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Green Chemistry, Circular Growth

Moving Global Supply Chains Beyond Hazardous Chemicals



FOCUS

Hazardous chemicals in the textile, plastics, construction and agriculture value chains, and how green chemistry and circular economy principles move supply chains beyond them

FOR

Policymakers, regulators, industry and standard-setters working on chemical safety, biodiversity and circularity

Circular Innovation Lab · Copenhagen / New Delhi · November 2026

circularinnovationlab.com

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First published: November 2026

ISBN 13: 978-87-94507-00-4

ISBN 10: 87-94507-00-7

EAN: 9788794507004

Circular Innovation Lab (2026). Green Chemistry, Circular Growth: Moving Global Supply Chains Beyond Hazardous Chemicals. Circular Press.

Published by Circular Innovation Lab
www.circularinnovationlab.com
Copenhagen, Denmark

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Acknowledgments

This publication is the result of a collaborative effort, and Circular Innovation Lab is grateful to everyone who contributed their time, expertise, and insight to its development.

A special thank-you goes to Hilda van der Veen, Ludovic Bernaudat, Tapiwa Nxele, and Anil Sookdeo for their valuable feedback, which meaningfully strengthened the analysis and helped sharpen the report throughout its development.

We also extend our sincere thanks to the contributors, editors, and reviewers whose careful reading and considered comments shaped the final work.

Executive Abstract

Context. Hazardous chemicals are pervasive across global value chains and contribute materially to biodiversity loss and human health risks through soil, water, and air contamination, through direct exposure by inhalation or ingestion, and through indirect exposure via contaminated food and consumer products. Despite the breadth of these pathways, chemical pollution remains an under-recognized driver of ecological decline. Its effects are frequently subtle, cumulative and delayed, impairing reproduction and ecosystem function while entering food chains and consumer pathways at concentrations that evade routine detection. Fragmented research coverage and regulatory frameworks that lag the pace of chemical innovation further constrain both a comprehensive understanding of the problem and the design of proportionate responses.

Scope and objectives. This paper examines the presence of hazardous chemicals in the supply chains of four industries selected for their scale and material intensity: textiles, plastics, construction and agriculture. It traces chemical lifecycles from production through use to disposal, identifying where risks to biodiversity and human health arise at each stage. The analysis addresses the mechanisms through which harm is transmitted, namely persistence, bioaccumulation and toxicity, and connects these to ecological outcomes including habitat degradation and the disruption of ecosystem functions, and to human health outcomes including respiratory disease, cancers, and developmental disorders. Biodiversity is treated throughout as the overarching system within which human health outcomes are situated, rather than as a parallel concern. The paper then sets out how green chemistry and circular design can move these supply chains beyond hazardous chemicals while retaining the economic value these industries create.

Methodology. The study applies an authority-based qualitative hazard-screening methodology to compare the intrinsic hazards of selected chemicals across the four sectors. Substances were selected according to their prevalence in global value chains and their function as representative additives, monomers, metals or persistent compounds. Each substance is assessed against six intrinsic hazard criteria applied consistently throughout: acute toxicity, carcinogenicity, persistence, bioaccumulation, endocrine disruption and mutagenicity. Qualitative classifications drawn from recognized international authorities are translated into an ordinal scoring scale, permitting comparative prioritization within and across sectors.

Findings. Construction records the highest mean ordinal hazard score among the substances assessed, driven principally by the persistence, bioaccumulation, and carcinogenicity associated with lead, mercury, asbestos, polychlorinated biphenyls, and benzene. Plastics and textiles also return elevated mean scores, though their hazard profiles are shaped by different chemical functions, including plasticizers, monomers, flame retardants, heavy metals, and volatile organic compounds. Agriculture presents a lower sector average, reflecting the comparatively low intrinsic hazard of fertilizers under the selected criteria; this average nonetheless masks the substantially higher hazard profile of highly hazardous pesticides such as paraquat and MSMA. The recurrence of the same substances across multiple sectors indicates that contamination pathways are structural rather than sector-specific, and that redesigning a limited number of recurring chemical functions, such as plasticizers, stabilizers and flame retardants, could deliver system-wide benefits.

Limitations. Several constraints qualify these results. The approach relies on hazard classifications that, while standardized, do not fully capture chemical interactions or synergistic effects. Data availability varies across substances, and certain materials, asbestos among them, lack complete quantitative parameters. The translation of qualitative classifications into ordinal values introduces a degree of interpretive judgment, which is mitigated but not eliminated by consistent application within a single analytical framework. Scores reflect intrinsic hazard alone and therefore exclude concentration, frequency and exposure pathway. The analysis is further bounded to chemicals in primary products, leaving certain cross-sector contamination routes outside its scope.

Implications. The findings underscore the need for systemic rather than substance-by-substance intervention. Because hazardous substances recur across industrial sectors, redesign at the source offers greater leverage than downstream control. The paper's recommendations therefore start with green chemistry, which designs hazards out of molecules, materials and processes before they enter circulation. Circular economy principles then keep those safer materials in use, supported by transparency and traceability instruments and collaborative governance arrangements. The result is what this paper calls circular growth: economic value created by keeping safe materials and products in use, rather than by extracting, using and discarding them. Central to this argument is an explicit tension: circularity delivers its environmental, societal and economic benefits only where the loops being closed are free of hazardous chemicals, and material circulation in their presence risks distributing contamination rather than eliminating it, while eroding the value of secondary materials. Addressed together, these measures can move global supply chains beyond hazardous chemicals and make them levers of environmental resilience, biodiversity conservation and human health protection.

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List of Abbreviations

AN	Ammonium nitrate
BPA	Bisphenol A
BPF	Bisphenol F
BPS	Bisphenol S
CAGR	Compound annual growth rate
CE	Circular economy
COPD	Chronic obstructive pulmonary disease
EPD	Environmental product declarations
EPR	Extended producer responsibility
GBF	Kunming-Montreal Global Biodiversity Framework (GBF)
GFC	Global Framework on Chemicals
GHS	Globally Harmonized System
HHP	Highly hazardous pesticides
HPD	Health product declarations
HPDC	Health Product Declaration Collaborative
IARC	International Agency for Research on Cancer
LCA	Life cycle assessment
MSMA	Monosodium methanearsonate
NGO	Non-Governmental organization
PCB	Polychlorinated biphenyl
PCOS	Polycystic ovary syndrome
PFAS	Per- and polyfluoroalkyl substances
PFC	Perfluorocarbons
POP	Persistent organic pollutant
PPA	Polymer processing additives
PVC	Polyvinyl chloride
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SDG	Sustainable development goal
THM	Trihalomethanes
UNEA	United Nations Environment Assembly
VOC	Volatile organic compound
WHO	World Health Organization

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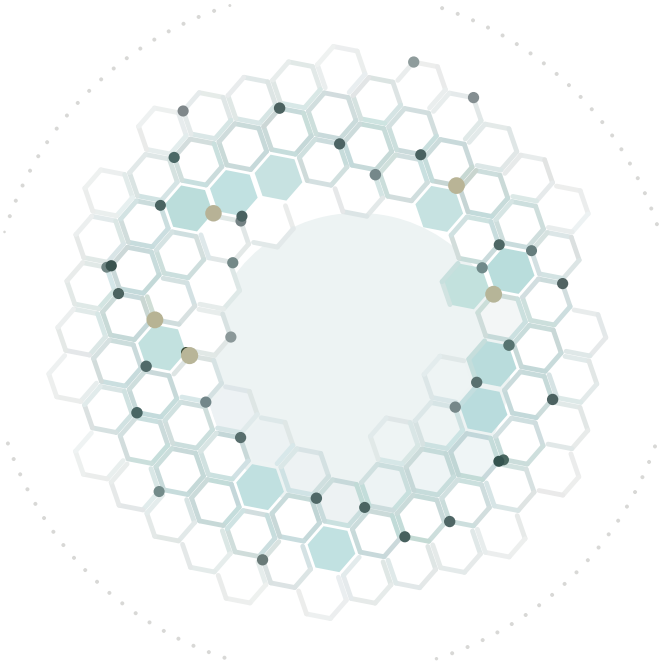
CHAPTER 1



Introduction

Hazardous chemicals run through construction, textiles, plastics and agriculture. Green chemistry and safe circularity can move these value chains beyond them.

IN THIS CHAPTER

1.1 The Scale and Relevance of the Issue
1.2 Research Gaps
1.3 Objectives and Scope

1.1 The Scale and Relevance of the Issue

Hazardous chemicals are deeply embedded in most modern industries, particularly construction, textiles, plastics, and agriculture (EEA, 2024c). Their widespread use and frequent mismanagement in production processes and products that sustain industrial and economic growth pose serious risks for both human health and the environment (Wang et al., 2020). In 2023, the European Union alone produced 218 million tonnes of chemicals, of which 167 million tonnes (77%) were hazardous to human health and 68 million tonnes hazardous to the environment (European Commission, 2024b). Globally, the chemical industry generated approximately 6.67 trillion dollars in revenue in 2023, with production projected to grow by 3.4% in 2024 (Deloitte, 2025a; EEA, 2024b; European Commission, 2024b; Statista, 2025). Many of these substances, once released, exert cascading effects on biodiversity, ecosystems, and ultimately human well-being (UNEP, 2021b). They contribute notably to soil degradation, water and air contamination, and the erosion of ecosystem services essential for life (Dubey, 2024). While the number of deaths associated with chemicals and chemical pollution is difficult to assess, it is estimated that pollution linked to hazardous chemicals caused 1.6 million deaths in 2016 alone (ChemSec, 2023a; UNEP, 2021b). More recently, data from the Global Burden of Diseases, Injuries, and Risk Factors Study shows that chemical pollution contributes to at least 1.8 million deaths each year globally (Fuller et al., 2022).

The difficulty in estimating impacts arises because they are not always immediate; rather, they often emerge gradually, manifesting as developmental abnormalities, physiological disruptions, or behavioral changes across both human and wildlife populations.[1] This highlights how the chemical foundations of modern economies are closely linked to ecological harm, with consequences that extend far beyond the sites of production or use. The chain of impact is thus both vertical (spanning from molecular alterations to species-level collapse) and horizontal, crossing sectoral and geographical boundaries. Within the triple planetary crisis of climate change, biodiversity loss and pollution, chemical use feeds directly into the latter pillar with widespread consequences for the former two. Despite this, chemical pollution is currently under-emphasized, with significant knowledge gaps in both the production and end-of-life stage of chemical products.

The globalized nature of supply chains amplifies the risks of insufficiently monitored and controlled chemical use significantly. Chemicals produced or released in one region do not remain contained there; instead, they travel across borders through water systems, atmospheric circulation, and traded goods, creating transboundary threats to biodiversity and ecosystems (UNEP, 2021a). Supply chain fragmentation further complicates chemical management, as products often pass through multiple countries with varying regulatory standards before reaching end consumers. Moreover, highly toxic elements and carbon-based chemical substances that resist breaking down in nature bioaccumulate and biomagnify through food chains, leading to long-

1 For instance, copper exposure impairs predator recognition in fish, increasing their vulnerability to predation (Gosavi et al., 2020), while the antidepressant fluoxetine has been shown to alter male mating behavior and sexual selection in certain fish species (Fursdon et al., 2019). Such disruptions not only reduce survival rates but also divert organisms' energy away from reproduction and other vital functions, a process further exacerbated by endocrine-disrupting chemicals interfering with hormonal regulation (ChemSec, 2023b).

term ecological damage (Naidu et al., 2021). In this sense, chemical pollution is embedded in a linear economic model. Its impacts may originate upstream in extraction, mining, energy production, and material processing, or at the later stages of chemical design and synthesis, before manifesting downstream across soils, waters, air, bodies, and ecosystems. The spread of its impacts illustrates its core relevance to addressing the principles of WHO's One Health Paradigm; the health of humans is fundamentally connected to that of animals and the planet - if not all are safeguarded, human well-being is threatened.

The interconnected impacts of chemical pollution also challenge industrial and economic resilience due to the financial embeddedness of chemical industries and the longevity of their impact. Chemical production in Europe has declined in recent years (-13% in 2023), but Europe still remains one of the largest consumers of non-pharmaceutical chemicals, and suffers from increasing pollution of so-called "forever chemicals." Global chemical production is projected to continue expanding, with Asia-Pacific leading growth at 5.6% annually, at the same time as chemical pollution is one of the greatest environmental threats to humanity (BASF, 2024; EEB, 2025; Group Atradius, 2024; Naidu et al., 2021). Research into chemical sources, pathways, and environmental fate is vital not only for mitigating ecological damage, but also for enabling industries to transition toward safer alternatives, optimize practices, and reduce dependency on substances with significant health and environmental costs. In this sense, effective chemical management is a prerequisite for balancing sustainability goals with economic competitiveness, and for growth that does not depend on hazardous substances. Where uncertainties remain, a precautionary principle is non-negotiable for truly sustainable chemical management, given the sensitivity of the systems at hand, societal as well as environmental.

Implementing an upstream-by-design approach, with green chemistry at its core, is necessary for effective systemic change to take place, beyond end-of-pipe techniques and leakage-sensitive policy. Discussions about hazardous chemicals must exceed technical and regional assessments. Their impacts accumulate across scales, threatening global ecological stability, industrial resilience, and public health. This calls for international coordination, institutional responsibility, and global governance frameworks that are capable of managing risks that transcend borders and generations.

In response to these risks, multiple global initiatives such as global frameworks and multilateral environmental agreements (MEAs) have emerged to align chemical management with broader sustainability and biodiversity goals, such as the UN Sustainable Development Goals.[2] [3] Connecting governance efforts to international policy objectives demonstrates how upstream design and regulatory alignment can reinforce both environmental protection and industrial resilience. However, these initiatives often struggle to keep pace with the rapid evolution of global supply chains and the introduction of new chemical substances. Bridging this governance lag requires integrating green chemistry, life-cycle thinking and circular design principles into

2 Global initiatives include but are not limited to: the Global Framework on Chemicals (GFC), Kunming-Montreal Global Biodiversity Framework, Global Alliance on Highly Hazardous Pesticides (GAHHP), Strategic Approach to International Chemicals Management (SAICM), Global Impact Coalition, Minamata Convention on Mercury, and Basel, Rotterdam, and Stockholm Conventions.

3 The primary SDGs these global initiatives contribute to are SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 14 (Life Below Water), and SDG 15 (Life on Land).

industrial strategies from the outset, so that chemical innovation is safe by design rather than assessed after the fact. This underlines the importance of moving from reactive management to proactive upstream interventions, where design choices anticipate environmental and health risks before they materialize.

Working upstream by design, green chemistry and safe circularity together have the potential to move global supply chains beyond hazardous chemicals: first by designing hazards out of new products and decontaminating the existing material stock, then by closing the loop on materials that are safe to keep in use. This is the foundation for circular growth: economic value created by keeping safe materials and products in use, rather than by extracting, using and discarding them. Achieving it necessitates a system-level approach, looking at exposure mechanisms and highlighting vulnerable groups, to ensure an effective and just transition. This paper sets out to lay that foundation, aligning technical demands with human and environmental needs.

1.2 Research Gaps

Unlike more visible threats such as habitat destruction, the effects of chemical pollution are often delayed and subtle, which partly explains why they remain under-recognized and underexplored. However, chemical pollution is gradually receiving increased attention as scientists begin to gauge the full scale of the crisis. Growing evidence warns that neglecting chemical pollution could seriously undermine global efforts to protect biodiversity and reverse current species declines (Sigmund et al., 2023).

The subtlety of chemical pollution's impact often hinders immediate detection and regulatory scrutiny (Amolegbe et al., 2022; Saaristo et al., 2018). This challenge is further compounded by the fragmented nature of existing research, as most studies have narrow focuses on specific chemicals, species, or ecosystems, leaving significant gaps in understanding cumulative impacts, interactions between different pollutants, and long-term consequences for ecosystems (Halpern & Fujita, 2013). The lack of integrated studies that connect environmental and health effects across chemical life cycles creates a major blind spot: exposure data often exist in isolation from toxicity or epidemiological findings, preventing a holistic understanding of human and ecological risks. The complex interactions between chemicals may amplify the harmful effects of chemical pollutants, but research is only beginning to unravel these dynamics (Sigmund et al., 2023).

The current body of research is also geographically limited, as most knowledge on chemical pollution stems from studies conducted in Europe and North America (Brack et al., 2022). The rapidly industrializing countries in Asia, Africa, and Latin America face acute chemical pollution challenges that are often coupled with weak regulatory mechanisms and inadequate waste management infrastructure (Sharma et al., 2025). The lack of data from these regions constrains the understanding of global trends and regional characteristics of chemical pollution. Furthermore, many countries in these geographic regions rely heavily on the informal sector, where vulnerable groups such as children, women, and marginalized communities often face higher exposure risks. Research and the development of regulatory mechanisms must ensure the shift away from hazardous chemicals and prioritize their protection.

The regulatory landscape similarly struggles to keep pace with the emergence of new synthetic chemicals and their unintended consequences (Jacobs et al., 2024). Most existing regulatory frameworks rely on outdated risk assessment models that consider threshold levels of individual chemicals rather than the cumulative and interactive effects of chemical mixtures (Bopp et al., 2019; Kienzler et al., 2016). New formulations rapidly enter the market (about 2,000 new chemicals enter the market each year (Brander, 2022)), and as a result, regulatory systems and toxicological testing frameworks lag years behind, meaning products are often approved long before their potential risks to ecosystems or human health are understood. The result is a growing 'innovation-to-assessment gap': a structural imbalance where scientific and regulatory capacity cannot keep up with chemical innovation. This lag between scientific understanding and regulatory action perpetuates gaps in policy effectiveness. More research is therefore needed to emphasize the joint risks of certain chemical groups to inform effective preventive policy.

Unless these research gaps are addressed, the full role of chemical pollution in biodiversity loss and ecosystem degradation cannot be comprehensively understood. These gaps risk resulting in misinformed or narrowly scoped policies and interventions, which fail to address the scale of the crisis and further threaten global environmental conservation goals. This paper therefore argues that bridging these gaps requires both methodological innovation and stronger integration between environmental science, toxicology, and policy studies, among other disciplines. Filling these knowledge gaps is essential for informing effective chemical management and global environmental policies that adequately reflect the scale of the crisis, for protecting human well-being from the cumulative and long-term effects of chemical exposure, and for directing green chemistry innovation toward the substances and sectors where it can do the most good.

1.3 Objectives and Scope

This paper examines how global supply chains can move beyond hazardous chemicals, starting from their impacts on biodiversity, ecosystem health, and human well-being. It explores how chemicals used across industries, particularly textiles, plastics, construction, and agriculture, enter supply chains and interact with the environment, posing risks to soil, water, and air quality, and, through ripple effects, to human health. Heavy metals also warrant particular attention as they represent a core subset due to their widespread industrial use, persistence in the environment, and acute as well as chronic toxicity. They are therefore also included in the paper, despite not typically being defined as hazardous chemicals. When referring to the total group of chemicals covered by the paper, that is hazardous chemicals and heavy metals, the term "hazardous substances" will be used to signal the inclusion of heavy metals.

By tracing chemicals throughout their life cycles, from research to production to disposal, the paper identifies the stages that present the highest risks to biodiversity and ecosystems. The paper addresses chemical persistence, bioaccumulation, and toxicity, highlighting the specific pathways through which chemicals impact biodiversity and human health. A comparative and classification framework is developed to rank hazardous chemicals according to their intrinsic hazard, taking into account their roles at different supply chain stages and their interactions with environmental pathways.

Beyond this assessment, the paper outlines a strategic roadmap for transitioning toward safer, biodiversity-protective supply chains. The roadmap starts with green chemistry, which intervenes at the design stage to prevent pollution before it occurs. The circular economy then keeps those safer materials in use, shifting away from the traditional linear "take-make-dispose" model, so that chemical safety becomes a basis for circular growth. Increased transparency along supply chains and collaborative governance make both verifiable and enforceable. This paper links these strategies to global sustainability and biodiversity objectives, including pollution reduction and species protection targets under the Kunming-Montreal Global Biodiversity Framework. The paper also connects hazardous chemical pollution to relevant global sustainability initiatives, such as the Paris Agreement, the Global Framework on Chemicals (GFC), and commitments from COP conferences, to put the relevance and urgency of addressing the problem into perspective. Additionally, in this paper, biodiversity is treated as the overarching system at risk, with overall environmental health as the primary indicator over the medium- to long-term. Human health is the most immediate impact area and thus the near-term focus for policy and industry action, as well as an ever-relevant public concern. The paper concentrates on the routine hazardous effects of industrial chemicals under "normal" conditions, rather than following major accidents, which often drive regulatory and research responses. For example, the Bhopal Gas Tragedy (1984), in which methyl isocyanate (MIC) may have caused up to 22,000 deaths and injured over half a million people, illustrates how delayed recognition of chemical hazards can have serious consequences (Harvard T.H. Chan School of Public Health, 2024). Decades later, gaps in regulatory oversight and transparency persist, underscoring the need to study chemical effects proactively to prevent long-term harm to all forms of life.

This paper first establishes the scale and pathways of chemical harm, then sets out green-chemistry and circular-economy responses. It consists of an overview of hazardous chemicals in the value chains of the chosen high-impact sectors and the impact of those chemicals on biodiversity and health. A systematic qualitative ranking of the outlined hazardous chemicals is then performed across the sectors, focusing on intrinsic chemical hazards and chemicals used in primary products. Given the qualitative nature of this assessment, the ranking evaluates substances individually and does not attempt to quantify cumulative or mixture effects arising from the simultaneous release of multiple hazardous substances. Assessing such interactions would require more data-intensive and substance-specific methods, like exposure modeling and the evaluation of potential additive, synergistic, or antagonistic effects. However, these rankings form the basis for prioritizing action, identifying knowledge gaps, highlighting opportunities for innovation, and offering policy and research recommendations to guide global supply chains toward environmental sustainability and biodiversity conservation. By proactively addressing chemical risks, the paper seeks to support resilient industrial practices that align with human health, ecosystem protection and circular growth.

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CHAPTER 2



Background: Hazardous Chemicals in Global Value Chains

A cross-sector view of where hazardous chemicals originate, how they move through ecosystems, and who is exposed.

IN THIS CHAPTER

2.1 Ecosystems
2.2 Chemicals
2.3 Industry profiles
2.4 Exposure Groups
2.5 Cumulative and Systemic Risks

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Figure 9 Global distribution of childhood lead exposures in 2019

While hazardous chemicals are present in various value chains, this paper focuses on textiles, plastics, construction, and agriculture as these industries are deeply intertwined with everyday life and global development; they provide essential goods and services for billions of people, generate significant market value, and drive economic growth worldwide. In practical terms, the global textile market was valued at approximately $2.12 trillion in 2025, with a projected compound annual growth rate (CAGR) of 7.24% through 2035; the plastics industry was valued at $678.6 billion in global market size in 2025, and projected to expand to $1.018 trillion by 2035; construction was valued at approximately $11.39 trillion in 2024 and is projected to reach $16.11 trillion by 2030; and agriculture is forecast to grow by an annual rate of 3.31%, with exports totaling $865.2 billion in 2025. These industries together support millions of jobs and represent indispensable links in global supply chains (Precedence Research, 2026a, 2026b; Deloitte, 2025b; MarketsandMarkets, 2025; NMSC, 2025; Statista, 2025). Understanding their scale and economic importance sets the stage for examining how hazardous chemicals permeate each sector and drive both environmental and human health risks.

The environmental footprint of these industries is significant. Construction and manufacturing of goods and materials are responsible for an estimated 57% of global carbon emissions, while textiles, plastics, and agriculture contribute heavily to water use, chemical pollution, and waste generation (One Click LCA, 2025). Many of these impacts are rooted in the traditional linear "take-make-dispose" model of growth, which relies on the extensive use of hazardous chemicals at multiple stages: from production and processing to consumer use and eventual disposal. Chemicals such as dyes, flame retardants, plasticizers, fertilizers, and pesticides are embedded throughout these value chains, often entering the environment and posing risks to human health and biodiversity. Yet, each industry holds considerable opportunity for transformation: circular economy principles, sustainable materials, and pollution-prevention practices are being developed and could be scaled up to reduce contamination, improve resource efficiency, and support climate resilience (Eurostat, 2024; Fidra, 2025a; Qmarkets, 2025; StartUs Insights, 2025; GOV.UK, 2024). If pollution from hazardous chemicals were effectively minimized in these industries, through green chemistry, better management, transparency, and technological innovation, major reductions in environmental and health impacts could be achieved, supporting sustainable development, cleaner value chains and circular growth worldwide.

The chemicals highlighted in this paper were chosen according to their prevalence across global supply chains, their persistence in the environment, the severity of their impacts on biodiversity and human health, and the existence of regulatory gaps that leave these risks insufficiently addressed. Chemicals such as phthalates and some heavy metals are prevalent across multiple industries. Other chemicals on the other hand, such as chlorine, pesticides and asbestos, are more tied to certain industries. The substances also vary in their historic and industry-specific use, not to mention in their unique chemical properties and pollution mechanisms. Understanding these differences in the production, use, and disposal of the chemicals is necessary to understand both their impact and the safer alternatives green chemistry can offer. It is also essential to consider that broader biodiversity and human health consequences differ depending on context. The release, persistence, and bioaccumulation of these substances do not occur in isolation; they interact within complex ecosystems, affecting not only soil, water, and air quality but also the health of living organisms and their interactions. At the same time, social and technical conditions

technical conditions contribute to the cause, type, and distribution of impact. Thus, these interconnected impacts, focusing on how chemical pollution undermines biodiversity, disrupts ecological balance, and poses significant, long-term risks to human health, will also be explored in depth. This is done in the following sections, with an initial summary of the pre-existing conditions of ecosystems and the relevant chemicals within the chosen industries, followed by an outline of the substance-specific dynamics within the industry profiles, and a holistic look at different exposure groups and system interactions.

2.1 Ecosystems

The widespread use of hazardous chemicals across industrial and agricultural sectors has reshaped the equilibrium of natural ecosystems. Once released into soils, water, or the atmosphere, they interfere with essential ecological processes like nutrient cycling and trophic interactions, important pillars to sustain ecosystem stability and biodiversity. Their persistence and mobility allow them to spread across habitats and species, fragmenting ecological networks, and driving long-term declines in species richness and ecosystem integrity. Since the Industrial Revolution, rapid industrialization and intensification of agriculture have accelerated the release of hazardous chemicals and transformation of natural habitats (Dirzo et al., 2014; Qi et al., 2002). **Terrestrial ecosystems**, and particularly soils, form the foundation of biological productivity and are both the initial entry point and long-term reservoir for much of the world's chemical contamination. The mineral and organic composition of soils, as well as humidity and particle size, makes it an important agent for sequestration of contaminants. Ideally, these very characteristics, combined with its function as habitat for diverse groups of microorganisms, would make soil an important decontaminating agent of hazardous chemicals through their adsorption in soil particles, and their consequential degradation or transformation. Nonetheless, soil also constitutes the main path for contaminants reaching other environmental compartments like groundwaters, surface waters, and the atmosphere. As hazardous chemicals embed themselves within this environment via electrostatic attraction, ion exchange, and precipitation reactions, they interact with soil minerals, organic matter, and living organisms, leading to changes in terrestrial biodiversity. Soil also can act as a source of contaminants through the weathering of its own organic and mineral constituents (Sarkar et al., 2021). The dual role of soil as both contaminant sink and source reveals a temporal paradox: what initially appears as environmental protection through sequestration becomes delayed contamination as bound chemicals slowly release into groundwater and biota over decades. This means soils function as accumulative sinks with long-term retention where today's contamination burden determines tomorrow's exposure landscape, effectively preprogramming future pollution episodes that will manifest long after the original inputs have ceased, making soil contamination functionally irreversible on policy-relevant timescales.

Important environmental agents are impacted because of these effects. **Pollinators**, like bees, butterflies, or beetles, are important enablers for plant reproduction. In turn, plants form the foundation of trophic chains, sustaining energy flow and nutrient transfer, essential for whole ecosystem dynamics (NSF, 2018). Similarly, **soil organisms**, ranging from microorganisms like bacteria and fungi to invertebrates like nematodes and earthworms, play an important role as decomposers,

nutrient recyclers, and regulators of soil structure and function (Das et al., 2023). The decline of these key agents also directly threatens human food systems; about 40% of global agricultural production relies on insect labor, while the production of more than 75% of the world's major crop types benefits from pollinators (Slow Food, 2023; Kortsch et al., 2024). As higher trophic levels in terrestrial food chains, **wildlife populations** reflect the cumulative effect of hazardous chemicals circulating through soils, vegetation, and lower organisms (Saaristo et al., 2018).

Aquatic ecosystems play a central role in regulating natural cycles and sustaining biodiversity. Freshwater and marine systems, such as coral reefs and fisheries, act as interfaces between terrestrial, atmospheric, and oceanic processes (Poff et al., 2002). They host diverse organisms that contribute to atmospheric regulation through carbon dioxide absorption, nutrient cycling, and climate moderation (Behrenfeld et al., 2006; Jiao et al., 2014; Malin & Kirst, 1997). Aquatic ecosystems' role in carbon dioxide absorption and climate regulation means that chemical contamination degrading these systems can create a positive feedback loop with climate change: pollution may reduce oceanic and freshwater capacity to absorb atmospheric CO_2, accelerating warming that further stresses aquatic life already compromised by toxic exposures. The ocean alone absorbs 30% of all CO_2 emissions (United Nations, n.d.).

Compared to other aquatic ecosystems, **freshwater systems** are among the first to receive hazardous chemical inputs from agricultural runoff and industrial effluents. These systems are especially sensitive to imbalance of nutrients, particularly nitrogen and phosphorus, as this can lead to oxygen depletion from algal and cyanobacterial blooms (Akinnawo, 2023). As hazardous chemicals travel downstream, aided by water's ability to act as an effective carrier, they can eventually reach **marine environments**. Within marine systems, coral reefs and fisheries arise as biodiversity hotspots and providers of ecosystem services supporting other human activities. Recent studies highlight how coral reefs have reached a tipping point of accelerated dieback, threatening the livelihoods of millions of people who depend on them (Lenton et al., 2025). In **fisheries**, long-term contamination from hazardous substances can destabilize aquatic ecosystems, from microbial processes to human sustenance (Anik et al., 2025; Garai et al., 2021; Mustafa et al., 2024; Stahl et al., 2023; Zhou, 2022).

2.2 Chemicals

Modern value chains are associated with complex chemicals designed to meet the demand for intricately specialized products. At the same time, chemicals that provide the desired function or output at the lowest price are desired from an efficiency perspective, which can favor aggressive chemicals with high environmental and health risks.

Per- and Polyfluoroalkyl Substances (PFAS) are one example of this. These are fluorinated chemicals containing at least one fully fluorinated methyl or methylene carbon atom (OECD, 2021), a large group that includes both long-chain and short-chain compounds (Rekik et al., 2024). They are known for their durability and hydrophobic and oleophobic properties (water-repelling and oil-repelling, respectively), making them widely used in consumer products as well as in industrial processes. Global PFAS market consumption reached 788,700 tonnes in 2024, projected to exceed 832,000 tonnes in 2025 (EEA, 2024a, 2024c; Towards Chemicals And Materials Analytics

and Consulting, 2026). The strong carbon-fluorine bonds make the degradation of PFAS rather difficult. It is possible for the substances to persist in the environment for several decades, where they accumulate in groundwater, marine environments, and living organisms, earning their name of "forever chemicals" (Coulson, 2024; Cousins et al., 2020).

Incorrect disposal is one of the major contributors to PFAS pollution. In 2022, the US EPA reported that about 64 tonnes of PFAS were disposed of on land, highlighting their omnipresence in the environment (US EPA, 2024e). Once released, PFAS accumulate within soils, waters, and sediments (De Silva et al., 2021). From there, they can affect exposed organisms by impairing reproduction, development, immune response, and even the behavior of organisms (Lukić-Bilela et al., 2023). This is most likely amplified by their widespread presence in water bodies like rivers and oceans, where they also can influence the metamorphosis of amphibians (Celino-Brady et al., 2021; Fauvelle et al., 2021; Simon et al., 2024).

PFAS may act as endocrine and metabolic disruptors, with mounting evidence linking them to serious health impacts in humans (UNEP, 2023a). Exposure to PFAS has also been linked with specific immunological, hepatic, reproductive, and carcinogenic effects (CDC, 2024a). PFAS readily penetrate the skin barrier, with 15 of 17 tested compounds absorbed at rates above 5% of the exposure dose. In some cases, absorption into the bloodstream reaches 13.5%, with an additional 38% remaining in the skin for slow release over time (Ragnarsdóttir et al., 2024). Newer, shorter-chain PFAS compounds (marketed as safer replacements) may be even more readily absorbed, with one compound showing four times the absorption rate of its predecessor (Li et al., 2025).

Similarly, **Bisphenol A (BPA)**, a building block of polycarbonate plastics and epoxy resins, may also act as an endocrine disruptor (Celino-Brady et al., 2021). BPA is commonly found in items such as reusable water bottles, food-can linings, and eyeglass lenses, where it provides strength and clarity. BPA has been detected worldwide, including in marine waste that accumulates on beaches, where it can bioaccumulate in aquatic organisms and disrupt ecosystems. In the US alone, over 450 tonnes of BPA are released into the environment each year (US EPA, 2025b). When released into the environment, particularly into water bodies, it disrupts aquatic organisms' endocrine systems, impairing reproduction and growth from early life stages (Wu & Seebacher, 2020). In humans, it can mimic the hormone estrogen, thus disrupting normal hormone functions, impacting reproductive and metabolic processes, normal cell growth and the development of tissues and organs (Manzoor et al., 2022; Yuan et al., 2023). Evidence indicates that BPA exposure may impair prostate and uterus development, lower sperm counts, induce early puberty in children, promote tumor growth, weaken immune responses, and alter brain chemistry and behavior (Hafezi & Abdel-Rahman, 2019; Nebraska Medicine, 2022).

Polychlorinated biphenyls (PCBs) are another potential endocrine disruptor. These synthetic chemicals are problematic because they can volatilize (evaporate into the air) or migrate from degrading materials, contaminating indoor environments especially under heat or UV light exposure. Because of their high toxicity, they were listed in Annexes A and C under the Stockholm Convention on Persistent Organic Pollutants (2001), which came into force in 2004, mandating parties to ban production and new uses of PCBs, and to lead environmentally sound waste management of products containing and contaminated with PCBs by 2028. Today, they exist primarily as a legacy chemical in buildings (Secretariat of the Stockholm Convention, n.d.). Their long-lasting qualities make them accumulate in food chains for extended periods of time, causing

population declines and altered food web dynamics through impaired reproduction, growth, and immune response. Additionally, their accumulation in organisms may lead to secondary exposure to humans affecting the immune, reproductive, nervous, or endocrine systems (De Silva et al., 2021; US EPA, 2013c; IDEM, 2013). Further, both BPA and PCBs decrease microbial functionality and diversity (Zaborowska et al., 2021).

Phthalates pose similar issues. This group of esters was first synthesized in the 1920s and is used in construction materials, personal care items, medical equipment, food packaging, and textiles. The substances act as "plasticizers" to provide flexibility and durability while reducing brittleness. Global phthalate production was 6-8 million tonnes in 2024 (National Center for Biotechnology Information, 2024; Technavio, 2024; Islam et al., 2025). When contained in materials, the phthalates slowly leach out upon exposure to heat, ultraviolet (UV) light, mechanical abrasion or water. The leachate contaminates indoor air, household dust, and water sources and flows into the environment through manufacturing discharges and from discarded products. In landfills, they can migrate into soil and groundwater. Additionally, phthalates are released during disposal or recycling, and incinerating phthalate-plasticized PVC can generate highly hazardous by-products such as dioxins (Endocrine Society, 2020; Liu et al., 2024; Wang & Qian, 2021). Phthalates are released continuously and are now widespread in the environment and in food. They can affect multiple organ systems, causing chronic hormonal disruption even after short-term exposure and can cause endocrine disruptions hindering reproductive and developmental capabilities (Wang & Qian, 2021). In humans, certain phthalates have been linked to conditions like breast cancer, developmental issues in children, obesity, and asthma, as well as increasing risks for cardiovascular diseases and allergic diseases (Baneshi et al., 2023; Seymour, 2021). **Heavy metals**, defined as metallic elements with high density, serve as a critical lens for understanding chemical hazards because their persistence and bioaccumulative properties create irreversible contamination (Alengebawy et al., 2021). Unlike organic compounds that may eventually degrade, heavy metals are elements, meaning they cannot be broken down, although they can change chemical form (for example, mercury to methylmercury), and their toxicity persists and accumulates over time (Turner & Filella, 2021).

Biodiversity impacts are reflected through impacted behavioral and reproductive capabilities in both aquatic and terrestrial ecosystems (Game & Wildlife Conservation Trust, n.d.; Olympian Water Testing, n.d.; Sonne et al., 2023). Release of heavy metals may disrupt microbial communities, reduce plant activity and nutrient cycling, endangering whole ecosystems and populations (Das et al., 2023; Kumar et al., 2022). Regarding human health impacts, heavy metals are known endocrine disruptors, irritating agents, and oxidative stressors (Lalrinfela et al., 2024). Some heavy metals are also known to impair organ systems, from the nervous system causing developmental complications, to the circulatory system causing anemia and possible carcinogenicity (UKHSA, 2025; WHO, 2024a). Chronic dietary exposure has been associated with neurological and developmental issues, as well as cardiovascular diseases and cancer (Alengebawy et al., 2021). Some metals, notably mercury in the form of methylmercury, concentrate in predators through biomagnification[4] (WHO, 2024b). Metal poisoning, for example from lead shot, also reduces

4Biomagnification refers to the increasing concentration of a substance as it moves through the food chain (US EPA, n.d.a).

reproductive success and increases mortality in wildlife (Game & Wildlife Conservation Trust, n.d.). Additionally, sensitive groups such as pollinators, decomposers, and apex predators are particularly affected, escalating risks to the very ecosystems that they help sustain through their roles in population balance and species propagation (Das et al., 2023).

Mercury is classified as a serious environmental and health pollutant due to its mobility through atmospheric transport and bioaccumulation into living organisms. For example, the US EPA classifies mercury as a hazardous waste, and because of its high toxicity and persistence, a release of one pound (about two tablespoons) or more has to be reported to the federal authorities (US EPA, n.d.c). Approximately 16 tonnes of mercury were released into the air during 2022 in the US alone, a decrease compared to previous years (US EPA, 2024d). Once released, mercury volatilizes and circulates through the atmosphere before depositing into bodies of water, where it gets transformed into methylmercury, a highly hazardous compound that bioaccumulates in aquatic organisms and enters the human food chain. Mercury affects organisms' fertility and growth and causes cardiotoxicity, pulmonary diseases, and renal disease, leading to increased mortality. Moreover, its bioaccumulation through the food chain poses risks to humans' nervous systems and developmental dysfunctions (Bernardi et al., 2025; Kessler, 2013; Wu et al., 2024). Beyond mercury, specific metals and metalloids like **lead**, **arsenic**, **cadmium** and **chromium** pose significant risks through bioaccumulation.

Asbestos is also of critical concern. It refers to a group of naturally occurring fibrous silicate minerals that are hazardous and carcinogenic. Exposure to airborne asbestos fibers can cause severe respiratory diseases such as asbestosis, lung cancer, and mesothelioma. In 2019, occupational asbestos exposure resulted in 26,820 mesothelioma deaths globally, with 91.7% of mesothelioma deaths and 85.2% of disability-adjusted life years attributable to occupational asbestos exposure (Chen et al., 2024). Global production remains around 1.1 million tonnes per year, with an estimated 125 million workers still exposed worldwide (ILO, 2021). Asbestos fibers deposited in soil and water systems reduce microbial diversity and disrupt nutrient cycling, and asbestos fibers dispersed through dusts can affect respiratory systems of terrestrial fauna. In humans, it increases risks for diseases like lung cancer, mesothelioma, and asbestosis (Li et al., 2023a; CDC, 2024b).

Volatile Organic Compounds (VOCs) represent another major airborne source of chemical risk, particularly in indoor environments. VOCs are organic chemicals with high vapor pressure and low water solubility, making them readily evaporate into the air. Research shows that between 36.4% and 39.7% of the global population is exposed to harmful VOC levels, with outdoor exposure to benzene, formaldehyde and acetaldehyde linked to 0.60 to 0.85 million lifetime cancer cases globally, nearly three-quarters of them from benzene (Xiong et al., 2024). Many of the most VOC-intensive products rely on urea-formaldehyde and phenolic resins, which release formaldehyde, classified by the International Agency for Research on Cancer (IARC) as a Group 1 carcinogen, meaning it is proven to cause cancer in humans (Zhou, 2022). In the environment, they participate in ground-level ozone formation, damaging plant tissues and altering ecosystem dynamics (Zhou et al., 2023).

Chlorine and **chlorine-related compounds**, that is, compounds with at least one chlorine atom (Cl) in their structure, include some that deplete the ozone layer (long-lived chlorinated gases such as CFCs and carbon tetrachloride; US EPA, 2024a) and some that are carcinogenic, and

many are otherwise hazardous to the environment and human well-being. Their use may result in chlorinated byproducts like trihalomethanes (THMs) and dioxins being released to the environment through wastewater effluent or volatilization to the air, particularly in poorly managed systems, where they harm aquatic life (Li et al., 2023b). Additionally, their release into water bodies may also increase chemical oxygen demand, reducing available oxygen and therefore further stressing aquatic environments (Chen et al., 2001). In coral reefs, the discharge of chlorine-related compounds like chlorinated paraffins and hazardous runoff accelerates coral bleaching and mortality (Jafarabadi et al., 2021). Moreover, chlorinated products are known skin irritants capable of causing burns and respiratory problems, while chlorinated paraffins in particular have been linked to cancer, developmental, reproductive, and endocrine disorders (Huang et al., 2023). Sustained low-level exposure is also associated with asthma, skin sensitization, and allergic contact dermatitis, as well as immune system and thyroid disruption (Mu et al., 2023; National Research Council, 2000; Schrenk et al., 2020).

Within agriculture, **nitrogen- and phosphorus-based fertilizers** and **pesticides** contribute to pollution of hazardous chemicals. Synthetic fertilizers, particularly nitrogen-based fertilizers, play an important role in nitrous oxide (N_2O) global emissions, produced through microbial processes in fertilized soils; the synthetic nitrogen fertilizer supply chain as a whole accounts for about 2% of global greenhouse gas emissions (Menegat et al., 2022). These hazardous chemicals are linked to respiratory issues, irritation, neurological symptoms, and notably methemoglobinemia ("blue baby syndrome") (Tagkas et al., 2024). Furthermore, phosphate exposure has been associated with autoimmune disorders and hepatic failure (Ahmad et al., 2023). Environmentally, excessive application of fertilizers threatens microbial diversity, and causes nutrient imbalances. Eutrophication occurs through imbalances in nitrogen and phosphorus in particular, and it is responsible for algal and cyanobacterial blooms. These rapid population increases deplete oxygen and lead to eventual aquatic biodiversity loss, affecting not only ecosystem health but also human activities (Akinnawo, 2023).

Pesticides cause environmental concern regarding biodiversity when their intended impact on unwanted organisms expands and disrupts entire food chains (Isenring, 2010; Pathak et al., 2022). They can disrupt the navigation and reproduction of pollinators, which in turn affects plant biodiversity (NSF, 2018). Similarly, pesticides can also disrupt the ecosystem services of soil organisms, such as decomposition, nutrient recycling, and regulation of soil structure and function (Sarkar et al., 2021). Herbicides, the most widely used type of pesticide accounting for 50% of all pesticide use (Statista, 2024), raise distinct health concerns, particularly some widely used active ingredients such as glyphosate or atrazine. They are linked to chronic health effects like cancer (IARC classifies both as probably carcinogenic to humans, Group 2A; Guyton et al., 2015; IARC, 2025), neurodegenerative diseases like Parkinson's, and reproductive and developmental disorders (National Institute of Environmental Health Sciences, 2023). Organophosphate and carbamate pesticides inhibit acetylcholinesterase enzymes, which are responsible for regulating nerve-muscle communication, leading to neurological symptoms including headache, eye irritation, and burning sensations (Suratman et al., 2015). Chronic exposure is associated with impairments in executive functions, psychomotor speed, memory, attention, and coordination, but also respiratory effects and endocrine disruptions (Muñoz-Quezada et al., 2016; Sharma, 2025).

Several pesticides are also listed as Persistent **Organic Pollutants (POPs)**, as are PCBs and some PFAS. The Stockholm Convention defines POPs as chemicals that remain intact for extended periods, travel long distances, accumulate in fatty tissues, and biomagnify through food chains. While the convention aims to eliminate the production, use, and unintentional release of POPs, and has 186 Parties, significant challenges remain (Stockholm Convention, n.d.). These are in large part attributed to the complexity of the global supply chains of POPs and informational deficits (IISD Earth Negotiations Bulletin, 2025). In one overview, it was concluded that a cumulative 31,306 kilotonnes of 25 manmade POPs had been synthesized and commercialized globally between the 1930s and 2020, with a resulting cumulative release of 20,348 kilotonnes into the environment (Li et al., 2023c).

Put together, the above-mentioned chemicals and chemical groups all have the potential to endanger human well-being and the environment. The different risk areas, where they overlap and where they can magnify each other, necessitate further insight into the specific industry profiles, vulnerable groups and systemic risks to better understand their complexity.

2.3 Industry profiles

2.3.1 Chemicals in the Textile Industry

The textile industry heavily depends on hazardous chemicals throughout its supply chain, from raw material processing to finishing. These inputs enable properties such as colorfulness, durability, or stain and water resistance, but also introduce risks across the life-cycle, such as worker exposure, manufacturing side streams and wastes, consumer contact residues, and unwanted releases at end-of-life disposal. Additionally, outsourcing manufacturing to the Global South entails lower labor and manufacturing costs, but due to difficulties enforcing environmental regulation and social compliance, new challenges arise. Overarching disparities between origin and manufacturing countries create added challenges for global supply chains (ILO, 2016). Among the most pressing challenges are inconsistent monitoring, weak enforcement, and limited availability of viable substitutes, which persist despite growing restrictions and may be further complicated by cross-border trade (Khandaker, 2025; Bibi et al., 2024; Textile Focus, 2020). This geography of chemical risk reflects a troubling pattern where affluent consumer markets externalize the toxic burden of production onto populations in manufacturing regions, effectively creating sacrifice zones[5] where workers and communities bear disproportionate health costs while multinational brands capture economic value (Bick et al., 2018; ILO, 2021). This results in a structural incentive for the continued use of hazardous substances because those making procurement decisions remain insulated from the health and environmental consequences their choices impose on distant communities.

Among these hazardous chemicals are **chlorine** and **chlorine-related compounds**, that is, compounds with at least one chlorine atom (Cl) in their structure, like chlorine-based bleaches, which

5A "sacrifice zone" refers to a territory where toxic contamination, industrial pollution, ecosystem degradation, or health risks are disproportionately concentrated, often affecting socially marginalized or economically vulnerable communities. The concept highlights the existence of pollution hotspots, and the broader political-economic dynamics through which some places and populations are made to bear the environmental costs of production, consumption, extraction, or development so that benefits can be enjoyed elsewhere (Juskus, 2023).

break color-causing molecules through their strong oxidizing power, and chlorinated paraffins. Chlorine-based bleaching continues despite the hazardous effects it may have. Hydrogen peroxide now accounts for over 70% of bleaching worldwide, but sodium hypochlorite is still used in cost-sensitive markets to remove organic stains and impurities and brighten fabrics (Hashem & Farag, 2025). European chlorine production exceeded 8 million tonnes in 2024 (EU-27 + UK, Norway, Switzerland), with monthly production outputs around 672,768 tonnes in August alone. Industrial incidents continue to release bulk chlorine, e.g., a 10,000-pound leak in 2025 (Click2Houston, 2025; EuroChlor, 2024, 2025; National Center for Biotechnology Information, 2018; TexFash, 2022).

Due to the toxicity of chlorine and chlorine-related compounds they pose a highly hazardous threat to the textile industry and the environment overall. The chemical transformation of chlorine into THMs and dioxins represents a particularly insidious form of pollution because the parent compound's volatility and reactivity mean that even facilities with basic containment generate secondary toxins through unintended chemical reactions in wastewater systems (US EPA, 2024a). This creates a situation where the hazard proliferates beyond the original substance. Textile facilities effectively become distributed sites of dioxin synthesis, with the most dangerous compounds forming not during controlled manufacturing but in the unmanaged chemical chaos of inadequate treatment infrastructure common in export-processing zones. **PFAS** are used within the textile industry as fabric treatments in finishing processes, which bestow water, oil, and stain resistance, especially for outdoor apparel and technical fabrics. They result in durable hydrophobic (water-repellent) layers. These processes produce PFAS emissions into the environment through the air and water. Additionally, residual PFAS also leach out from discarded textiles into soil (Svedlund & Skedung, 2022) and water bodies over time (Gu et al., 2021).

The textile sector accounts for approximately 35% of global fluoropolymer demand and about a third of all PFAS use in the EU (between 41,000 and 143,000 tonnes a year), and over 64 tonnes of PFAS from all reported sectors were disposed of on land in 2022, as shown in Figure 1. In the EU, the textile sector represents one of the most significant sources of PFAS pollution, being used in garments, home textiles, leather, and technical applications (EEA, 2024a, 2024c; US EPA, 2024e).

Phthalates are incorporated into textiles through screen-printing inks and PVC-based fabric coatings, where they act as "plasticizers" to provide flexibility and durability, particularly in sportswear, raincoats, and decorative prints. Textile applications represent a significant share of global phthalate production; wastewater monitoring in textile clusters reports phthalate concentrations of 1-8 mg/L in effluents (Dhameliya & Ambasana, 2023; National Center for Biotechnology Information, 2024; Technavio, 2024). Phthalates used in textile printing readily transfer from clothing to skin, enabling continuous dermal exposure during wear, particularly for children and sensitive individuals (Wang & Qian, 2021). Environmental contamination from leachate originates from both discarded textiles and textile-derived microplastics (Liu et al., 2024; Wang & Qian, 2021).

The high presence of phthalates in textile products suggests the pervasive influence of these chemicals within parts of the textile industry. However, results are not sufficient to conclude that phthalates are always deliberately added during manufacturing. Greenpeace detected phthalates

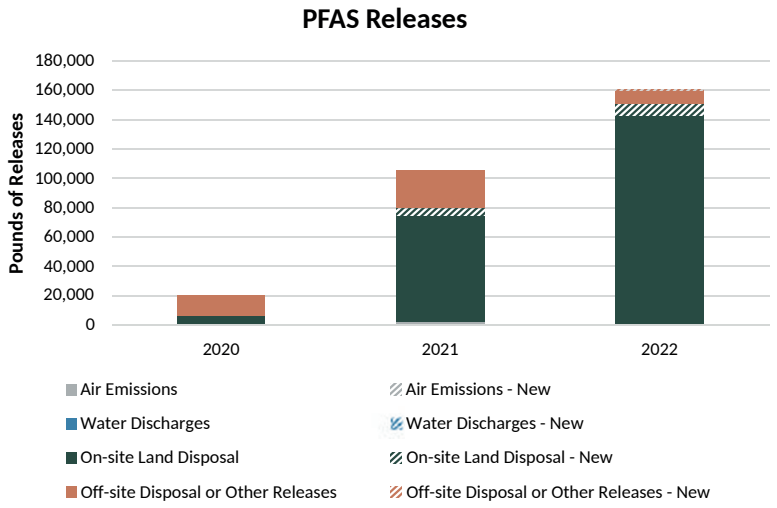


Figure 1: PFAS releases by environmental medium. Source: US EPA (2024e)

in 33 out of 35 textile products tested globally, but concentrations varied widely, from 5.6 to 110,000 mg/kg. Only two samples contained concentrations above 1,000 mg/kg, suggesting their likely use as plasticizers in those specific plastisol formulations. In the remaining samples, lower concentrations may indicate contamination from other substances used in plastisol formulations, including inks, pigments, alternative plasticizers, or shared manufacturing environments (Brigden et al., 2013). Therefore, the evidence points less to a uniform industry-wide dependence on phthalates than to a more complex pattern of intentional use, incidental contamination, and weak chemical control across textile supply chains.

Within the supply chain, **lead** comes in during the dye and pigment stage in manufacturing. While some of the lead binds to the fibers to impart color during the dyeing process, an important fraction of it remains with either the wastewater or solid waste; if not properly treated, this can accumulate in soil and water bodies, leading to chronic environmental contamination. The presence of lead in textile dyeing and pigment applications is less a functional requirement than a risk introduced through the sector's chemical choices. This makes the issue primarily one of selection and substitution, rather than an inherent property of textile processes.

Mercury enters via formulation into some dyes and preservatives, acting as an antimicrobial agent to treat pigments (Velusamy et al., 2021). However, the volatile nature of mercury usually results in releases during the production process, especially where processes are not contained. Mercury leaves the supply chain either through air emissions, wastewater containing soluble mercury compounds, or as residue in discarded textiles (Al-Tohamy et al., 2022; Kessler, 2013).

To address the risks posed by these and other hazardous chemicals in textiles, the industry requires a multi-pronged approach. First, safe design and substitution through green chemistry and safer inputs in dyes, coatings, and finishing agents should be prioritized to mitigate the environmental impacts that undermine ecosystems on a systemic scale, threatening biodiversity; as well as the health impacts that remain as an immediate focus for policy and industrial action. This upstream approach is critical as it prevents hazardous chemicals from entering circulation, so that textiles can later be reused and recycled safely. Coherent cross-border regulation and enforcement are equally critical, aided by tools like ecolabels, disclosure schemes, and other traceability

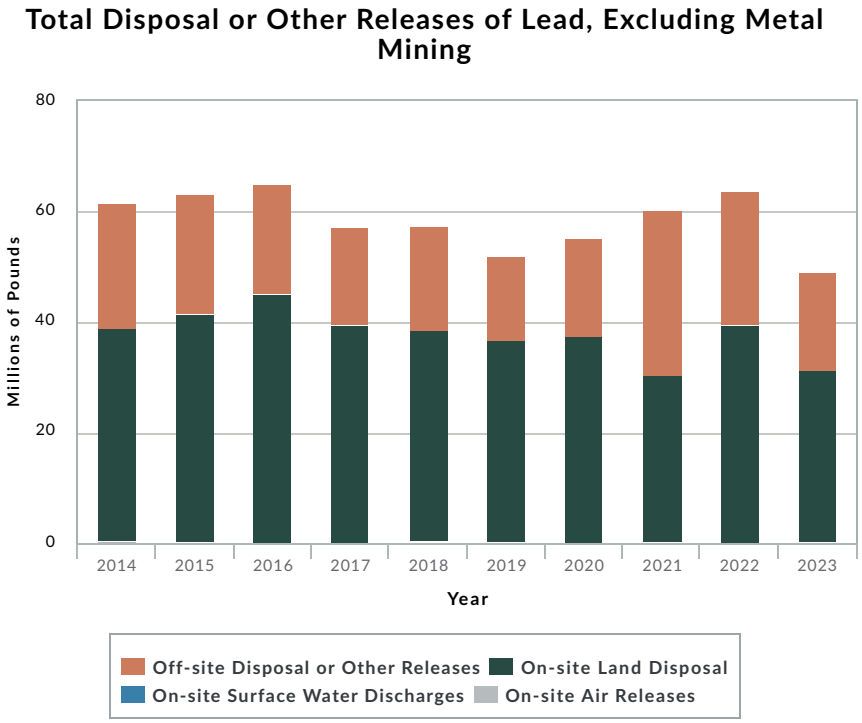


Figure 2: Total Disposal or Other Releases of Lead, Excluding Metal Mining. Source: US EPA (2024c)

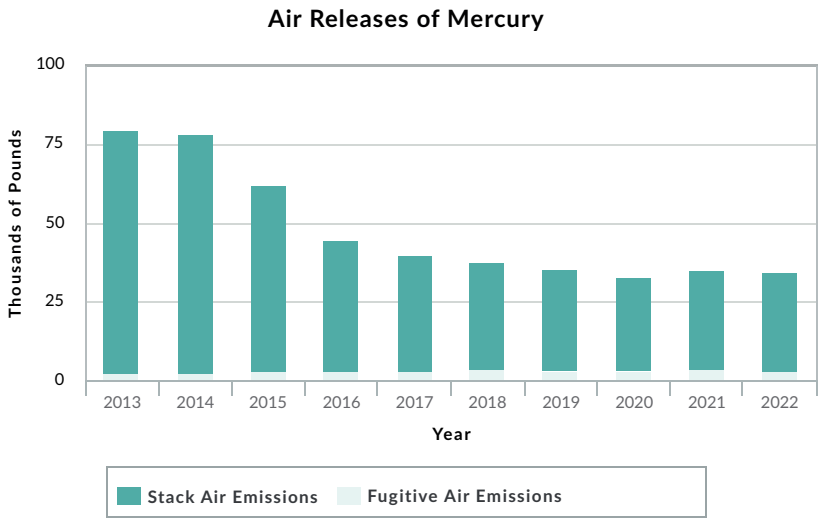


Figure 3: Air Releases of Mercury. Source: US EPA (2024d)

mechanisms to ensure alignment between trade partners, strengthen regulatory oversight, and enable informed choices by consumers and buyers. Finally, overarching financial incentives and green investment mechanisms remain essential to overcome cost barriers of safer textile chemistries, supporting the development and scaling of alternatives such as bio-based dyes and pigments, enzymatic or oxygen-based bleaching agents, fluorine-free finishing treatments, and phthalate-free coatings, to ensure impactful and long-lasting interventions.

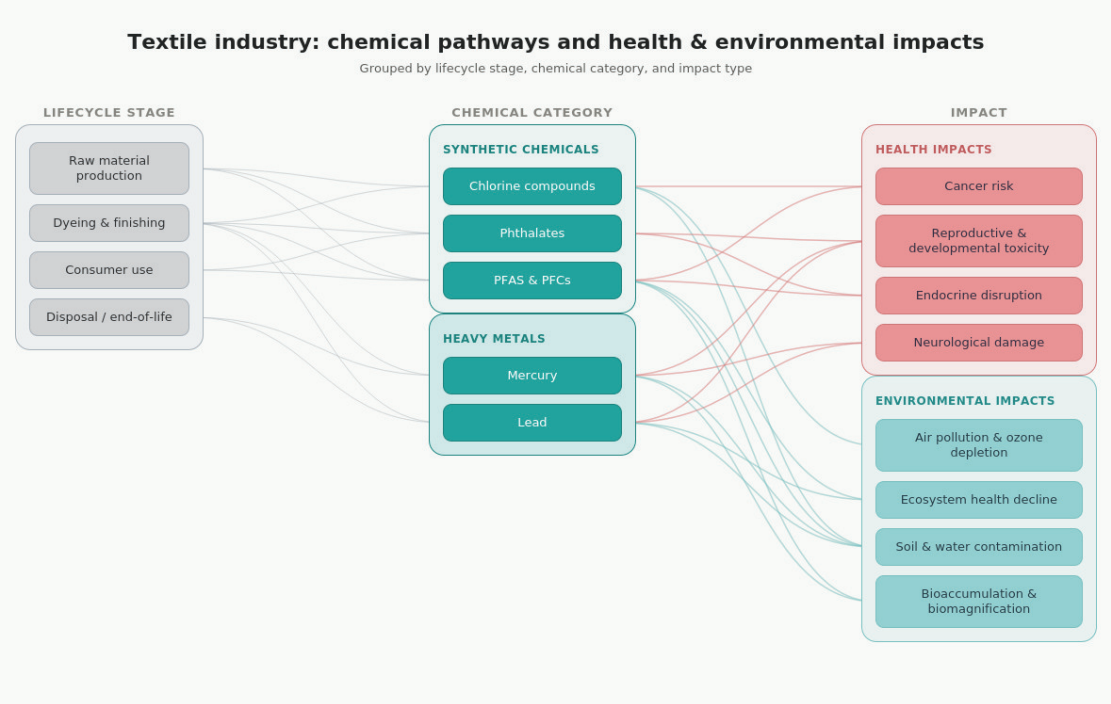


Figure 4: Chemical Pathways and Health/Environmental Impacts in the Textile Industry

2.3.2 Chemicals in the Plastic Industry

Just as textiles demonstrate how hazardous substances permeate products in constant contact with consumers, plastics represent another everyday-use sector where these challenges become especially visible and pressing. The plastic industry depends heavily on chemical additives that not only enhance the properties of plastic products but also introduce environmental hazards to its value chain. The global plastics production was estimated at approximately 400 million tonnes in 2023, generating around 1,000 to 1,200 million tonnes of CO_2 annually, resulting in a typical emissions intensity of 2.5 to 3.0 tonnes of CO_2 per metric ton of plastics produced (Witte et al., 2025). Moreover, other hazardous chemicals are widely used to make plastic products suitable for different applications, making human exposure to these chemicals virtually unavoidable, with over 40% of plastics produced globally used in food packaging alone (OncoDaily, 2025).

These hazardous chemicals are present throughout the life cycle of plastics, starting from initial production, where they act as catalysts and solvents, to the formulation stage, where they serve as plasticizers, flame retardants, pigments, and antioxidants. While such additives make plastics suitable for a wide range of applications (from packaging and electronics to construction), they also raise major concerns regarding environmental sustainability and human health. Plastic pollution has been identified as exceeding safe planetary boundaries, with research showing that plastic pollution exacerbates the impacts of all nine planetary boundaries, including climate change, ocean acidification, and biodiversity loss (Villarrubia-Gómez et al., 2024). Along with this pollution, unwanted release of other hazardous chemicals used to enhance the product properties may occur through processes like leaching or degradation. These semi-degraded plastics function as vectors for smaller chemicals, increasing their availability, particularly hazardous chemicals with known negative biological or environmental effects like phthalates, PFAS, heavy metals, and bisphenol A (Teuten et al., 2009). The finding that plastic pollution exacerbates all nine planetary boundaries simultaneously reveals it as a systemic destabilizer rather than a sectoral environmental

problem, functioning as a connecting threat that amplifies disparate ecological crises. This cross-boundary impact profile is particularly dangerous because it means addressing plastics cannot be siloed within waste management or marine protection.

Phthalates are used to make plastics more flexible and to reduce brittleness, particularly in consumer goods, medical devices, and building materials. They act by embedding among the polymer chains, reducing interactions between these chains enabling them to move more freely, thus providing flexibility (SpecialChem, 2024). They are especially prevalent in polyvinyl chloride (PVC), where they account for up to 60% of the material's weight (Yan et al., 2021). In the supply chain, phthalates are added during the manufacturing phase as additives; during the use phase, they remain embedded in the polymer matrix but are not chemically bound. Because they are only physically mixed in rather than permanently chemically bonded, phthalates can gradually leach out, especially under heat, ultraviolet (UV) exposure, or mechanical abrasion. They can be found in processed foods, high-fat dairy products, and meat, as well as personal care products like shampoos, lotions, makeup, and perfume (Nebraska Medicine, 2022; PEHSU, n.d.; Wang & Qian, 2021).

PFAS are another important group of chemicals frequently used in plastics. Thanks to their hydrophobic and oleophobic properties (water-repelling and oil-repelling, respectively), they are commonly applied as coatings or additives in food packaging, nonstick cookware, and water-resistant clothing. PFAS provide durability, stain resistance, and protection against degradation. They can be transported into the environment through microplastics, further spreading pollution. During disposal, PFAS can be released through landfill leachate, wastewater, or incineration. Even during use, small amounts may migrate into food or water. In ecosystems, their spread through microplastics causes developmental abnormalities and higher mortality rates for both terrestrial and aquatic organisms (UNEP, 2023a). The mobilization of PFAS via microplastics can create a synergistic pollution dynamic where physical and chemical contamination amplify each other. Microplastic-associated adsorption creates a concentrated interfacial reservoir of PFAS, effectively enhancing the bioavailability and translocation of these compounds into organisms and tissues that generally exclude dissolved-phase contaminants. This coupling means neither can be addressed sufficiently in isolation as the physical particle pollution provides the delivery mechanism that makes the chemical pollution more bioavailable and toxic (Wang et al., 2025; Isukuru et al., 2026). And so, as plastic waste fragments into smaller particles, it may become more dangerous through enhanced chemical delivery, inverting the traditional pollution assumption that dispersion reduces risk.

In plastics manufacturing, **heavy metals** such as **lead**, **cadmium**, and **chromium** are often used as stabilizers, catalysts, or pigments to enhance durability, heat resistance, and coloration. Despite regulatory measures to phase them out, these metals continue to circulate in recycled plastics and some industrial applications, sustaining risks to human health and the environment. Throughout the plastic lifecycle, heavy metals can be released into the environment via production emissions, wastewater discharge, product degradation, and improper disposal. Incineration and recycling processes can also re-emit them into air, soil, and water. Because heavy metals are elements, they cannot be broken down, although they can change chemical form, meaning their toxicity persists and accumulates over time (Turner & Filella, 2021).

Another widely used chemical in the plastic sector is **BPA**. Polycarbonate plastics are produced through polymerization, a chemical reaction that links small molecules (monomers) into long chains (polymers), with BPA serving as the primary monomer. Under heat or acidic conditions, BPA can leach from plastics into food and beverages during use, and later be released at end-of-life through landfill leachate, incineration, or improper disposal, contaminating wastewater and freshwater ecosystems and posing significant environmental and health risks (Ighalo et al., 2024; Morin et al., 2015). To address the persistent risks associated with hazardous chemicals in plastics, the sector must prioritize green chemistry: substitution and innovation in materials chemistry. Replacing hazardous additives such as phthalates, PFAS, BPA, and heavy metal stabilizers with safer alternatives is essential, with bio-based plasticizers, non-fluorinated repellents, and less hazardous catalysts already emerging as viable options. At the same time, coherent international regulation is necessary to phase out the most harmful substances and harmonize standards across borders, ensuring that recycling streams and secondary materials are not contaminated by legacy chemicals. Tools such as ecolabels, disclosure requirements, and digital product passports could increase transparency and enable both regulators and consumers to make informed choices. Finally, green investment mechanisms and targeted financial incentives are required to accelerate the transition, supporting innovation of safer polymers, advanced recycling technologies that minimize hazardous outputs, and large-scale deployment of alternatives. Without such systemic measures, hazardous chemicals will continue to undermine both the circular economy and public health (OECD, 2018; UNEP, 2023a).

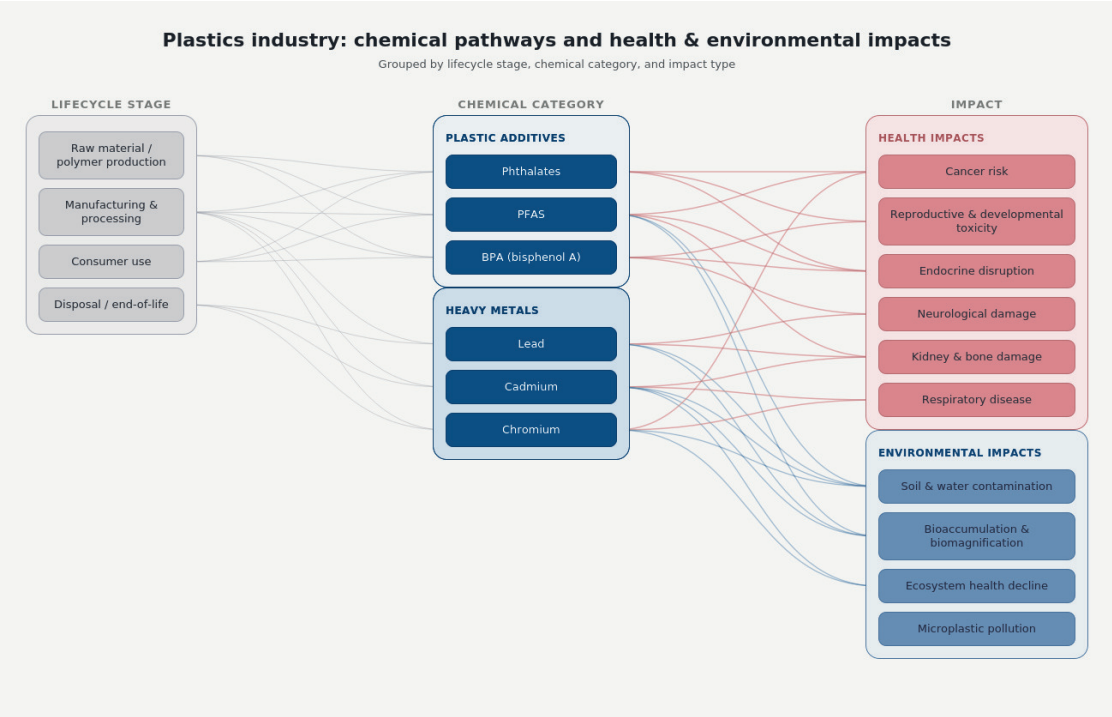


Figure 5: Chemical Pathways and Health/Environmental Impacts in the Plastics Industry

The tension between circular economy ambitions and chemical safety reveals a deeper contradiction in sustainable development discourse: the drive to extend material lifecycles through recycling

assumes materials are fundamentally safe to perpetuate, yet plastics are precisely not such materials; they are toxic composite systems whose extended circulation prolongs harm. This creates an unresolved strategic dilemma where waste reduction goals conflict with exposure reduction imperatives, forcing policymakers to choose between landfilling hazardous plastics (eliminating circulation but concentrating contamination) or recycling them (distributing contamination but maintaining circulation). The way forward likely requires abandoning the premise that current plastic formulations merit circularity, instead treating the existing stock as legacy waste requiring phase-out while building circular systems exclusively around inherently safe materials designed through green chemistry, a far more radical transformation than current recycling-focused circularity frameworks acknowledge.

2.3.3 Chemicals in the Construction Industry

Unlike plastics and textiles, which are mostly embedded in items directly handled by consumers, other sectors, like construction, may embody hidden chemical risks that shape the safety and sustainability of our built environment. The construction sector represents one of the world's largest industrial ecosystems, valued at approximately US$11.39 trillion in 2024 and projected to reach US$16.11 trillion by 2030 (NMSC, 2025). The industry employs an estimated 174 million people globally, making it the world's second-largest employer (Talk.Build, n.d.), and contributes roughly 13% to global GDP (StoneNews, 2025). This scale underscores construction's pivotal role in infrastructure development, housing, and economic growth worldwide. However, its environmental footprint is equally substantial. Buildings and construction are responsible for approximately 39-40% of global energy-related greenhouse gas emissions, with 28% from operational emissions and 11% from materials and construction (World Green Building Council, 2019; ABC News, 2024). Global construction and demolition waste reaches approximately 2.2 billion tonnes annually, accounting for more than one-third of all global solid waste generation (Slowey, 2018). The dominance of operational emissions over embodied emissions in current accounting has historically misdirected efficiency efforts toward building use-phase rather than material selection, inadvertently incentivizing energy-efficient buildings constructed with carbon-intensive, chemically hazardous materials. This is a regulatory blind spot that optimizes for climate while ignoring toxicity.

The construction sector also generates persistent chemical pollution through building materials as they are designed to last for several decades. This means that hazardous chemicals incorporated during construction remain active and bioavailable throughout their entire life cycle (University of Michigan, 2021). These exposures affect not only building occupants but also manufacturing workers, construction personnel, and surrounding communities, extending from material production through renovation and end-of-life disposal (Closkey, 2023).

Polychlorinated biphenyls (PCBs) were once widely used in industrial and construction materials, including electrical equipment, paints, and adhesives. PCBs were banned in the United States in 1979 due to their toxicity and persistence, and their production and new uses are now prohibited for the Parties to the Stockholm Convention on Persistent Organic Pollutants (2001) (Secretariat of the Stockholm Convention, n.d.). Despite this ban, PCBs remain in older buildings, particularly in caulking and sealants applied from the 1950s to the 1970s, as well as in legacy electrical equipment, posing ongoing risks to human health and the environment (US EPA, 2016a). When

such buildings are renovated or demolished, new hazardous waste streams are generated. If not handled with specialized safety protocols, PCB-containing debris can spread contamination to air, soil, and water, resulting in long-lasting ecological damage.

Because of their fire-resistant and insulating properties, **asbestos** fibers were historically used in roofing, drywall, floor tiles, and coatings. Although several types of asbestos have been banned or severely restricted in most countries, large quantities remain embedded in existing infrastructure. Nevertheless, production and use continue for specific industrial and construction applications, particularly in countries such as India, China, Russia, Kazakhstan, and Brazil (Chen et al., 2020; Frank & van Zandwijk, 2024; World Bank, 2023). Still, the greatest concern is legacy asbestos: materials installed in older buildings. While intact asbestos is relatively inert, unsafe renovation or demolition can release microscopic fibers into the air, where they persist for long periods and pose serious health hazards. Removing asbestos safely requires costly, specialized abatement procedures.

VOCs are commonly used in paints, varnishes, adhesives, solvents, refrigerants, and cleaning agents (US EPA, 2025c). VOCs are released in gaseous form from both solids and liquids, and concentrations indoors are often much higher than outdoors (Mangotra & Singh, 2024). Construction and furnishing products are among the most VOC-intensive, including fiberboards, particleboards, and surface finishes such as paints, lacquers, and varnishes. Because these products are also widely used in furniture, they greatly increase VOC-emitting surfaces inside homes and workplaces.

Phthalates represent another major group of hazardous chemicals in construction, primarily used as plasticizers to make polyvinyl chloride (PVC) flexible in flooring, sealants, caulks, carpet backing, adhesives, insulation, wiring, and wall coverings (Wang & Qian, 2021). Studies have found associations between phthalates in indoor dust from PVC flooring and respiratory problems including asthma and wheezing among children (Bornehag et al., 2005). The US EPA has found health risks to workers from inhalation exposure to common phthalates in construction materials, adhesives, sealants, and paints (Erickson, 2025).

Heavy metals, such as lead and mercury, are also one of the most significant groups of hazardous substances in construction. Due to their widespread use, they represent a long-term concern throughout the building life cycle. **Lead**, for instance, is a hazardous heavy metal historically used in paints, water pipes, and window putty in older buildings. Over time, lead-based paints and coatings deteriorate, producing hazardous dust that can contaminate indoor environments and expose occupants. When buildings are renovated or demolished, these lead particles are further released, and debris disposed of in landfills can leach lead into soil and groundwater (WHO, 2024a). **Mercury**, another heavy metal of concern, enters the construction supply chain primarily through fluorescent lamps, electrical switches, and certain coatings. It can be released during the use and maintenance of this lighting and electrical equipment, and it may also escape as coating erodes over time. Demolition and disposal create additional risks: mercury-containing debris in landfills can contaminate soil and water, while loss of containment during handling or incineration can release mercury into the atmosphere, where it poses severe ecological and health hazards.

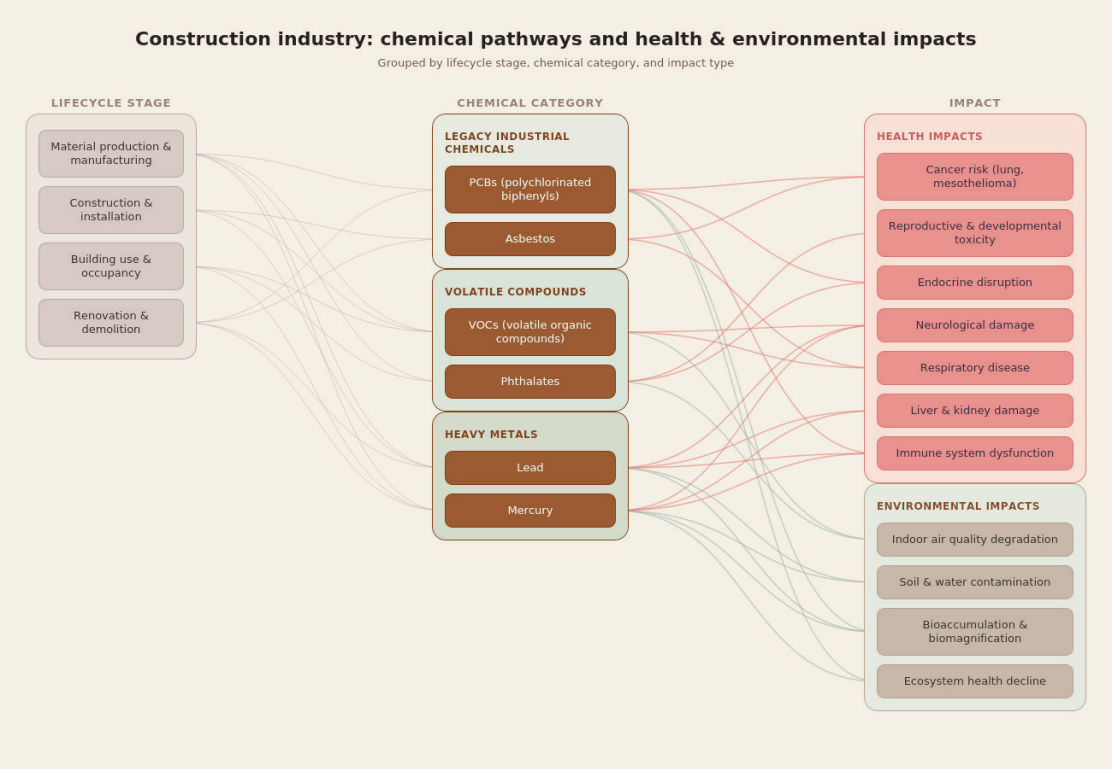


Figure 6: Chemical Pathways and Health/Environmental Impacts in the Construction Industry

To reduce chemical risks in construction, a comprehensive strategy of green chemistry substitution, safer design, and controlled phase-out of legacy materials is urgently needed. Formaldehyde usage (a VOC and Group 1 carcinogen commonly present in particleboard and fiberboard resins) should be progressively eliminated where feasible, and replaced with low-emission or non-toxic adhesives and binders (Huang et al., 2022). For this, challenges regarding formaldehyde-free resins must be addressed, particularly those related to performance limitations stemming from low reactivity and resource availability, which ultimately hinder their economic viability; as well as boosting regulatory drivers and toxicological investigations on alternative systems that incentivize phase-out and facilitate adoption (Chrobak et al., 2022; Gonçalves et al., 2021). Similarly, phasing out mercury in lighting systems, safe abatement of legacy asbestos, and strict protocols for handling PCB-containing materials during demolition are critical steps to limit ongoing contamination. However, implementation remains constrained by high remediation costs, technical limitations, and uneven regulatory capacity across regions. Effective policy action will also require harmonized international standards to manage hazardous substances in building products, ensuring that materials circulate safely in both domestic and global markets. At the same time, market-based incentives and green financing instruments can play a transformative role, encouraging innovation in low-emission construction products, formaldehyde-free engineered wood, and safer insulation and finishing materials. Given that people spend the majority of their time indoors, prioritizing indoor air quality through stricter VOC regulations and certification schemes (such as green building labels) is central to safeguarding health while advancing the sustainability of the built environment.

2.3.4 Chemicals in the Agriculture Industry

Just as construction embeds chemical risks into long-lived materials, agriculture introduces them into the very systems sustaining life. Both sectors represent pillars of society, whose chemical dependencies carry deep implications for sustainability and human well-being. For the last five decades, agriculture has been reshaped by the dual pressures of accelerating climate change and unprecedented population growth, forcing production systems to adapt under increasingly unstable conditions (Mendelsohn, 2007). In response, farming has become progressively industrialized, aimed at maximizing yield and efficiency per hectare, transforming agriculture into a highly managed system resembling industrial production extending beyond natural ecological boundaries. While agrochemical inputs have enabled higher outputs and buffered agriculture against climate volatility, they have also introduced significant risks across ecosystems and human health. The industrialization of agriculture under climate stress has created a chemical dependency trap: as climatic instability undermines traditional farming resilience, producers compensate with intensified chemical inputs that temporarily stabilize yields while degrading the ecological foundations that long-term food security requires. This generates a positive feedback loop where environmental degradation from chemical overuse necessitates yet more chemical intervention, progressively narrowing the viable pathway back to sustainable production systems. Fertilizers are a fundamental pillar of modern agriculture, providing essential nutrients that sustain crop growth and global food production (Alnaass et al., 2021). Fertilizers are generally classified according to their chemical composition, with the two broad categories being natural and synthetic fertilizers. Among the different types of synthetic fertilizers, **nitrogen- and phosphorus-based fertilizers** dominate worldwide use. Nitrogen fertilizers are derived mainly from ammonia, produced through the Haber-Bosch process, in which atmospheric nitrogen is reacted with hydrogen to yield ammonia. Nitrogen-based fertilizers can be credited with feeding nearly half the planet's population (Blois, 2023). Phosphorus-based fertilizers, in contrast, rely on mined phosphate rock, a finite resource, an estimated 93% of whose global demand in 2023 went to food production (Scholz et al., 2025). Once manufactured, fertilizers enter the agricultural supply chain as raw materials that are packaged, distributed, and applied directly to soil, where they release nutrients for plant uptake. While effective for boosting yields and securing food supply, their risks emerge from over-application and poor management. The main environmental concern associated with fertilizers, emphasized here due to its broad and cascading effects, is the disproportionate nutrient input leading to eutrophication. This is responsible for algal and bacterial blooms and oxygen depletion (Akinnawo, 2023). Human health impacts are evident for vulnerable groups like agricultural workers or neighboring communities (Tagkas et al., 2024). **Pesticides** are a broad group of chemical substances used in agriculture to control unwanted organisms including insects, weeds, and fungi; thus yielding different specific products like insecticides, herbicides, and fungicides (US EPA, 2013d). They function by targeting specific biological processes or systems in pests, inhibiting growth, reproduction, or survival (Zhou et al., 2024a). A major ecological concern regarding pesticides is the loss of non-target biodiversity like pollinators and microbial communities (Pathak et al., 2022). Another pressing issue is their widespread over-application, which can lead to species, such as weeds, bacteria, or insects, developing resistance and demanding higher doses, thus increasing their risks (Gaines et al., 2020).

Beyond synthetic fertilizers and pesticides, another long-recognized source of contamination from the agricultural sector is **heavy metals**. They are usually introduced through phosphate-based fertilizers, irrigation water, pesticide formulations, and possibly livestock manure. Additionally, their long-lasting qualities granted by their non-degradability can exacerbate their impacts, and their strong chemical bonds with soil particles make their removal or neutralization more difficult (Rashid et al., 2023). **Cadmium** is naturally present in phosphorite rocks, which are used as the raw material for phosphate fertilizers, with concentrations varying depending on the specific type of rock. Then cadmium, in particular cases, can be assimilated by plants, thus entering the food chain affecting ecosystems and ultimately humans consuming contaminated products, accounting for 90% of cadmium intake in the non-smoking population, leading to bone demineralization and kidney diseases (Suciu et al., 2022). Furthermore, heavy metal content can reduce soil fertility and overall health, for example by changing soil pH, possibly increasing solubility and mobility of other hazardous chemicals like lead or zinc (Adamczyk-Szabela and Wolf, 2022).

To address the risks posed by fertilizers, pesticides, and heavy metals in agriculture, the sector requires a comprehensive strategy of substitution, safer management, and stricter oversight. Excessive reliance on synthetic inputs has contributed to soil degradation, biodiversity loss, and contamination of water systems, making the promotion of biofertilizers, organic amendments, integrated pest management, and low-toxicity biopesticides a priority (Boonupara et al., 2023). Biofertilizers and biopesticides are green chemistry alternatives, discussed further in Chapter 5. However, adoption remains constrained by uneven access to technology, geography-specific conditions, higher short-term costs, and the need to maintain productivity in highly competitive global markets (Hancock, 2025; Zhou et al., 2024b). At the same time, coherent international regulation and harmonized residue standards are essential to safeguard food safety, prevent the buildup of hazardous substances, and address divergent regulatory responses to widely used products such as glyphosate. Transparency mechanisms including certification schemes, ecolabels, and traceability systems can further strengthen accountability across supply chains, enabling consumers and retailers to make informed choices while rewarding sustainable producers. Finally, green investment mechanisms and targeted financial incentives remain vital to overcome barriers to adoption, ensuring farmers, particularly in low- and middle-income countries, have the means to transition toward safer practices, thereby protecting ecosystems, human health, and long-term food security. The acknowledgment that safer alternatives face "higher short-term costs" and pressure from "highly competitive global markets" exposes the fundamental incompatibility between chemical-intensive industrial agriculture and sustainable food systems under current trade regimes. Global commodity markets reward lowest-cost production regardless of externalized environmental and health burdens, meaning farmers adopting safer but more expensive practices face competitive disadvantage and potential bankruptcy, while those externalizing costs through chemical overuse capture market share. This dynamic, in which sustainability becomes economically irrational for individual producers, reveals that meaningful agricultural transition requires not just technical alternatives but fundamental restructuring of food trade rules to internalize environmental costs or protect sustainable producers from predatory undercutting by chemical-intensive competitors.

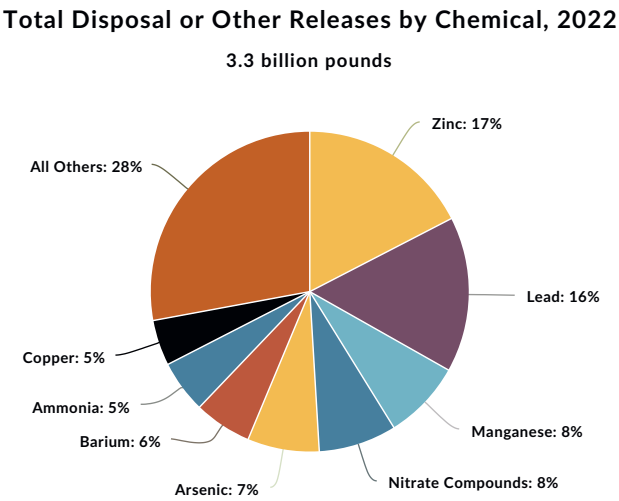


Figure 7: Total Disposal or Other Releases by Chemical, 2022 (in the United States). Source: US EPA (2024g)

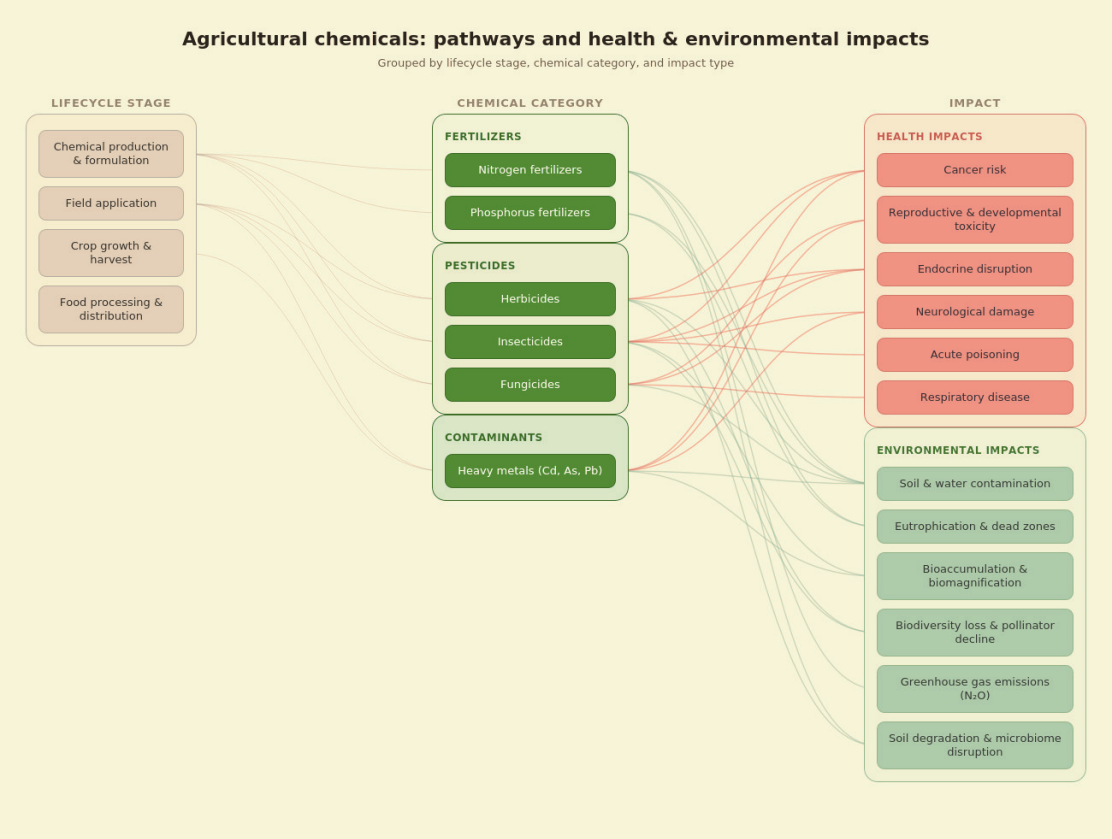


Figure 8: Chemical Pathways and Health/Environmental Impacts in the Agriculture Industry

2.4 Exposure Groups

Exposure to hazardous substances occurs through multiple pathways, including direct contact in the workplace, ingestion of contaminated food and water, or inhalation of polluted air. To understand these risks, it is essential to consider occupational exposure, consumer exposure, community-level impacts, and the particular vulnerabilities of certain population groups.

2.4.1 Occupational Exposure

Occupational exposure represents the most direct pathway through which humans encounter hazardous chemicals. Workers in chemical-intensive industries face severe health risks from prolonged contact with hazardous substances. Exposure occurs through multiple pathways (inhalation, absorption, ingestion, and bioaccumulation in tissues) creating cumulative, long-term health consequences that underscore the urgent need for stronger occupational safety regulations. The cumulative nature of occupational exposure creates a time-based inequality where employment duration determines toxic burden, with health costs manifesting years after employers have extracted productive value, a temporal displacement that weakens employer liability and shifts long-term healthcare costs onto public systems (Anderson & Meade, 2014). **Textile workers** face significant exposure to heavy metals, including lead and mercury used in dyes, along with chlorine-based bleaches and phthalates during processing. Such exposure has been linked to reproductive and developmental problems (Anderson & Meade, 2014). Mercury, in particular, can cause neurobehavioral effects including memory loss, depression, behavioral changes, and sleep disturbances, with some effects persisting decades after exposure ends (Álvarez-Solorza et al., 2022). A study of women working in mercury-exposed environments found that 32.5% developed occupational overuse syndrome, compared to 6.7% of controls, with all affected individuals having worked more than five years in mercury-exposed environments (Wu et al., 2024). Heavy metals in textiles, including cadmium, cobalt, copper, nickel, hexavalent chromium (a highly toxic form of chromium often used in dyes and anti-corrosive finishes), lead, and mercury, can act as "metalloestrogens". This means that they bind to estrogen receptors and disrupt normal endocrine function by altering gene expression, hormone signaling, and cellular growth processes (effects similar to those of synthetic endocrine-disrupting chemicals), which can ultimately contribute to reproductive disorders and hormone-related cancers (Fucic et al., 2018).

In **plastics manufacturing**, workers are exposed to BPA and phthalates. A study revealed that up to 98% of BPA exposure is attributable to plastic-related uses, contributing significantly to occupational health risks (Trasande et al., 2024). Such occupational exposure has been linked to higher incidences of metabolic, reproductive, and degenerative diseases, as well as certain cancers. The high percentage of BPA exposure that stems from plastic-related uses creates a sector-specific occupational disease profile that cannot be addressed by solely targeting environmental risks.

Construction workers encounter a broad spectrum of chemical hazards. Asbestos remains a primary concern, with heavy exposure strongly associated with increased lung cancer risk (Järvholm & Aström, 2014). Painters exposed to benzene, ethylbenzene, toluene, and xylene show declining pulmonary function correlated with years of exposure (Nishida & Yatera, 2022). Heavy metals including lead, cadmium, and chromium accumulate in the blood and organs of construction workers, with welders often exhibiting cadmium levels above the World Health Organization (WHO)-recommended limits (Dehghani et al., 2021).

Agricultural workers are regularly exposed to pesticides, which can have severe neurological and carcinogenic effects. Systematic reviews show strong evidence linking occupational pesticide exposure to asthma development, with suggestive evidence for chronic bronchitis and chronic obstructive

pulmonary disease (COPD) (Ye et al., 2013). Organophosphate and carbamate pesticides inhibit cholinesterase (an enzyme essential for nerve function), triggering pro-inflammatory molecules that cause chronic airway inflammation, pulmonary fibrosis (lung scarring), and both obstructive (difficulty exhaling) and restrictive (difficulty expanding lungs) breathing problems. Agricultural workers face eight-fold higher risk of respiratory distress compared to the general population, with seasonal spikes during spring pesticide applications (Beyond Pesticides, 2020). Long-term occupational exposure also increases reproductive risks, including spontaneous abortions, fetal death, and elevated risks of non-Hodgkin lymphoma, childhood cancers, and Parkinson's disease (Jaga & Dharmani, 2003; National Institute of Environmental Health Sciences, 2023). The issue is also geographic, as agricultural workers in developing countries face severe pesticide exposure due to inadequate safety measures and weak regulatory enforcement, with studies estimating around 220,000 annual deaths in low- and middle-income countries (de Assis et al., 2021).

2.4.2 Consumer Exposure

Consumer exposure to hazardous chemicals from supply chains occurs through daily contact with contaminated products, from clothing and packaging to construction materials and food. These exposures create chronic health risks that arise through skin contact, inhalation, and ingestion, often without the consumer's awareness.

Clothing and textiles are one of the most common exposure pathways. Chemicals such as phthalates, PFAS, and heavy metals used in dyes and finishes can be absorbed directly through the skin (Ragnarsdóttir et al., 2024). Sweat amplifies this process; under humid or high-temperature conditions, absorption can increase more than a thousandfold compared to dry contact conditions (Li et al., 2025). Children's clothing is of particular concern, as longer skin contact and greater sensitivity make them more vulnerable to these chemicals. Similarly to occupational exposure, heavy metals used in textile dyes pose chronic health risks through
dermal contact, by acting as metalloestrogens, which can interfere with hormone regulation (Fucic et al., 2018). Phthalates used in textile printing readily transfer from clothing to skin, enabling continuous dermal exposure during wear, particularly for children and sensitive individuals.
Plastic food packaging and containers represent another major source of chemical exposure. BPA, widely used in polycarbonate plastics, leaches from food and beverage containers into their contents, especially when containers are heated or washed with strong detergents (Jeon, 2022). Even products labeled "BPA-free" often contain substitute chemicals such as bisphenol F (BPF) and bisphenol S (BPS), which behave alike because of their structural similarities and can also migrate into food. Large-scale analyses of plastic packaging across multiple countries confirm that most materials contain mixtures of endocrine- and metabolism-disrupting compounds (Stevens et al., 2024; Moon, 2019). Migration occurs mainly through diffusion and volatilization, with temperature, food acidity, storage time, and packaging characteristics all affecting the migration rates (Khokhar & Pawar, 2025). Heavy metals can also migrate from packaging, especially in acidic foods or old containers. Even glass or paper-based packaging is not entirely safe; certain glass coatings and printed paper packaging can release trace levels of metals or solvents into food (Khokhar & Pawar, 2025; Kourkopoulos et al., 2025).

Indoor air pollution from **construction materials** is another chronic, though less visible, risk. Recent studies estimate a prevented economic burden of approximately 4 billion USD (based on

US EPA's value of statistical life) stemming from reductions in airborne lead in the US (Clay et al., 2025). Many building materials continuously release VOCs from paints, solvents, adhesives, lacquers, and sealants which contribute to indoor air pollution, making inhalation the dominant exposure pathway for building occupants. For example, formaldehyde from particleboard furniture can fully emit into indoor air over time, with most emissions occurring within the first two months after installation (Huang et al., 2019). Modern synthetic materials including composite wood, PVC flooring, nylon carpets, and polyurethane foams intensify indoor contamination through continuous outgassing of volatile compounds. These emissions contribute to declining indoor environmental quality and prolonged occupant exposure (Tran et al., 2020). Asbestos fibers in older buildings remain a major concern, as aging insulation materials can release friable asbestos into the air (ChemCare, 2024). Lead contamination also persists in older construction through paints and water pipes, with lead-based paint still constituting a significant source of chronic exposure in residential environments (Closkey, 2023).

Chemical residues in food represent one of the most direct and widespread routes of exposure. Pesticide residues on produce are widespread; human biomonitoring in five European countries found residues of two or more pesticides in 84% of samples from children and adults (Lazarević-Pašti et al., 2025). Residues have also been found in staple foods elsewhere, including beans, rice, and meat in Brazil (da Silva et al., 2024). Ultra-processed foods (including ketchup, processed potatoes, soy sauce, and cream) tend to concentrate these residues because they often combine multiple treated ingredients. Nitrate contamination from agricultural fertilizer use also poses a serious threat, particularly through drinking water. Long-term exposure to nitrate-contaminated water has been associated with preterm birth, neural tube defects, and certain cancers, including colorectal and ovarian cancer (Ammons et al., 2025; Lin et al., 2023; Ward et al., 2018). Moreover, heavy metals from contaminated agricultural soils migrate into the food supply through plant uptake and bioaccumulation. Consumption of mercury-contaminated seafood has been linked to damage to the nervous system, especially the developing brain (Marnane, 2018; UKHSA, 2025; WHO, 2024b). The universality of multi-pesticide residues means contamination has become the baseline state of food supply rather than an avoidable exception, eliminating consumer choice as a viable exposure reduction strategy, necessitating systemic agricultural reform.

2.4.3 Community and Public Health

The impacts of hazardous chemicals on **communities and the public** extend far beyond occupational or consumer exposure. Both rural and urban residents face chronic exposure through air, water, and soil contamination, with the heaviest burdens often falling on low-income and minority communities.

In **rural areas**, pesticide drift (the airborne movement of pesticide particles or vapors from treated fields to nearby areas) and fertilizer runoff (when rain or irrigation washes excess nitrates and phosphates from farmland into waterways, polluting drinking water and fueling algal blooms) are major sources of chemical exposure. Agricultural activities using hazardous chemicals are deteriorating water quality and increasing waterborne diseases such as dysentery, diarrhea, and jaundice (Bashir et al., 2020). Between 1998 and 2006, researchers identified 2,945 cases of acute illness linked to pesticide drift across 11 US states. Rural residents living in agriculture-intensive

regions faced 69 times higher risk of pesticide poisoning from drift exposure compared to other regions (Lee et al., 2011). The annual incidence of pesticide drift-related illness ranged from 1.39 to 5.32 per million people, with the highest rates recorded in five California counties (42.2 cases per million person-years). Pesticide drift affects both workers and nearby residents; about half of all reported cases occurred at work (47%), while the rest (53%) involved non-occupational exposure. Children under 15 made up 14% of all cases and were the most vulnerable group among non-occupational exposures. Studies in developing countries confirm that rural communities are regularly exposed to pesticides through spray drift or residue buildup, with farmers, field workers, and their families frequently reporting acute poisoning during or shortly after spraying (Tudi et al., 2022; Lee et al., 2011). In Brazil, pesticide drift has repeatedly affected schools, Indigenous territories, and Afro-Brazilian communities. Residents commonly report symptoms such as nausea, headaches, dizziness, and vomiting after nearby pesticide applications, often experiencing these symptoms repeatedly during plantation spraying seasons (Pearshouse & Bieber, 2018). Indigenous agricultural communities are particularly at risk: in Mexico's Yaqui Valley, women and children show detectable levels of banned pesticides in their blood and breast milk, correlated with higher rates of birth defects, cancer, and neurological disorders (Lopez-Carmen et al., 2022).

Urban populations face a different but equally persistent challenge: exposure to legacy contaminants embedded in old infrastructure. Materials containing VOCs, PCBs, asbestos, and lead continue to emit pollutants decades after installation. PCBs in caulking and sealants are particularly prevalent in multiunit housing and older commercial buildings, leading to sustained low-level exposure for city residents (Diamond et al., 2010). As mentioned earlier, asbestos exposure remains a concern. Measured asbestos concentrations in urban buildings typically range from non-detectable to around 0.2 fibers per milliliter of air (TEM f/mL) (ATSDR, 2001a). For comparison, the US occupational exposure limit is 0.1 f/mL, meaning that upper-range concentrations in aging or damaged buildings can exceed safe limits for prolonged exposure (OSHA, 2019). Meanwhile, as mentioned above, lead and VOCs persist in old buildings, continuing to expose residents through dust and drinking water, creating long-term respiratory and neurological health risks.

Incineration of plastics, textiles, and plastic medical waste releases dioxins, furans, and chlorine compounds, among the most hazardous and persistent pollutants known. These chemicals travel long distances through the air and accumulate in soil, water, and food chains. Important air pollution results from harmful particulates and gases being pumped into the atmosphere by factories, vehicles, open waste burning, pesticides, and commercial and household products. Together with poor management of chemicals and waste, poor air quality significantly affects human health in general. The WHO estimates that every year, diseases linked to air pollution kill around 7 million people (UNEP, 2019). Although it is methodologically difficult to discern the effects of incineration from those of other pollution sources, such as transport, factories, and refineries, waste incineration is consistently associated with several significant health risks (Tait et al., 2020). Research shows that even at low concentrations, dioxins and furans act as potent carcinogens and endocrine disruptors, capable of impairing reproductive, immune, and developmental health (Fayshal, 2024). Their persistence and bioaccumulation make them a long-term hazard for both human and environmental health. Burning textiles adds further complexity, as fabrics often contain chlorine-based polymers like PVC or flame retardants that generate additional hazardous

compounds, along with heavy metals such as chromium, cadmium, and lead (Pinto & Peleg Mizrachi, 2025). VOCs from textile incineration contribute to smog formation and respiratory health impacts. Incineration of plastic medical waste is another major source of dioxins, driven by the widespread use of PVC plastic in medical products like tubing and IV bags (Abahussain et al., 2025). Exposure to these emissions can cause respiratory irritation, coughing, and chest tightness, as well as long-term systemic effects including cancer and immune dysfunction. Moreover, burning chlorine-based disinfectants can produce chlorinated polycyclic aromatic hydrocarbons, compounds even more toxic than their parent chemicals (Parveen et al., 2022). These chemicals are highly resistant to degradation, bioaccumulate in living organisms, and exhibit strong mutagenic and carcinogenic properties, posing serious health risks for populations near incineration sites. Although modern incinerators in the UK and EU now operate under stricter standards (set by the Waste Incineration Directive, now Chapter IV of the Industrial Emissions Directive), systematic reviews still emphasize public concern over cumulative and localized exposures, especially in neighborhoods already burdened by multiple pollution sources (UKHSA, 2025).

2.4.4 Vulnerable Groups

The health impacts of hazardous chemicals disproportionately affect the **most vulnerable groups**. Children, women, and marginalized communities face heightened risks from air, water, soil, and product contamination, with long-term consequences for development, reproduction, and overall well-being.

Children are particularly sensitive to hazardous chemicals, since their organs and systems are still developing, and their behaviors (such as hand-to-mouth activity) can increase exposure. Lead and mercury exposure impairs brain development, resulting in lower IQ, impaired memory, attention deficits, and behavioral issues. Even low-level lead exposure is linked to a significant decrease in cognitive performance and academic achievement (Grandjean & Landrigan, 2014; ATSDR, 2001b). Mercury exposure, especially from contaminated food or environmental sources, can cause permanent neurological damage, including developmental delays, learning difficulties, and impaired motor skills (Karagas et al., 2012). BPA and phthalates disrupt hormonal balance and interfere with puberty and reproductive development. BPA exposure has been linked to earlier puberty and abnormal breast and prostate development, while phthalates similarly affect fetal and adolescent growth by disturbing hormone signaling and reproductive tract formation (Kasper-Sonnenberg et al., 2017).

Women face elevated health risks from chemicals like PFAS and phthalates, which are linked to reproductive problems, pregnancy complications, and increased breast cancer risk. Phthalate exposure can disrupt ovarian function, alter menstrual cycles, reduce fertility, increase polycystic ovary syndrome (PCOS), lead to poor IVF outcomes, and increase the odds of pregnancy loss or preterm birth (Land et al., 2025). It can also interfere with hormone production, follicle development, and embryo implantation, contributing to subfertility and adverse pregnancy outcomes. Exposure to PFAS compounds can impair reproductive hormone function, leading to reduced fertility, menstrual irregularities, and adverse pregnancy outcomes. Research also links PFAS to increased breast cancer risk and abnormal levels of key pregnancy hormones such as prolactin and human chorionic gonadotropin (Rickard et al., 2022; Cohen et al., 2023).

Marginalized communities (including low-income groups and communities of color) often face higher cumulative chemical exposures because they are more likely to live near industrial sites, hazardous waste facilities, or contaminated water sources. These populations experience higher rates of exposure to lead, mercury, pesticides, PFAS, and other hazardous substances (Mueller et al., 2024). Globally, more than 716 million people living in extreme poverty (under $1.90 per day) are exposed to unsafe air pollution levels, with 57% concentrated in Sub-Saharan Africa, where weak healthcare systems heighten pollution-related mortality (Rentschler & Leonova, 2023). In these regions, industrial pollution disproportionately harms marginalized groups such as migrant workers, women, and children, many of whom work in informal manufacturing sectors with little to no safety protection. Water pollution is a major vector of chemical exposure (Babuji et al., 2023), with PFAS, heavy metals, and pesticides disproportionately affecting low-income and minority communities. Analysis of 7,873 US community water systems across 18 states found that PFAS detection was significantly more likely in systems serving higher proportions of people of color (Liddie et al., 2023). Globally, similar inequalities persist: in Haiti, children in lower-income households have 2.4 times the risk of contracting an enteric disease as those in high-income households, and in India, only 6% of the poorest households have access to treated water compared with 56% of the wealthiest (Adelodun et al., 2021). Indigenous communities face the greatest risks, as extractive industries contaminate their lands with cyanide, mercury, lead, and cadmium, while hazardous pesticides banned in developed countries continue to be exported to and used in their territories (UN Press, 2022).

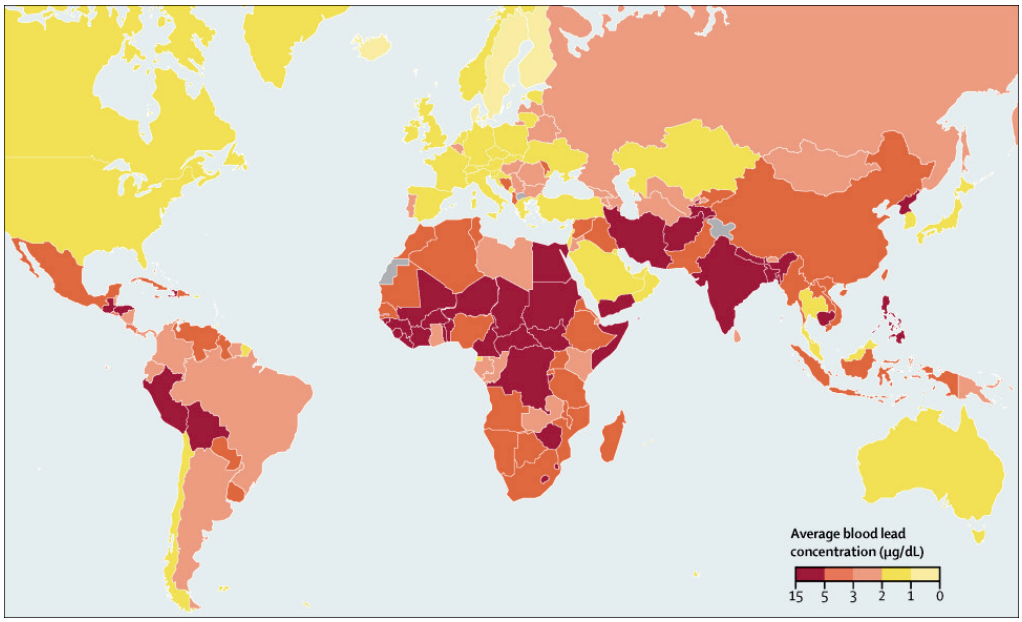


Figure 9: Global distribution of childhood lead exposures in 2019. Source: Fuller et al., 2022

Community water systems that serve larger proportions of Hispanic/Latino and non-Hispanic Black residents are significantly more likely to have detectable levels of multiple PFAS compounds. Each additional industrial plant, airport, or military training site within a community's watershed was linked to sharp rises in PFAS contamination levels; specifically, 10-108% higher concentrations of perfluorooctanoic acid (PFOA) and 20-34% higher levels of perfluorooctane sulfonic acid (PFOS). Waste management sites also contributed heavily to PFAS levels, particularly in regions serving Hispanic/Latino and Black communities (Liddie et al., 2023). The systematic

correlation between racial demographics and contamination levels demonstrates that chemical exposure patterns follow social boundaries rather than natural distribution, with pollution concentrating in communities with less political capacity to resist facility siting, effectively translating social marginalization into differential biological harm. Similar environmental injustices are evident in Europe, where lower socio-economic groups, migrants, and ethnic minorities face disproportionate exposure to air pollution, noise, and extreme temperatures. Poorer households often cluster near busy roads or industrial areas with higher concentrations of particulate matter and nitrogen dioxide (EEA, 2018). Regional hotspots in eastern and southern Europe combine high pollution levels with poverty and social vulnerability, while the elderly, children, and those in poor health are especially affected (EEA, 2018). Marginalized communities therefore not only encounter more sources of exposure (such as industrial emissions, legacy pollutants, and substandard housing) but also have reduced access to healthcare and social support to mitigate these risks.

Among rural water systems in the US, every one-percentage-point increase in the share of residents living below the poverty line corresponded to a 10% higher likelihood of PFAS detection. These populations therefore experience higher rates of chronic disease, reproductive disorders, and developmental delays compared with more advantaged groups. Interestingly, in urban areas, the relationship was weaker or even reversed, possibly reflecting stricter monitoring and better water treatment infrastructure (Johnston & Cushing, 2020).

2.5 Cumulative and Systemic Risks

While hazardous chemicals can have straightforward effects on biodiversity or human health, there are also indirect, cumulative, and systemic risks, arising when multiple chemical exposures, persistent pollutants, and environmental stressors interact, producing effects greater than those of individual substances alone. These compounded risks are unevenly distributed, with marginalized communities and populations in developing countries, often living near chemical-intensive industries, contaminated waterways, or polluted farmlands, bearing the heaviest burdens and facing long-term intergenerational and global inequities. The subsequent ranking process, described in detail in section 3 and executed in section 4, is single-substance by design and can thus not represent the interactions described here. However, the below discussion should not be read as inconsequential to the ranking; it serves to contextualize the findings beyond its methodological limitations, into a world where chemical exposure rarely is single-substance. Understanding this is key for not underestimating the impact potential of the chemicals in the ranking.

2.5.1 Pollution and Persistent Chemical Exposure

Pollution remains one of the most pervasive threats to public health, with chemical contaminants infiltrating air, water, and soil. The combination of multiple pollutants and their **persistence** in the environment creates cumulative and long-lasting risks that extend far beyond direct exposure.

Humans are rarely exposed to a single chemical at a time. Instead, they encounter mixtures, sometimes called **"chemical cocktails"**, containing multiple pesticides, PFAS, phthalates, heavy metals, and other contaminants. According to a comprehensive literature review, synergistic interactions

(where chemicals amplify each other's toxicity) occur in approximately 7% of pesticide mixtures, 3% of metal combinations, and 26% of antifoulant mixtures. Although they are relatively uncommon, when synergistic interactions do occur, the combined effects can be two to ten times stronger than each chemical acting alone (Cedergreen, 2014). Certain pesticides that block nerve enzymes (cholinesterase inhibitors) can enhance toxicity when combined with other chemicals. Similarly, azole fungicides, used in agriculture and antifouling paints, can interfere with how the body breaks down other chemicals, creating synergistic effects. Even when individual chemicals are present at levels below their toxic thresholds, mixtures targeting the same biological systems (like multiple phthalates or PFAS compounds) can add up to cause significant harm (Kortenkamp, 2007). The Maximum Cumulative Ratio (MCR) approach identifies which chemicals drive most of this mixture toxicity by comparing the total risk of a mixture to the largest risk contributed by any single component, where a higher MCR indicates a higher number of compounds significantly contributing to overall risk. This analysis reveals that just a few key chemicals typically account for most of the risk, with ratios ranging from 1.2 to 5.8 depending on mixture complexity, suggesting that targeting these key drivers could substantially reduce overall toxicity (Bopp et al., 2019). This suggests regulatory efficiency gains from prioritizing high-impact compounds rather than treating all mixture components equally, though this approach risks underestimating cumulative effects from numerous low-dose co-exposures that individually appear negligible.

POPs resist breaking down in the environment and in human bodies, accumulating over decades through bioaccumulation (building up in individual organisms) and biomagnification (concentrating as they move up food chains). PFAS compounds can remain in human blood for years or even decades; some, like perfluorooctanoic acid (PFOA), have elimination half-lives of 2-4 years, meaning it takes that long for the body to remove half the chemical (Guo et al., 2019). PCBs, though banned decades ago, continue accumulating in fatty tissues. Arctic populations show particularly high concentrations due to long-range transport through air and water currents and dietary exposure through traditional foods (Friedrich, 2016). Climate change is now altering these patterns: warming temperatures release POPs from environmental storage sites (such as melting ice) and change food web dynamics that affect bioaccumulation in marine mammals and other wildlife. POPs concentrate in organisms higher up food chains, including humans, reaching concentrations potentially thousands of times greater than in the surrounding environment (Noyes et al., 2025).

2.5.2 Chronic Disease Burdens

The growing prevalence of **chronic diseases** reflects the long-term biological toll of sustained chemical exposure. Conditions such as cancer, hormonal disorders, and respiratory illnesses increasingly emerge not as isolated cases, but as systemic outcomes of continuous interaction between environmental pollutants and human physiology.

Persistent chemical exposures have been linked to **cancer clusters**, particularly for asbestos-related lung cancers, PCB-associated skin cancers, and pesticide-linked blood cancers. The International Agency for Research on Cancer (IARC) classified PCBs as Group 1 carcinogens (definitively cancer-causing in humans) based on occupational cohort studies showing increased risks of melanoma, with suggestive evidence for non-Hodgkin lymphoma and breast cancer (Iwasaki et al., 2023). One of the clearest demonstrations of such long-term risks is Japan's Yusho cohort: a

group of people accidentally poisoned in 1968 by PCB- and dioxin-contaminated rice bran oil. The Yusho case remains one of the world's most studied environmental poisoning events, with affected individuals showing persistently elevated mortality rates from all cancers, especially lung cancer in men and liver cancer in women, even fifty years after exposure (Onozuka et al., 2020). However, systematic reviews of studies examining cancer near toxic waste sites reveal methodological challenges that prevent establishing definitive cause-and-effect relationships. Most studies lack individual-level exposure measurements, rely on residential proximity as a stand-in for actual exposure, and fail to adequately account for other contributing factors (Russi et al., 2008).

Chronic exposure to **endocrine-disrupting chemicals** creates widespread health problems by interfering with hormones that regulate reproduction, metabolism, and development. Meta-analyses show consistent links between phthalate and BPA exposure and reproductive problems including poor sperm quality, diminished egg reserves, infertility, PCOS, and pregnancy complications (Tzouma et al., 2025). PFAS exposure correlates with reduced fetal growth, excess body fat, and increased obesity risk through disruption of metabolic hormones. These chemicals work by disrupting the hypothalamic-pituitary-gonadal axis (the hormonal control system for reproduction) where chemicals like BPA mimic or block estrogen, altering the release of key reproductive hormones. Epigenetic modifications (changes in how genes are expressed without altering the DNA itself) from phthalate and PCB exposure impair the production of eggs and sperm and may create effects that pass to future generations (ibid.). Oxidative stress represents another critical mechanism: BPA and PFAS increase reactive oxygen species (unstable molecules that damage cells), harming sperm membranes, decreasing motility, impairing egg quality, and causing mitochondrial dysfunction (energy production problems) in reproductive cells. Thyroid dysfunction is also particularly concerning; phthalates block thyroid-stimulating hormone receptors and interfere with thyroid hormone transport proteins, leading to hypothyroidism (underactive thyroid), altered metabolism, and developmental disorders (Shin & Kim, 2024).

Cumulative exposure to asbestos, VOCs, and pesticides creates substantial **chronic respiratory diseases**, particularly among workers. Specific pesticides significantly increase allergic rhinitis (hay fever) risk, while fumigants cause both acute respiratory irritation and neurological effects (Beyond Pesticides, 2020). Chronic exposure to multiple pesticide classes creates cumulative respiratory damage, with particular risks for farmer's lung, chronic bronchitis, and COPD. Asbestos exposure continues causing respiratory disease decades after initial contact, with latency periods of typically 20-30 years for lung abnormalities and 35-40 years for mesothelioma. Combined exposures to asbestos and other respiratory irritants create additive or synergistic effects that accelerate disease progression and worsen chronic respiratory conditions (Norbet et al., 2015).

2.5.3 Intergenerational and Global Justice Dimensions

Ecosystems form a complex web of interdependence linking health of the environment, animals, and humans; a relationship now recognized under the "One Health" approach promoted by the Quadripartite (FAO, UNEP, WHO and WOAH) (WHO, 2023). They provide **services** that sustain all forms of life, regulating natural cycles like climate and water, maintaining fertility and enabling food production, representing the foundation on which human well-being, economic activity, and social stability rely. The One Health paradigm reinforces a critical insight for chemical management: interventions that protect ecosystem health are inherently protective of human health,

and address hazardous chemical exposure. This requires recognizing environmental degradation as a direct threat to the ecological foundations of society itself.

The persistence of hazardous chemicals, such as the ones referred to as "forever chemicals", amplifies their impacts **across generations and geographies**. Substances such as PFAS, PCBs, organochlorine pesticides like dichlorodiphenyltrichloroethane (DDT), and other POPs accumulate in the environment and human bodies, causing long-term effects especially during critical windows of vulnerability such as gestation and early infancy. These compounds travel through biological barriers such as the placenta and mammary glands, exposing newborns and developing fetuses through placental transfer and breastfeeding (Björvang & Mamsen, 2022; Björvang et al., 2021; Krönke et al., 2021). Prenatal contact with endocrine-disrupting chemicals alters hormone signaling, DNA methylation, and other epigenetic mechanisms that regulate development, potentially transmitting these effects to subsequent generations (Björvang & Mamsen, 2022; Brander et al., 2022). Such changes may impair organ formation, immune competence, and reproductive capacity, and have also been associated with birth defects, reduced birth weight, and neurodevelopmental disorders (Aguilera et al., 2023; WHO, 2010). These effects highlight how exposure to hazardous chemicals is not confined to a single generation, but shapes the health, development, and inheritance of future generations.

The global distribution of hazardous chemicals production and exposure reveals deep **structural inequalities between the Global North and Global South**. Developing countries may bear a disproportionate share of the environmental and health burdens generated by globalization of chemical-intensive industries such as textiles, plastics, and construction. Weak regulatory frameworks, limited monitoring, and economic dependence on export-oriented production make these regions attractive for manufacturing outsourcing (Zou et al., 2023). Consequently, communities in South and Southeast Asia, Latin America, and parts of Africa face elevated exposure to chemicals such as PFAS, phthalates, and heavy metals released from various industries (Thanh & Unger, 2025; EEA, 2024c; IPEN, 2024; Marital, 2025; OECD, 2025; Petrlik et al., 2021).

Meanwhile, it is commonly seen how industrialized countries sustain high consumption levels while outsourcing potentially environmentally damaging stages of production. This dynamic, rooted in the outdated economic model of take-make-dispose, externalizes ecological and health costs to producing countries while retaining cheaper consumer goods and cleaner domestic environments. This reveals a feedback loop in which pollution and hazardous chemicals exposure is not reduced, but rather displaced (Zou et al., 2023; Tong et al., 2022; Environment & Society Portal, 2021). The geographic separation between consumption in the Global North and production in the Global South creates a moral hazard where consumer markets remain insulated from the health and environmental costs their purchasing decisions impose on distant manufacturing communities. This divide prevents market signals from internalizing these externalities and ensures that cost advantages from weak environmental enforcement perpetuate rather than correct global inequality.

03

CHAPTER 3



Methodology

A transparent, replicable method for ranking chemical hazards across sectors

IN THIS CHAPTER

3.1 Scope of Study
3.2 Data Sources
3.3 Sectoral Hazard Classifications
3.4 Qualitative to Ordinal Ranking Process

FIGURES AND TABLES

Table 1 Selected chemicals for evaluation for each sector
Table 2 Raw scoring scale for each hazard criterion

3.1 Scope of Study

This study applies an authority-based qualitative hazard-screening methodology to compare the intrinsic hazards of selected chemicals used in the textile, plastic, construction, and agriculture sectors. According to public and international entities, hazardous chemicals are substances that are classified as physical, health, or environmental hazards and are capable of causing harm to human health or the environment (European Environment Agency, 2023; US EPA, 2025a).

The assessment focuses on representative substances, active compounds, or chemical classes that determine the toxicological profile of the selected products or applications. For example, the analysis considers active pesticide compounds in agriculture, relevant nitrogen or phosphorus sources in fertilizers, and representative additives, monomers, metals, or persistent compounds in textile, plastic, and construction value chains. Chemical families and emerging categories, such as flame retardants and Highly Hazardous Pesticides (HHPs), were selected based on their prevalence in global supply chains, persistence, severity of documented impacts on biodiversity and human health, and relevance to regulatory or knowledge gaps.
The methodology is designed to support comparative prioritization within and across sectors. It is not a full chemical risk assessment and does not quantify exposure, dose, product-use conditions, release pathways, cumulative effects, or mixture effects. Instead, it classifies substances according to their inherent hazard properties using established international classification systems. Process-level or context-dependent outcomes, such as eutrophication, acidification, exposure probability and sector-specific release pathways, are excluded from the scoring framework to maintain comparability across sectors. Where relevant, these issues are discussed qualitatively in the sectoral analysis but are not included in the aggregate hazard score.

3.2 Data Sources

The selected chemicals are shown in Table 1. Each substance is assessed using six intrinsic hazard criteria, applied consistently throughout the study: acute toxicity, carcinogenicity, persistence, bioaccumulation, endocrine disruption and mutagenicity.

To strengthen reproducibility, each criterion is assigned using a designated primary authority (see Appendix A for substance-specific data). Acute toxicity and germ-cell mutagenicity are scored using ECHA CLP classifications. Carcinogenicity is scored using classifications from the International Agency for Research on Cancer (IARC). Persistence and bioaccumulation are scored using REACH Annex XIII criteria. Endocrine disruption is scored using the EU endocrine disruptor lists (EDlists.org, 2026) and, for substances not on them, the Appendix A sources (see Table 2). Supporting sources, including toxicological profiles, safety data sheets, LD_{50}[6] values, BCF/BAF values, half-life values and scientific publications, are used to contextualize the narrative and verify substance-specific information; they determine a score only where Section 3.4 says so.

6 Median lethal dose (LD_{50}), the lethal dose required to kill 50% of a test animal population, a standard measure of acute toxicity.

Where more than one acute-toxicity route is classified, the score is based on the most severe acute-toxicity route. Other GHS hazard statements, such as corrosion, sensitization, aquatic toxicity or organ-specific toxicity, may be included in the narrative where relevant, but they are not combined into the acute-toxicity score unless they correspond directly to the acute-toxicity criterion.

Where a chemical family or element includes species with substantially different hazard profiles, the scored entity is labeled according to the exact species, compound, or class used by the relevant authoritative source. For example, chromium is not scored generically where the classification refers specifically to hexavalent chromium compounds, and cadmium is labeled according to the IARC grouping "cadmium and cadmium compounds" where that grouping is used. Where a representative substance is used to characterize a broader category, this is identified in the complete scoring tables (see Appendix B).

Table 1: Selected chemicals for evaluation for each sector

Textile	Plastic	Construction	Agriculture
Heavy metals (Cr, Co, Pb)	Heavy metals (Cd)	Heavy metals (Pb, Hg)	Nitrogen fertilizer (AN, urea)
Phthalates (DEHP)	Phthalates (DBP, DEHP)	Asbestos	Phosphorus fertilizer
VOCs (formaldehyde, tetrachloroethylene)	Bisphenol A (BPA)	PCBs (Aroclor 1254)	HHPs (paraquat)
Permethrin	Monomers (VCM, styrene)	VOCs (benzene)	HHPs (MSMA)
Carmoisine (Azorubine)	POP flame retardants (PBDEs)	-	HHPs (cypermethrin)

3.3 Sectoral Hazard Classifications

This section provides a general overview of the selected chemicals and their classifications. Full hazard classification data for each sector can be found in Appendix A.

3.3.1 Textile Industry

The textile sector encompasses a broad range of chemical inputs, including heavy metals (chromium, cobalt, and lead), phthalates (di-2-ethylhexyl phthalate, DEHP), volatile organic compounds (formaldehyde and tetrachloroethylene), and other functional agents such as permethrin and carmoisine (azorubine). Chromium, particularly its hexavalent form (Cr(VI)), exhibits high acute toxicity and is classified as carcinogenic to humans (IARC Group 1), with high environmental persistence and potential endocrine-disrupting properties; sodium dichromate, the Cr(VI) compound scored here, is a germ-cell mutagen (CLP Muta. 1B). Cobalt shows moderate acute toxicity and, as cobalt(II) chloride, is probably carcinogenic to humans (IARC Group 2A), along with low bioaccumulation potential in fish and suspected endocrine-disrupting and mutagenic properties. Lead demonstrates moderate acute toxicity, extreme environmental persistence and low bioaccumulation in aquatic organisms (fish BCF 5-300), with potential endocrine-disrupting properties; inorganic lead compounds are probably carcinogenic to humans (IARC Group 2A) and lead is toxic to reproduction

to reproduction (CLP Repr. 1A), although it is not classified as a mutagen. DEHP presents low acute toxicity but significant persistence, bioaccumulation, and known endocrine-disrupting activity. VOCs such as formaldehyde and tetrachloroethylene exhibit variable hazard profiles. Formaldehyde is highly toxic and carcinogenic to humans, while tetrachloroethylene has low acute toxicity but is highly persistent and probably carcinogenic (IARC Group 2A). Formaldehyde is a suspected mutagen (CLP Muta. 2); tetrachloroethylene is not classified as a mutagen. Both are suspected endocrine disruptors. Permethrin, a biocidal agent in textile treatments, shows moderate acute toxicity, low persistence, and low bioaccumulation potential, but is a potential endocrine disruptor and suspected mutagen. Carmoisine, a synthetic azo dye, demonstrates low acute toxicity and low persistence and bioaccumulation, while not being classified or not meeting criteria to be considered an endocrine disruptor, mutagen, or carcinogen. Together, hazardous chemicals present in the textile sector are defined by their persistence and chronic biological effects, particularly carcinogenicity and endocrine disruption. These findings emphasize the challenge of balancing textile performance with safer chemical practices, as the high-exposure nature of these products continues to drive chronic exposure to these and other hazardous chemicals.

3.3.2 Plastic Industry

The plastic sector includes hazardous chemicals across various applications, including heavy metals (cadmium), phthalates (DEHP and dibutyl phthalate, DBP), bisphenol A (BPA), monomers (vinyl chloride monomer (VCM) and styrene), and functional compounds like flame retardants (polybrominated diphenyl ethers, PBDEs). Cadmium exhibits moderate to high acute toxicity, is a known carcinogen to humans (IARC Group 1), and is highly persistent, with low bioaccumulation potential in fish, suspected mutagenicity and endocrine-disrupting properties. DEHP, a commonly used plasticizer classified as a Substance of Very High Concern (SVHC), exhibits low acute toxicity but persistence and bioaccumulation, particularly in aquatic ecosystems, with known endocrine-disrupting and potentially carcinogenic properties (IARC Group 2B). DBP shows low acute toxicity, low persistence, and limited bioaccumulation, though it is an identified endocrine disruptor (REACH SVHC) and was classified by IARC as possibly carcinogenic to humans (Group 2B) in 2026 (IARC, 2026); it is not classified as a mutagen. BPA has low acute toxicity, is readily biodegradable and has low bioaccumulation potential; nonetheless, it is a known endocrine disruptor and is toxic to reproduction (CLP Repr. 1B).

Monomers such as VCM have low acute toxicity but are carcinogenic to humans (IARC Group 1); VCM is genotoxic, although not classified as a germ-cell mutagen under CLP, and it breaks down quickly in air and has low bioaccumulation potential; it is also a suspected endocrine disruptor. Styrene shows moderate acute toxicity, low persistence and low bioaccumulation, but is probably carcinogenic to humans (IARC Group 2A) and a suspected endocrine disruptor. PBDEs, a persistent organic pollutant (POP) used primarily as a flame retardant, exhibit low acute toxicity yet extreme persistence and bioaccumulation potential, coupled with known endocrine-disrupting potential, although they are not classified as mutagens and IARC has not classified PBDEs as a group (decaBDE is Group 3).

Overall, the plastic sector's hazard profiles are characterized by their persistence and biological interference. The main chemical risk emerges from additives and legacy compounds that remain in circulation through product generations and complicate the recycling process and undermine its benefits by extending exposure beyond a single product life cycle.

3.3.3 Construction Industry

The construction sector features a diverse group of hazardous materials including heavy metals such as lead and mercury, asbestos, PCBs such as Aroclor 1254, and VOCs such as benzene. Lead exhibits moderate acute toxicity but is highly persistent in the environment with extremely high soil residence time (up to 2,000 years), and low bioaccumulation potential in aquatic organisms (fish BCF 5-300). Furthermore, inorganic lead compounds are probably carcinogenic to humans (IARC Group 2A), and lead is toxic to reproduction (CLP Repr. 1A) and a potential endocrine disruptor. Mercury, assessed here as methylmercury, the form to which some of it is converted in the environment, shows extreme acute toxicity, very high bioaccumulation potential, and long-term persistence depending on the environmental medium; methylmercury compounds are possibly carcinogenic to humans (IARC Group 2B). It is also a suspected endocrine disruptor, but it is not classified as a mutagen. Asbestos is classified as carcinogenic to humans (IARC Group 1) and highly persistent in air and dust, representing a long-term inhalation hazard.

Aroclor 1254 demonstrates moderate acute toxicity, is highly persistent in the environment, and shows very high bioaccumulation potential. PCBs are carcinogenic to humans (IARC Group 1) and suspected endocrine disruptors. Benzene, a well-known volatile organic compound, exhibits moderate acute toxicity, low persistence (it breaks down in air and biodegrades), but is carcinogenic to humans (IARC Group 1) and a suspected endocrine disruptor and a germ-cell mutagen (CLP Muta. 1B). Collectively, the construction sector is characterized by high persistence and carcinogenicity, driven by the presence of heavy metals, PCBs, and asbestos. The main chemical risk for this sector lies in the continued legacy contamination from persistent and bioaccumulative substances, and the uncontrolled release through demolition or erosion processes, representing exposure risks to workers and the environment.

3.3.4 Agriculture Industry

The agricultural sector assessment covers representative substances used in fertilizers, particularly ammonium nitrate (AN), urea, and superphosphate; and pesticides under the classification of HHPs, such as paraquat, cypermethrin and monosodium methanearsonate (MSMA), the latter categorized as an arsenical pesticide. Fertilizers such as AN, urea, and superphosphate exhibit low acute toxicity, are not classified as carcinogenic, and demonstrate low persistence due to their high solubility and rapid degradation in soil. These also show no bioaccumulation potential and lack endocrine-disrupting or mutagenic potential, indicating relatively low intrinsic hazard when used under controlled conditions. In contrast, pesticide-related
compounds raise greater concerns. MSMA and paraquat are characterized by moderate to extreme acute toxicity. Paraquat is not likely to be carcinogenic to humans (EPA category E) but demonstrates high soil persistence (half-life up to 20 years), with suspected endocrine-disrupting and mutagenic effects. MSMA is possibly carcinogenic to humans (IARC Group 2B), has a soil half-life of 55 days (Nufarm Australia Limited, 2022), and its degradation products may release inorganic arsenic (Eldan & Masue-Slowey, 2024), a known carcinogen for humans (Group 1) under IARC classification.

Overall, the agricultural sector reveals a sharp contrast between low-hazard fertilizers and high-hazard pesticide active components. On one hand, fertilizers contribute minimal direct toxicological risk but remain highly relevant due to their nutrient runoff and eutrophication potential. Conversely, pesticide compounds represent the primary chemical hazard, underscoring how the sector's primary chemical risks stem from the reliance on highly toxic and persistent pesticides.

3.4 Qualitative to Ordinal Ranking Process

An ordinal scale assigns scores from 1 to 5 to each chemical based on its hazard classification for each criterion, where the total score is the summation of each individual result. This allows for a relative ranking of chemicals within and across sectors, highlighting those posing the most significant potential hazard to biodiversity, the environment, and humans based on available data. The scoring system is as follows:

Table 2: Raw scoring scale for each hazard criterion

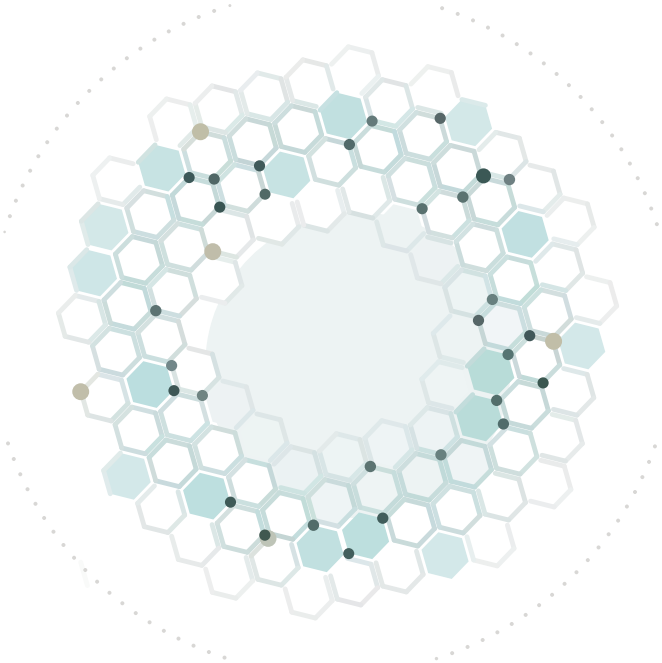
Criterion	Primary source	Raw scoring scale
Acute toxicity	ECHA CLP	Category 1 = 5; Category 2 = 4; Category 3 = 3; Category 4 = 2; not classified = 1. Where several exposure routes are classified, the most severe acute-toxicity route is used.
Carcinogenicity	IARC	Group 1 = 5; Group 2A = 4; Group 2B = 3; Group 3 =2; or not evaluated = 1
Persistence	REACH Annex XIII	Very persistent = 5; persistent = 3; not persistent = 1. Persistence is assessed using REACH P/vP criteria, based on half-life thresholds in water, soil, or sediment.
Bioaccumulation	REACH Annex XIII	Very bioaccumulative = 5; bioaccumulative = 3; not bioaccumulative = 1. Bioaccumulation is assessed using REACH B/vB criteria, based primarily on BCF/BAF thresholds.
Endocrine disruption	EU ED lists (EDlists.org); Appendix A sources	On EDlists.org List I = 5; on List II or III, or a known, suspected or potential endocrine disruptor in the Appendix A sources = 3; otherwise = 1.
Mutagenicity	ECHA CLP germ-cell mutagenicity classification	Category 1A/1B = 5; Category 2 = 3; not classified = 1. Only germ-cell mutagenicity classifications are scored. Broader genotoxicity evidence may be flagged narratively but does not change the score.

Each score is assigned using the designated primary source for that criterion. Supporting sources, including toxicological profiles, safety data sheets, LD_{50} values, BCF/BAF[7] values, half-life values and scientific publications, are used only to contextualize the narrative or verify borderline cases, with two exceptions: where a substance has no CLP acute toxicity classification, its acute toxicity data in Appendix A are placed in the CLP category ranges, and endocrine disruptors are otherwise identified from the Appendix A sources (see Table 2). Where sources conflict, the designated authority for the criterion prevails. Harmonized or legally adopted classifications are prioritized over dossier or notified data, and experimental data are prioritized over modeled estimates.

7BCF = bioconcentration factor; BAF = bioaccumulation factor.

04

CHAPTER 4



Results and Cross-Sector Findings

Where the hazards concentrate, and where green chemistry substitution matters most.

IN THIS CHAPTER

4.1 Sectoral Hazard Ranking Results

4.2 Cross-Sector Findings and Interpretation

4.3 Limitations and Considerations

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Figure 10 Textile industry scoring

Figure 11 Plastics industry scoring

Figure 12 Construction industry scoring

Figure 13 Agriculture industry scoring

Figure 14 Mean ordinal scores for each industry

The following qualitative evaluation presents the hazard profiles of the chosen chemicals across each sector based on the six previously mentioned evaluation criteria. The profiles provide a basis to identify priority areas of concern and are then developed upon in the subsequent section with the ranking process described above. Together, this basis forms a comprehensive summary of the hazards associated with the chemical use of the respective industries, as well as a comparison between the industries as a whole and between the chemical groups within the industries.

4.1 Sectoral Hazard Ranking Results

The following subsections present the ranking outputs for the textile, plastic, construction, and agriculture sectors. The ranking is based on the aggregate ordinal scores assigned to each chemical or chemical group across the selected hazard criteria.

4.1.1 Textile Industry

Figure 10 presents the hazard scores for the priority substances in the textile industry. Chromium demonstrated the highest hazard potential in the textile sector, ranking first with a total score of 23, followed by cobalt (18) and formaldehyde (17); lead and DEHP ranked fourth with 16, followed by tetrachloroethylene (15), permethrin (10) and carmoisine (7). The high scores of the heavy metals are from consistently high scores across several risk categories, whereas for the VOCs, the scores of formaldehyde and tetrachloroethylene are attributed to high carcinogenicity and acute toxicity and high carcinogenicity and persistence, respectively.

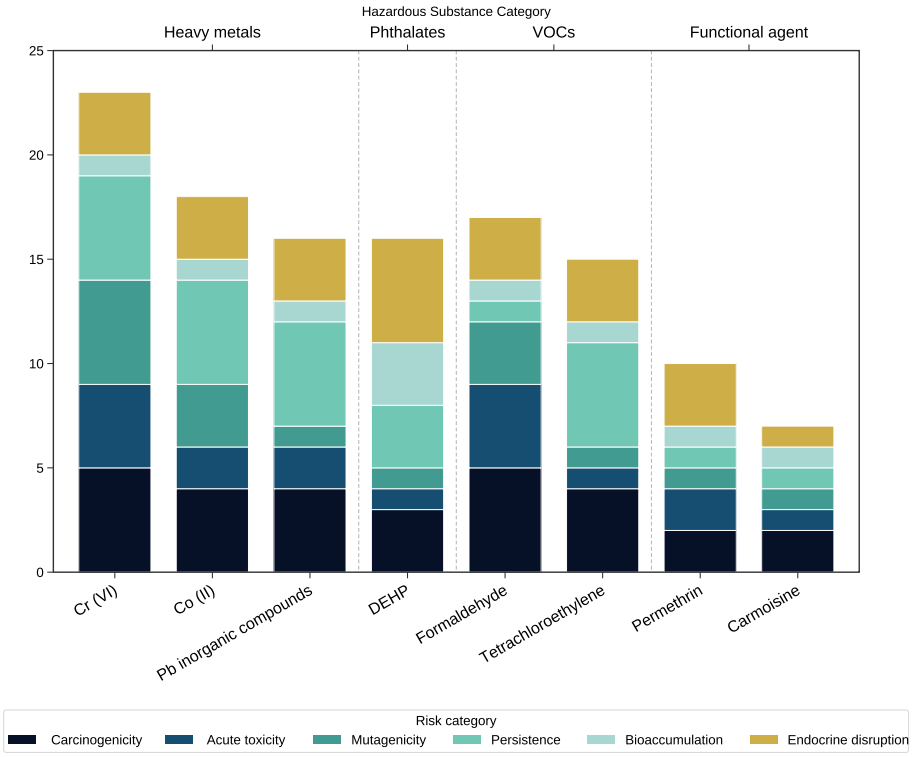


Figure 10: Textile industry scoring

This highlights heavy metals and VOCs as important targets for green chemistry substitution in textiles. Their combined persistence, carcinogenicity, and endocrine-disrupting potential are of particular concern given the continuous human contact with textiles and their labor-intensive manufacturing.

4.1.2 Plastic Industry

Figure 11 presents the hazard scores for the priority substances in the plastic industry with the heavy metal cadmium having exhibited the highest hazard potential with a score of 21. DEHP and flame retardants (PBDEs) followed, both with a score of 16. DBP and the two monomers in plastic production, VCM and styrene, each scored 12, and BPA scored 10 points. While BPA demonstrated a high score in endocrine disruption, its low scores across the other criteria did not compare to cadmium's high scores for carcinogenicity, acute toxicity and persistence, PBDEs' maximum scores for persistence and bioaccumulation, or DBP receiving a high score for endocrine disruption and a medium score for carcinogenicity.

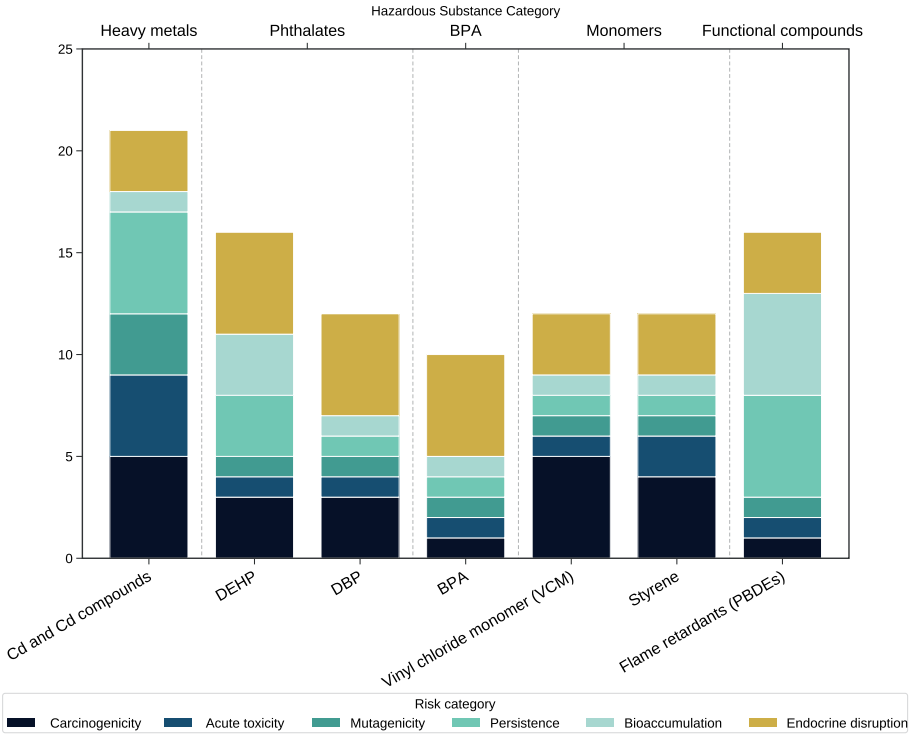


Figure 11: Plastics industry scoring

Overall, the ranking reflects a sector dominated by carcinogenic, persistent, bioaccumulative, and endocrine-disruptive substances. These findings underscore the need to strengthen green chemistry substitution of additives, while ensuring regulatory coherence across product value chains to prevent the reintroduction of restricted chemicals through recycling and imported materials, so that recycled plastics can circulate safely.

4.1.3 Construction Industry

Figure 12 presents the hazard scores for the priority substances in the construction industry. Mercury, scored as methylmercury, and PCBs emerged as the most hazardous chemicals in the

construction sector, both ranking first with a total score of 21. Benzene followed with a score of 17, lead with 16 and asbestos with 14. Among the four sectors studied, the hazardous substances in the construction sector had the most consistent total scores with each other, indicating the importance of addressing these hazards in the construction industry.

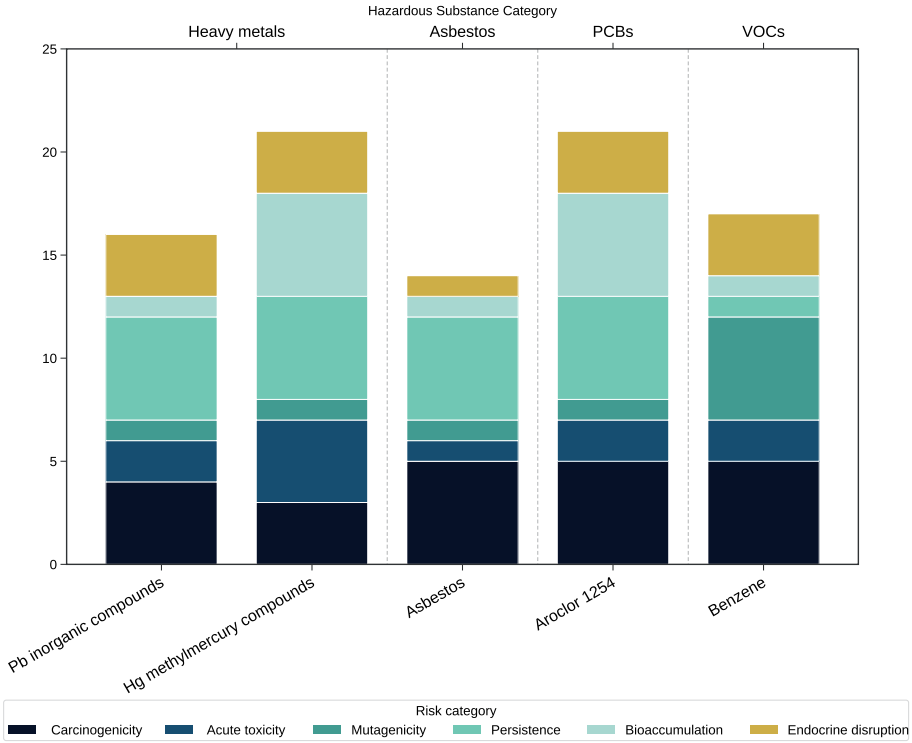


Figure 12: Construction industry scoring

Overall, the ranking highlights the dominance of persistent, bioaccumulative, and carcinogenic substances within this sector, particularly associated with legacy contamination and long-term exposure pathways. These findings suggest that priority should be placed on safe management and abatement of these legacy contaminants and stricter occupational safety standards that translate through geographic and generational borders. Additionally, of importance is the need for comprehensive control of demolition and management practices to ensure material safety and subsequent waste valorization. For new construction, materials that are safe by design can prevent the next generation of legacy contamination.

4.1.4 Agriculture Industry

Figure 13 presents the hazard scores for the priority substances in the agriculture industry. Paraquat ranked first with the highest total score of 15, demonstrating the most significant hazard potential, while MSMA ranked second with a score of 10, emphasizing the danger of HHPs. Cypermethrin followed with a score of 9, and the remaining substances, urea, superphosphate and ammonium nitrate (AN), all scored 6. Paraquat's higher ranking is primarily due to its high acute toxicity and persistence and its suspected endocrine-disrupting effects, whereas MSMA received medium scores for acute toxicity and carcinogenicity and a low score for persistence.

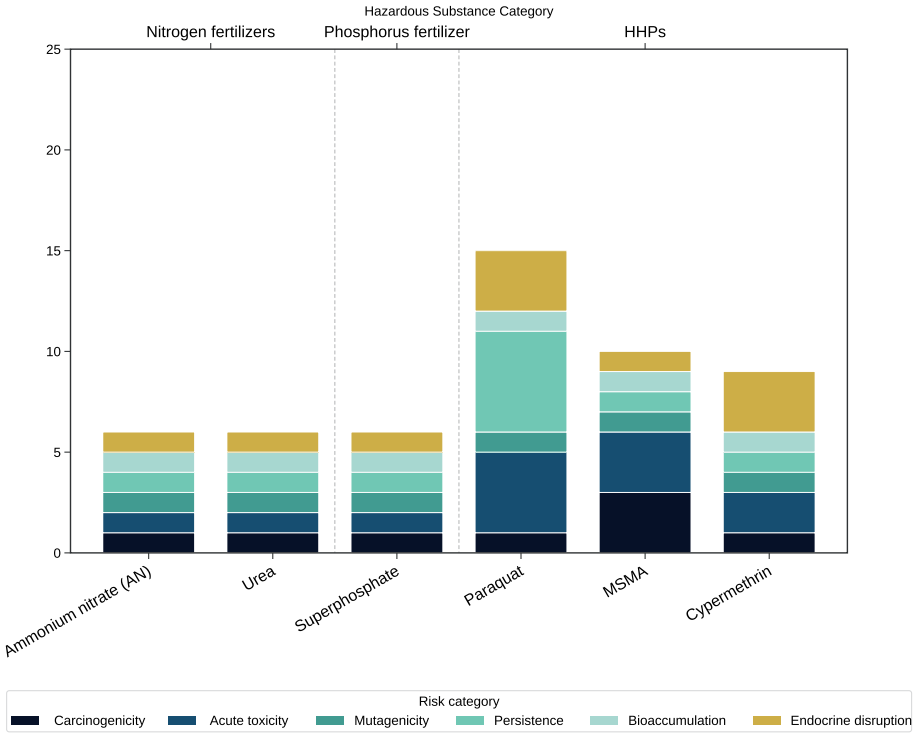


Figure 13: Agriculture industry scoring

Overall, the agricultural ranking reinforces the dominance of pesticide-related hazards over fertilizer-related ones. While the total scores overall are lower than those of the other industries studied, agricultural hazardous substances and their health and biodiversity effects must not be dismissed. These results also suggest that regulatory and substitution efforts should ideally prioritize HHPs, whose intrinsic toxicity and environmental persistence demand stricter measures, and their replacement with green chemistry alternatives such as biopesticides. However, while the intrinsic hazards of fertilizers are low, their exposure mechanisms and extensive use mean that they still have a high impact potential and should therefore not be neglected. This demonstrates how the rankings overall should be interpreted. The hazard rankings can inform policy on chemical mechanisms, impact categories and severity, but they should always be complemented with contextual data on exposure mechanisms and volumes to accurately estimate chemical risks.

4.2 Cross-Sector Findings and Interpretation

Across all four sectors, the ranking results reveal repeating patterns of chemical risk, where the same groups of hazardous substances reappear under different technical functions. Heavy metals, persistent organic compounds, and volatile solvents consistently exhibit the highest hazard potential, largely due to their persistence, bioaccumulative capacity and chronic toxicity to both humans and the environment. Heavy metals, such as lead, cadmium, or chromium, are present in multiple sectors where they contribute to long-term environmental contamination and occupational exposure. Similarly, POPs, such as PBDEs, PCBs and certain PFAS, demonstrate high stability and mobility, impacting ecosystems for decades once released. VOCs, like formaldehyde and benzene, further amplify hazard profiles through acute toxicity, carcinogenic potential

and their contribution to indoor pollution. Together, these overlapping groups act as systemic contaminants whose impacts transcend production boundaries.

The cross-sector reappearance of these substances highlights the structural nature of chemical risks; industrial systems rely on highly versatile but limited chemicals with inherent hazards. Compounds used as stabilizers, flame retardants, or plasticizers in one sector may reappear in another, revealing how chemical design choices propagate through interconnected value chains. For instance, phthalates arise in both the plastic and textile sectors as plasticizers; or permethrin, a synthetic pesticide, functions both as an agricultural pesticide and in fabric treatments in textile manufacturing. Moreover, many products themselves circulate between sectors, amplifying the spread of hazardous substances, such as plastics used in construction or in textiles for packaging and coating applications. Redesigning such sector-crossing substances through green chemistry and safe-by-design practices could therefore yield system-wide benefits rather than isolated ones, and help keep hazardous chemicals out of the material loops on which circular growth depends. These insights complement global efforts, for instance, those under the Kunming-Montreal Global Biodiversity Framework (Target 7) or Sustainable Development Goals (9, 12, 14, and 15), as well as other initiatives seeking to address systemic challenges and promote integrated approaches to sustainability.

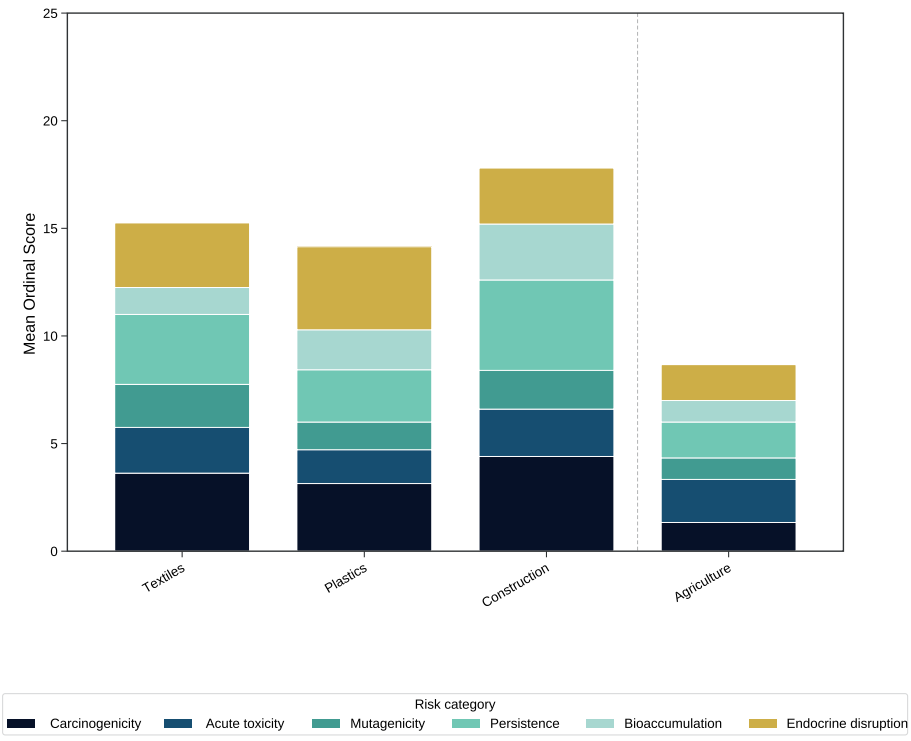


Figure 14: Mean ordinal scores for each industry

To support cross-sector interpretation, mean ordinal hazard scores were calculated for each sector and hazard criterion by averaging the scores of the selected chemical groups within that sector. This aggregation is intended as an exploratory screening tool rather than a statistical comparison of sectoral risk. Because the scores are ordinal and the chemical groups were selected purposively rather than through a representative sectoral inventory, the resulting means should be interpreted as indicative of the hazard profile of the chemicals assessed, not as a definitive

ranking of sectors as a whole. Nevertheless, the comparison helps identify where selected sectors show consistently elevated hazard characteristics, such as persistence, carcinogenicity, or bioaccumulation, and where further assessment or regulatory attention may be warranted.

The cross-sector comparison suggests that construction has the highest mean ordinal hazard score among the selected substances, largely driven by the high persistence, bioaccumulation, and carcinogenicity associated with lead, mercury, asbestos, PCBs, and benzene. Plastics and textiles also show elevated mean scores, although their hazard profiles are shaped by different chemical functions, including plasticizers, monomers, flame retardants, heavy metals and VOCs. Agriculture presents lower average scores because fertilizers have relatively low intrinsic hazard scores under the selected criteria; however, this average masks the higher hazard profile of HHPs such as paraquat and MSMA.[8]

4.3 Limitations and Considerations

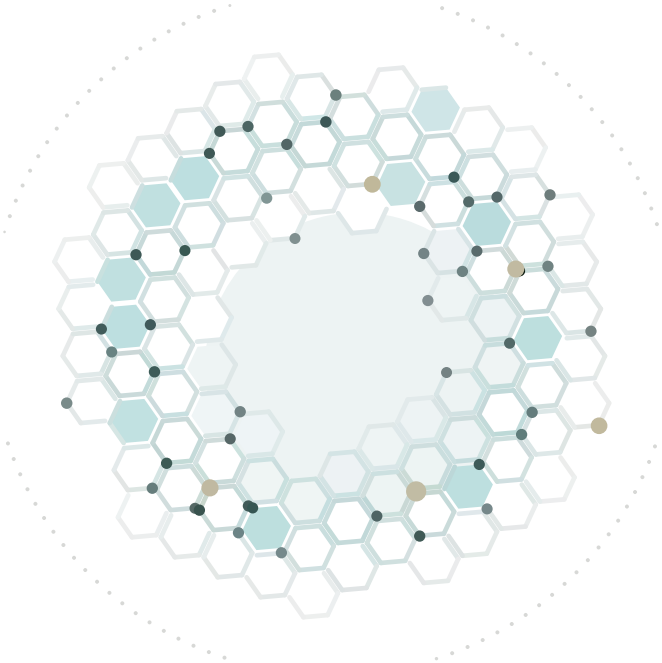
This methodology aims at providing a structured and comparable assessment of hazardous chemicals across sectors; nonetheless, some limitations must be acknowledged. The approach relies on hazard classifications that, although standardized, may not fully capture the complexity of chemical interactions and synergistic effects. Secondly, data challenges were present due to the variability in data availability across substances. For example, asbestos lacks quantitative parameters such as LD_{50}, BCF or degradation half-life, making it difficult to ensure full data coverage. The qualitative nature of this scoring system also introduces some degree of subjectivity, as it involves interpreting and translating qualitative data into numerical values. However, this may not be inherently problematic provided that the criteria are applied consistently within a single analytical framework.
Furthermore, this assessment focuses on intrinsic chemical hazards, therefore not accounting for exposure-based factors such as concentration, frequency, or pathways of exposure. The exclusion of process-level indicators further narrows the scope, as these may depend on sector-specific conditions that could hinder cross-sector comparability. Finally, the analysis is limited to chemicals used in primary products and does not account for the use of products containing hazardous chemicals as auxiliary materials in other sectors, for example plastic pipes used in construction, leaving certain cross-sector contamination pathways outside of the study's boundaries.

These considerations define the boundaries and purpose of the evaluation. Maintaining methodological consistency and transparency ensures meaningful results within this framework and allows for future studies to enhance the robustness and policy relevance of this type of assessment.

8Scores represent mean ordinal hazard scores for the selected chemical groups only. They do not account for exposure, production volumes, quantities released, concentration, use patterns, environmental fate under specific conditions, or omitted substances. Differences between sectors should therefore be interpreted as indicative patterns rather than statistically robust sector rankings.

05

CHAPTER 5



Recommendations and Roadmap

A practical roadmap: green chemistry at the source, safe circularity, supply-chain transparency and collaborative frameworks.

IN THIS CHAPTER

5.1 Green Chemistry: Safer Design at the Source

5.2 Circular Economy: From Safe Materials to Circular Growth

5.3 Supply Chain Transparency and Traceability

5.4 International and Collaborative Frameworks

FIGURES AND TABLES

Figure 15 12 Principles of Green Chemistry

Figure 16 Key International Frameworks for Moving Supply Chains Beyond Hazardous Chemicals

Having identified the most significant hazardous substances across global supply chains and traced their pathways to ecosystems and human populations, this paper has demonstrated the far-reaching consequences for biodiversity and public health. Through systematic categorization based on persistence, bioaccumulation, and toxicity, the analysis has established which chemicals call for the greatest attention and where intervention is most critical. The following recommendations outline actionable strategies to mitigate these risks, focusing on four key areas: advancing green chemistry principles, transitioning toward circular economy models, enhancing supply chain transparency and traceability, and fostering collaborative governance approaches that engage stakeholders across sectors and borders. The persistence of hazardous chemical use, despite decades of documented harm, reveals that technical solutions alone prove insufficient. Powerful economic incentives, regulatory fragmentation, and unequal power dynamics between producers and affected communities have systematically blocked implementation of known alternatives, requiring recommendations to directly confront these political-economic barriers rather than assume that technical feasibility ensures adoption.

The four areas follow one logic, reflected in this paper's title. Green chemistry comes first, because it designs hazards out at the source. Circularity follows, because keeping materials in use creates lasting value only when those materials are safe: secondary materials often carry more concentrated and more diverse chemicals than virgin ones (EEA, 2022), which reduces their safety and economic value (Fidra, 2025b). Transparency then makes it possible to prove that materials are clean, and binding regulation, supported by collaborative frameworks, levels the playing field so that safer producers are not undercut by those who externalize contamination costs. Together, these areas describe a path to circular growth beyond hazardous chemicals.

5.1 Green Chemistry: Safer Design at the Source

Green chemistry offers a practical and effective approach to moving major industrial value chains beyond hazardous chemicals (Clark, 2022). By intervening at the molecular level during the design stage, it prevents pollution before it occurs (Anastas & Warner, 1998). By advancing safer molecular design, green chemistry aligns with the Paris Agreement's goals for low-carbon industrial transformation and supports SDG 3 (Good Health and Well-being), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), by promoting cleaner industrial processes and reducing toxic exposures that undermine both human and environmental health. It is also a precondition for circular growth: the circular economy keeps materials in loops, and green chemistry helps ensure that what circulates is non-toxic and regenerative by addressing chemical safety at the source. Its twelve guiding principles form the scientific backbone for a sustainable chemical industry (ibid.).

5.1.1 Textile Industry

Green chemistry in the textile sector seeks to replace toxic dyes, bleaches, finishes, and additives with bio-based, biodegradable, and non-toxic alternatives, while maintaining product quality and durability. Since textile production traditionally relies on hazardous substances such as azo dyes, chlorine-based bleaches and PFAS, redesigning processes and materials is essential to enable

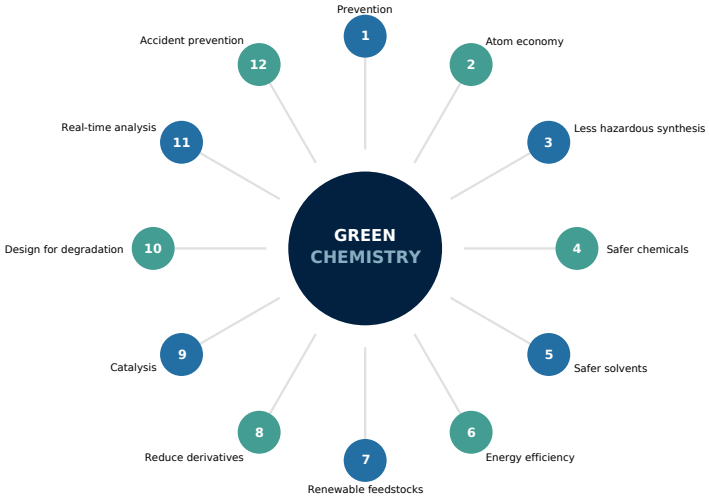


Figure 15: 12 Principles of Green Chemistry

safe reintegration into the biological and technical cycles shown in the butterfly diagram in Section 5.2 (Raj et al., 2022; Voukkali et al., 2024).

In dyeing, natural colorants and biologically derived pigments are increasingly used as alternatives to synthetic dyes containing heavy metals. Fermentation-based colorants (derived from plants, fungi, and microorganisms) can achieve comparable color performance while offering higher biodegradability (Fried et al., 2022). Industry initiatives such as **Patagonia's Clean Color Collection**, which uses Archroma's **EarthColors®** from agricultural by-products (Laughlin, 2017), and **H&M's** investment in algae-based dyes through its Global Change Award (Mundell, 2025), showcase how large brands integrate green chemistry into design and innovation. Enzymatic processes represent another major advance in sustainable textile production. Enzymes such as laccases (for bleaching and decolorizing) can replace harsh chemicals under milder, less energy-intensive conditions (Loi et al., 2021), and cellulases are used for biopolishing, although cellulase treatment causes some loss of fabric strength (Ikbal et al., 2024). Policymakers and industry alliances should support R&D grants for enzyme-based and bio-colorant innovation, helping smaller producers transition away from toxic synthetics. Similarly, oxygen-based bleaching agents like hydrogen peroxide degrade into water and oxygen without leaving harmful residues while delivering the same performance as chlorine (Jamaluddin et al., 2023; Walawska et al., 2024). Emerging low-water technologies, such as plasma treatment and supercritical CO_2 dyeing, eliminate water altogether and enable CO_2 recovery and reuse (Global Textile Times, 2025), illustrating how chemical innovation can advance both environmental and resource efficiency goals. To replace PFAS in water- and stain-repellent coatings, green chemistry promotes fluorine-free finishes based on plant oils, natural waxes and polysaccharides (bio-based) or on silicones, which give good water repellency but generally not oil repellency; silicones also carry their own concerns, such as residual D4, D5 and D6 siloxanes (Rungruangkitkrai et al., 2024; Whiting et al., 2020). In addition, bio-based plasticizers synthesized from renewable resources such as vegetable oils, citric acid, and castor oil offer safer alternatives to phthalates, maintaining flexibility and performance in coated textiles and synthetic fibers (Hosney et al., 2018; Sun et al., 2024).

Beyond chemical reformulation, green chemistry supports a shift toward sustainable fibers such as jute, kenaf, abaca, and linen, which require fewer chemical treatments, while bio-based polyesters and polylactic acid (PLA) produced from agricultural residues serve as renewable substitutes for petroleum-based synthetics (Cobbing & Ruffinengo, 2013; McKay et al., 2024; Sanivada et al., 2020). To accelerate adoption, governments could introduce fiscal incentives such as green procurement standards and tax rebates for certified non-toxic textiles, while supporting harmonized eco-labeling systems to improve transparency for consumers and global brands. Together, these innovations demonstrate how green chemistry enables a systemic shift toward safer, circular, and resource-efficient textile production.

5.1.2 Plastics Industry

Green chemistry in the plastics industry seeks to eliminate toxic additives and reduce dependency on fossil resources by developing bio-based polymers from renewable feedstocks such as corn, sugarcane, cassava, and agricultural residues (European Bioplastics, n.d.; Swetha et al., 2023). These innovations aim to make plastics safer, more biodegradable, and fully compatible with circular economy objectives of reuse and recycling.

Companies such as **NatureWorks** and **Corbion** produce PLA polymers (Ingeo® and Luminy®) with low carbon footprints, while **Mitsubishi Chemical's BioPBS™** offers biodegradable plastics derived from plant sugars suitable for packaging and films (Spherical Insights, 2025). At the additive level, non-toxic stabilizers and bio-based plasticizers are displacing harmful compounds (Qadeer et al., 2022; Nimbasia Stabilizers, 2024). For example, calcium-zinc stabilizers have replaced cadmium in PVC applications, and **Dow Chemical**'s ECOLIBRIUM™ line uses renewable feedstocks to produce phthalate-free plasticizers with equivalent performance (Lott, 2014; AIChE, 2012). To address BPA and other endocrine disruptors, BPA-free polymers such as **Tritan™ copolyester** now provide transparent, durable alternatives for food-contact materials (Eastman, 2025). Researchers have also developed bio-based polycarbonates synthesized from lignin and other plant phenols, offering strength and clarity without endocrine-disrupting effects (Garrison et al., 2021; Stockholm University, 2024). In addition, fluorine-free solutions are replacing PFAS in coatings and polymer processing. Silicone-based and bio-based coatings replicate hydrophobic performance, and fluorine-free polymer processing additives (PPAs) improve processability without environmental persistence (Daken Chemical, 2024). A striking example of biomimicry comes from RMIT University, where researchers developed lotus-leaf-inspired bioplastics whose microstructured surfaces naturally repel water, bacteria, and dirt, achieving self-cleaning without added chemicals (Kaszubska, 2022). Policymakers could strengthen extended producer responsibility (EPR) frameworks and create certification systems for biodegradable and non-toxic plastics, ensuring market recognition for safe materials. Public funding should also prioritize pilot-scale bioplastic facilities and cross-sector R&D platforms to overcome high production costs and scalability barriers.

Under the Horizon Europe BELOOP project, the Packaging Hub will investigate the barriers and conditions affecting the practical implementation and wider adoption of bio-based food packaging solutions as alternatives to conventional fossil-based multilayer plastics. Tecnopackaging is leading the development and adaptation of bio-based packaging solutions for demanding applications, such as hot-filled and sterilized products. Fruselva will contribute its expertise to

assessing prototype performance before piloting them across EROSKI retail environments, consumer feedback rooms, and its "Food School" network, as well as through OCRE's participatory research and community engagement activities in four rural municipalities in Aragón. OCRE will explore how local communities understand, perceive and respond to bio-based packaging solutions, identifying barriers and opportunities for their adoption and generating insights that could support the transferability of circular consumption practices to other rural territories. By project completion, the technology aims to reach a validation level of TRL 6.[9] Overall, green chemistry innovations in the plastics sector are reshaping material design and production, from molecular synthesis to product lifecycle management. By substituting toxic additives, using renewable feedstocks, and designing polymers for recyclability and safe degradation, these advancements bring the industry closer to circular, non-toxic material cycles.

5.1.3 Construction Industry

Green chemistry is also reshaping the construction sector, long associated with toxic emissions and hazardous materials. The sector's transition toward low-impact and renewable chemistry improves not only environmental outcomes but also indoor air quality and worker safety. This shift contributes to SDG 11 (Sustainable Cities and Communities) by aligning building materials with health and sustainability goals.

In coatings and paints, plant-derived solvents such as d-limonene (extracted from citrus peels) increasingly replace petroleum-based solvents and benzene-containing products while maintaining effective degreasing properties (ICC Citrus, n.d.; RawSource, 2025). Water-based paints and adhesives reduce VOC emissions, with solvent-based adhesives emitting on average about 8,450 µg/m³ of VOCs after three days, against 28 µg/m³ for water-based methylcellulose adhesives (Kozicki & Guzik, 2021). In protective coatings, polymer-based materials are preferred for corrosion resistance, yet these can degrade over time, allowing moisture and oxygen to penetrate. To improve durability without resorting to heavy metals, researchers have developed coatings incorporating alkaline-earth metal compounds and biodegradable polymeric stabilizers derived from natural resources (Ulaeto et al., 2023). These innovations preserve structural integrity while remaining environmentally benign.

Safer materials have also replaced asbestos. Cellulose fibers derived from wood pulp offer equivalent thermal and acoustic insulation without the fiber hazards of asbestos, although they rely on added fire retardants such as borates (Rodgers, 2024), some of which, like boric acid, are classified under CLP as toxic to reproduction (Repr. 1B). Their dense structure minimizes airflow and heat transfer, improving building energy efficiency by reducing heating and cooling needs (GreenFiber, 2024). Other alternatives, such as mineral-based silicates and polymer composites, provide additional non-toxic, thermally resistant materials suitable for insulation and structural applications (Fajdek-Bieda & Wróblewska, 2024). At the structural level, carbonated concrete (which injects captured CO_2 into fresh mixtures) permanently sequesters carbon by forming calcium

9Circular Innovation Lab is a partner in the BELOOP consortium. This contribution is supported by the European Union's Horizon Europe project BELOOP (Grant Agreement No. 101291625). Co-funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

carbonate, simultaneously strengthening the material and reducing emissions (Firoozi et al., 2024). This innovation turns carbon emissions (traditionally an environmental liability) into a building material performance advantage.

Industry leaders like **IKEA** have also started to adopt bio-based adhesives to replace formaldehyde resins, reducing VOCs and embedding renewable feedstocks in large-scale production (Circular Bio-based Europe, 2023). Similarly, the development of ecological additives in concrete, roofing, and plumbing materials aims to create products that are durable, recyclable, and chemically safe across their life cycle. Governments should update green building codes to prioritize low-VOC and bio-based materials, while introducing mandatory disclosure of chemical content in construction products. Subsidies for carbonated concrete and low-emission coatings could accelerate market transformation toward net-zero construction.

Overall, green chemistry in the construction sector extends from material sourcing to product formulation and finishing, promoting energy-efficient manufacturing, low-toxicity, and improved recyclability.

5.1.4 Agriculture Industry

Agriculture provides one of the clearest examples of how green chemistry can restore ecological balance while sustaining productivity. The sector's reliance on synthetic fertilizers and pesticides has long driven soil degradation, water pollution, and biodiversity loss (Fenibo et al., 2021). Green chemistry redesigns these inputs to be biodegradable, renewable, and non-toxic, addressing SDG 2 (Zero Hunger) and SDG 15 (Life on Land).

Biofertilizers exemplify this approach by using naturally occurring microorganisms (such as nitrogen-fixing bacteria and phosphorus-solubilizing species) to provide essential nutrients to crops, while gradually improving soil fertility and structure (Ammar et al., 2023; Timofeeva et al., 2023). Unlike conventional synthetic fertilizers that release reactive nitrogen or phosphorus into the environment, biofertilizers reduce chemical residues, minimize runoff and eutrophication, and support long-term soil health and microbial diversity. Green chemistry also encourages the use of biopesticides derived from plant extracts or microbial metabolites, which are often more selective than broad-spectrum synthetics and break down quickly in the environment (Ayilara et al., 2023; US EPA, 2024f). For example, azadirachtin, extracted from neem seeds, disrupts pest growth and reproduction and degrades quickly, although it can have sublethal effects on some natural enemies and pollinators (Kilani-Morakchi et al., 2021). The scalability of such compounds has improved through biocatalysis and synthetic biology, fields that use enzymes or genetically engineered microorganisms to produce complex bioactive molecules efficiently (Paul et al.,
2018). Emerging technologies such as nanobiopesticides have been shown to improve the performance and stability of biological agents. For instance, silver nanoparticles synthesized via green routes using plant extracts exhibit antimicrobial and insecticidal activity, meaning they can target harmful microbes and insect pests (Ayilara et al., 2023). This allows for lower application doses, reducing runoff and environmental exposure.

Major agrochemical companies such as **BASF** and **Bayer** have started integrating these principles into R&D pipelines, developing biological crop protection products and data-driven optimization tools to reduce field-level emissions (Scott, 2019). These initiatives signal a broader transition

toward biologically derived, low-toxicity inputs, demonstrating how agriculture can become more sustainable without compromising productivity. To ensure wider adoption, policymakers should strengthen approval frameworks for biopesticides and biofertilizers, streamline testing and market entry processes, and incentivize farmers through subsidies or carbon credit schemes for adopting non-toxic agricultural inputs. Capacity-building programs can also train smallholders in the application and management of green agrochemicals.

In sum, green chemistry in agriculture demonstrates that productivity and environmental integrity can coexist when innovation is guided by ecological principles. By redesigning inputs at the molecular level, promoting biological alternatives, and closing nutrient cycles, it not only restores soil health and biodiversity but also reduces dependence on fossil-based and toxic agrochemicals.

5.1.5 Challenges

Despite rapid innovation across industries, the widespread implementation of green chemistry faces persistent structural, economic, and regulatory challenges. High production and capital costs remain a central obstacle, as bio-based inputs, enzymatic processes, and renewable feedstocks often require more expensive sourcing and manufacturing than conventional petrochemical pathways. Limited availability of certain bio-based raw materials further constrains scalability, particularly in regions without established biomanufacturing infrastructure. Technical compatibility with existing production and recycling systems also poses difficulties, as many green alternatives must undergo costly reformulation or equipment adaptation before integration. Regulatory fragmentation adds another layer of complexity: differences in national standards, certification schemes, and testing requirements hinder global harmonization and slow the commercialization of safer substitutes. Moreover, achieving consistent quality and performance across supply chains demands rigorous industry-wide standardization and verification mechanisms, which remain unevenly applied. Finally, green chemistry's sector-specific challenges (such as the need for stable storage and region-specific formulations in agriculture or compliance with stringent building codes in construction) underscore that successful transition requires not only technological advancement but also coordinated policy support, capacity building, and sustained market incentives to drive systemic adoption.

Hence, green chemistry marks a real shift in how industries think about production: not just controlling pollution after the fact, but designing safer materials from the start. It shows that environmental protection and innovation can work together, yet scaling it up remains difficult. Making green chemistry the norm rather than the exception will depend on political will, investment, and the willingness of industries to rethink the way they design and use chemicals altogether. Where it succeeds, it opens the way for the circular strategies in the next section, because keeping products and materials in circulation is worthwhile only when they are non-toxic.

5.2 Circular Economy: From Safe Materials to Circular Growth

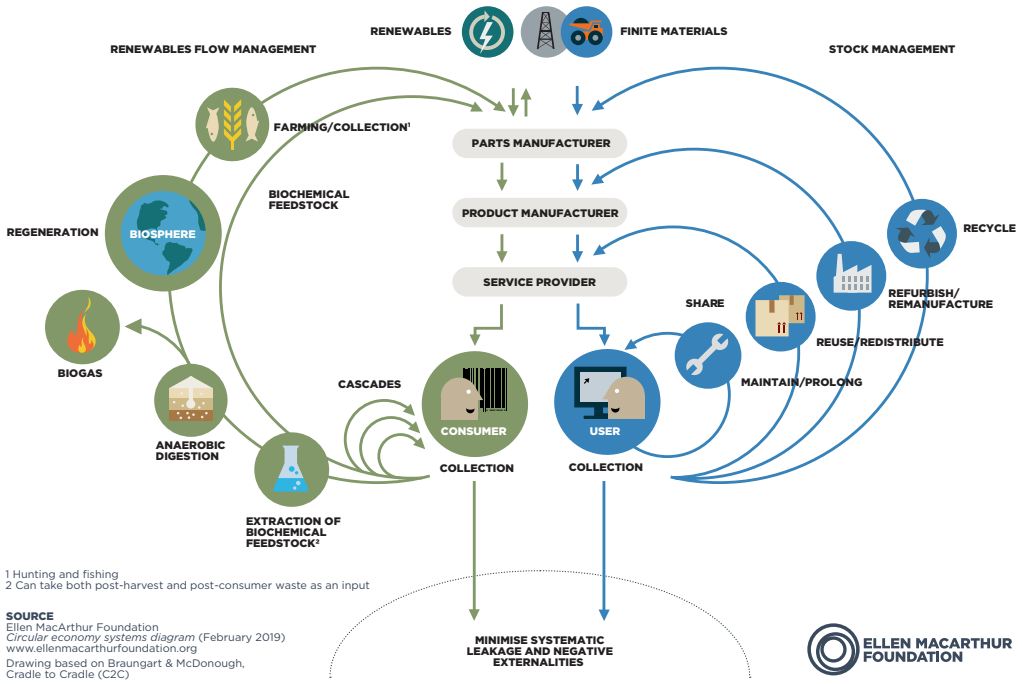
The **Circular Economy (CE)** represents a paradigm shift from the traditional linear "take-make-dispose" model toward a regenerative system designed to eliminate waste, circulate materials at

their highest value, and restore natural systems (Ellen MacArthur Foundation, 2023). This transformation is essential for reaching the objectives of the Paris Agreement, and curbing the proliferation of hazardous chemicals in global supply chains, aligning directly with the UN SDGs, particularly SDG 12 (Responsible Consumption and Production), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action), which call for decoupling economic growth from environmental degradation. This paper calls the aim circular growth: economic value created by keeping safe materials and products in use, rather than by extracting, using and discarding them. Building on the safer inputs that green chemistry provides, and integrating chemical safety into design, production, and material management, it offers pathways to reduce contamination and foster sustainable industrial practices. Hence, it is necessary for governments to develop national CE roadmaps that explicitly integrate chemical-safety criteria, provide fiscal support for non-toxic material innovation, and adopt binding eco-design standards that prioritize safe recyclability. Unlike the linear economic model which relies on large quantities of cheap materials and energy, the circular economy extends product lifecycles and minimizes waste. Circularity is implemented through circular supply chains and circular business models. A circular supply chain is a closed-loop system of production aimed at minimizing waste and environmental impact by keeping materials in continuous use. While different contexts may require different strategies, the circularity case is stronger for preventative and value-conserving efforts. The R-hierarchy is a framework to classify and rank circularity strategies, from most to least sustainable, based on these considerations. Actions fall under the categories refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, or recover, and should be considered in that order. The core idea is to reduce dependence on virgin resource extraction, which is consequently an alternative pathway to minimizing waste management costs. In parallel, circular business models rethink how industries create and deliver value, reducing reliance on hazardous and finite resources and embedding sustainability at the core of corporate strategy. Together, these mechanisms translate circular principles into practice, ensuring that chemical safety becomes integral to production and consumption systems.

To institutionalize these mechanisms, governments could establish 'Circular Economy Hubs': spaces where businesses share resources, pilot symbiotic production systems, and access public incentives tied to circular performance. However, the viability of circular business models remains constrained by the same market failures that perpetuate linear production: externalized environmental and health costs make hazardous virgin materials artificially cheaper than safe alternatives, creating adverse selection where circular businesses operating under higher safety standards cannot compete on price with linear producers externalizing contamination costs. This requires regulatory intervention to level the competitive playing field rather than relying on voluntary market transformation. With that said, successful examples of circularity hubs already exist. In Danish Kalundborg, production facilities have for over 50 years shared and reused residual waste, water, and energy streams, creating a mutually beneficial industrial symbiosis within circular economy principles (Kalundborg Symbiosis, n.d.).

The Ellen MacArthur Foundation’s "butterfly diagram" further conceptualizes the circular economy process, showing two interlinked cycles (the biological and the technical) where materials are either safely returned to the biosphere or continuously reused within the economy. The diagram underscores how restorative design and safe material recirculation are essential to achieving a regenerative

industrial metabolism consistent with the SDGs' integrated vision of environmental and social well-being. Translating this into policy requires embedding chemical hazard screening in product design regulations, ensuring that materials destined for recirculation meet non-hazardous, traceable, and separable material standards. The challenge lies in correctly identifying hazardous substances as a part of the technical cycle where they should be tracked, contained, and ideally phased out. This is also true for 'bio-based' products, as these are not biodegradable/non-toxic if they contain hazardous substances.



Source: Ellen MacArthur Foundation

The design phase represents the most critical intervention point for chemical safety in circular systems. Decisions about materials, additives, and assembly methods lock in contamination risks or safety benefits for the entire product lifecycle. However, design decisions currently optimize for production cost and performance rather than end-of-life safety, because manufacturers face no liability for downstream contamination. Design for circularity must integrate three core principles: **design for disassembly** (using reversible fasteners and avoiding permanent adhesives to enable material separation), **design for durability** (extending product life to reduce resource throughput), and **design for non-toxicity** (substituting hazardous additives during development rather than attempting remediation during recycling). To ensure safe circularity within chemicals, design for non-toxicity must be prioritized. Only when non-toxicity is guaranteed is it of interest to repurpose and increase the durability of products, so that hazardous substances are not recirculated or emitted during repurposing processes.

The **EU's Ecodesign for Sustainable Products Regulation (ESPR)** exemplifies policy attempts to mandate these principles by requiring minimum durability, repairability, and recyclability standards while restricting hazardous substances (European Commission, 2024a). Yet implementation faces

industry resistance around cost increases and reduced design flexibility, revealing how design-for-circularity mandates threaten production systems optimized around opposite principles. Material passports and digital product information represent essential enabling tools for closing the loop safely, providing documentation of chemical content and disassembly instructions that follow products through their lifecycle. However, proprietary concerns have limited adoption, as manufacturers resist disclosing formulations that they consider trade secrets, creating information asymmetries that prevent safe material management, demonstrating how competitive secrecy blocks the transparency circular systems require. It is advised that policy expand beyond trade-secret barriers, setting requirements for the minimum chemical-content data of a passport, for who is responsible for data provision across the life cycle, and for how the information can be used to sort contaminated waste from clean waste streams. The EU is already underway with enabling this by making digital passports mandatory under the ESPR (European Commission, 2024a). In this way, the ESPR captures the important role of transparency in paving the way for ecodesign products that consider life cycle impacts and avoid hazardous substances ahead of production.

The effectiveness of CE in addressing chemical hazards stems from its preventive logic and examining upstream approaches; it intervenes at the design and production stages before harmful substances enter circulation (Ellen MacArthur Foundation, 2023; Kirchherr et al., 2023):

- **Eliminate waste and pollution**:

By integrating safer design choices from the outset, particularly considering the substitution of hazardous chemicals with safer alternatives, products can be created without toxic additives and with optimized material efficiency. With over 80% of a product's environmental impact determined at the design stage (European Parliament, 2023), this phase offers the greatest leverage for preventing waste and contamination. The risk of regrettable substitution must be emphasized, as replacing one hazardous chemical with another does not offer a solution. This includes considerations across the substitute's entire life cycle such that it does not compromise on other important areas such as product safety, quality, and longevity. Put concretely, an alternative is only an alternative if it does not itself risk unacceptable harm to the environment and human well-being. REACH puts the burden on manufacturers and importers to show that their substances can be used safely ("no data, no market"), and its authorization procedure pushes the substitution of substances of very high concern.

- **Circulate products and materials**:

Practices such as reuse, repair, refurbishment, remanufacturing, and recycling keep materials in use while minimizing the need for virgin chemical production. Designing for disassembly also facilitates safer recycling, reducing the risk of reintroducing hazardous additives into secondary materials. However, these R-strategies reduce virgin demand only when the circulating products are non-toxic. This requires controlled removal of hazardous legacy materials.

- **Regenerate natural systems**:

Circular systems aim to restore ecosystems by replacing synthetic, non-degradable substances with bio-based, non-hazardous, and biodegradable alternatives, where life-cycle analysis has verified reduced environmental and toxicity burden. Through renewable energy use and regenerative

agricultural practices, circularity contributes to long-term soil health, water quality, and biodiversity recovery, supporting SDG 15 (Life on Land) and SDG 14 (Life Below Water).

5.2.1 Circular Economy Across Sectors

Among 715 chemicals identified in **textile production**, 228 are carcinogenic, mutagenic or toxic to reproduction, 322 are skin sensitizers, and 25 are endocrine disruptors (Bour et al., 2023). Persistent chemicals like flame retardants and PFAS also hinder textile recycling, despite their limited functional benefits (Fidra, 2025b). Circular applications in textiles now focus on designing safe materials for recyclability, developing fiber-to-fiber recycling processes that do not perpetuate chemical contamination, and implementing extended producer responsibility (EPR) systems where manufacturers remain accountable for the entire product lifecycle (ibid.). Innovative examples include wool-based fire barriers and inherently flame-resistant materials that achieve safety without hazardous additives (ibid.). Circular business models such as **Mud Jeans' "Lease A Jeans"** and chemical leasing schemes (where suppliers sell a chemical's function rather than its volume) encourage efficiency, transparency, and waste reduction (Circle Economy, 2022; Mud Jeans, n.d.). In textiles, policy could expand EPR to cover all textile sub-sectors, harmonize restrictions on PFAS and other persistent chemicals at regional and global levels, and mandate clear labeling for recycled textiles and textiles free of hazardous chemicals.

Plastics pose significant challenges, as flame retardants in electronic waste complicate recycling and increase costs, while contaminants from secondary plastics often appear in new consumer products like toys or kitchen utensils (Fidra, 2025b). To prevent such contamination at the source, manufacturers should be required to identify and phase out hazardous additives during product design, integrating principles of eco-design that minimize chemical complexity and enhance recyclability. Circular business strategies promote refillable packaging, modular design, and EPR programs to recover materials safely (Closed Loop Partners, n.d.). Companies such as **ReSolved Technologies** offer closed-loop plastic recycling solutions by separating different types of plastics and removing additives, including legacy additives, enabling material recycling for the same type of product use (StartUs Insights, 2023). Ensuring accountability and transparency across the value chain (through public disclosure of chemical content, traceability systems, and third-party verification) would further strengthen these efforts. Governments could set mandatory recycled-content targets, ban intentionally added microplastics, and require chemical-safety assessments within national plastics action plans under United Nations Environment Assembly (UNEA) and related commitments. When recycling infrastructure cannot distinguish contaminated from clean material streams, circular economy goals may conflict with chemical safety. Currently, secondary materials typically contain more concentrated and more diverse chemicals than virgin materials (EEA, 2022). This is a technical limitation which suggests that certain contaminated plastics may need controlled removal from circulation rather than perpetual recycling, to decontaminate material stocks. Therefore, policymakers need to establish explicit hierarchies that prioritize safety over waste diversion when the two objectives cannot be simultaneously achieved.

The **construction sector** faces difficulties due to hazardous substances in demolition waste which hinder safe material recovery (Ahkola et al., 2024). The **NonHazCity 3 project** offers a model for local-level collaboration by developing criteria for "tox-free, circular, and climate-friendly buildings" tailored to decision-making processes at public authority levels (Ismail et al., 2024). Through

multi-stakeholder engagement, the project engages municipalities, builders, and residents, emphasizing sustainable practices involving non-toxic, low-carbon, and recyclable materials. To scale this approach, building codes should incorporate tox-free criteria, environmental product declarations (EPDs) should be mandatory for construction materials, and circularity certification should be a condition for public building contracts. Construction industries operate under competitive pressures and thin profit margins where voluntary safety improvements prove economically challenging without regulatory mandates. The sector's fragmented structure, with numerous small contractors competing primarily on price, creates collective action problems where individual firms cannot afford safety investments that competitors avoid, necessitating regulatory floors that apply universally rather than relying on market-driven voluntary adoption.

In **agriculture**, circular bioeconomy models can maintain productivity while phasing out synthetic chemical inputs. This is possible through closed-loop nutrient cycling, converting organic waste into compost and biochar to replace synthetic fertilizers, using integrated biological systems for natural pest management, and implementing soil health restoration practices (Fidra, 2025b; Khanna et al., 2024). Circular business models foster resource sharing among farmers and create local exchange platforms for surplus produce, reducing food waste and promoting regional resilience (Saxena et al., 2025). To ensure long-term adoption, education and training programs should equip farmers with knowledge of regenerative and circular practices, emphasizing soil stewardship, biodiversity enhancement, and low-input farming techniques. These practices align with SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production), integrating food security with ecological integrity. Policymakers should support circular agriculture through targeted incentives for nutrient recovery infrastructure, subsidies for on-farm composting and biochar production, and differential taxation that discourages persistent agrochemicals. The transition to circular agriculture faces a temporal challenge. Conversion periods of 3-5 years often show yield reductions as soil ecosystems recover, creating financial pressure that can force farmers back to conventional methods before benefits materialize. Farmers operating under debt and year-to-year income variability struggle to absorb interim productivity losses, requiring transition support that compensates for temporary yield reductions rather than merely providing information about eventual outcomes.

5.2.2 Chemical Safety and Policy Integration

Implementing circularity requires adherence to the waste hierarchy (prevention, reduction, reuse, recycling, recovery, and disposal) (University of Exeter, 2024). For hazardous chemicals, upstream prevention and reduction at the source are the only safe tiers of the hierarchy, as downstream recycling and recovery risk perpetuating contamination through material loops, therefore conflicting with the higher-priority goal for eliminating toxic exposure. Despite this awareness, only a small proportion of hazardous substances are currently regulated within the EU (Johansson, 2022), leaving waste facilities to manage complex chemical burdens often beyond their technical capacity. Policy coordination is thus needed here: there must be an integration of chemicals and waste legislation (for example, aligning REACH with waste frameworks), standardization of contaminant thresholds and an expansion of monitoring capacity at treatment facilities. It is also necessary to shift the burden of proof toward manufacturers to demonstrate safety rather than regulators proving harm across markets.

Achieving true circularity requires preventing hazardous chemicals from entering material cycles in the first place, which requires implementing robust source control measures that prevent harmful substances from entering systems and reducing the burden on treatment facilities. **Batch.Works** exemplifies source-control circularity through traceable recycled materials, digital on-demand manufacturing, and short supply chains (StartUs Insights, 2023). The food sector shows similar applications through **Circular Food**'s patented technology that converts by-products of distillation and fermentation processes into flours, turning waste into a resource (ibid.). NGOs like CHEM Trust warn, however, that circularity must remain "clean" and free from toxic exposure, urging regulators to close loopholes that permit higher contaminant thresholds in recycled materials (CHEM Trust, n.d.). To protect public health and market trust, governments should set legally binding contaminant limits for recycled materials, maintain national non-hazardous material registries, and require digital traceability (product passports) for high-risk material streams. Progress toward chemical-safe circularity relies on multi-stakeholder collaboration. Participatory governance, financing mechanisms, and industrial coordination are essential to scaling innovation and compliance (Dam et al., 2025). **Industry symbiosis** provides practical evidence of how collaboration can accelerate circularity: through a "Sustainable Synergies" project in Denmark, 25 companies exchanged surplus materials to reduce waste and procurement costs while generating new revenue streams, and contributed to an annual reduction of GHG emissions by an estimated 10,000 tonnes of CO_2 (State of Green, 2017). Likewise, the **European Chemical Industry Council** promotes joint screening of toxic substances, standardized safe production, and harmonized recycling practices (Weetman, 2025). National governments should convene public-private platforms to share material-flow data, co-fund R&D on safe recycling technologies and align national standards with international chemical-safety frameworks. Multi-stakeholder collaboration offers benefits but also raises governance questions about representation and decision-making authority. Industry participants often possess technical expertise and implementation capacity that make their involvement essential, yet they also have commercial interests that may conflict with stringent safety standards. Effective collaboration requires structures that balance industry input with independent oversight and meaningful participation from affected communities.

5.2.3 Challenges

Despite its potential, the circular economy faces persistent and interlinked obstacles. As previously discussed for plastics, a central challenge lies in the persistence of hazardous substances that create toxic recycling loops, where chemicals like flame retardants, PFAS, and bisphenols contaminate recycled materials, reducing their safety and economic value (Fidra, 2025b). Removing these substances is often technically and economically unfeasible, so secondary materials frequently contain higher concentrations and a greater diversity of chemicals than virgin ones (EEA, 2022). One study found that PFAS concentration was twice as high in recycled plastics as in virgin material (Daggubati et al., 2025). These loops exemplify the paradox of circularity: without rigorous chemical control and non-toxic-by-design, recycling can inadvertently amplify rather than mitigate exposure risk, thus removing the circular benefit. For instance, plastics can contain over 6,000 different chemicals, with many additives creating contamination issues during recycling (Johansson, 2022). Legacy chemicals (such as substances now banned but still present in older products) pose a particular challenge, as they re-enter material flows through recycling. These contaminants undermine both the credibility and the feasibility of circular systems by

preventing safe reuse and diminishing market confidence in recycled goods (ibid.). For certain contaminated streams, responsible policy may require controlled disposal rather than perpetual recycling, acknowledging that some materials represent accumulated contamination that should be removed from circulation rather than continuously reprocessed. This should then be avoided for future products through mindful and preventative design.

Beyond chemistry, systemic obstacles impede adoption. Many hazardous substances perform critical industrial functions, and identifying cost-effective, high-performance, and safe substitutes remains a challenge. For example, the shift from BPA to BPS in plastics and food packaging, as BPS has a similar structure but is less regulated, still allows a hazardous substance to enter circulation, a case of regrettable substitution (Fidra, 2025b; Moon, 2019). These failures do not stem from a lack of conceptual clarity about substitution, but from economic incentives and regulatory gaps that reward performance rather than inherently safer redesign. Without stronger regulatory requirements for hazard-based substitution, circular systems risk locking in new generations of hazardous chemicals that continue to contaminate recycled streams. Economic barriers are significant: transitioning to circular production requires upfront investment in R&D, infrastructure, and monitoring systems, with benefits accruing only in the long-term. Small and medium-sized enterprises in particular struggle with limited access to capital and technical capacity. Information asymmetry is another major bottleneck. Most supply chains lack comprehensive traceability of chemical content, particularly for complex imports, leading to a blind spot that perpetuates contamination. Infrastructure constraints compound this issue; many recycling plants were built for volume throughput, and for single-component materials, rather than chemical control, lacking the detection technology needed to ensure purity (Lubongo & Alexandridis, 2022). Finally, fragmented governance undermines consistency. Regulatory frameworks for chemicals, waste, and recycling are often misaligned, and some jurisdictions even allow higher contaminant thresholds in recycled materials than in virgin products (OECD, 2026). This kind of policy contradiction can erode public confidence in circularity. Overall, policy needs to distinguish genuine technical barriers from economic and institutional ones: the former require innovation support, while the latter demand regulatory intervention to level competitive conditions between hazardous and safer alternatives.

In short, while the circular economy provides a powerful framework for keeping safer materials in use, achieving it in practice demands overcoming deep-rooted technical, economic, and institutional barriers. Moving forward will require clean inputs from green chemistry, clear incentives, stronger data systems, and coordinated regulation to make chemical safety and circular growth work hand in hand.

5.3 Supply Chain Transparency and Traceability

Supply chain transparency and traceability have emerged as critical mechanisms for moving industrial sectors beyond hazardous chemicals. **Transparency** refers to the open disclosure of information about production processes, materials, and chemical inputs, while **traceability** encompasses the ability to track these elements across a product's entire lifecycle, from raw material extraction to end-of-life management. Together, they form the backbone of responsible production and consumption, directly contributing to SDG 8 (Decent Work and Economic

Growth), SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 16 (Peace, Justice and Strong Institutions). Moreover, by optimizing resource flows and reducing waste, transparent supply chains indirectly support the Paris Agreement's mitigation objectives, and strengthen accountability, empower consumers, and ensure that the shift toward circularity is also a shift toward safety. Transparency is thus the foundation from which necessary policy can be enforced. Transparency also underpins market confidence in recycled goods, which contaminants otherwise erode (Johansson, 2022).

5.3.1 Textile Industry

The textile industry presents a particularly complex challenge for supply chain transparency due to its fragmented, multi-tiered structure spanning numerous countries and subcontractors (Schaëfer et al., 2025). Traceability mechanisms are needed to monitor the entire lifecycle of chemicals (from fiber cultivation and dyeing to finishing, distribution, and recycling) ensuring that hazardous substances are identified and replaced with safer alternatives at every stage. Such systems reinforce environmental stewardship while enhancing accountability and building consumer trust.
Effective chemical management begins with traceability mechanisms at the manufacturing stage. Digital chemical management platforms, enhanced by blockchain technology, now document the origin, composition, and flow of chemicals, enabling manufacturers, regulators, and consumers to verify compliance and ensure products are free from hazardous materials (Agrawal et al., 2021; Badhwar et al., 2023; Turker & Altuntas, 2014). Life Cycle Assessments (LCAs) complement these systems by guiding procurement decisions toward lower-impact formulations. Transparency extends to fiber and material sourcing. Supply chain traceability encourages the use of biodegradable fibers such as jute, kenaf, abaca, and linen, which require minimal chemical treatment (Elfaleh et al., 2023). Their traceability is enhanced through digital tagging and third-party audits verifying eco-friendly cultivation and processing practices (Cobbing & Ruffinengo, 2013). Similarly, advances in natural dye innovation (such as biotechnology-based dyes derived from plants, fungi, and microorganisms) are increasingly adopted thanks to complete tracking systems that guarantee the exclusion of harmful synthetic chemicals (Fried et al., 2022). Companies like **Colorifix** exemplify this shift by developing microorganism-based dyeing processes with full digital documentation of environmental performance (Colorifix, n.d.). At the processing stage, traceability systems monitor the replacement of chlorine-based bleaches with oxygen-based or enzymatic treatments (Loi et al., 2021; Shen & Smith, 2015) and the phase-out of PFAS through verification of fluorine-free hydrophobic coatings (Holmquist et al., 2016; Singh et al., 2023). Traceable supply chains also confirm substitution of toxic phthalates with bio-based plasticizers from vegetable oils and citric acid (Sun et al., 2024). End-of-life traceability is increasingly integrated into textile systems. Take-back schemes and recycling programs now record fiber composition and chemical treatments, allowing for safer material recovery and reuse. Advanced sorting technologies such as near-infrared spectroscopy and radio frequency identification (RFID) systems enable accurate fiber identification and track chemical content through to end-of-life (Piribauer & Bartl, 2019; Subic et al., 2012). Under the revised Waste Framework Directive, all EU Member States must set up textile EPR schemes by 17 April 2028 (separate collection of textiles has been mandatory since 1 January 2025); producers will have to finance the collection, sorting and recycling of textiles, with fees modulated according to ecodesign criteria such

as durability and recyclability (Directive (EU) 2025/1892). **Lenzing's** blockchain-based system for Tencel™ fibers tracks every step from sustainably managed forests to finished garments, ensuring environmental compliance at every stage (Ioveva & Winkelmeier, 2020).

Governments and industry alliances should provide financial incentives and technical support for small and medium-sized textile producers to adopt digital chemical management platforms and blockchain tracking systems. Standardized reporting formats and internationally recognized certification schemes should be promoted to ensure interoperability across borders. Policymakers could also mandate periodic third-party audits to verify supplier compliance with chemical safety and sustainability standards. These collective actions are vital to improve transparency and traceability.

5.3.2 Plastics Industry

In the plastics industry, transparency and traceability face distinct challenges arising from the chemical complexity of polymer formulations. Unlike surface treatments in textiles, most hazardous additives in plastics are physically mixed into, not chemically bound to, the polymer matrix, so they can migrate out, yet they remain hard to identify and extract (Logan et al., 2024). Achieving transparency therefore requires systems capable of monitoring chemical inputs throughout polymer synthesis, compounding, and end-of-life stages.

To address this, **Extended Producer Responsibility (EPR)** mechanisms increasingly demand that manufacturers disclose complete additive inventories to enable safer recycling and limit toxic recirculation in circular material flows. **Material Flow Analysis (MFA)** and digital product passports help identify points where hazardous substances can be replaced before polymers enter the market. These systems are essential because plastics recycling often reintroduces legacy contaminants from products manufactured under outdated standards, undermining trust in circular models (Johansson, 2022; Wang et al., 2024). Transparency-driven progress is visible in several initiatives. Manufacturers have phased out cadmium-based PVC stabilizers in favor of calcium-zinc stabilizers (Li et al., 2022; Nimbasia Stabilizers, 2024). Vegetable oil- and citric acid-based bio-plasticizers now replace phthalates, with audits ensuring that final products are free of endocrine-disrupting properties (Singh et al., 2023). For polycarbonate plastics, tracking systems follow BPA-free innovations such as Tritan copolyester and lignin-derived bio-based polycarbonates, while recycling plants use digital traceability to separate BPA-containing materials and prevent contamination of recycled streams (Kaszubska, 2022). Similarly, silicone- and bio-based coatings for non-stick and grease-proof uses are verified through transparency frameworks that confirm performance and PFAS-free composition (Daken Chemical, 2024).

To test how transparency tools shape consumer trust and mitigate greenwashing, the Spanish pilot of the BELOOP project, in collaboration with retailer EROSKI, is evaluating consumer responses to bio-based food packaging. By embedding Digital Product Passports (DPPs), clear claims, and harmonized shelf-level signage, the pilot assesses whether transparent material disclosures help consumers distinguish genuine circular properties from vague marketing terms, correct disposal errors, and build lasting market confidence.

Regulators should require full disclosure of additive inventories and encourage the development of standardized digital product passports or ecolabels to facilitate safe recycling and prevent

legacy contaminant recirculation. Subsidies or tax credits could be offered to companies adopting bio-based and non-toxic polymers, helping offset higher production costs and incentivizing transparent practices. International cooperation should harmonize additive safety standards and reporting protocols to prevent hazardous substances from entering global recycling streams.

5.3.3 Construction Industry

The construction sector faces unique transparency challenges because building materials remain in use for decades or centuries, making documentation a long-term governance issue rather than a short-term compliance task (Wahlström et al., 2019). Paints, insulation, concrete additives, sealants, and plumbing materials can all contain hazardous substances that remain hidden for generations (ibid.; Ahkola et al., 2024).

Achieving transparency therefore requires not only traceability at the point of production but also systems that preserve chemical information over time through instruments like **Health Product Declarations (HPDs) and Environmental Product Declarations (EPDs)**. HPDs provide standardized disclosure of a product's chemical ingredients, associated health hazards, and compliance with safety benchmarks, allowing architects and contractors to make informed material selections. EPDs, meanwhile, quantify a product's environmental impact, such as carbon footprint, resource use, and emissions, based on a verified life cycle assessment, enabling comparison between different materials. Furthermore, digital material passports are emerging, integrating HPD and EPD data into a centralized digital format, and ensuring that information on chemical composition, recyclability, and maintenance requirements is retained and accessible across decades (HPDC, n.d.; UKGBC, n.d.). Blockchain-enabled tracking now verifies the elimination of lead-based pigments, while third-party certifications confirm the safety of polymeric or bio-based coatings (Gottesfeld, 2015; British Coatings Federation, n.d.). Similarly, transparency frameworks document the sourcing and fire-safety performance of cellulose fibers replacing asbestos, ensuring traceable compliance with emission and recycling standards (GreenFiber, 2024; Selby, 2024). These documentation systems ensure both worker safety and long-term building performance.

VOC emissions from adhesives and sealants are increasingly tracked through transparent supply chains; firms such as **Bostik** provide full digital records linking plant-based solvent sourcing to final application (Bostik, n.d.). Such transparency ensures that environmental and occupational health standards are upheld while facilitating procurement policies that favor low-emission, verifiably sustainable products. Broader certification frameworks such as **Cradle to Cradle Certified®** expand this logic, requiring detailed material health disclosure and continuous phase-out planning for hazardous substances (C2C Certified, n.d.). Authorities should mandate long-term chemical documentation through HPDs, EPDs, and digital material passports for all new building materials. Public procurement policies can favor contractors and manufacturers with verifiable supply chain transparency and low-toxicity certifications. Policies should also support the integration of digital traceability infrastructure to maintain material records over extended building lifespans.

5.3.4 Agriculture Industry

In agriculture, transparency and traceability ensure that food production is both safe and ecologically sound, addressing SDG 2 (Zero Hunger), SDG 12, and SDG 15 (Life on Land). Unlike fixed industrial facilities, agriculture operates across dispersed landscapes, complicating oversight (Khursheed

et al., 2022). Effective transparency therefore requires "farm-to-fork" systems tracking every chemical input (from fertilizers and pesticides to soil conditioners and irrigation aids) throughout their lifecycle (European Commission, 2020; Farmonaut, n.d.).

Biofertilizers based on nitrogen-fixing microorganisms and phosphorus-solubilizing bacteria are now tracked from microbial cultivation to field application through certified systems that ensure they contain no synthetic additives or heavy metal contaminants (Daniel et al., 2022). Such traceability frameworks also guarantee that these products enhance soil fertility without leaving toxic residues, promoting long-term soil regeneration. In cases of heavy metal contamination, traceability extends to monitoring chelating agents and biodegradable polymers used for remediation. The use of genetically modified plants and soil microbes is documented from deployment through post-restoration verification, ensuring accountability and ecological safety (Yin et al., 2024; Rebello et al., 2021). Advanced monitoring tools such as Internet of Things (IoT) sensors, satellite monitoring and digital ledgers can now provide real-time information on chemical application rates and runoff (Digital Matter, 2025; Rajak et al., 2023). Transparency is equally critical in pesticide management, where biopesticides derived from natural sources offer safer alternatives to conventional chemicals. Supply chain systems verify the purity, origin, and environmental degradability of these substances, ensuring they pose minimal risk to non-target organisms such as pollinators and soil fauna (Ayilara et al., 2023; Mawcha et al., 2025; Prabhu et al., 2025). Audits monitor every step of the process ensuring both product efficacy and ecological integrity (Kilani-Morakchi et al., 2021; Ozone Biotech, 2025; Singh & Chaturvedi, 2013). Collectively, these transparent practices not only reduce chemical hazards but also foster consumer confidence in sustainably produced agricultural goods.

5.3.5 Challenges

Despite notable progress, achieving full transparency and traceability across industries remains constrained by a combination of technical, economic, and institutional barriers. In the textile sector, the complexity of multi-tier supply chains limits visibility beyond first-tier suppliers, especially where subcontracting is widespread (Jones, 2024). Chemical suppliers often resist full disclosure for intellectual property reasons, while cost barriers restrict adoption of digital systems among small and medium-sized enterprises that dominate production in developing countries. The absence of standardized data formats and terminologies further complicates interoperability between traceability platforms (Agrawal et al., 2021). Finally, ensuring accuracy of self-reported supplier data remains difficult without robust, resource-intensive third-party auditing, particularly in regions lacking regulatory oversight (Textile School, 2025).

In the plastics industry, the complexity of additive chemistry remains a structural barrier to full transparency. Plastic formulations may contain dozens of additives making complete disclosure difficult even for cooperative suppliers. Analytical detection limits add to this challenge, as trace quantities of hazardous chemicals can persist undetected. Moreover, global recycling flows mix polymers from jurisdictions with differing regulatory standards, enabling contaminants to cross borders through trade in recycled materials (Houssini et al., 2025). Furthermore, verified hazard-free polymers often cost more than conventional materials, disincentivizing transparency. The construction sector faces unique challenges due to its fragmented and project-based nature. Long and multi-layered subcontracting chains disrupt documentation continuity (Yoshimura,

n.d.). Information decay occurs as records are lost or outdated over long building lifespans (Wahlström et al., 2019). Regulatory hurdles, especially lengthy fire-safety testing for bio-based materials, and price sensitivity in procurement further delay adoption (Cook et al., 2022; Lee et al., 2024; Wu et al., 2021). Transparency frameworks remain dependent on strong regulatory alignment, market incentives, and digital infrastructure that can sustain chemical traceability over entire building lifecycles (UKGBC, n.d.).

In agriculture, transparency is hindered by the decentralized nature of farming and the dominance of informal markets (Bökle et al., 2024; Gavai et al., 2025; Jouanjean et al., 2020; Marie, n.d.). Environmental variability (differences in soil, temperature, and rainfall) complicates data comparability. Legacy contamination from historical pesticide use also obscures source attribution. Finally, biological products' performance can vary under different environmental conditions, making it challenging to establish uniform verification protocols. Overcoming these constraints will require investments in digital monitoring tools, farmer training, and cooperative platforms that balance scientific precision with accessibility. By addressing these barriers, transparency in agriculture can evolve from a compliance mechanism into a cornerstone of ecological restoration and sustainable food production.

Across all sectors, jurisdictional inconsistencies continue to generate compliance burdens and regulatory loopholes that allow hazardous substances to circulate through less regulated markets. Even where data are technically public, information asymmetries persist due to language barriers, cost, and complexity. Developing countries face particular challenges from limited technical capacity and enforcement, perpetuating global inequities in chemical safety. Training programs should equip informal workers and farmers with skills to implement and maintain transparent records, while cooperative platforms can facilitate data sharing and verification. Policy frameworks should incentivize the adoption of certified products, ensuring environmental safety and consistency in product performance. Transparency and traceability now define how trust is built between producers and consumers. Technologies like blockchain and digital tagging aim to open once-opaque supply chains, allowing people to see not only where products come from, but what they contain. Still, the challenge ahead lies in using technology not just to reveal, but to create systems where traceability proves that safer, cleaner production is more than a promise.

5.4 International and Collaborative Frameworks

Collaborative approaches are essential mechanisms for moving industrial supply chains beyond hazardous chemicals, recognizing that chemical management challenges transcend organizational, sectoral, and national boundaries. These multi-stakeholder initiatives unite governments, industries, civil society, academia, and international institutions to develop shared standards, pool expertise, and coordinate implementation. Together, they translate scientific understanding into practical governance and ensure that sustainable chemical management advances collective global goals. Such cooperation reflects the spirit of SDG 17 (Partnerships for the Goals) by fostering multi-stakeholder collaboration necessary for achieving sustainable development, while simultaneously advancing SDG 12 (Responsible Consumption and Production) through coordinated chemical safety action. The necessity for collaborative frameworks also reflects the WHO's

One Health paradigm, which recognizes that human health, animal health, and environmental health are fundamentally interconnected. Chemical contamination that degrades ecosystems simultaneously threatens human populations through the biological and hydrological systems linking them, requiring integrated governance that addresses health holistically rather than through siloed sectoral approaches (WHO, 2023).

5.4.1 Sectoral Collaboration and Industry Initiatives

5.4.1.1 Textile Industry

The **Zero Discharge of Hazardous Chemicals (ZDHC)** stands as the most comprehensive multi-stakeholder organization in the textile sector, encompassing brands, suppliers, solution providers, and chemical producers and service providers. Unlike traditional certification systems, ZDHC represents a coordinated governance model that unites private and public actors under a shared policy framework for global chemical phase-out. Its **Roadmap to Zero Program** aims to eliminate harmful chemicals including phthalates, PFAS, heavy metals, and VOCs from the global textile value chain (ZDHC, 2021). The **Manufacturing Restricted Substances List and ZDHC Gateway Platform** provide standardized criteria and digital tools to verify compliance and share formulation data, enabling chemical transparency and reducing duplicative testing efforts (ZDHC, n.d.). Complementing ZDHC, the **Bluesign® System** applies an **Input Stream Management** approach, targeting hazardous substances such as heavy metals, fluorinated compounds, and phthalates at the earliest production stages (Bluesign, n.d.). By certifying inputs rather than end products, Bluesign shifts responsibility upstream, incentivizing chemical suppliers to redesign products according to ecological criteria. The **European Apparel and Textile Confederation (EURATEX)** represents industry interests while aligning with **EU REACH** regulation, focusing on eliminating hazardous chemicals including PFAS, phthalates, and heavy metals from textile supply chains (EURATEX, n.d.). Initiatives like the BizNGO network of **Clean Production Action (CPA)**, **ChemSec's Marketplace and the Ellen MacArthur Foundation's Make Fashion Circular** Initiative collectively promote safer material innovation and circular design principles (ChemSec, n.d.; CPA, n.d.; Ellen MacArthur Foundation, 2022). These collaborative platforms embody SDG 17's emphasis on knowledge-sharing and technology transfer, while their focus on eliminating toxic substances supports SDG 3 and SDG 12.

Despite these successes, challenges persist. Many small and medium-sized suppliers, particularly in developing countries, lack resources to participate fully in voluntary initiatives. Power asymmetries within supply chains mean that costs and risks of chemical substitution often fall disproportionately on suppliers with limited profit margins. Geographic fragmentation complicates collaboration, as production stages may occur across numerous countries with varying regulatory environments.

5.4.1.2 Plastics Industry

Collaboration in the plastics sector is expanding through initiatives such as the **Circular Design Challenge**, a platform where designers and innovators develop products based on principles of recyclability, safe reuse, and the elimination of toxic additives (Circular Design Challenge, n.d.). The **Plastics Pact Network**, jointly led by the Ellen MacArthur Foundation and the Waste and Resources Action Programme (WRAP), now operates in 19 countries with participation from over

900 organizations worldwide. According to the 2024 Scaling Impact report, the global Pacts have eliminated more than 360,000 tonnes of problematic and unnecessary plastics, redesigned over 850,000 tonnes of packaging to be reusable, recyclable, or compostable, increased recycling rates by 9%, and achieved a 44% rise in recycled content, avoiding 2.2 million tonnes of virgin plastic use (Ellen MacArthur Foundation, 2024; WRAP, 2024). The **Business Coalition for a Global Plastics Treaty,** comprising over 250 businesses and financial institutions, amplifies this momentum by advocating for a legally binding international agreement to curb hazardous additives and standardize chemical safety across the plastics value chain (Business Coalition for a Global Plastics Treaty, n.d.). In March 2022, the UNEA agreed to a resolution to negotiate an internationally binding instrument to end plastic pollution by addressing its full life cycle, and established the **Intergovernmental Negotiating Committee (INC) on Plastic Pollution** (UNDP, n.d.). Similarly, the **European Chemical Industry Council (CEFIC)** encourages safe chemical management within the plastic sector through collaboration with regulators, industry players, and environmental organizations, supporting the development of legislation to eliminate hazardous material use in plastic products (CEFIC, n.d.).

However, limitations include the sector's global scope and product diversity creating coordination challenges. Legacy additives in recycled plastics pose persistent problems, as collaborative initiatives focusing on virgin plastic production cannot fully address contamination from historical production. Economic pressures toward low-cost production also create tensions between voluntary commitments and competitive pressures.

5.4.1.3 Construction Industry

The **Health Product Declaration Collaborative (HPDC)** standardizes disclosure of chemical ingredients in building materials, providing **Health Product Declarations (HPDs)** that inform architects, engineers, and clients about product composition and potential hazards (HPDC, n.d.). Integration of HPDs into **Building Information Modeling (BIM)** enhances transparency throughout design and procurement processes. The **Construction Industry Research and Information Association (CIRIA) and Toxics Use Reduction Institute (TURI)** promote collaborative research to minimize hazardous chemical use, such as asbestos, PCBs, and VOCs, while the **Construction Innovation Hub** accelerates the development of low-carbon, recyclable, and bio-based materials (CIRIA, n.d.; Construction Innovation Hub, n.d.; RSK Group, 2024; TURI, 2024). Collectively, these initiatives illustrate how collaborative governance can embed safety and sustainability within the construction industry's innovation ecosystem. Yet structural constraints persist. The sector's project-based nature and procurement systems that prioritize lowest-cost bids often discourage transparent and innovative materials. The slow diffusion of new technologies, combined with conservative risk cultures, delays widespread adoption. Long building lifespans also complicate feedback loops needed to update material safety practices.

5.4.1.4 Agriculture

The **Sustainable Agriculture Initiative (SAI) Platform** is a global coalition that promotes chemical reduction and ecological farming by bringing together producers, retailers, and food companies (SAI Platform, n.d.). Through its **Farm Sustainability Assessment (FSA)** tool, the platform evaluates environmental performance, encouraging adoption of **Integrated Pest Management (IPM)**, organic practices, and regenerative approaches that improve soil health and biodiversity

(ISCC, 2024). **Fairtrade International** advances this work by training smallholder farmers to adopt natural pest control, composting, and organic fertilization, linking chemical safety with market incentives for sustainably certified products (FairTrade, n.d.; Kutaula et al., 2022). The **Regenerative Agriculture Alliance** complements these efforts by promoting cover cropping, crop rotation, and composting, thereby strengthening soil structure and microbial diversity while reducing dependence on synthetic pesticides and fertilizers (Regenerative Agriculture Alliance, n.d.; UFA, 2022). These agricultural collaborations advance SDG 2 (Zero Hunger), SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), and SDG 15 (Life on Land) by demonstrating that food security and ecosystem health are mutually reinforcing goals. These agricultural collaborations also exemplify One Health principles in practice. By reducing pesticide use, they simultaneously protect farmworker health, preserve pollinator populations essential for crop production, prevent water contamination affecting downstream communities, and maintain soil microbial communities that sustain long-term agricultural productivity.

Agricultural collaborations face unique challenges. Smallholder farmers, who constitute the majority globally, often lack access to training, resources, and markets necessary for transitioning to less chemical-intensive practices. Agroecological knowledge is often location-specific, complicating universal guidance across diverse climates and soils. Agricultural extension services may lack expertise in alternative methods. Price volatility creates economic uncertainty discouraging long-term investments in soil health and ecosystem restoration.

5.4.2 Global and Regional Regulatory Frameworks

Achieving chemical safety and circularity at scale depends on coherent international governance that aligns policy, science, and markets. A constellation of global conventions and frameworks forms the foundation of this governance architecture, operationalizing SDG 17 through binding or voluntary commitments and shared institutional mechanisms.

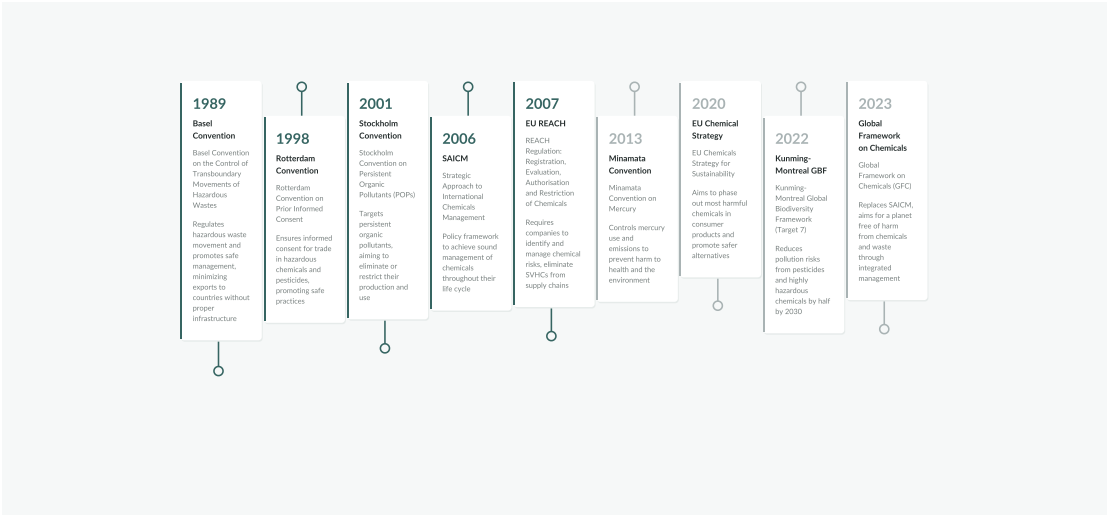


Figure 16: Key International Frameworks for Moving Supply Chains Beyond Hazardous Chemicals

At the global level, the **Basel (1989)**, **Rotterdam (1998)**, and **Stockholm (2001)** Conventions (often referred to as the BRS Conventions) create a coordinated system for managing hazardous chemicals and waste. The **Basel Convention** governs transboundary waste movements, requiring prior informed consent and environmentally sound management (Basel Convention, 1989). The

Rotterdam Convention strengthens trade transparency through its Prior Informed Consent (PIC) procedure, under which importing countries decide whether to accept chemicals listed in Annex III, and through export notification, under which exporting countries must notify importing countries before exporting chemicals they have banned or severely restricted (Rotterdam Convention, 1998). The **Stockholm Convention on Persistent Organic Pollutants (POPs)** complements these by targeting long-lived toxic chemicals such as dioxins, PCBs, and certain pesticides. Collectively, the BRS Conventions operationalize the principle of shared responsibility and advance SDG 12 (Responsible Consumption and Production) and SDG 17 (Partnerships for the Goals). However, the effectiveness of conventions requiring "prior informed consent" and "environmentally sound management" depends critically on the capacity of recipient countries to evaluate risks and enforce standards. Asymmetries in technical expertise and regulatory resources mean that formal consent procedures can become pro forma approvals rather than genuine informed decisions.
Other global instruments expand this scope. The **Minamata Convention on Mercury (2013)** phases out or restricts listed mercury-added products and processes, phases out primary mercury mining, and requires countries with artisanal gold mining to reduce and, where feasible, eliminate mercury use. The **Montreal Protocol (1987)**, and its **Kigali Amendment (2016)**, remains exemplary in demonstrating how binding commitments, scientific consensus, industry cooperation, and equitable financing through the Multilateral Fund can deliver measurable results in global chemical phase-out. Its universal ratification and adaptive governance model provide a template for addressing complex chemical challenges (UNEP, 2025). The Montreal Protocol's success offers critical lessons: universal participation required financial mechanisms (Multilateral Fund) that funded developing country transitions rather than expecting voluntary compliance. Clear alternatives existed and were supported through technology transfer, and the atmospheric science of ozone depletion provided unambiguous evidence linking emissions to harm. Replicating this success for chemicals like PFAS faces greater challenges: more diffuse causal pathways, incumbent industry resistance, and insufficient transition financing, suggesting that Montreal's governance architecture alone cannot guarantee similar outcomes without addressing these structural differences.

The **Strategic Approach to International Chemicals Management (SAICM)**, adopted in 2006, initiated global cooperation on chemical lifecycle governance, promoting lifecycle management and capacity building in over 100 countries. Its successor, the **Global Framework on Chemicals (GFC)**, adopted in 2023, envisions "a planet free of harm from chemicals and waste," establishing 28 targets across pollution prevention, transparency, and innovation (UNEP, 2023b). Supported by the Bonn Declaration and GFC Implementation Fund, it calls for phasing out highly hazardous pesticides in agriculture by 2035, where their risks are not managed and safer, affordable alternatives exist, and enhancing capacity-building in developing regions. ICCM5 endorsed the formation of a **Global Alliance on Highly Hazardous Pesticides (GAHHP)** in 2023, and in 2024 UNEA invited countries and stakeholders to join it. The GAHHP will work to achieve the strategic objectives under the GFC related to HHPs, with specific reference to **Target A7**, which states that stakeholders have taken effective measures to phase out highly hazardous pesticides in agriculture by 2035, where the risks have not been managed and where safer and affordable alternatives are available, and **Target D5**, that by 2030, governments implement policies and programs to increase safer and more sustainable agricultural practices (United Nations, 2025).

Parallel frameworks, such as the **Kunming-Montreal Global Biodiversity Framework (GBF), link** chemical governance to ecosystem health, particularly through **Target 7**, which mandates reducing pollution from pesticides, plastics, and hazardous chemicals to non-harmful levels, and **Target 15**, requiring corporations to disclose biodiversity impacts (CBD, 2023). This integration between chemical safety and biodiversity marks a critical shift toward systemic environmental governance, though national implementation remains uneven. The GBF's integration of chemical pollution with biodiversity targets represents institutional recognition of One Health principles: that ecosystem degradation from chemicals directly threatens human health through disrupted food systems, compromised water quality, and diminished natural disease regulation.

The **Globally Harmonized System of Classification and Labelling of Chemicals (GHS)**, developed by the United Nations, provides the foundational framework for standardizing chemical hazard communication worldwide. By establishing consistent criteria for classifying chemicals according to their health, environmental, and physical hazards, and standardizing labeling and safety data sheet requirements, the GHS facilitates international trade while protecting workers, consumers, and the environment (UNECE, n.d.). The **Organisation for Economic Co-operation and Development (OECD) Chemicals Program** complements the GHS by developing internationally agreed test guidelines and assessment methodologies that reduce duplicative testing, promote animal welfare, and accelerate the evaluation of chemical safety. These technical harmonization efforts reduce barriers to safer chemical innovation and support developing countries in building regulatory capacity (OECD, n.d.).

At the regional level, the European Union has advanced a cohesive regulatory model through its **Chemicals Strategy for Sustainability** (2020) and **REACH Regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals).** Under REACH, SVHCs on the Candidate List trigger information duties, and those placed on the Authorisation List can be used only if authorized, which requires showing that risks are adequately controlled or that benefits outweigh risks and no suitable alternative exists, creating a strong incentive for substitution. The **RoHS Directive** complements REACH by restricting lead, mercury, cadmium, and certain flame retardants in electronics, ensuring safer recycling streams. The **Classification, Labelling and Packaging (CLP) Regulation**, aligned with the above-mentioned **Globally Harmonized System (GHS)**, standardizes hazard classification and labeling (European Commission, 2023). Together, these instruments operationalize the "Safe and Sustainable by Design" (SSbD) approach and serve as models for regulatory harmonization worldwide (Abbate et al., 2025; Cefic, 2022; Esko, 2025). REACH's reversal of burden of proof (requiring manufacturers to demonstrate safety rather than regulators proving harm) represents a fundamental shift in regulatory philosophy. Its effectiveness depends on adequate assessment capacity and political will to restrict substances when evidence remains incomplete.

In the United States, the **Toxic Substances Control Act (TSCA)** and EPA's voluntary **Design for the Environment (DfE)** program, now Safer Choice, evaluate substitutes across multiple endpoints, preventing regrettable substitutions and promoting transparency (US EPA, 2013b; Jacobs et al., 2016). The **Emergency Planning and Community Right-to-Know Act (EPCRA**) established the **Toxics Release Inventory (TRI)**, creating public access to data on toxic chemical releases and waste management and encouraging voluntary emission reductions (US EPA, n.d.b). Similar progress in **China's MEE Order No. 12** and **Korea's K-REACH** demonstrates the growing convergence of chemical safety regulations across economic regions (K-REACH, n.d.; Yordas Group,

n.d.). Together, these frameworks establish a growing baseline for global chemical transparency, encouraging convergence across major economic regions.

5.4.3 Towards Integrated Global Governance

Collectively, these collaborative and regulatory frameworks illustrate the evolution of an integrated global architecture for chemical safety. They reveal that progress depends not only on technical innovation but on harmonized governance, equitable financing, and sustained capacity-building. The combination of multi-stakeholder initiatives (like ZDHC and SAI Platform), multilateral conventions (like Basel, Rotterdam, Stockholm, and Minamata), and regional mechanisms (like REACH and TSCA) constitutes a comprehensive system that connects industry transformation to global sustainability goals.

Together, they complement the Paris Agreement on Climate Change, the Kunming-Montreal Global Biodiversity Framework, and the 2030 Agenda for Sustainable Development, addressing the interconnected crises of pollution, biodiversity loss, and climate change through a unified approach to chemical governance. Embedding chemical safety within these multilateral agendas helps ensure that economic growth and innovation, including the circular growth this paper argues for, remain compatible with planetary health and human well-being. This integration reflects growing recognition, accelerated by COVID-19, that environmental, climate, and health crises are not separate challenges but interconnected manifestations of unsustainable development patterns, and therefore require coordinated intervention across domains traditionally treated as distinct policy areas.

5.4.4 Challenges

Despite this comprehensive architecture of international and collaborative frameworks, significant challenges constrain effective implementation. Financial barriers remain acute, particularly for developing countries that lack resources for monitoring, enforcement, and capacity-building. The GFC Implementation Fund represents progress, but funding remains insufficient relative to global needs. Regulatory fragmentation persists, and enforcement capacity varies dramatically, with some countries rigorously implementing rules while others lack political will or institutional capability. Information asymmetries limit transparency, as chemical data may be technically available but functionally inaccessible to downstream users and affected communities. Regulatory lag allows new substances to circulate before comprehensive tracking rules are applied, perpetuating a reactive rather than preventive approach. Power imbalances within global value chains mean that costs and risks of chemical substitution often fall disproportionately on suppliers in developing countries with limited profit margins and negotiating power. Voluntary initiatives, while valuable, cannot substitute for binding regulations with adequate enforcement mechanisms.

Progressing forward requires strengthening institutional capacity, increasing financial flows to developing countries, harmonizing regulatory standards, closing enforcement gaps, and ensuring that chemical safety governance genuinely reflects the principles of equity and shared responsibility enshrined in SDG 17. Only through such comprehensive, coordinated action can the global community realize the vision of a world free from chemical harm.

06

CHAPTER 6



Conclusion

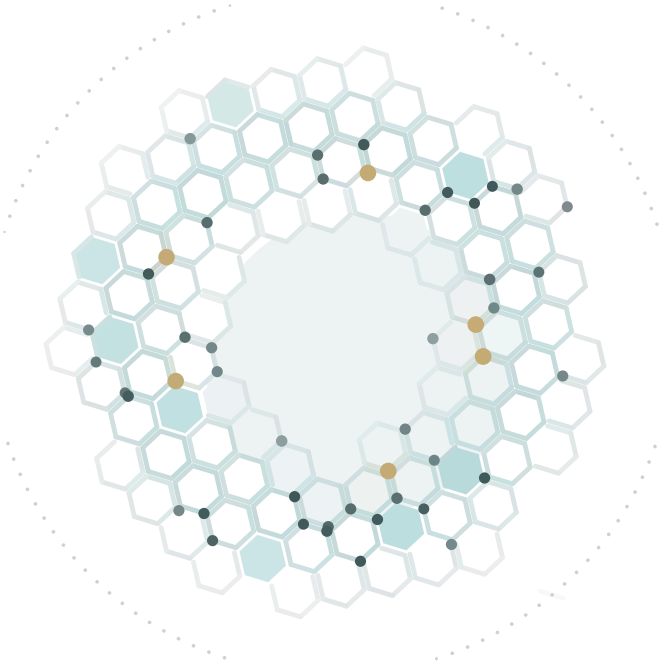
Bringing the evidence together into one case: design hazards out with green chemistry, then grow through safe circularity.

In conclusion, this paper has examined the pervasive presence of hazardous chemicals across four critical global supply chains: textiles, plastics, construction, and agriculture, tracing their life cycles from production through disposal, and identifying the stages at which environmental and health risks are most acute. By analyzing patterns of persistence, bioaccumulation, and toxicity, the research has illuminated how these substances threaten not only biodiversity and ecosystem integrity but also human health across multiple scales. The cross-sector analysis reveals that cumulative and systemic effects amplify risks in ways that single-industry assessments often fail to capture, underscoring the urgent need for integrated, cross-sector chemical management approaches.

The findings address a significant gap in current understanding. Chemical pollution remains comparatively underrecognized and underregulated, particularly in rapidly industrializing regions where oversight mechanisms may be weak or absent. By connecting chemical impacts to global sustainability frameworks and providing comparative insight across sectors, this research establishes a baseline for policy interventions, industrial reforms, and future scientific inquiry aimed at reducing chemical hazards at their source. These insights directly inform the sectoral and international recommendations outlined earlier, which start with green chemistry and extend through circularity, transparency, collaboration, and harmonized regulatory frameworks.

Several limitations warrant acknowledgment. The methodology relies on established hazard categories that may not fully represent the real-world complexity of chemicals and their effects, and data availability, or lack thereof, may have influenced the assessment. While the scoring system is structured and transparent, it necessarily involves elements of judgment. Moreover, this study focuses on intrinsic chemical hazards rather than conducting comprehensive risk assessments that incorporate exposure levels or context-specific scenarios. Certain cross-sector contamination pathways were also excluded from this assessment, and only chemicals used in primary products were examined. Future research should therefore explore the cumulative effects of chemical mixtures, investigate long-term ecological consequences, monitor emerging substances of concern, integrate socio-economic and governance dimensions into risk evaluation frameworks, and investigate cross-sector contamination pathways.

Looking forward, there is considerable potential for transformative change. Green chemistry principles, and the development and adoption of safer alternatives, can keep hazards out of materials and processes at the source. The transition toward circular economic systems can then keep those safer materials in use, while enhanced supply chain transparency and collaborative governance models verify and sustain both. By explicitly linking these strategies to sectoral and global recommendations, industries and policymakers can align economic activity with biodiversity conservation and human health protection. This upstream-by-design approach has the potential to eliminate hazards before they occur, creating the necessary conditions for safe circularity and circular growth. The challenge ahead is not merely technical but institutional and cultural: requiring coordinated action across borders, sectors, and stakeholder groups, with the intentional inclusion of informal workers, to build a safer, more sustainable chemical future. This may initially require measures outside of the R-hierarchy; closing the loop depends on first decontaminating the material stock with controlled disposal of hazardous substances to make it worthwhile. Only when materials are non-toxic, and either safely biodegradable or recoverable without contamination, ensuring protection of human well-being and the environment, can safe circularity commence, and with it growth that no longer depends on hazardous chemicals.



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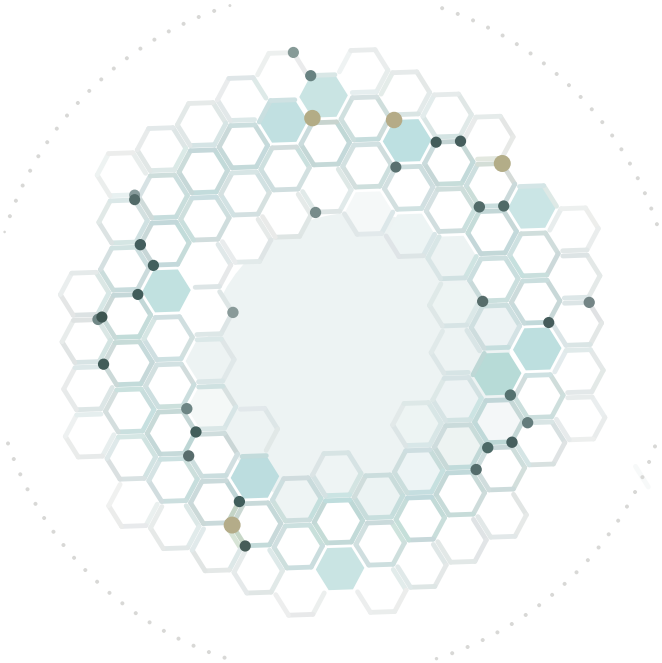

Appendices

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Appendix A · Qualitative Hazard Classification by Sector

Detailed qualitative hazard assessments for the selected chemicals in each sector, across the six intrinsic hazard criteria and their regulatory classification.

A1 · Textile sector

Chemical	Acute toxicity	Carcinogenicity	Persistence	Bioaccumulation	Endocrine disruption	Mutagenicity	Noticeable classifications and regulations
Heavy metals **(chromium, Cr)** solid	High to moderate acute toxicity - Highly toxic to aquatic life - Mainly hexavalent chromium, Cr(VI) (LD_{50} 52 mg/kg)	Carcinogenic to humans (Cr(VI))	Highly persistent (months- to years-long half-life)	Not bioaccumulative under REACH criteria	Potential endocrine disruptor	Mutagenic (Muta. 1B)	- GHS H272 (2), H350 (1B), H340 (1B), H360FD (1B), H330 (2), H301 (3), H312 (4), H372 (1), H314 (1B), H334 (1), H317 (1), H400 (1), H410 (1). - IARC Group 1 - ATSDR
Heavy metals **(cobalt, Co)** solid	Acute Tox. 4 (H302), harmonised CLP classification	Probably carcinogenic to humans	Highly persistent	Low bioaccumulation potential in fish (no biomagnification; higher in molluscs)	Suspected endocrine disruptor	Suspected mutagenic	- IARC Group 2A - GHS H350i (1B), H341 (2), H360F (1B), H302 (4), H334 (1), H317 (1), H400 (1), H410 (1) - ATSDR - EU CMR
Heavy metals **(lead, Pb)** solid	- Moderate acute toxicity - Very toxic for aquatic life - Specific for lead compound (e.g. 450 mg/kg for lead acetate; IDLH 100 mg Pb/m^3)	- Classified as probable carcinogen - Specific inorganic (2A) and organic (3) lead compounds	High environmental persistence (up to 2000 years in the soil)	Low bioaccumulation potential in aquatic organisms (fish BCF 5.1-300; mean value 155)	Presents endocrine disruption potential	Not classified but potential mutagenicity suspected	- ECHA SVHCs - GHS H360Df (1A), H332 (4), H302 (4), H373 (2), H400 (1), H410 (1) - NTP - ATSDR - OSHA - IARC Group 2A
Phthalates **(di-2-ethylhexyl phthalate, DEHP)**	Low acute toxicity (LD_{50} ~25 g/kg)	Possibly carcinogenic	Persistent in the environment (particularly in aquatic systems, sediments, and biota)	Moderate to high bioaccumulation (particularly aquatic species)	Known endocrine disruptor	Not classified but potential mutagenicity suspected	- ECHA SVHCs - IARC Group 2B - ATSDR - GHS H360FD (1B)

Chemical	Acute toxicity	Carcinogenicity	Persistence	Bioaccumulation	Endocrine disruption	Mutagenicity	Noticeable classifications and regulations
VOCs **Formaldehyde**	High acute toxicity (LD_{50} 600 mg/kg)	Carcinogenic to humans	Low persistence (highly biodegradable)	Low bioaccumulation potential (BCF 1-5)	Suspected endocrine disruptor	Suspected mutagenic	- GHS H330 (2), H302 (4), H314 (1B), H317 (1A), H350 (1B), H341 (2) - IARC Group 1 - ATSDR
VOCs **Tetrachloroethylene**	Low acute toxicity (LD_{50}2630 mg/kg)	Probably carcinogenic to humans	Highly persistent in the ground water and soil.	Low to moderate bioaccumulation (BCF 49)	Suspected endocrine disruptor	Not classified or considered	- GHS H351 (2), H411 (2) - IARC Group 2A - ATSDR
Permethrin	Moderate toxicity (LD >1 g /kg)	Not classifiable as carcinogen.	Low persistence	Low bioaccumulation (BCF = 500)	Potential endocrine disruptor	Not classified but suspected mutagenic	- GHS H302 (4), H317 (1), H332 (4), H400 (1), H410 (1) - IARC Group 3
Carmoisine (Azorubine)	Low acute toxicity	Not classifiable as carcinogen.	Low persistence	Low bioaccumulation	Does not meet criteria	Not classified or considered	- GHS H315 (2), H319 (2A) - IARC Group 3 - EFSA

A2 · Plastic sector

Chemical	Acute toxicity	Carcinogenicity	Persistence	Bioaccumulation	Endocrine disruption	Mutagenicity	Noticeable classifications and regulations
Heavy metals **(cadmium, Cd)**	Moderate to high toxicity (LD_{50} 250 mg/kg)	Carcinogenic to humans	Highly persistent	Low bioaccumulation potential in fish (high BCF in plants and bivalves)	Known endocrine disruptor	Suspected mutagenic	- IARC Group 1 - ECHA SVHCs - GHS H350 (1B), H341 (2), H361fd (2), H330 (2), H372 (1), H400 (1), H410 (1)
Phthalates **(di-2-ethylhexyl phthalate, DEHP)**	Low acute toxicity (LD_{50} ~25 g/kg)	Possibly carcinogenic	Persistent in the environment (particularly in aquatic systems, sediments, and biota)	Moderate to high bioaccumulation (particularly aquatic species)	Known endocrine disruptor	Not classified but potential mutagenicity suspected	- ECHA SVHCs - IARC Group 2B - ATSDR - GHS H360FD (1B)
Phthalates **(dibutyl phthalate, DBP)**	Low acute toxicity (LD_{50} ~8,000 mg/kg)	Possibly carcinogenic to humans - IARC Group 2B (2026)	Low to moderate persistency	Low bioaccumulation (BCF < 100)	Known endocrine disruptor	Not classified	- GHS H400 (1), H360Df (1B) - EU CMR

Chemical	Acute toxicity	Carcinogenicity	Persistence	Bioaccumulation	Endocrine disruption	Mutagenicity	Noticeable classifications and regulations
Bisphenol A (BPA)	Low acute toxicity (not classified) (LD_{50} 3,250-4,100 mg/kg)	Not classified as carcinogenic - Suspected potential	Low persistence (readily biodegradable)	Low bioaccumulation potential (BCF < 100)	Known endocrine disruptor	Not classified but suspected mutagenic	- GHS H360F (1B), H335 (3), H318 (1), H317 (1), H400 (1), H410 (1) - ATSDR
Monomer **(vinyl chloride monomer, VCM)**	Low acute toxicity (LC_{50} ~150,000 ppm (2h))	Carcinogenic to humans	Not persistent (high volatilization)	Low potential for bioaccumulation	Suspected endocrine disruptor	Not classified (genotoxic)	- ATSDR - ECHA - GHS H220, H350 (1A) - IARC Group 1
Monomer **Styrene**	Moderate acute toxicity (LD_{50} ~5,000 mg/kg)	Probably carcinogenic to humans	Low persistence (half-life in air: ~2 days)	Low bioaccumulation potential (BCF < 100)	Suspected endocrine disruptor	Not classified but suspected mutagenic	- GHS H361d (2), H332 (4), H372 (1), H315 (2), H319 (2) - IARC Group 2A - ATSDR
POPs **Flame Retardants (polybrominated diphenyl ethers, PBDEs)**	Low acute toxicity.	Not classified by IARC as a group (decaBDE: Group 3)	Highly persistent	High bioaccumulation potential (BCF > 5,000)	Known endocrine disruptor	Not classified but suspected mutagenic	- IARC Group 3 (decaBDE) - Stockholm Convention

A3 · Construction sector

Chemical	Acute toxicity	Carcinogenicity	Persistence	Bioaccumulation	Endocrine disruption	Mutagenicity	Noticeable classifications and regulations
Heavy metals **(lead, Pb)** solid	- Moderate acute toxicity - Very toxic for aquatic life - Specific for lead compound (e.g. 450 mg/kg for lead acetate; IDLH 100 mg Pb/m^3)	- Classified as probable carcinogen - Specific inorganic (2A) and organic (3) lead compounds	High environmental persistence (up to 2000 years in the soil)	Low bioaccumulation potential in aquatic organisms (fish BCF 5.1-300; mean value 155)	Presents endocrine disruption potential.	Not classified but potential mutagenicity suspected	- ECHA SVHCs - GHS H360Df (1A), H332 (4), H302 (4), H373 (2), H400 (1), H410 (1) - NTP - ATSDR - OSHA - IARC Group 2A
Heavy metals **(mercury, Hg - methyl-mercury)** liquid	Extremely toxic - Very toxic to aquatic life (fatal by all routes; CLP Acute Tox. 2)	Possibly carcinogenic to humans	High environmental persistence (dependent on form and medium, in the range of 2-10s of years)	Very high bioaccumulation and biomagnification in aquatic food webs (fish BAF of 2,700,000 L/kg for top predators) (US EPA)	Suspected endocrine disruptor	Not classified	- Minamata Convention - GHS H300 (2), H310 (2), H330 (2), H351 (2), H360Df (1A), H362, H372 (1), H400 (1), H410 (1) - IARC Group 2B - ATSDR - EPA

Chemical	Acute toxicity	Carcinogenicity	Persistence	Bioaccumulation	Endocrine disruption	Mutagenicity	Noticeable classifications and regulations
Asbestos solid	Generally not considered acutely toxic	Carcinogenic to humans	Highly persistent in air	Low potential for bioaccumulation	Does not meet criteria	Not classified but suspected mutagenic	- UK HSE - ATSDR - IARC Group 1 - OSHA
PCBs **(Aroclor 1254)**	Moderate acute toxicity (LD_{50}1,010 mg/kg)	Carcinogenic to humans	Highly persistent (months to years)	Very high bioaccumulation potential - Compound specific BAF (2,000-10,000,000)	Suspected endocrine disruptor	Not classified but potential mutagenicity suspected	- Stockholm Convention - GHS H373 (2), H400 (1), H410 (1) - IARC Group 1 - ATSDR
VOCs **Benzene** liquid	Moderate acute toxicity (organ specific toxicity) (LD_{50} Oral 930 mg/kg)	Carcinogenic to humans	Moderate to low environmental persistence (highly volatile)	Low bioaccumulation potential (BCF = 11)	Suspected endocrine disruptor	Mutagenic (Muta. 1B)	- CDC - GHS H304 (1), H315 (2), H319 (2), H340 (1B), H350 (1A), H372 (1) - ATSDR - IARC Group 1 - EPA Group A

A4 · Agriculture sector

Chemical	Acute toxicity	Carcinogenicity	Persistence	Bioaccumulation	Endocrine disruption	Mutagenicity	Noticeable classifications and regulations
Nitrogen Fertilizers **(ammonium nitrate, AN)** solid	Low acute toxicity (LD_{50} 5,000 mg/kg)	Not classified as carcinogenic	Soluble in water, does not persist in soil	Does not bioaccumulate (highly water soluble)	Does not meet criteria	Not classified or considered	- GHS H272 Category 3, H319 Category 2 - EPA - ATSDR
Nitrogen Fertilizer (**urea**) solid	- Not classified as acutely toxic (LD_{50}14,300 mg/kg)	Not classified as carcinogenic	Water soluble, does not persist.	Does not bioaccumulate (highly water soluble)	Does not meet criteria	Not classified or considered	- GHS not classified - EPA
Phosphorus fertilizer **(Superphosphate)** Solid	Low acute toxicity (LD_{50} > 2000 mg/kg)	Not classified as carcinogenic	Low environmental persistence.	Does not bioaccumulate (readily degrades)	Does not meet criteria	Not classified or considered	- GHS H318 (Eye Dam. 1), not harmonized

Chemical	Acute toxicity	Carcinogenicity	Persistence	Bioaccumulation	Endocrine disruption	Mutagenicity	Noticeable classifications and regulations
Highly Hazardous Pesticides (HHPs) **(Paraquat)** Solid	- Toxic if swallowed (rat oral LD_{50} about 150 mg/kg); fatal if inhaled - Very toxic to aquatic life with long-lasting effects	Not classified as carcinogenic - EPA Category E	High soil persistence (Half-life up to 20 years)	- Low potential for bioaccumulation	Suspected endocrine disruptor	Suspected but no classification or considered	- EPA Category E (evidence of non-carcinogenicity) - GHS H330 Category 2, H311 Category 3, H301 Category 3, H372 Category 1, H315 Category 2, H319 Category 2, H335 Category 3, H400 Category 1, H410 Category 1
Highly Hazardous Pesticides (HHPs) **(monosodium methanearsonate, MSMA)** Solid	- Moderate acute toxicity (LD_{50}>700 mg/kg)	Possibly carcinogenic to humans (MMA, IARC Group 2B) - Degradation products (inorganic arsenic, IARC Group 1)	Low persistence (soil half-life 55 days)	- Low to moderate potential for bioaccumulation	Does not meet criteria - Suspected degradation byproducts	Not classified or considered - Suspected degradation byproducts potential	- GHS H301 Category 3, H331 Category 3, H400 Category 1, H410 Category 1 - IARC Group 2B (MMA); Group 1 for inorganic arsenic - Nufarm (2022), SDS: soil half-life 55 days
Highly Hazardous Pesticides (HHPs) **(cypermethrin)** Semi-solid	Moderate acute toxicity (CLP Acute Tox. 4, oral and inhalation)	Not evaluated by IARC - US EPA: possible human carcinogen	Low persistence (soil DT_{50} about 22 days)	Below the REACH B threshold (fish BCF 331-1,204)	Under EU evaluation (EDlists.org List II)	Not classified	- GHS H302 Category 4, H332 Category 4, H335 Category 3, H373 Category 2, H400 Category 1, H410 Category 1 - EU ED List II (2025) - PAN HHP list

Appendix B · Ordinal Ranking Scores

Numeric ordinal scores (1-5 per criterion) used to rank chemicals by cumulative intrinsic hazard.

B1 · Textile Sector

Chemical	Carcinogenicity	Acute toxicity	Mutagenicity	Persistence	Bioaccumulation	Endocrine disruption	Total score
Heavy metals **(chromium (VI), Cr - sodium dichromate)**	5	4	5	5	1	3	23
Heavy metals **(cobalt (II), Co - cobalt(II) chloride)**	4	2	3	5	1	3	18
Heavy metals **(lead, Pb - inorganic compounds)**	4	2	1	5	1	3	16
Phthalates **(di-2-ethylhexyl phthalate, DEHP)**	3	1	1	3	3	5	16
VOCs **Formaldehyde**	5	4	3	1	1	3	17
VOCs **Tetrachloroethylene**	4	1	1	5	1	3	15
Permethrin	2	2	1	1	1	3	10
Carmoisine (Azorubine)	2	1	1	1	1	1	7

B2 · Plastic Sector

Chemical	Carcinogenicity	Acute toxicity	Mutagenicity	Persistence	Bioaccumulation	Endocrine disruption	Total score
Heavy metals **(cadmium, Cd - cadmium and cadmium compounds)**	5	4	3	5	1	3	21
Phthalates **(di-2-ethylhexyl phthalate, DEHP)**	3	1	1	3	3	5	16
Phthalates **(dibutyl phthalate, DBP)**	3	1	1	1	1	5	12
Bisphenol A (BPA)	1	1	1	1	1	5	10
Monomer **(vinyl chloride monomer, VCM)**	5	1	1	1	1	3	12
Monomer **Styrene**	4	2	1	1	1	3	12
POPs **Flame Retardants (polybrominated diphenyl ethers, PBDEs)**	1	1	1	5	5	3	16

B3 · Construction Sector

Chemical	Carcinogenicity	Acute toxicity	Mutagenicity	Persistence	Bioaccumulation	Endocrine disruption	Total score
Heavy metals **(lead, Pb - inorganic compounds)**	4	2	1	5	1	3	16
Heavy metals **(mercury, Hg - methylmercury compounds)**	3	4	1	5	5	3	21
Asbestos (all forms)	5	1	1	5	1	1	14
PCBs **(Aroclor 1254)**	5	2	1	5	5	3	21
VOCs **Benzene**	5	2	5	1	1	3	17

B4 · Agriculture Sector

Chemical	Carcinogenicity	Acute toxicity	Mutagenicity	Persistence	Bioaccumulation	Endocrine disruption	Total score
Nitrogen Fertilizers **(ammonium nitrate, AN)**	1	1	1	1	1	1	6
Nitrogen Fertilizer **(urea)**	1	1	1	1	1	1	6
Phosphorus fertilizer **(Superphosphate)**	1	1	1	1	1	1	6
Highly Hazardous Pesticides (HHPs) **(Paraquat)**	1	4	1	5	1	3	15
Highly Hazardous Pesticides (HHPs) **(monosodium methanearsonate, MSMA)**	3	3	1	1	1	1	10
Highly Hazardous Pesticides (HHPs) **(cypermethrin)**	1	2	1	1	1	3	9

CIRCULAR INNOVATION LAB

Green Chemistry, Circular Growth

Moving Global Supply Chains Beyond Hazardous Chemicals

FROM THE PAPER

The findings underscore the need for systemic rather than substance-by-substance intervention. Because hazardous substances recur across industrial sectors, redesign at the source offers greater leverage than downstream control.

Central to this argument is an explicit tension: circularity delivers its environmental, societal and economic benefits only where the loops being closed are free of hazardous chemicals, and material circulation in their presence risks distributing contamination rather than eliminating it, while eroding the value of secondary materials.

Green chemistry principles, and the development and adoption of safer alternatives, can keep hazards out of materials and processes at the source. The transition toward circular economic systems can then keep those safer materials in use, while enhanced supply chain transparency and collaborative governance models verify and sustain both.



ISBN 978-87-94507-00-4

Circular Innovation Lab (2026). Green Chemistry, Circular Growth: Moving Global Supply Chains Beyond Hazardous Chemicals. Circular Press.

Circular Press · Circular Innovation Lab · Copenhagen · New Delhi · www.circularinnovationlab.com