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Planetary boundaries for recalcitrant materials and toxic chemical pollutants: specifications for sustainable safe operating zones

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Announced as "the greatest and most consequential day of deregulation in U.S. history," 12 March 2025 marks the retreat of the United States Environmental Protection Agency from remedial and preventive policies that were informed by decades of consequential research in environmental science and public health. The USEPA administrator boasted further: "We are driving a dagger straight into the heart of the climate change religion to drive down cost of living for American families, unleash American energy, bring auto jobs back to the U.S. and more." The retreat threatens science-based regulations that have commanded the attention of researchers, policymakers, healthcare providers, non-governmental stewards of environments and ecosystems, and the general public. An example of such regulations targets mercury pollution, perhaps the only toxic chemical for which a specific UN action, the Minamata Convention, is dedicated. The linkage of mercury emissions to coal combustion as a source of energy that also drives climate change and particulate matter pollution that transcends national boundaries to cause diseases worldwide implies that the adverse impacts of USEPA's retreat will not be borne only by the US population, but also by the global human population and wildlife. The retreat from progressive agendas on environmental sustainability is not unique to the US. Note the European Commission's relaxation of reporting rules in the 2025 Competitiveness Compass. We may very well witness a "race to the bottom" as other countries sacrifice environmental regulations in pursuit of corporate profits.

KEYWORDS

environmental pollution, planetary boundaries, safe operating zones, toxic chemicals, recalcitrant materials

The scope and scale of urgent challenges in a turbulent environment

Announced as "the greatest and most consequential day of deregulation in U.S. history," 12 March 2025 marks the retreat of the United States Environmental Protection Agency from remedial and preventive policies that were informed by decades of consequential research in environmental science and public health. The USEPA administrator boasted further: "We are driving a dagger straight into the heart of the climate change religion to drive down cost of living for American families, unleash American energy, bring auto jobs back to the U.S. and more."

(United States Environmental Protection Agency, 2025). The retreat threatens to erase a broad range of science-based regulations that have commanded the attention of researchers, policymakers, healthcare providers, non-governmental stewards of environments and ecosystems, and the general public (Ogunseitan, 2023a). An example of such regulations is the one that targets mercury pollution, perhaps the only toxic chemical for which a specific United Nations Convention, The Minamata Convention on Mercury has been dedicated (Ogunseitan, 2017). The linkage of mercury emissions to coal combustion as a source of energy that is also a driver of climate change and respirable particulate matter that travel across national boundaries to cause diseases worldwide implies that the adverse impacts of USEPA's retreat will not be borne only by the US population, but also by the global human population and wildlife. The retreat from progressive agendas on environmental sustainability is not unique to the United States. Similar moves are noted in the European Commission's relaxation of reporting rules in the 2025 Competitiveness Compass (European Commission, 2025). We may very well witness a "race to the bottom" as other countries and regions sacrifice environmental regulations in the pursuit of competitive advantage regarding new natural and unsustainable resources to keep up with the technological revolution enabled by artificial intelligence and corporate financial profits. The retreat also comes at a time when research is intensifying to characterize the impacts of emerging toxic environmental pollutants such as microplastics (Singh et al., 2022) and recalcitrant "forever chemicals" such as per- and polyfluoroalkyl substances (PFAS) (Fenton et al., 2021; Wilson and Ogunseitan, 2017), and complex material mixtures present in hazardous electronic waste (Ogunseitan, 2023b). Government funding for research in environmental science may be scarcer in the US over the next 4 years, but this need not stop the creativity of the international scientific community in the pursuit of the most pressing question for this and future generations: How can we keep recalcitrant materials and toxic chemicals used in international commerce within the safe operating zones of planetary boundaries?

The concept of planetary boundaries provides a framework for understanding the limits within which humanity can safely inhabit Earth (Rockström et al., 2009). Among these boundaries, toxic chemical pollution has emerged as a critical concern, with far-reaching implications for human health, ecosystem integrity, and global environmental stability. The complexities of transgressing the planetary boundary for toxic chemical pollution and environmentally-recalcitrant materials is a major challenge for scientists and for those dedicated to the translation of research results into policies that protect human populations and planetary health. Exploring the specifications necessary for establishing and maintaining a safe operating zone is an ambitious and necessary endeavor.

Evidence suggests that humanity has already transgressed the safe operating zone for chemical pollution (Landrigan et al., 2018; Persson et al., 2022). The proliferation of synthetic chemicals, many of which are persistent and bio-accumulative, has led to widespread contamination of ecosystems and organisms worldwide. Some key indicators of this transgression include the ubiquitous presence of microplastics in marine and freshwater environments, as well as in the food chain, and in human tissues including the brain, the detection of persistent organic pollutants in remote areas, including the Arctic and deep ocean sediments, the decline of insect populations, partially attributed to pesticide use, and the bioaccumulation of heavy metals and other toxicants in apex predators and human populations. (Nihart et al., 2025; Pasquini et al., 2024). These indicators and ecosystem sentinels underscore the urgent need for a comprehensive approach to managing chemical pollution and defining safe operating zones.

Figure 1 depicts some of the adverse consequences of indiscriminate use of toxic chemicals and recalcitrant materials, the ultimate undesirable outcome of transgressing planetary boundaries being species extinction and ecosystem collapse at local and global scales. Rethinking fundamental research approaches, including translational science and multidisciplinary remediation technologies is necessary to establish sustainably safe operating zones for existing, new, and emerging chemicals and materials. Research priorities should align with knowledge of toxicological modes of action. Chemicals known to target phylogenetically-conserved physiological processes and reproductive fitness are likely to have broad spectrum impacts on biodiversity and can potentially lead to local extinction of species. For example, despite the well-documented toxicity of lead (Pb) and its compounds, it continues to be a major environmental risk factor for humans and other organisms. Lead has no known use in biological systems, and it interferes with the function of aminolevulinate dehydratase, a phylogenetically-conserved enzyme that is essential for the synthesis of pigmented biomolecules including hemoglobin and chlorophyll (Ogunseitan et al., 2000). Lead poisoning affects a third of the world's population of children and leads to nearly 1 million premature deaths annually, and 1 US$ trillion in lost economic potential (Global Alliance on Health and Pollution, 2025).

Future opportunities for understanding the planetary boundary for chemical pollution

The planetary boundary for chemical pollution is unique among the nine identified boundaries due to its diverse and pervasive nature. Unlike boundaries such as climate change or ocean acidification, which can be quantified using specific metrics like atmospheric CO_2 concentrations, chemical pollution encompasses a vast array of substances with varying impacts on different environmental compartments. The interplay between toxicology, pollution, and the environment continues to shape global ecosystems and human health. As the urgency to address ecological degradation mounts, a focused exploration of critical questions, policy frameworks, and innovative solutions becomes indispensable. Chemical pollution includes persistent organic pollutants (POPs), heavy metals, plastics, and emerging contaminants such as pharmaceuticals and nanomaterials. Individually, these pollutants can have long-lasting effects on ecosystems, biodiversity, and human health, but we have not really grasped their collective impacts through complex pathways and synergistic interactions. It is also necessary to pursue a better understanding of the ripple effects of pollution, including how it exacerbates climate change, disrupts food chains, and contributes to health disparities. Without an urgent, integrative approach, the consequences may become irreversible. One of the primary challenges in addressing the chemical pollution boundary is the difficulty in quantifying a single, comprehensive metric. Unlike other planetary boundaries, there is no universally accepted threshold for chemical pollution beyond which Earth system functioning is

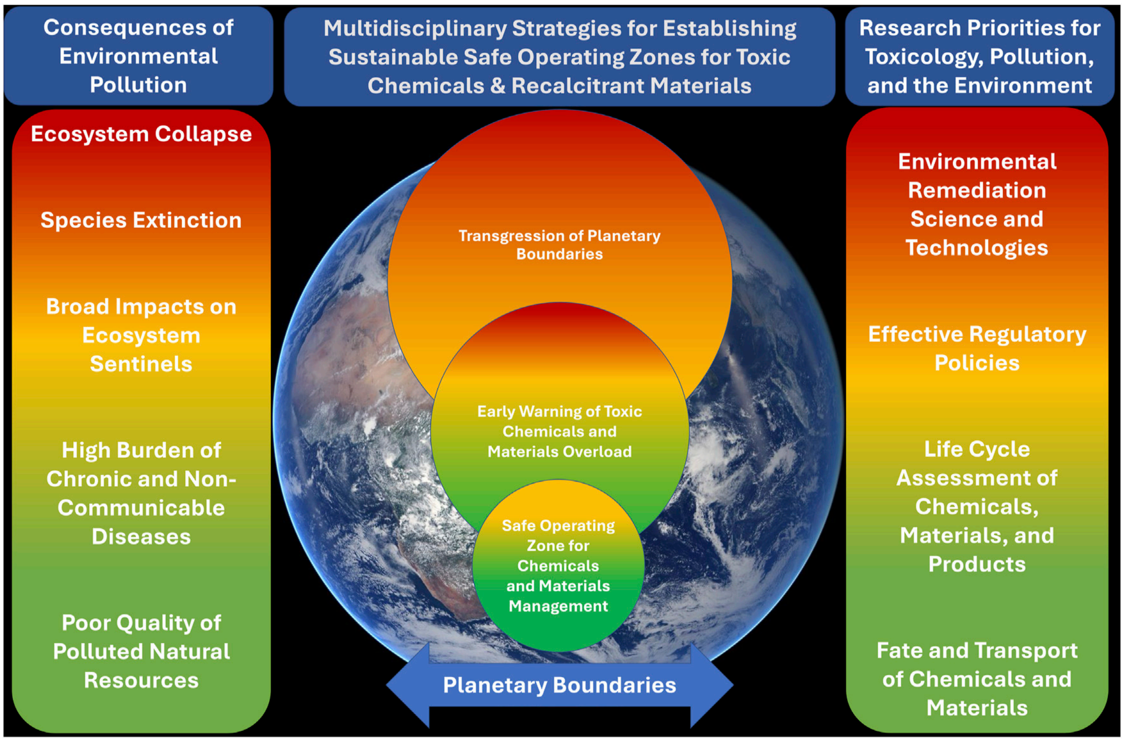

FIGURE 1
Schematic diagram of planetary boundaries including thresholds for safe operating zones of toxic chemicals and recalcitrant materials, early warning zones, and transgression of these boundaries (Middle Panel). The adverse consequences of environmental pollution become more severe with increasing production, use, and disposal of toxic chemicals and recalcitrant materials, leading progressively from depreciated quality of natural systems to ecosystem collapse (Left Panel). The roadmap for research priorities in toxicology, pollution, and the environment extend from creating active inventories, fate and transport studies, remediation technologies, and preventive regulatory policies. A collaborative multidisciplinary framework of research is necessary to support initiatives such as the circular economy to stay within or regain the safe operating zone for toxic chemicals and recalcitrant materials. Satellite image of Earth is from NASA (https://images-assets.nasa.gov/image/GSFC_20171208_Archive_e001016/GSFC_20171208_Archive_e001016~large.jpg?w=1920&h=1080&fit=clip&crop=faces%2Cfocalpoint).

significantly altered. This complexity arises from the diverse nature of chemical pollutants, their varying persistence and toxicity, and the intricate web of interactions within ecosystems. Several theoretical and empirical approaches to quantify these boundaries are reasonable, including the total mass of chemicals released into the environment, the number of novel entities introduced into the biosphere, the concentration of specific indicator chemicals in various environmental compartments, and the overall toxic load on ecosystems and human populations. Each of these approaches has its merits and limitations, highlighting the need for a multifaceted integrative approach to understanding and managing chemical pollution, and the establishment of rigorous specifications for safe and resilient operating zones that account for the complexity and diversity of chemical pollutants.

Future research in this direction needs to support a broad-ranging infrastructure including the establishment of a comprehensive inventory of chemicals in use, their production volumes, and potential environmental and health impacts. This inventory should be regularly updated and include emerging contaminants. Risk assessments studies should consider not only individual chemicals but also their potential synergistic effects and long-term consequences, and such studies should be aligned with global monitoring networks to track the presence and concentration of key chemical pollutants in various environmental compartments. These networks should cover air, water, soil, and biota, with a focus on both urban and remote areas to capture the full extent of chemical pollution. In addition to chemical monitoring, effect-based approaches using biomarkers in sentinel species can provide early warnings of ecosystem stress due to chemical pollution. This approach can help capture the cumulative effects of multiple pollutants and their interactions. Transitioning to a circular economy model and promoting green chemistry principles are crucial for reducing the introduction of harmful chemicals into the environment. This includes designing chemicals and products for easy recycling, minimizing waste, and prioritizing the use of less toxic alternatives. Enabling a circular economy also demands setting clear, science-based targets for reducing the overall chemical footprint of human activities. These targets should consider both the quantity and toxicity of chemicals released into the environment and be regularly reviewed and updated based on the latest scientific evidence. Implementing comprehensive lifecycle assessments (LCA) for chemicals and products can help internalize the environmental costs of chemical pollution and incentivize cleaner production methods. However, LCA methods also need further development particularly in the assessment of composite materials such as metallic alloys, and in the modelling of future scenarios. The integration of Artificial Intelligence tools with LCA could be transformative in this direction, particularly for exploring the interactions between chemical pollution and other planetary boundaries, such as climate change and biodiversity loss (Singh and Ogunseitan, 2022). Implementing these specifications for safe operating zones faces several challenges. These include the economic interests of the chemical industry, the lack of data on many chemicals' environmental impacts, and the difficulty of addressing legacy pollutants already present in the environment.

Integrative solutions

How can we comprehensively assess and mitigate the long-term impacts of emerging pollutants on ecosystem structures, functions, and services, including dependent human population health? Transgressing the planetary boundary for toxic chemical pollution poses a significant threat to Earth system functioning and human wellbeing. Establishing and maintaining a safe operating zone requires a comprehensive, multifaceted approach that addresses the complexity of chemical pollution. By implementing robust monitoring systems, promoting sustainable chemistry practices, strengthening international governance, and fostering public awareness, we can work towards reducing our chemical footprint and safeguarding the planet's life-support systems for future generations. The challenge of chemical pollution exemplifies the interconnected nature of global environmental issues and underscores the need for systemic, transformative changes in how we produce, use, and manage chemicals and materials. As we navigate the Anthropocene, our ability to operate within the safe boundaries of chemical pollution will be crucial in determining the long-term sustainability and resilience of both human societies and the Earth system as a whole.

Given the transboundary nature of chemical pollution, strong international governance mechanisms are necessary. Such mechanisms should be built to resist the uncertainty of national political turbulence such as the retreat of the USEPA from effective regulations and evidence-informed policies. This includes harmonizing chemical regulations across countries, implementing and enforcing global treaties on chemical management, and establishing mechanisms for rapid response to emerging chemical threats. The absence of standardized thresholds for emerging pollutants leaves many toxic chemicals and recalcitrant materials unchecked in commerce and international supply chains. Additionally, policies frequently focus on individual pollutants without accounting for their cumulative and synergistic effects. This fragmented approach undermines comprehensive mitigation efforts. Governments and international bodies must adopt adaptive, science-driven frameworks that integrate real-time data and predictive models. Collaborations between policymakers, scientists, and industry stakeholders can enhance the relevance and enforceability of regulations. Furthermore, fostering global agreements to monitor and mitigate cross-boundary pollution will ensure cohesive action in addressing shared environmental challenges.

The coming decade is likely to bring a host of challenges. Climate change will act as a force multiplier, intensifying pollution's effects and complicating toxicological studies. Unless we invent innovative research approaches, methods, and capacity to meaningfully interpretate disparate results, the rapid proliferation of synthetic chemicals and recalcitrant nanomaterials will outpace our ability to understand their long-term impacts. The convergence of toxicology, pollution, and environmental challenges demands immediate, coordinated action. By addressing burning questions, closing policy gaps, preparing for future hurdles, and fostering innovative strategies, the scientific community can navigate this critical juncture with resilience and excellent research skills. The path forward hinges on collaboration, adaptability, and a commitment to safeguarding our planet for future generations. Let this be a clarion call to unite science, policy, and community in the pursuit of a sustainable, equitable, and thriving world.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

OO: Formal Analysis, Methodology, Validation, Conceptualization, Project administration, Investigation, Writing – original draft, Writing – review and editing, Resources, Visualization.

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