the biosphere. A suite of smart metrics could help set actionable targets, measure progress, and better align climate change and pollution mitigation efforts. Multiple metrics must be integrated to assess impacts of chemicals, in the present and over time (Caldeira et al., 2024; Kosnik et al., 2022). Actionable metrics require access to reliable data on chemical identities, volumes used, and foreseen uses, including for mixtures (Committe of Combination of effects and assessing chemicals in groups, 2019). Such metrics may inform the development of indicators to follow chemical risks and impacts, as well as progress of actions to avoid harm. Useful examples of indicators include the EU chemicals indicator framework (European Commission, 2020a; European Environment Agency, 2023, 2024) and the indicators prepared for the 2023 Global Framework on Chemicals (Friege et al., 2024). However, these focus on monitoring compliance with chemicals policies and legislation, and do not address the complex tradeoffs between climate mitigation efforts and chemicals production/consumption discussed here. We suggest some possible metrics in Table 2.

Unanticipated events, scientific progress, slow implementation of actions, changing political realities, and successes and failures in achieving sustainability are all inevitable. Therefore, performance metrics (Table 2) and real-world outcomes must be continuously evaluated to best allocate efforts and resources where they are most needed. A dynamic and nimble approach will align with the needs of a fast-changing world.

4. Conclusions

Humanity has several big challenges to tackle, including how to achieve equitable well-being without exceeding the planetary boundaries that are the foundation for sustained human life on earth. An alternative to the current linear "take-make-waste" model is critical to addressing the systemic risks from the multiple interrelated planetary health crises the world is experiencing. This involves producing and using fewer chemicals and materials, and ensuring that those used are safe and sustainable by design.

The chemical industry – manufacturers, a multitude of international supply chains, customers and users, as well as regulators at the national and international level – is a socio-technical system (Markard et al. 2012) that is still at the beginning of its socio-technical transition toward more sustainable practices. It is a system with a considerable energy and materials footprint and with strong impacts on human and environmental health, great technical diversity, great economic importance and, accordingly, substantial inertia.

This system of the chemical industry has not been in the focus of transition studies (Köhler et al. 2019). We propose that the chemical industry should be investigated more extensively in sustainability transition research, which would provide a better understanding of the persistent lock-ins present in the system (Blumenthal et al., 2022) and other obstacles to the transition. Aims for the transition have been outlined in the Global Chemicals Outlook II (United Nations Environment Programme, 2019) and by Kümmerer et al. (2020), Fenner and Scheringer (2021), and also in the present work. However, the way by which these aims can be reached is still largely unclear. As pointed out by Markard et al. (2012) and Köhler et al. (2019), there are several areas where a better understanding of a socio-technical system and its ability to undergo a transition is needed, including the power, politics, and policies of the transition; the type and extent of agency of the different actors in the system; and the geographical dimension and differentiation of the transition process. All of these aspects are highly relevant for the transition of the chemical industry as a large, complex, globalized, and powerful system.

It is not yet clear if any of the existing models of sustainability transitions will be adequate for an analysis and, ideally, facilitation of the chemical industry's transition. This is because the transition is still at its beginning and because it has to be fundamental, with substantial changes in chemical product development, manufacture, marketing, and regulation. Currently, there are still many lock-ins of unsustainable production patterns; most problematic is the growth imperative, with a projected growth in chemical production by a factor of 1.5 between now and 2030 and further growth until 2050 (United Nations Environment Programme, 2019). This pathway is clearly not sustainable and needs to be modified.

In conclusion, changes in societal consumption patterns, industrial production processes, chemical feedstocks, and materials economies will be inevitable. Ideally, these changes will take place as a result of a managed transition process rather than as a necessity due to environmental collapse.

The thoughts presented here are only a starting point meant to spark future conversations. We recognize that these proposed changes will require an enabling environment of education, policies, and investments, as well as societal and cultural change. Transforming the chemicals and materials economy needs a global perspective, incentives to level the playing field, fair standards, and environmental justice (Bauer et al., 2022). Climate change mitigation and sustainable chemistry must be integrated to account for the full complexity of these global threats.

Table 2
Possible metrics to assess chemical use and sustainability.

Metric
Total number and tonnage of chemicals on the market per year and cumulative over time
Annual tonnage of fossil fuels extracted and fractions used to make chemicals and plastics
Annual tonnage of chemicals and plastics produced from fossil fuels and from bio-based resources
Number and annual tonnage of most harmful substances and substances of concern (e.g., as defined by the EU Chemicals Strategy for Sustainability (European Commission, 2020b)) in use and in the environment
Fraction of chemicals by volume that meet safety criteria (e.g., the U.S. Environmental Protection Agency's Safer Choice Master Criteria for Safer Chemical Ingredients (U.S. EPA, 2013))
Identities and concentrations of chemicals found in environmental monitoring, occupational monitoring, and biomonitoring, globally and locally
Volume of resources that cannot be regenerated (e.g., landfilled or incinerated waste, highly persistent compounds)
Avoided harm to human health (cancer, antimicrobial resistance, loss of fertility and immune system functioning) from decreased production of hazardous chemicals
Frequency and extent of exceedances of concentrations that cause harm to humans and ecosystems
Ecosystem vital signs (for example, see the Puget Sound, 2021)

Author statement

SB wrote a first draft after discussion with all co-authors. All co-authors extensively discussed the reviewers' comments and contributed to the revisions, including actual edits of the text. This multi-author work required extensive rounds of discussions and refinement.

CRediT authorship contribution statement

Simona A. Bălan: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Conceptualization. **Saskia K. van Bergen:** Writing – review & editing, Writing – original draft, Conceptualization. **Ann Blake:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Topher Buck:** Writing – review & editing, Writing – original draft, Conceptualization. **Scott Coffin:** Writing – review & editing, Writing – original draft, Visualization, Conceptualization. **Jamie C. DeWitt:** Writing – review & editing. **Gretta Goldenman:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Frank A. von Hippel:** Writing – review & editing. **Sophia von Hippel:** Visualization. **Christopher P. Leonetti:** Writing – review & editing, Investigation, Conceptualization. **David Rist:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Martin Scheringer:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Xenia Trier:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data were used for the research described in the article.

References

Alcántar, K., Blake, A., Edwards, S., Singla, V., 2017. Selecting safer alternatives to toxic chemicals and ensuring the protection of the most vulnerable: a discussion draft. Natural Resources Defense Council (NRDC) & CHANGE. https://www.nrdc.org/sites/default/files/toxic-chemicals-vulnerable-populations-report.pdf.

American Chemistry Council, 2023. 2023 Guide to the Business of Chemistry. https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/resources/2023guide-to-the-business-of-chemistry.

Anastas, P.T., Warner, J.C., 1998. Green Chemistry: Theory and Practice. Oxford University Press.

Arp, H.P.H., Kühnel, D., Rummel, C., MacLeod, M., Potthoff, A., Reichelt, S., Rojo-Nieto, E., Schmitt-Jansen, M., Sonnenberg, J., Toorman, E., Jahnke, A., 2021. Weathering plastics as a planetary boundary threat: exposure, fate, and hazards. Environ. Sci. Technol. 55 (11), 7246–7255. https://doi.org/10.1021/acs.est.1c01512.

Ateia, M., Scheringer, 2024. From "forever chemicals" to alternatives. Science (1979) 384.

Attina, T.M., Hauser, R., Sathyanarayana, S., Hunt, P.A., Bourguignon, J.-P., Myers, J.P., DiGangi, J., Zoeller, R.T., Trasande, L., 2016. Exposure to endocrine-disrupting chemicals in the USA: a population-based disease burden and cost analysis. Lancet Diabetes. Endocrinol. 4 (12), 996–1003. https://doi.org/10.1016/S2213-8587(16)30275-3.

Balan, S., Andrews, D., Blum, A., Diamond, M., Fernandez, S., Harriman, E., Lindstrom, A., Reade, A., Richter, L., Sutton, R., Wang, Z., Kwiatkowski, C., 2023. Optimizing chemicals management in the United States and Canada through the essential-use approach. Environ. Sci. Technol. 57 (4). https://pubs.acs.org/doi/10.1021/acs.est.2c05932.

Bauer, F., Nielsen, T.D., Nilsson, L.J., Palm, E., Ericsson, K., Fråne, A., Cullen, J., 2022. Plastics and climate change—Breaking carbon lock-ins through three mitigation pathways. One Earth. 5 (4), 361–376. https://doi.org/10.1016/j.oneear.2022.03.007.

Bharadwaj, R., Mitchell, T., 2022. Strengthening anticipatory risk response and financing mechanisms for social protection. https://www.iied.org/sites/default/files/pdfs/2023-03/21286IIED.pdf.

Bjørn, A., Diamond, M., Owsianiak, M., Verzat, B., Hauschild, M.Z., 2015. Strengthening the link between life cycle assessment and indicators for absolute sustainability to support development within planetary boundaries. Environ. Sci. Technol. 49 (11), 6370–6371. https://doi.org/10.1021/acs.est.5b02106.

Blumenthal, J., Diamond, M., Hoffmann, M., Wang, Z., 2022. Time to break the "lock-In" impediments to chemicals management. Environ. Sci. Technol. 56, 3863–3870. https://doi.org/10.1021/acs.est.1c06615.

Boyd, D., Orellana, M., 2022. The Right to a Clean, Healthy and Sustainable Environment: Non-toxic Environment: Report of the Special Rapporteur On the Issue of Human Rights Obligations Relating to the Enjoyment of a Safe, Clean, Healthy and Sustainable Environment [dataset]. United Nations. https://doi.org/10.1163/2210-7975_HRD-9970-2016149.

Brahney, J., Mahowald, N., Prank, M., Cornwell, G., Klimont, Z., Matsui, H., Prather, K.A., 2021. Constraining the atmospheric limb of the plastic cycle. Proc. National Acad. Sci. 118 (16), e2020719118. https://doi.org/10.1073/pnas.2020719118.

Caldeira, C., Abbate, E., Moretti, C., Mancini, L., Sala, S., 2024. Safe and sustainable chemicals and materials: a review of sustainability assessment frameworks. Green Chem. 26 (13), 7456–7477. https://doi.org/10.1039/D3GC04598F.

Campbell, B.M., Beare, D.J., Bennett, E.M., Hall-Spencer, J.M., Ingram, J.S.I., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J.A., Shindell, D., 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. Ecol. Society 22 (4). https://doi.org/10.5751/ES-09595-220408 art8.

Committe of Combination of effects and assessing chemicals in groups, 2019. Future Chemical Risk Management: Accounting for Combination Effects and Assessing Chemicals in Groups. Swedish Government. https://www.government.se/contentassets/ee36b3e49c354bb8967f3a33a2d5ca50/future-chemical-risk-management-accounting-for-combination-effects-and-assessing-chemicals-in-groups-sou-201945/.

De Schoenmakere, M., Gillabel, J., 2017. Circular by Design: Products in the Circular Economy. Publications Office of the European Union.

Department of Toxic Substances Control, 2024. Photovoltaic (PV) Modules (Including Solar Panels) Universal Waste Management—Frequently Asked Questions. https://dtsc.ca.gov/solar-panel-faqs/.

Diamond, M.L., de Wit, C.A., Molander, S., Scheringer, M., Backhaus, T., Lohmann, R., Arvidsson, R., Bergman, Å., Hauschild, M., Holoubek, I., Persson, L., Suzuki, N., Vighi, M., Zetzsch, C., 2015. Exploring the planetary boundary for chemical pollution. Environ. Int. 78, 8–15. https://doi.org/10.1016/j.envint.2015.02.001.

EIA, 2020. Annual Energy Outlook 2020: With Projections to 2050. U.S. Energy Information Administration (EIA). https://www.eia.gov/outlooks/aeo/pdf/aeo2020.pdf.

Estill, C.F., Slone, J., Mayer, A.C., Phillips, K., Lu, J., Chen, I.-C., Christianson, A., Streicher, R., Guardia, M.J.L., Jayatilaka, N., Ospina, M., Calafat, A.M., 2019. Assessment of spray polyurethane foam worker exposure to organophosphate flame retardants through measures in air, hand wipes, and urine. J. Occup. Environ. Hyg. 16 (7), 477–488. https://doi.org/10.1080/15459624.2019.1609004.

European Commission, 2020a. Annex to the Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Chemicals Strategy for Sustainability: Towards a Toxic-Free Environment. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A667%3AFIN#document2.

European Commission. 2020b. Chemicals strategy for sustainability: towards a toxic-free environment. https://ec.europa.eu/environment/pdf/chemicals/2020/10/Strategy.pdf.

European Commission. 2021. EU taxonomy for sustainable activities. https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en.

European Commission, Joint Research Centre, 2022. Safe and Sustainable by Design Chemicals and Materials: Framework for the Definition of Criteria and Evaluation Procedure for Chemicals and Materials. Publications Office. https://data.europa.eu/doi/10.2760/487955.

European Environment Agency, 2013. Late Lessons from Early Warnings: Science, Precaution, Innovation. Publications Office. https://data.europa.eu/doi/10.2800/73322.

European Environment Agency, 2019a. Sustainability Transitions: Policy and Practice (9/2019). Publications Office of the European Union. https://www.eea.europa.eu/publications/sustainability-transitions-policy-and-practice.

European Environment Agency, 2019b. The European Environment: State and Outlook 2020: Knowledge for Transition to a Sustainable Europe (Chapter 10). Publications Office. https://data.europa.eu/doi/10.2800/96749.

European Environment Agency, 2021a. Plastics, the Circular Economy and Europe's Environment: A Priority for Action. Publications Office. https://data.europa.eu/doi/10.2800/5847.

European Environment Agency. 2021b, February 4. Designing safe and sustainable products requires a new approach for chemicals. https://www.eea.europa.eu/themes/human/chemicals/delivering-products-that-are-safe.

European Environment Agency, 2023. Chemicals and Health. https://www.eea.europa.eu/publications/zero-pollution/health/chemicals.

European Environment Agency, 2024. EU Indicator Framework for Chemicals. Publications Office. https://data.europa.eu/doi/10.2800/10922.

European Parliament, 2024. Right to Repair: Making Repair Easier and More Appealing to Consumers | News | European Parliament. April 23. https://www.europarl.europa.eu/news/en/press-room/20240419IPR20590/right-to-repair-making-repair-easier-and-more-appealing-to-consumers.

Fantke, P., Illner, N., 2019. Goods that are good enough: introducing an absolute sustainability perspective for managing chemicals in consumer products. Curr. Opin. Green. Sustain. Chem. 15, 91–97. https://doi.org/10.1016/j.cogsc.2018.12.001.

Fenner, K., Scheringer, M., 2021. The need for chemical simplification as a logical consequence of ever-increasing chemical pollution. Environ. Sci. Technol. 55 (21), 14470–14472. https://doi.org/10.1021/acs.est.1c04903.

Friege, H., Heidbüchel, E., Zeschmar-Lahl, B., 2024. Indicators for Sustainable Management of Chemicals: Contributions to Upcoming Development Work Under the New Global Framework For Chemicals. German Environment Agency. https://www.umweltbundesamt.de/publikationen/indicators-for-sustainable-management-of-chemicals.

Fuller, R., Landrigan, P.J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M., Caravanos, J., Chiles, T., Cohen, A., Corra, L., Cropper, M., Ferraro, G., Hanna, J., Hanrahan, D., Hu, H., Hunter, D., Janata, G., Kupka, R., Lanphear, B., Yan, C., 2022. Pollution and health: a progress update. Lancet Plan. Health 6 (6), e535–e547. https://doi.org/10.1016/S2542-5196(22)00090-0.

Groh, K., vom Berg, C., Schirmer, K., Tlili, A., 2022. Anthropogenic chemicals as underestimated drivers of biodiversity loss: scientific and societal implications. Environ. Sci. Technol. 56 (2), 707–710. https://doi.org/10.1021/acs.est.1c08399.

Hamilton, L.A., Feit, S., Muffett, C., Kelso, M., Malone Rubright, S., Bernhardt, C., Schaeffer, E., Moon, D., Morris, J., Labbe-Bellas, R., 2019. Plastic & Climate: The Hidden Costs of a Plastic Planet. Center Int. Environ. Law. https://www.ciel.org/wp-content/uploads/2019/05/Plastic-and-Climate-FINAL-2019.pdf.

Hauschild, M.Z., Kara, S., Røpke, I., 2020. Absolute sustainability: challenges to life cycle engineering. CIRP Annals 69 (2), 533–553. https://doi.org/10.1016/j.cirp.2020.05.004.

Hope, B.K., 2006. An examination of ecological risk assessment and management practices. Environ. Int. 32 (8), 983–995. https://doi.org/10.1016/j.envint.2006.06.005.

International Energy Agency, 2018. The Future of Petrochemicals. International Energy Agency (IEA). https://www.iea.org/reports/the-future-of-petrochemicals.

International Energy Agency, 2020. Energy Technology Perspectives 2020. International Energy Agency (IEA). https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf.

International Energy Agency. The Role of Critical Minerals in Clean Energy Transitions. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

Kähler, F., Carus, M., Porc, O., vom Berg, C., 2021. Turning off the tap for fossil carbon: future prospects for a global chemical and derived material sector based on renewable carbon. Industrial Biotechnol. 17 (5), 245–258. https://doi.org/10.1089/ind.2021.29261.fka.

Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M.S., Nykvist, B., Wells, P., 2019. An agenda for sustainability transitions research: state of the art and future directions. Environ. Innov. Soc. Transit. 31, 1–32. https://doi.org/10.1016/j.eist.2019.01.004.

Kosnik, M.B., Hauschild, M.Z., Fantke, P., 2022. Toward assessing absolute environmental sustainability of chemical pollution. Environ. Sci. Technol. 56 (8), 4776–4787. https://doi.org/10.1021/acs.est.1c06098.

Kristiansson, E., Coria, J., Gunnarsson, L., Gustavsson, M., 2021. Does the scientific knowledge reflect the chemical diversity of environmental pollution? – a twenty-year perspective. Environ. Sci. Policy. 126, 90–98. https://doi.org/10.1016/j.envsci.2021.09.007.

Kümmerer, K., Clark, J.H., Zuin, V.G., 2020. Rethinking chemistry for a circular economy. Science (1979) 367 (6476), 369–370. https://doi.org/10.1126/science.aba4979.

Liess, M., Foit, K., Knillmann, S., Schäfer, R.B., Liess, H.-D., 2016. Predicting the synergy of multiple stress effects. Sci. Rep. 6 (1), 32965. https://doi.org/10.1038/srep32965.

MacLeod, M., Breitholtz, M., Cousins, I.T., Wit, C.A.de, Persson, L.M., Rudén, C., McLachlan, M.S, 2014. Identifying chemicals that are planetary boundary threats. Environ. Sci. Technol. 48 (19), 11057–11063. https://doi.org/10.1021/es501893m.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field of research and its prospects. Res. Policy. 41, 955–967. https://doi.org/10.1016/j.respol.2012.02.013.

Meadows, D., 1999. Leverage Points: Places to Intervene in a System. The Sustainability Institute. http://www.donellameadows.org/wp-content/userfiles/Leverage_Points.pdf.

Minovi, D., Huang, A. 2021. The Chemical Industry: An Overlooked Driver of Climate Change. The Problem and Policy Solutions. Policy Paper #1 for the Louisville Charter. https://comingcleaninc.org/assets/media/images/Louisville%20Charter%20content/plank%201%20policy%20paper.pdf.
Mossali, E., Picone, N., Gentilini, L., Rodrìguez, O., Pérez, J.M., Colledani, M., 2020. Lithium-ion batteries towards circular economy: a literature review of opportunities and issues of recycling treatments. J. Environ. Manage. 264, 110500. https://doi.org/10.1016/j.jenvman.2020.110500.
Persson, L., Carney Almroth, B.M., Collins, C.D., Cornell, S., de Wit, C.A., Diamond, M.L., Fantke, P., Hassellöv, M., MacLeod, M., Ryberg, M.W., Søgaard Jørgensen, P., Villarrubia-Gómez, P., Wang, Z., Hauschild, M.Z., 2022. Outside the safe operating space of the planetary boundary for novel entities. Environ. Sci. Technol. 56 (3), 1510–1521. https://doi.org/10.1021/acs.est.1c04158.
Posthuma, L., Brack, W., Van Gils, J., Focks, A., Müller, C., De Zwart, D., Birk, S., 2019. Mixtures of chemicals are important drivers of impacts on ecological status in European surface waters. Environ. Sci. Eur. 31 (1), 71. https://doi.org/10.1186/s12302-019-0247-4.
Puget Sound, Partnership., 2021. Puget Sound Vital Signs. https://www.psp.wa.gov/evaluating-vital-signs.php.
Renn, O., Laubichler, M., Lucas, K., Kröger, W., Schanze, J., Scholz, R.W., Schweizer, P, 2022. Systemic risks from different perspectives. Risk Analy. 42 (9), 1902–1920. https://doi.org/10.1111/risa.13657.
Rockström, J., Gupta, J., Qin, D., Lade, S.J., Abrams, J.F., Andersen, L.S., Armstrong McKay, D.I., Bai, X., Bala, G., Bunn, S.E., Ciobanu, D., DeClerck, F., Ebi, K., Gifford, L., Gordon, C., Hasan, S., Kanie, N., Lenton, T.M., Loriani, S., Zhang, X., 2023. Safe and just Earth system boundaries. Nature 619 (7968), 102–111. https://doi.org/10.1038/s41586-023-06083-8.
Rockström, J., Steffen, W., Noone, K., Persson III, Å., F, S.C., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., Wit, C.A.de, Hughes, T., Leeuw, S.van der, Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Liverman, D., 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecol. Society 14 (2). http://www.jstor.org/stable/26268316.
Roy, M.A., Cousins, I., Harriman, E., Scheringer, M., Tickner, J.A., Wang, Z, 2022. Combined application of the essential-use and functional substitution concepts: accelerating safer alternatives. Environ. Sci. Technol. 56 (14), 9842–9846. https://doi.org/10.1021/acs.est.2c03819.
Ryberg, M.W., Owsianiak, M., Clavreul, J., Mueller, C., Sim, S., King, H., Hauschild, M.Z, 2018. How to bring absolute sustainability into decision-making: an industry case study using a planetary boundary-based methodology. Sci. Total Environ. 634, 1406–1416. https://doi.org/10.1016/j.scitotenv.2018.04.075.
Schreder, E., Kemler, B, 2021. Path of toxic pollution: how making "forever chemicals" for food packaging threatens people and the climate. Toxic-free future, safer chemicals healthy families. Mind the Store. https://48h57c2l31ua3c3fmq1ne58b-wpengine.netdna-ssl.com/wp-content/uploads/2021/09/Report-Daikin-Path-of-Toxic-Pollution.pdf.
Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., Ludwig, C, 2015a. The trajectory of the Anthropocene: the great acceleration. Anthropocene Rev. 2 (1), 81–98. https://doi.org/10.1177/2053019614564785.
Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S, 2015b. Planetary boundaries: guiding human development on a changing planet. Science 347 (6223), 1259855. https://doi.org/10.1126/science.1259855.
Tickner, J.A., Geiser, K., Baima, S, 2022. Transitioning the chemical industry: elements of a roadmap toward sustainable chemicals and materials. Environ.: Sci. Policy Sustain. Develop. 64 (2), 22–36. https://doi.org/10.1080/00139157.2022.2021793.
Tickner, J.A., Schifano, J.N., Blake, A., Rudisill, C., Mulvihill, M.J., 2015. Advancing safer alternatives through functional substitution. Environ. Sci. Technol. 49 (2), 742–749. https://doi.org/10.1021/es503328m.
Tickner, J., Geiser, K., Baima, S., 2021. Transitioning the chemical industry: the case for addressing the climate, toxics, and plastics crises. Environ.: Sci. Policy Sustain. Develop. 63 (6), 4–15. https://doi.org/10.1080/00139157.2021.1979857.
Trasande, L., Krithivasan, R., Park, K., Obsekov, V., Belliveau, M, 2024. Chemicals used in plastic materials: an estimate of the attributable disease burden and costs in the United States. J. Endocr. Soc. 8 (2), bvad163. https://doi.org/10.1210/jendso/bvad163.
Trasande, L., Zoeller, R.T., Hass, U., Kortenkamp, A., Grandjean, P., Myers, J.P., DiGangi, J., Hunt, P.M., Rudel, R., Sathyanarayana, S., Bellanger, M., Hauser, R., Legler, J., Skakkebaek, N.E., Heindel, J.J., 2016. Burden of disease and costs of exposure to endocrine disrupting chemicals in the European Union: an updated analysis. Andrology 4 (4), 565–572. https://doi.org/10.1111/andr.12178.
Trowbridge, J., Goin, D.E., Abrahamsson, D., Sklar, R., Woodruff, T.J, 2023. Fossil fuel is the common denominator between climate change and petrochemical exposures, and effects on women and children's health. Int. J. Gynecol. Obstetrics 160 (2), 368–371. https://doi.org/10.1002/ijgo.14408.
U.S. EPA. Chemicals and production of spray polyurethane foam—why it matters [Data and Tools]. https://www.epa.gov/saferchoice/chemicals-and-production-spray-polyurethane-foam-why-it-matters.
United Nations. The 2030 Agenda for Sustainable Development (A/RES/70/1). https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf.
United Nations Environment Programme. Global Chemicals Outlook II. From Legacies to Innovative Solutions. (DTI/2230/GE). https://www.unep.org/explore-topics/chemicals-waste/what-we-do/policy-and-governance/global-chemicals-outlook.
United Nations Environment Programme, 2021. Making Peace with Nature. A Scientific Blueprint to Tackle the Climate, Biodiversity and Pollution Emergencies (DEW/2335/NA). https://www.unep.org/resources/making-peace-nature.
U.S. EPA. Safer Choice Master Criteria for Safer Chemical Ingredients. https://www.epa.gov/saferchoice/safer-choice-master-criteria-safer-chemical-ingredients.
U.S. EPA. End-of-life solar panels: regulations and management [Guidance (OMB)]. https://www.epa.gov/hw/end-life-solar-panels-regulations-and-management.
Wang, Z., Walker, G.W., Muir, D.C.G., Nagatani-Yoshida, K., 2020. Toward a global understanding of chemical pollution: a first comprehensive analysis of national and regional chemical inventories. Environ. Sci. Technol. 54 (5), 2575–2584. https://doi.org/10.1021/acs.est.9b06379.
Watari, T., Nansai, K., Nakajima, K, 2020. Review of critical metal dynamics to 2050 for 48 elements. Resour., Conserv. Recycl. 155, 104669. https://doi.org/10.1016/j.resconrec.2019.104669.
Wiedmann, T., Lenzen, M., Keyßer, L.T., Steinberger, J.K, 2020. Scientists' warning on affluence. Nat. Commun. 11 (1), 3107. https://doi.org/10.1038/s41467-020-16941-y.
Woodruff, T.J., Charlesworth, A., Zlatnik, M.G., Pandipati, S., DeNicola, N., Latif, I., 2023. Code OB: we need urgent action on climate change and toxic chemicals. Int. J. Gynecol.Obstetrics 160 (2), 363–365. https://doi.org/10.1002/ijgo.14566.
World Health Organization. (2021). The public health impact of chemicals: knowns and unknowns—data addendum for 2019. https://www.who.int/publications/i/item/WHO-HEP-ECH-EHD-21.01.
Yadav, V.G., Yadav, G.D., Patankar, S.C., 2020. The production of fuels and chemicals in the new world: critical analysis of the choice between crude oil and biomass vis-à-vis sustainability and the environment. Clean. Technol. Environ. Policy. 22 (9), 1757–1774. https://doi.org/10.1007/s10098-020-01945-5.
Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A.I., Fawzy, S., Rooney, D.W., Yap, P.-S., 2023. Circular economy strategies for combating climate change and other environmental issues. Environ. Chem. Lett. 21 (1), 55–80. https://doi.org/10.1007/s10311-022-01499-6.
Zheng, J., Suh, S, 2019. Strategies to reduce the global carbon footprint of plastics. Nat. Clim. Chang. 9 (5), 374–378. https://doi.org/10.1038/s41558-019-0459-z.