

A Review on Chemical Contaminants and Their Multifaceted Impacts on Ecosystem Health

Shashi Saxena*, Raju Ranjan Kumar, Ankit Kumar, MD Faizan, Saurabh Kumar

Mahadeva Lal Schroff College of Pharmacy, Aurangabad, Bihar

ABSTRACT

Chemical pollution is now recognized as a leading global threat to ecosystems and human health [18, 22, 31]. Modern industrial and agricultural activities have released millions of tons of synthetic chemicals into air, water and soil, often without full understanding of long-term impacts [20, 31]. Notable historical events – such as the publication of *Silent Spring* in 1962 – helped launch environmental awareness [5]. Rachel Carson's *Silent Spring* famously documented how the pesticide DDT and other chemicals caused wildlife declines and human hazards [5].

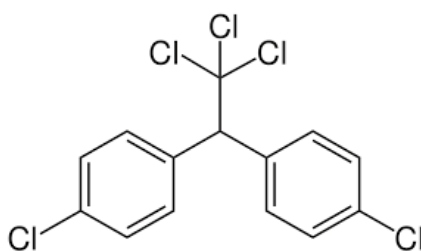


Figure 1. DDT

After World War II there was a “love affair with chemicals,” with widespread adoption of plastics, pesticides, and synthetic compounds [20]. Only decades later did scientists and the public begin to recognize that many of these substances persisted in the environment, bioaccumulated in food chains, and triggered widespread ecological damage [20]. Contaminant releases such as the mercury dumping in Japan's Minamata Bay (1950s–60s) and the toxic Love Canal landfill (1970s) catalysed environmental regulation and the birth of modern pollution science [4, 23]. In the Minamata case, factory effluent led to methylmercury in fish, causing neurological disease in people and animals – a “devastating” lesson that placental barriers do not block methylmercury [4].

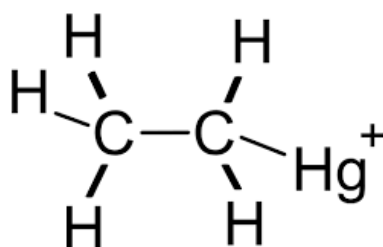


Figure 2. Ethylmercury

Love Canal, a former chemical dump, overflowed into a residential neighbourhood, contaminating soil and water with benzene and other toxins; residents saw miscarriages and birth defects [23]. These incidents spurred laws like the U.S. Clean Water Act (1972), Clean Air Act (1970), and later global treaties (e.g. Stockholm Convention on POPs) to control chemicals that harm ecosystems [22].

This review surveys chemical pollution today, covering major contaminant classes, their sources and fate, ecological impacts, and links to human health. We examine monitoring methods, policy frameworks, and remediation strategies, illustrated by real-world case studies. Conceptual models (e.g. bioaccumulation pathways, transport diagrams) and recent scientific findings are integrated. We conclude with recommendations and emerging research directions for protecting ecosystem health in the face of chemical pollution.

MAJOR CLASSES OF CONTAMINANTS

Chemical pollutants come in many forms. Heavy metals (e.g. lead, mercury, cadmium, arsenic) are naturally occurring but become toxic when mobilized by mining, industry, or combustion [18]. Major sources include mining and smelting, oil refining, and manufacturing processes [18]. For instance, mercury used in artisanal gold mining or chlor-alkali plants can volatilize and travel long distances in the atmosphere [18]. Lead and arsenic contamination often stem from mining and coal burning, while cadmium is released by metal smelters and batteries [18].

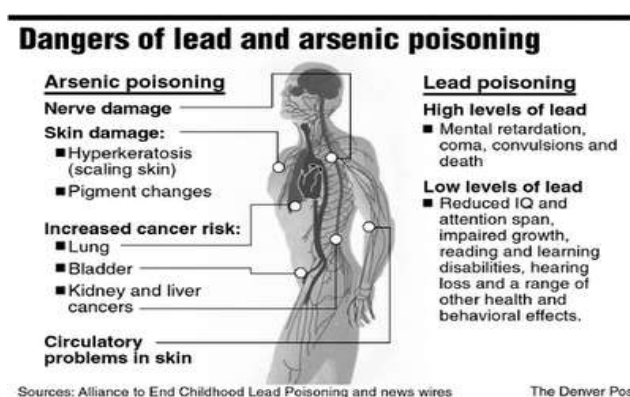


Figure 3. Danger of lead and arsenic poisoning

Pesticides (herbicides, insecticides, fungicides) are widely applied in agriculture and vector control [6]. They enter the environment through spray drift, runoff, and accidental spills [6]. Modern agriculture's use of neonicotinoids, glyphosate, and organophosphates, along with legacy organochlorines (e.g. DDT), has vastly expanded the chemical load in soils and waterways [6]. Industrial chemicals such as PCBs (polychlorinated biphenyls), dioxins/furans, solvents (e.g. trichloroethylene), and PFAS ("forever chemicals") have been used in manufacturing and consumer products [22, 25]. PCBs and dioxins are persistent organic pollutants (POPs) that bioaccumulate and travel globally via air and water [22]. PFAS(per-and polyfluoroalkyl substances) appear in firefighting foams, textiles, non-stick cookware coatings, and many plastics; they have been widely detected in water, soil worldwide [25]. Other emerging contaminants include pharmaceuticals and personal-care products (PPCPs) – antibiotics, hormones, analgesics, and sunscreens used by humans and livestock – which enter waterways via sewage and manure [15]. These micropollutants are only partially removed by wastewater treatment, leading to trace pharmaceuticals in rivers, lakes and even drinking water [15]. Plastics and microplastics (particles <5 mm from degraded plastic waste) are ubiquitous new contaminants [1, 2, 17]. An estimated 8–12 million metric tons of plastic waste enter the ocean each year, where it fragments into trillions of microplastic particles that accumulate in gyres, beaches, and sediments [1, 2]. Nanomaterials and novel synthetic compounds (flame retardants, endocrine disruptors) are added to the mix, many with uncertain ecological effects.

KEYWORDS:

Heavy metals: Mercury, lead, cadmium, arsenic (sources: mining, smelters, coal combustion, e-waste recycling) [18].

Pesticides: DDT, organophosphates, neonicotinoids, glyphosate (sources: agriculture runoff, drift, improper application) [6].

Industrial organic chemicals: PCBs, dioxins, PAHs, benzene, phthalates (sources: manufacturing, waste incineration, fossil fuel extraction) [22].

PFAS (forever chemicals): PFOA, PFOS, GenX (sources: AFFF firefighting foam, stain-resistant coatings, food packaging) [25].

Pharmaceuticals and personal care: Antibiotics, hormones, analgesics (sources: sewage effluent, agricultural manure, pharmaceutical discharge) [15].

Plastics and microplastics: Polyethylene, polypropylene, polystyrene fragments (sources: plastic waste, microbeads, Fiber shedding) [1, 2, 17].

Each class has different chemical properties (solubility, persistence, bioaccumulation potential) that affect its transport and impacts [20]. Persistent organic pollutants (POPs) like PCBs and DDT resist degradation, staying in the environment for decades [22]. PFAS are highly stable to heat and chemicals, leading them to accumulate in soil and water [25]. In contrast, some pesticides and pharmaceuticals biodegrade relatively quickly but can

still cause acute toxicity or produce harmful metabolites [15]. Overall, the diversity of contaminants means ecosystems are exposed to complex “cocktails” of chemicals with additive or synergistic effects.

Sources, Environmental Transport, and Fate

Chemical contaminants enter ecosystems through a mix of point sources (industrial discharge pipes, wastewater outfalls, landfill leachate) and nonpoint sources (agricultural runoff, atmospheric deposition, urban stormwater) [6, 20]. For example, heavy metals originate from specific sites like mine tailings, smelter emissions and industrial wastewater, but atmospheric emissions can disperse metals widely (mercury, lead and cadmium can travel long distances in the atmosphere) [18]. Pesticides are applied broadly across fields, and excess is washed into streams and groundwater [6]. In agriculture, over-irrigation and rain cause pesticide runoff; volatilization can carry them onto nearby lands; and leaching moves water-soluble chemicals into aquifers [6]. Urban and industrial pollutants (solvents, petrochemicals) often seep from landfills or spill sites into soil and groundwater [23]. Marine sources include ship discharge (oil antifoulants) and plastic litter [1]. Atmospheric transport is critical for volatile or particulate-bound pollutants; POPs exemplify this, as many POPs detected in the Arctic have travelled from mid-latitude sources by air and ocean currents [22].

Once released, contaminants follow complex fate pathways (see Figure 1). In water, pollutants may remain dissolved or adsorb to particles and settle into sediments [20]. In soil, chemicals can bind to organic matter or clay, reducing mobility, or remain in soil water and leach downward [20]. Adsorption and degradation are key fate processes. For instance, pesticides may bind tightly to soils rich in organic carbon (e.g. glyphosate) or remain mobile if weakly adsorptive [6]. Chemical degradation occurs by photolysis or microbial action (e.g. some herbicides break down under sunlight), while biotransformation can convert a compound into less/more toxic metabolites [15]. However, highly persistent chemicals (like PFAS or PCBs) resist these processes and remain bioavailable for years [22,25].

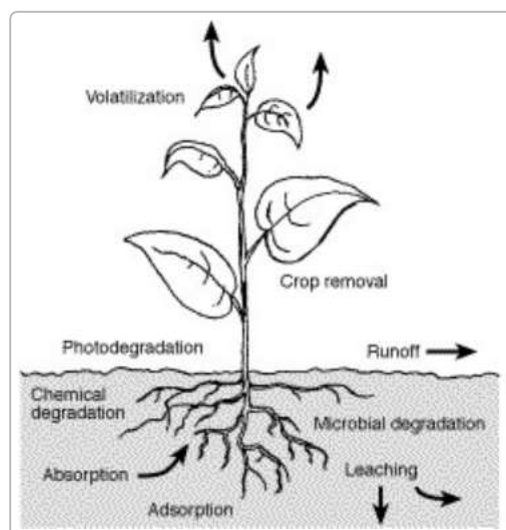


Figure 4. Conceptual diagram of pesticide fate pathways (adapted from Fishel 2017). Pesticides can volatilize to air, run off into surface water, leach into groundwater, or adsorb to soil particles. They may undergo photodegradation on plant surfaces or microbial/chemical breakdown in soil. These processes determine how far and how long pesticides persist in the environment

Over time, contaminants bioaccumulate and biomagnify in food webs [24]. An organism may absorb pollutants faster than it can excrete them, causing tissues to concentrate the chemical (bioaccumulation). For example, fish absorb methylmercury from water and prey, storing it in muscle [24]. As one predator eats many prey, contaminant levels rise up the chain (biomagnification), so top predators bear the highest burdens [24]. Figure 4 illustrates the multiple pathways pesticides can take in a crop-soil-water system [6].

Pesticides can volatilize to air, run off into surface water, leach into groundwater, or adsorb to soil particles [6]. They may undergo photodegradation on plant surfaces or microbial/chemical breakdown in soil [6]. These processes determine how far and how long pesticides persist in the environment [6]. Other transport mechanisms include surface water flow (moving contaminants downstream), groundwater flow (spreading pollutants through aquifers), atmospheric deposition (chemicals returning from air to land/ocean by rain or dust), and biological vectors (migratory birds carrying seeds with pollutants, etc.). For plastics currents concentrate debris in gyres; the Great Pacific Garbage Patch is a prime example [2, 17]. In sum, environmental transport models show that contaminants released at one point can impact distant ecosystems through a combination of water, air and food-web pathways [20].

Ecological Impact and Biodiversity Loss

Chemical contaminants degrade ecosystem health by poisoning organisms, altering community structure, and disrupting ecosystem functions (nutrient cycling, pollination, etc.) [1, 10, 15, 24]. Terrestrial ecosystems bear multiple impacts. Soil pollution from heavy metals or persistent organics can reduce soil biota diversity and fertility. Contaminated soils lead to plant uptake of toxins (e.g. lead or cadmium in crops), impairing plant growth and transferring contaminants up the food chain [18]. Agricultural pesticide use has been linked to declines in insects and pollinators: for instance, a 2024 study found that intensive insecticide use (neonicotinoids, pyrethroids) was associated with up to a 43% reduction in the occurrence of wild bee species at monitored sites [8]. Similar impacts extend to beneficial invertebrates, birds and bats [8]. Amphibians are particularly sensitive: pesticide exposure is hypothesized to contribute to global amphibian declines by causing deformities and population crashes. Insect herbivores are suppressed by insecticides, while herbicide runoff can harm non-target plants [6]. Collectively, such losses in biodiversity weaken ecosystem resilience.

In aquatic ecosystems, contaminant effects are well-documented. Mercury from mines or coal plants becomes methylmercury in water and biomagnifies in fish – as seen in the Minamata tragedy (see Case Study) [4, 19, 24]. Top predators like birds and mammals (e.g. otters, seals, killer whales) suffer from high contaminant loads, reducing reproductive success [24]. Endocrine-disrupting chemicals (synthetic hormones, alkylphenols) cause “intersex” fish and amphibians: for example, treated sewage effluent carries estrogenic compounds that induce egg-cells in the testes of male fish [10]. Coral reefs and plankton communities also absorb plastics and toxins, impairing productivity [1, 2, 17]. A recent Mongabay report highlights that trillions of microplastic particles may “clog” the ocean’s biological carbon pump by altering plankton communities, potentially slowing carbon sequestration and disrupting nitrogen cycling [2]. Microplastics also physically injure filter-feeding organisms

and accumulate pollutants on their surfaces, effectively transporting other toxins through the marine food web [1]. Biodiversity loss from pollution is increasingly recognized [1, 26, 27]. Persistent contamination can reduce species richness and shift community composition. For instance, wetlands downstream of pollution sources often have fewer sensitive amphibians and more tolerant species. Pollutants can select for tolerant microbial communities, altering decomposition and nutrient processes. Several global assessments list chemical pollution among the top drivers of biodiversity decline (alongside habitat loss and climate change) [26, 27]. Even where mortality is not immediate, sub-lethal effects like impaired reproduction or growth can stabilize populations [8]. For example, chronic low-dose pesticide exposure has been implicated in long-term declines of pollinators and soil organisms [8]. In sum, by degrading habitat quality and acting as invisible stressors, chemicals contribute to biodiversity erosion and compromised ecosystem function.

Ecosystem–Human Health Connections

Ecosystem contamination often feeds back to human health [18, 22, 31]. We depend on ecosystem services (clean water, food, pollination), which are threatened by pollutants [1, 8, 15, 24]. Bioaccumulation in food chains is a major link: toxins that accumulate in fish, shellfish or game animals can end up on our dinner plates [24]. This is famously illustrated by mercury: people consuming contaminated fish (especially pregnant women) can suffer neurological harm, as tragically occurred in Bay [4, 19]. Similarly, lead in drinking water (e.g. Flint, Michigan) originated from corroding pipes – a form of environmental contamination posing direct human risk (not covered here but illustrative) [31]. Pesticide residues in produce can have chronic health effects, endocrine disruption and cancer risk [6, 10]. Contaminated water sources cause disease outbreaks and developmental problems [15]. The love canal incident, for instance, raised concerns about cancer and birth defects benzene laden drinking water [23]. Chemical pollution also operates through the One Health paradigm: human health is linked to wildlife and ecosystem health [22]. For example, when pollinators decline due to pesticides, crop yields (and human nutrition) may suffer [8]. Toxins cycling through ecosystems can amplify, so that even small environmental releases can lead to significant human exposures via air, water, or food [22]. The UNEP notes that many metals and POPs can travel globally and bioaccumulate, affecting wildlife and people far from emission sources [18, 22]. Children and vulnerable communities often bear disproportionate burdens (e.g. higher lead exposure in low-income areas) [31]. Thus, protecting ecosystem health (by controlling chemical contaminants) is intimately tied to safeguarding public health [18, 22, 31].

Environmental Monitoring Techniques

Effective monitoring is essential to track contaminant levels, identify hotspots, and assess trends [20]. Modern chemical analysis tools (chromatography, mass spectrometry, spectroscopy) are widely used to detect trace contaminants in air, water and soil [20, 34]. For example, gas chromatography (GC) coupled with mass spectrometry is “the most widely used chromatographic technique for environmental analyses”, enabling detection of complex organic mixtures [20]. Rapid field methods (biosensors, immunoassay test kits) also allow onsite screening for specific compounds [20]. Remote sensing and satellite data are beginning to map

broad-scale pollution (e.g. NASA's CYGNSS satellite was used to detect microplastic concentrations on the ocean surface) [2, 17]. Biomonitoring uses organisms as sentinels [24]. The NOAA Mussel Watch program, for instance, measures heavy metals and PCBs in mussels across U.S. coasts, revealing long-term trends [24]. Declining contaminant levels in shellfish in some regions reflect regulatory success [24]. Freshwater mussels, macroalgae, lichens and fish are often used to gauge pollution. Environmental DNA (eDNA) and omics methods are emerging to detect ecological effects before population declines occur. Citizen science (e.g. water quality testing kits, microplastic surveys) is also expanding monitoring capacity [1]. In summary, a suite of chemical and biological methods – from high-precision lab analyses to community-based sampling – is employed to monitor environmental contamination [20].

Policy and Regulatory Frameworks

To address chemical pollution, nations have enacted environmental laws and participated in international agreements [19, 22, 31]. Key examples include the U.S. Clean Air Act and Clean Water Act, which set emission and effluent standards for industries [22]. The Toxic Substances Control Act (TSCA) and its European counterpart REACH require chemical manufacturers to test and register new substances [22]. Global treaties target the worst pollutants: the Stockholm Convention (2001) initially listed 12 “Dirty Dozen” POPs (including DDT, PCBs, dioxins) for elimination [22]. In 2013 the Minamata Convention was adopted to curb mercury use and emissions worldwide [19]. These agreements have led to bans on many legacy contaminants (e.g. DDT is banned in most countries) and ongoing monitoring of remaining uses [19, 22]. Contemporary policy is challenged by emerging contaminants [15, 25, 33]. PFAS (“forever chemicals”) illustrate this: only recently have governments begun to regulate them [21, 25]. In the U.S, the EPA in 2024 designated PFOA and PFOS (two common PFAS) as hazardous substances under the Superfund law and issued the first national drinking water standards for PFAS [21]. The EU and U.S. also restrict endocrine-disrupting chemicals (e.g. bisphenols, phthalates) in consumer products [10]. Despite these, many chemicals remain underregulated, especially mixtures and new synthetics.

At the same time, ecosystem-based regulatory approaches are developing. For example, some policies apply the precautionary principle, restricting chemicals whose safety is uncertain [31]. Integrated water framework directives (EU) and One Health initiatives aim to consider ecosystem impacts in risk assessment [22]. In practice, enforcement gaps and political factors can delay action. Nonetheless, successful policies (e.g. air pollution controls leading to reduced heavy metals in wildlife) demonstrate that regulation can reduce environmental contamination when supported by monitoring and public pressure [18].

Mitigation and Remediation Strategies

Reducing existing pollution and preventing new releases require both technological and management solutions. Source reduction is the first strategy: substituting safer chemicals (green chemistry), minimizing pesticide use through integrated pest management, and improving waste handling [6, 31]. For example, reducing the use of plastic bags and developing biodegradable materials can cut plastic inputs at the source [1]. Containment and cleanup methods then address pollutants already in the environment [16, 20]. Common remediation techniques

include: Physical removal: Dredging contaminated sediments or excavating polluted soils removes hotspots of heavy metals or PCBs [20]. Chemical treatment: Adding adsorbents (e.g. activated carbon) can bind organic pollutants; advanced oxidation (e.g. ozone or UV treatment) can degrade some toxins in water or soil [20]. Bioremediation: Using microbes or plants to degrade or extract contaminants [13, 15]. Certain bacteria can metabolize hydrocarbons or pesticides, while plants (phytoremediation) like sunflowers or willow can accumulate heavy metals from soil [13, 15]. Engineered wetlands: Constructed wetlands can treat runoff by filtering chemicals through plant- soil systems, harnessing microbial communities to break down pollutants.

Electrokinetic and thermal remediation technologies have emerged as advanced in situ methods for addressing contaminated soils and groundwater [11, 16]. Electrokinetic techniques utilize low-intensity electrical fields to mobilize ionic or polar contaminants toward designated collection points, where they can be extracted or neutralized (Smith et al., 2020) [16]. This method is particularly effective in low-permeability soils where conventional approaches often fail [16]. Thermal technologies—such as electrical resistance heating, thermal conduction heating, and steam-enhanced extraction—raise subsurface temperatures to volatilize or destroy organic contaminants, thereby improving pollutant removal efficiency (Jones & Kumar, 2019) [11].

In addition to these conventional methods, a range of innovative and emerging strategies are being developed to address persistent chemical pollutants [12, 13, 28]. For example, biochar-based filtration systems have demonstrated potential for adsorbing per- and polyfluoroalkyl substances (PFAS), a class of highly resistant compounds often referred to as “forever chemicals” due to their persistence in the environment (Lee et al., 2021) [12]. Similarly, engineered nanomaterials—such as zero-valent iron nanoparticles and photocatalysts like titanium dioxide—are being explored for their ability to accelerate the breakdown of both organic and inorganic contaminants (Wang & Zhao, 2020) [28]. Another promising area involves genetically engineered microorganisms, which are tailored to target and degrade specific pollutants through customized metabolic pathways, offering new frontiers in bioremediation (Nguyen & Patel, 2022) [13].

Despite these technological advances, the complete removal of diffuse and widely dispersed pollutants remains a major challenge [1]. Microplastics in marine ecosystems, for instance, are pervasive and vary significantly in size, origin, and composition, making their detection, collection, and degradation exceedingly difficult with current technologies (Andrews et al., 2020) [1]. This underscores the necessity of pollution prevention strategies in parallel with remediation efforts.

Policy instruments are critical in supporting these mitigation initiatives. Programs like Extended Producer Responsibility (EPR) for electronic waste and plastic packaging aim to transfer the burden of waste management from governments to producers, encouraging the development of environmentally sustainable products (OECD, 2016) [14]. In the United States, federal mechanisms such as the Comprehensive Environmental Response, Compensation, and Liability Act—commonly known as the Superfund program—provide legal and financial support for the remediation of hazardous waste sites (U.S. EPA, 2022) [23].

Ultimately, effective mitigation of chemical contamination requires a holistic, integrated approach [24]. This includes the implementation of strong regulatory frameworks, investment in emerging technologies, and the adoption of ecological restoration practices such as reforestation, wetland rehabilitation, and riparian buffer zone creation [1, 13, 15]. These strategies work synergistically to enhance the resilience of natural systems and reduce the mobilization and long-term impact of chemical contaminants on ecosystem health [1, 13, 15].

Case Studies: Lessons from Contamination Incidents

Minamata Disease (Mercury, Japan): Discovered in 1956, Minamata disease arose from industrial mercury discharge into Minamata Bay [4, 19]. Bacterial methylation of inorganic mercury produced methylmercury, which biomagnified in fish [4, 19, 24]. Thousands of people suffered neurological damage after eating contaminated seafood [4, 19]. This case underscores bioaccumulation risk and human vulnerability (especially fetuses) [4]. The disaster prompted Japan and later the global Minamata Convention to limit mercury emissions [19].

Love Canal Tragedy (Toxic Waste, USA): In the 1970s, toxic chemicals dumped underground at Love Canal, New York, leached into a neighbourhood of homes and a school [23]. Residents noted “puddles of noxious substances” on playgrounds and in basements [23]. Investigations found high levels of benzene and other carcinogens in air and water [23]. An unusually high rate of miscarriages and birth defects was documented nearby [23]. The Love Canal crisis led to the U.S. Superfund law for cleanup of hazardous sites and highlighted the human health impacts of unregulated chemical disposal [23].

Pesticide Runoff in the Amazon (Brazil): Large hydroelectric dams in the Amazon have been associated with degraded water quality and ecosystem disruption [9]. Local Indigenous residents report that reservoirs and canals carry not only sediment but also agricultural pesticide runoff from upstream soy plantations [9]. This polluted water causes fish kills, skin rashes and gastrointestinal illness [9]. The loss of clean water and fish stocks has undermined food security and health in river communities [9]. This case illustrates how chemical use in upland agriculture can spread via water into sensitive tropical ecosystems and impact human populations even far downstream [9].

Ocean Plastics and Microplastics: The Great Pacific Garbage Patch exemplifies how plastics accumulate in ocean gyres [2, 17]. NASA satellite mapping shows high microplastic concentrations in gyres and near coasts [2, 17]. Microplastics have been found throughout marine food webs, from plankton to whales [1, 2, 17]. Recent studies warn that trillions of microplastic particles could “clog” the ocean’s carbon pump by affecting plankton productivity [2]. Sea turtles and seabirds frequently ingest plastic debris, leading to starvation [1]. Unlike chemical spills, plastic pollution is diffuse and global, requiring international action [1, 2, 17]. These cases highlight that chemical and material contaminants often travel far from their sources, stressing the need for global solutions [1, 2, 9, 17, 19, 23].

Conceptual Models of Contaminant Dynamics

Understanding contaminant effects often relies on conceptual diagrams and models. Two key concepts are bioaccumulation pathways and fate-and-transport models [20]. Bioaccumulation models depict how contaminants move up a food chain: from soil/water, to plants or invertebrates, to prey fish, and to predators (e.g. humans) [24]. Such diagrams illustrate why top predators are most at risk [24]. Similarly, transport models diagram how chemicals travel through hydrological or atmospheric cycles, showing sources and sinks [20]. For example, fate-and-transport models of rivers can map chemical sources (industrial discharge, runoff) to downstream concentrations [20]. These conceptual models (often embedded in risk assessments) help policymakers visualize exposure pathways and prioritize monitoring or remediation [20].

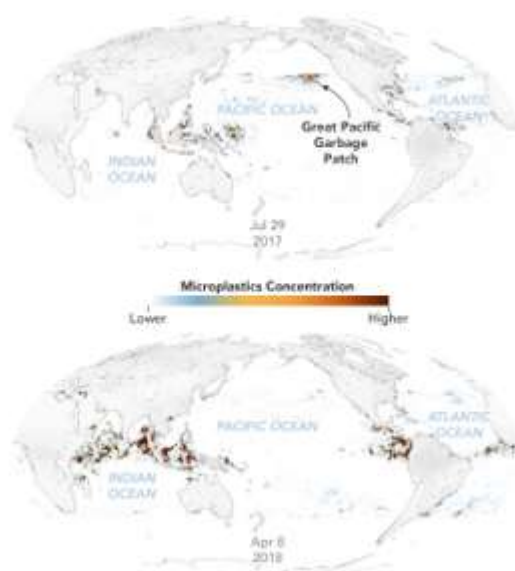


Figure 5. Global concentration of floating microplastics mapped by NASA (higher concentrations in red). Data reveal accumulation in the North Pacific Garbage Patch and coastal zones, and seasonal changes (top: July 2017; bottom: April 2018). Satellite analysis shows that major rivers (e.g. Yangtze, Ganges) contribute significant microplastic loads to the ocean.

Data reveal accumulation in the North Pacific Garbage Patch and coastal zones, and seasonal changes (top: July 2017; bottom: April 2018) [2, 17]. Satellite analysis shows that major rivers (e.g. Yangtze, Ganges) contribute significant microplastic loads to the ocean [2, 17]. Quantitative models also exist (e.g. pollutant dispersion models), but here we emphasize conceptual schematics as tools to communicate complex pathways [20]. Integrating these models with empirical data (e.g. satellite images, field measurements) strengthens understanding [2, 17, 20]. For instance, combining field plastic sampling with satellite mapping has begun to validate predictions of ocean microplastic distribution [2, 17]. Conceptual diagrams (like Figures 4 and 5) serve as organizing frameworks for thinking about how contaminants move through ecosystems and accumulate in organisms [6, 17].

Future Research Directions and Policy Recommendations

Emerging challenges require new science and policies [1, 15, 33]. Research needs include better understanding of contaminant mixtures, low-dose chronic effects, and interactions (e.g. pesticides plus pathogens) [1, 8, 10]. High on the agenda are PFAS, micro- and Nano plastics, and novel compounds (rare earth metals, nanoparticles) [1, 12, 21, 25, 33, 34]. Long-term ecological studies and monitoring of sentinel species (bees, amphibians, algae) can reveal hidden impacts [8]. We also need improved fate/transport models that link atmospheric, terrestrial and aquatic systems [20]. Advances in “omics” and remote sensing can track contaminants and biological responses at landscape scales [2, 17]. Further research is needed on emerging contaminants and issues of concern where toxicological data is limited, focusing on rapid generation of translationally relevant data for public health decision-making [1.2]. Incorporating knowledge from ecology and evolution into ecological hazard and risk assessments is also crucial [1.5]. Developing new capabilities for chemical identification and measurement, as well as chemical risk assessment for emerging residues, are vital research areas [1.7]. Wastewater-based epidemiology can be a valuable tool for monitoring population-level exposure [1.7]. Understanding the eco-evolutionary drivers of emerging resistance and addressing combined chemical exposures are also important research directions [1.7, 36].

Policy recommendations emphasize precaution and integration [31]. Governments should tighten controls on persistent, bio accumulative substances (as with the Stockholm and Minamata treaties) [19, 22]. New global agreements on plastics and chemical pollutants (beyond the existing treaties) are needed to match the scale of production [1, 2, 17]. National regulations should incorporate ecosystem health endpoints and One Health approaches, ensuring that environmental limits consider indirect human exposures [22]. For example, water quality standards (Clean Water Act) must address emerging contaminants, and agricultural policies should promote reduced pesticide use (e.g. subsidies for integrated pest management) [6, 23]. Public awareness and cross-sector collaboration are vital [1.1, 1.3, 2.5]. Encouraging transparency in industrial chemicals (e.g. public release of emission inventories) helps communities address local contamination. Investment in green chemistry and alternative technologies can mitigate pollution at the source [31]. Remediation funding (for Superfund and analogous programs) should prioritize cleanups that restore ecosystem services (wetland restoration, pollution filtration) [23].

Policy should aim for the overall reduction of chemical production and emissions [26, 27]. Broadening the scope of pollutants addressed beyond pesticides, nutrients, and plastic waste to include toxic metals, industrial chemicals, and consumer products is recommended [26, 27]. Strategies for reducing emissions through chemical simplification and grouping, reducing non-essential use, and innovative synthesis (e.g., “benign-by-design”) should be pursued, considering the full life cycle of chemicals [26, 27]. Setting up transparent data inventories in cooperation with industry can inform monitoring and progress towards goals [27]. Prioritizing chemicals that impact biodiversity is essential for effective regulation [27]. Effective regulatory frameworks and public health initiatives are needed, including improved waste management and targeted strategies for aquatic ecosystems [1.1]. Stricter regulations on harmful chemicals in agriculture and industry, and enhanced monitoring and enforcement of water quality standards are crucial [1.1]. Enacting evidence-based policy

frameworks, such as rigorous environmental and safety standards, making polluters pay, and removing environmentally harmful subsidies, are also important steps [31]. Protecting workers and vulnerable communities from chemical pollution should be a priority [31]. There should be a stronger link between science and policy, fostering international collaboration and robust legislation [2.2]. The health sector has a vital role to play through the One Health approach in reducing pollution [2.2]. Promoting a transition to a pollution-free planet is a key objective [2.2]. Incentivizing farmers to adopt nature-friendly practices and phasing out harmful pesticides are important agricultural policy recommendations [2.3]. Establishing duties on large companies to reduce pollution at the source and increasing funding for protected sites to support sustainable land management are also recommended [2.3]. A National Nature Service could support monitoring and habitat restoration efforts [2.3]. Recognizing a Right to a Healthy Environment can place nature and wellbeing at the heart of policy [2.3]. Increasing regulator mandates and budgets for monitoring is necessary [2.3]. Addressing the cross-system consequences of pollution requires integrated approaches [2.4]. Establishing a new science-policy panel can provide independent information to policymakers, integrating the assessment of chemicals, waste, and pollution, identifying research gaps, supporting science-policy communication, raising awareness, and assisting information-sharing and capacity building, including horizon scanning for emerging issues [2.5]. Voluntary, cooperative risk reduction actions on Emerging Policy Issues (EPIs) such as hazardous chemicals in electronics, endocrine-disrupting chemicals, pharmaceutical pollutants, perfluorinated chemicals, nanotechnology, highly hazardous pesticides, lead in paint, and chemicals in products, are important policy directions, accelerating national and value chain initiatives and improving access to information and knowledge [3.3]. Research on environmental pollution analysis methods and remediation strategies should be supported [3.4, 3.5]. Developing novel and integrated approaches for sustainable remediation of emerging pollutants is crucial [3.5]. Green chemistry and innovative tools for predicting bioremediation and degradation are key areas [3.5]. Closing the gap between theory and practice in pollution research and policy is essential for impactful policymaking [3.6].

Finally, the precautionary principle should guide action: if a chemical's safety is uncertain, its use should be minimized [31]. The long legacies of DDT, PCBs, and mercury remind us that "solution is not dilution". By integrating monitoring data, conceptual models and rigorous risk assessment, policymakers and scientists can better protect ecosystem and human health. In a world where chemical production continues to grow, proactive and science-driven regulation is essential to prevent future environmental disasters and preserve ecosystem resilience [31, 32]

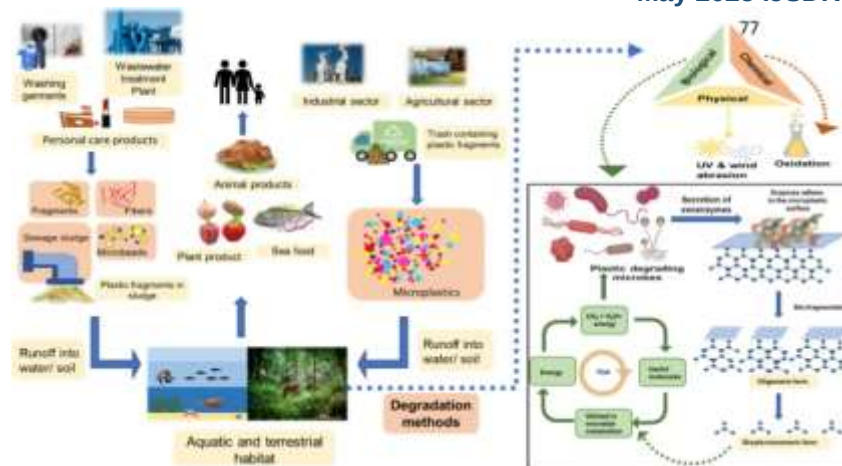


Figure 6. Graphical Abstract

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