Chemicals management approach to sustainable development of materials

Oladele A. Ogunseitan*

Throughout human history, the capacity to invent, manufacture, and use chemicals and materials has transformed concepts of development with path-dependent solutions to problems encountered in various industrial and societal sectors, including energy, transportation, food production, textiles, and personal care. It is increasingly clear that the trajectory of development initiated by some path-breaking materials is not sustainable. Recent developments in the concept of planetary boundaries have explored some reasons for unsustainability and ineffectiveness of current chemicals management practices. The reasons are almost always due to previously unknown chemical characteristics such as toxicity, reactivity, environmental recalcitrance, or increasing scarcity. In some cases, the suspected but ignored potential hazard of chemicals manifests slowly or becomes uncontrollable due to accumulation and biochemical or physical transformation in the environment. Consequently, environmental pollution by such chemicals is associated with alarmingly high levels of human mortality and disease burden worldwide. Recent examples include halogenated chemicals used as flame retardants and the thinning of the stratospheric ozone layer; bisphenol A used in plastics and microplastics widespread in biotic and abiotic ecosystem components, including the ocean; hormone mimicking chemicals such as phthalates in human tissues; neurotoxicity of lead used in solder materials, paints, and water distribution pipes; neurodevelopmental diseases associated with mercury used in ore beneficiation, in dental amalgams and lighting systems; and asbestos fibers used in ceiling tiles, roofs, and automobile brakes. These notorious examples have forced the introduction of retroactive policies to restrict the use of certain chemicals in materials development, and a few proactive policies designed to prevent the initial use of certain chemicals known or suspected to be hazardous. Improvements in the scientific knowledge and development of tools to screen for chemicals of concern have also led to the development of forecasting tools for improved management of chemicals. It could be impossible to foresee all potential risks associated with chemicals. Therefore, such management approaches can be most effective in supporting sustainable development of materials when they generate boundaries within which criteria for safety are understood and alternative assessments are continuous. This article situates the power of selected forecasting tools for early warning systems in a planetary boundary framework while highlighting gaps and incongruencies inherent in their use to support proactive and reactive regulatory policies, and for developing performance standards for lowering the chemical footprint of consumer products.

Managing chemicals in a planetary boundary framework

> "We live in a rapidly changing global society driven by megatrends. Global income is rising, and so is the demand for products for which chemistry is essential. From pharmaceuticals to metals in our phones, plant protection products, chemicals create many benefits. But they may also affect human health and the environment if not properly managed. We cannot achieve the sustainable development goals without the sound management of chemicals and waste."[1]

Oladele A. Ogunseitan, Department of Population Health and Disease Prevention, University of California, Irvine, USA; World Institute for Sustainable Development of Materials (WISDOM), University of California, Irvine, USA; Center for Innovation in Global Health, Stanford University, Stanford, CA, USA; dele@stanford.edu
*Corresponding author

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Since its creation in 1972, the United Nations Environment Program (UNEP) has struggled to promote sustainable solutions in the path toward better stewardship of hazardous chemicals.[2] The struggle is described in the second edition of the Global Chemicals Outlook and the largely unaccomplished goal set for the Strategic Approach to International Chemicals Management (SAICM), a multi-stakeholder and multisectoral forum established in 2002 with the expectation to champion the sound management of chemicals throughout their life cycle so that "by the year 2020, chemicals are produced and used in ways that minimize significant adverse impacts on the environment and human health."[3] The inadequacies of the original SAICM to forge an effective science-policy interface that could conduct assessments, inform policymakers and the public to raise awareness, and to facilitate the identification of issues of concern are currently being analyzed to avoid a similar fate for a proposed SAICM Successor Agreement.[4] Evidence that chemical pollutants continue to impose increasingly unprecedented damage on population health and environmental quality was presented in a landmark report of *The Lancet* Commission on Pollution and Health, which documented that diseases caused by pollution were responsible for an estimated 16% of all deaths worldwide each year, more than 3× the combined mortality rate of notorious infectious diseases such as AIDS, tuberculosis, and malaria.[5] The alarming adverse impacts of hazardous chemicals and materials, particularly due to toxicity and persistence in polluted systems, have stimulated initiatives to quantify limits or boundaries within which chemicals used to manufacture consumer products could be managed safely and effectively.

A recent assessment of the safe operating space of the planetary boundary framework for chemicals concluded that increasing trends of production and emissions of a wide variety of chemicals and materials (defined as novel entities because they are created, introduced, manufactured, or recirculated by humans relatively recently in a geological time frame) outpace our efforts at safety assessment and monitoring.[6,7] This gap constitutes a notable transgression of the planetary boundary and demands immediate action to return humanity to the safe operating space.[8–12] To enable such actions, there is a critical need for quantitative and qualitative tools for evaluation and prioritization schemes to distinguish chemicals for which production and use must cease immediately, and chemicals for which production and use can by managed within the planetary boundary's safe operating space. Such tools have been undergoing R&D for several generations, but they vary widely in their basic assumptions, capacity to accommodate data gaps, and transparency of the results that they generate for use in formulating regulatory policies or in reforming manufacturing procedures.

Chemicals transcending the planetary boundary's safe operating zone are generally characterized by high volume production and widespread use with direct biological effects due to their toxicity, persistence, ability to disrupt physical pathways, and/or their involvement in chemical reactions that cannot be easily mitigated once they contaminate ecosystems.[13] Metals such as lead and mercury are toxic to a wide range of biological species;[14–16] heavily used halogenated flame retardants such as polychlorinated biphenyl compounds (PCBs), and polybrominated diphenyl ethers (PBDEs), including decabromodiphenyl ether (decaBDE) are toxic and recalcitrant in the environment, where they contribute to the depletion of the planet's layer of ozone in the stratosphere thereby exhibiting global impacts.[17] Chemicals such as bisphenol A and phthalates not only have direct toxicity effects on organisms, but they are also associated with plastic products that are subject to physical disintegration leading to more burdensome microplastics that have spread worldwide.[18–20] Despite compelling evidence linking asbestos fibers to severe lung disease in every population that has been exposed, international trade in asbestos continues, further prolonging the likelihood of exposure for future generations.[21,22] Several chemicals and materials that have been targeted by various national regulatory policies and international conventions to reduce their impacts still pose risks because of the questionable effectiveness of current policy control measures.[23]

Tools for assessing how and why legacy chemical pollutants transcend the planetary boundary are useful, not only for the possibility of identifying corrective measures, but also for prospectively evaluating innovations for likelihood of adverse impacts occurring in the near and far future. Specific chemical informatics tools could focus on monitoring one or more variables that can be controlled through voluntary efforts or restrictive policies. The control variables include trends in production of new chemicals and materials, for example, the requirement for reporting Premanufacture Notice (PMN) and Significant New Use Notice (SNUN) mandated by regulatory policies.[24,25] A second example of control variables include trends in environmental releases of hazardous chemicals and materials, for example the Toxics Release Inventory (TRI) in the United States, and similar "Pollutant Release and Transfer Registers" in more than 50 countries around the world, which monitor the management of select toxic chemicals that could pose a threat to human health and environment quality through mandating industries to report how much of each chemical is released to the air, land, and water environments or managed through recycling, energy recovery, and treatment.[26,27] A third control variable is the trend in documented harmful impacts on human health and ecosystems, for example, the Global Burden of Disease assessments of general air pollutants or specific toxicants such as lead (Pb), based on a composite measure of morbidity and mortality, disability-adjusted life years (DALYs), associated with exposures.[28,29] Specific chemical management tools can serve as effective strategies to control variables in the planetary boundary framework if they are quantitatively feasible, robustly linked to relevant effects, and can comprehensively capture the planetary scale of the problem.[30–32] Several chemicals and groups of chemicals that currently threaten human health and environmental quality are locked in an unsafe planetary boundary space because of

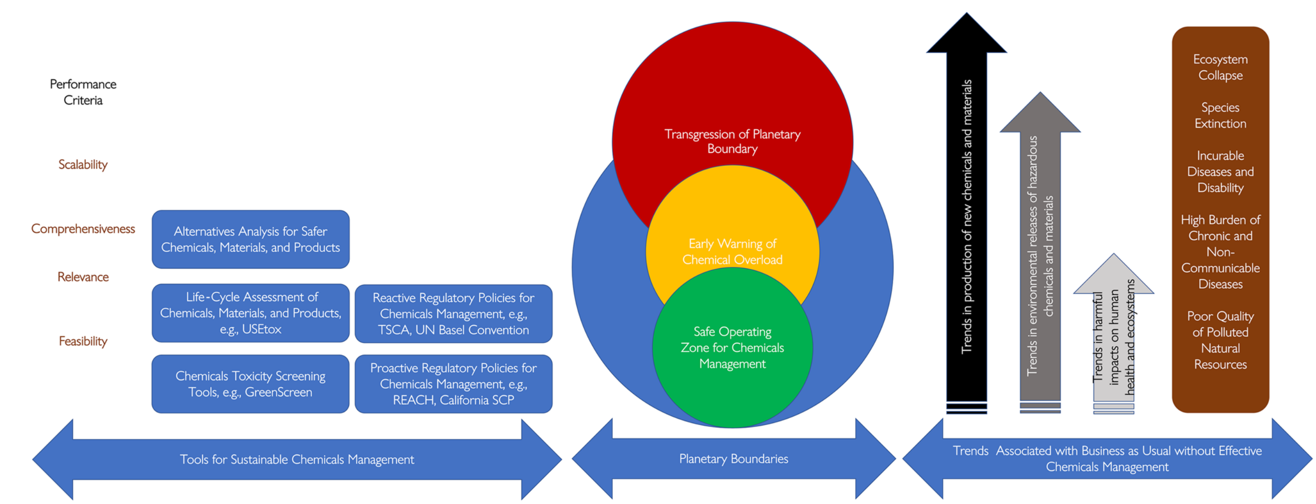

Figure 1. Schematic representation of the roles of chemicals management tools in suppressing trends toward transgression of planetary boundary for chemicals and materials manufacturing and waste disposal.

excess production, which implies that they will continue to circulate commercially or in the environment far into the future. The formulation, implementation, and enforcement of reactive regulatory policies at national, regional, and international levels are designed to address these types of chemicals and the pollution problems caused through improper management of ubiquitous consumer products such as electronic waste, plastics, and energy-storage systems.[33–35] Evaluation of reactive policies through the lenses of feasibility, relevance, and comprehensive scalability can help us understand the strengths and limitations of such policies in correcting threats to the safe space in the planetary boundary framework (**Figure 1**).

Reactive regulatory policies as tools for managing chemicals

Chemical manufacturing is a highly productive, profitable, and rapidly growing industry. The Chemical Abstracts Service (CAS) has registered 204 million organic substances, alloys, coordination compounds, minerals, mixtures, polymers, and salts that have been disclosed in publications since the early 1800s. Among the registered chemicals, approximately 350,000 chemicals or their mixtures are in commerce, about 20% of which were registered only in the past 10 years.[36] Production of scientific knowledge about the effects and fate of most of the chemicals in commerce has not kept pace with the widespread distribution of chemicals in products that end up in the environment. For many toxic chemicals that have been circulating for long periods of time, epidemiological studies are the first to reveal problems in terms of adverse health and environmental impacts typically long before reactive regulatory policies are proposed to restrict, ban, or phase-out chemical production and use. Many regulatory policies do not have a requirement for evaluating the safety of alternative chemicals developed and used to replace banned chemicals, which has led in some instances to the phenomenon of regrettable substitutions.

Among the most widely known reactive regulatory policies in the United States is the Toxic Substances Control Act of 1976 (TSCA), which was enacted following congressional determination that human populations and the environment are being exposed regularly to a large number of chemical substances and mixtures, and that a significant proportion of new chemicals pose unreasonable risk of injury to health and environmental quality through their manufacture, processing, distribution, use, and disposal. Therefore, TSCA aimed to (1) require from manufacturers, provision of information about the effects of chemicals and their mixtures on human health and the environment; (2) authorize the responsible agency to regulate chemicals known to present unreasonable risks and to act on chemicals presenting imminent hazards; and importantly, (3) avoid unnecessary impedance or economic barriers to technological innovation.[37] Inadequacies in the implementation and effectiveness of TSCA are well documented, and its reform was triggered in 2016 to respond to the fact that since the passage of the reactive regulation, less than 2% of the 85,343 chemicals in its inventory had been restricted, and only five chemicals had been banned.[38,39] Moreover, notoriously toxic and continuously litigated materials such as asbestos had not been outlawed at the national level. Also, TSCA did not have a transparent procedure for identifying safer alternatives to restricted chemicals, in part because of the complex multiagency approach to scrutinizing new chemicals.

For example, the US Food and Drug Administration continues to maintain that bisphenol A (BPA) used in plastic containers, packaging, and coatings is safe at the current levels measured in foods.[40] Meanwhile, the US Environmental Protection Agency publicly advertises the agency's concern with BPA by noting that it is a reproductive, developmental, and systemic toxicant in animal studies, and is weakly estrogenic. EPA notes further that there are questions about BPA's potential impact particularly on children's health and the environment.[41] Many manufacturers of plastics do make and sell BPA-free food and water containers, but they are not required to provide consumers with information on the safety of the chemical substitute or alternative to BPA. Still, consumer preferences can influence the pace of introduction of safer chemical and material alternatives in products, to the extent that scientifically accurate information is publicly accessible. The Safer Choice program under the EPA's Pollution Prevention (P2) initiative aims to provide information on safe chemical ingredients in consumer products, including laundry products, dish soaps, and car care products, with a publication of "Safer Choice-Certified" products.[42] In addition to providing information to the public, such certification can also serve as an asset for manufacturers of certified products to advertise and effectively compete for the attention of consumers who are conscious of the alternatives and seek to identify and purchase environmentally sustainable products. Similarly, voluntary adherence to sustainability standards for manufacturing processes and products are now well established, including the multicriteria Electronic Product Environmental Assessment Tool (EPEAT) standards managed by the Global Electronics Council (GEC),[43] and the "WELL Materials Features" of the US Green Building Council's Leadership in Energy and Environmental Design (LEED) certification for buildings.[44]

Proactive regulatory policies as tools for managing chemicals

The European Chemicals Agency (ECHA) is responsible for implementing the EU's Chemicals legislation, including the Registration, Evaluation, Authorisation, and Restriction of Chemicals (REACH) regulatory policy, which was enacted with three major aims: (1) to ensure a high level of protection of human health and the environment, (2) to enhance competitiveness and innovation in the chemicals manufacturing industry, and (3) to promote the development of alternative methods for the assessment of hazards of chemicals.[45] As of December 2022, ECHA reports that 26,695 chemicals have been registered through REACH, including a few chemicals for which manufacture has ceased.[46] By placing the burden of proof of chemical safety on industries, REACH's mantra "no data, no market" aims to prevent the introduction of risky chemicals and materials into commerce. Companies are expected to identify and manage the risks linked to the substances they manufacture and market within the EU. However, it is nearly impossible to gather prospective information across the entire life cycle of chemicals used in consumer products without real life assessment to capture unforeseeable interactions with biotic and abiotic components of ecosystems. Yet, in more than 10 years of implementation, only 71 chemical substances have been restricted under REACH (as of December 2022), including some notorious toxic chemical compounds and materials for which there were already decades of epidemiological evidence and environmental science data gathered to document their adverse impacts on people and the environment, such as asbestos fibers, vinyl chloride, benzene, and polybromobiphenyls.[47,48]

The California Safer Consumer Products (SCP) program, enacted in 2008 as the Green Chemistry Law aimed to reduce the use of hazardous chemicals and to accelerate the quest for safer alternative chemicals used in consumer products.[49] The law authorized the California EPA's Department of Toxic Substances Control (DTSC) to develop and implement proactive regulations designed to restrict the use of hazardous chemicals in products meant for the California marketplace. As of December 2022, there are 3315 candidate chemicals defined as ones that exhibit a hazard trait and/or an environmental or toxicological endpoint and are identified in one or more authoritative lists generated by other reputable agencies, including, for example, the list of chemicals known to cause cancer and/or reproductive toxicity and listed under California's Health and Safety Code section 25249.8 of the California Safe Drinking Water and the 1986 Toxic Enforcement Act.[50] Chemicals of Concern are a subset of candidate chemicals that are associated with a priority product. Five priority products have been processed with adoption of regulation to restrict the use of notorious toxic chemicals such as the tris(1,3-dichloroisopropyl)phosphate (TDCPP) used in children's foam-padded sleeping products, polyfluoroalkyl substances (PFAS) in carpets and rugs, and methylene chloride in varnish paint strippers.[51] The California SCP program includes a pathway for Alternatives Analysis (AA), which requires manufacturers of priority products to conduct a "comprehensive analysis" to determine if there are safer alternatives to the chemical of concern in their products. A compilation of AA procedural examples is presented by DTSC including alternatives to bisphenol A in thermal paper, phthalates as plasticizers in poly(vinyl chloride) plastics, perchloroethylene in dry-cleaning solvent, and decaBDE in electronic enclosures.[52] However, it is unclear if any of the companies selling regulated products on the SCP list have actually pursued the AA procedure to redesign and remanufacture their products to keep selling in California.[52] The difficulty for manufacturers to pivot quickly around regulations such as the SCP and its AA requirement is that the analyses can be expensive and time-consuming, and such regulations are not universal across states in the United States and internationally.[53] The California market is large but so is the market in China, India, Africa, and South America, where there may not be similarly restrictive regulations. Therefore, manufacturers may consider shifting their customer base instead of conducting the necessary research to identify safer alternatives and completely modifying their process for manufacturing consumer products. The two examples of the EU's REACH and California's SCP show the difficulty of comprehensiveness in attempts to proactively use safety data and assessments as the basis for control variables in the safe space of planetary boundary for chemicals. Voluntary initiatives by non-governmental organizations may overcome some of the barriers faced by proactive regulatory policies mandated by government agencies. For example, the Clean Electronics Production Network, a collaborative multi-stakeholder innovation group, provides resources for safer alternatives to assist companies and manufacturers to identify and use safer alternatives in the electronics supply chain, and for chemical suppliers in the supply chain to certify their products.[54]

Chemicals management in planetary sub-boundaries

The planetary boundaries framework recognizes nine risk segments, including novel entities such as chemicals and materials used globally. A quantitative planetary boundary has been difficult to determine for the novel entities segment in part because of gaps in knowledge about the effectiveness of current chemical management approaches and the uncertainty of innovation toward safer alternative chemicals and materials.[55] However, there could already be sufficient information to consider boundaries at scales smaller than the entire planet where episodes of toxic chemical exposures have caused the collapse or severe destabilization of communities. Radioactive fallout from nuclear disasters are examples in recent times where evacuation of entire cities or regions, defined here as planetary sub-boundaries, became necessary. In the context of chemical manufacturing, the 1984 accidental methyl isocyanate incident in Bhopal, India, is a noteworthy example. That incident caused the death of an estimated 3787 and serious injury of 574,366 persons; and it triggered the US Congress to enact the Emergency Planning and Community Right-to-Know Act (EPCRA) in 1986.[56,57] The law included mandatory communication of information on hazardous and toxic chemicals to inform the general public about facilities in their community that use, store, and release such chemicals into the environment. It has been shown that such community right-to-know programs stimulate civil activism that may empower communities and pressure local chemical manufacturers to act responsibly.[58] The spatiotemporal mapping of risk-laden facilities combined with demographic maps and health vulnerability assessments could help define a quantitative model of safe spaces for planetary sub-boundaries. Both reactive and proactive regulatory policies may be effective at such scales for effective management of hazardous chemicals and materials. Such models could be generalizable if parallel efforts are made to harmonize sustainability standards for chemicals management and elimination of current inconsistencies that exist in maximum contaminant levels (MCLs) for chemicals in polluted environments and in permissible exposure limits (PELs) of toxicants for the general population.[59,60]

Screening tools for chemicals management

Planetary sub-boundaries are not rigid because chemicals originating from one geographic region could have global impacts. Three criteria have been proposed for identifying chemicals that can threaten the entire Earth system, including the possibility of disrupting vital global ecosystem processes, for example, the biogeochemical cycling of elements such as nitrogen,[61,62] the possibility of a chemical having an effect that is not easily reversible, for example, endocrine disruptors that affect reproduction,[63] and chemicals that have yet unknown disruptive effects. Chemicals management policies and tools used for screening chemicals are part of the repertoire of early warning systems for preventing these types of chemicals from having global impacts. Research is needed to expand and deepen the existing knowledge bases for chemical screening tools and to develop criteria for standardizing their application in proactively identifying properties of chemicals that are likely to exert impacts globally.[11] The development of chemical screening tools has a long history in the fields of risk analysis and pharmacology, and many of the tools have been adopted for application in environmental health science.[64] The complexity of possible chemical interactions with biotic and abiotic ecosystem components necessitates the integration of screening tools developed for individual chemicals with life-cycle assessment (LCA) tools in predicting fate and effects in the environment.[65] The high number of scenarios and the variety of data sets needed for such integration have created an opportunity for the roles of machine learning and artificial intelligence.[66] The considerable progress in data collection and integration remains hampered by the difficult process of including human variability in terms of physiological and genetic systems and social behavior into widely used chemical screening tools such as GreenScreen, USEtox, and LCA software such as SimaPro.[67–69]

Prospects for increasing the significance of chemicals management

In November 2022, the world's human population reached 8 billion and is continuing to increase at a pace made possible in part by innovation in chemistry and materials use across all sectors of society including energy supply, transportation, clothing, communications, education, and social networks. The growth has also come at a cost to the planet, including expenditure of scarce or irreplaceable natural resources and toxic chemical pollution that has caused disease and death, and could cause the extinction of species. These concerns have generated new ways of thinking about strategies to increase the benefits of chemicals manufacturing while reducing the adverse impacts within the safe space of planetary boundaries. Several attempts to quantify the planetary boundary regarding chemicals are yet to reach consensus, but there is agreement that improvement in chemicals management is necessary to deal with current challenges posed by chemical pollution and to support equitable and just sustainable development within the hypothetical planetary safe space.[70] Advances in both reactive and proactive regulatory policies are contributing to more public awareness and expansion of best practices for chemicals stewardship across the supply chain of manufacturers of consumer products. The regulatory policies need tools for prioritizing the chemicals for which action is needed to prevent local or global catastrophes. It is necessary to continue refining methodological tools for comparative hazard and exposure assessment of chemicals, and for applying sustainable green-design strategies and life-cycle assessment approaches to evaluate the fate of chemicals in manufacturing processes and in consumer products. In concert, the development and evaluation of Alternatives Analysis methods to support decision-making procedures in chemical management will empower policymakers who are responsible for policing manufacturers and for assuring public and environmental safety.

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Conflict of interest

The author declares that there is no conflict of interest.

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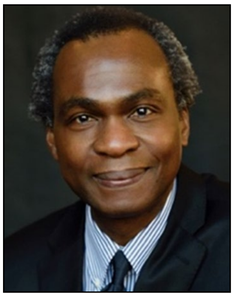

Oladele A. Ogunseitan holds the University of California Presidential Chair at the University of California, Irvine, where he is professor of population health and disease prevention. He is a visiting professor at the Center for Innovation in Global Health, Stanford University. Ogunseitan co-chairs Apple Inc.'s Green Chemistry Advisory Board and co-directs the World Institute for Sustainable Development of Materials (WISDOM), University of California, Irvine. He received his PhD degree in microbiology from The University of Tennessee and his MPH degree in environmental health sciences from the University of California, Berkeley. He served on California's Green Ribbon Science Panel and the Community Protection and Hazardous Waste Reduction Committee. He is an elected Fellow of Collegium Ramazzini. Ogunseitan can be reached by email at dele@stanford.edu.