Stout in Environmental Studies (SES)

DOI: https://doi.org/10.61424/3khbx588
Journal Homepage: https://stoutjournals.org/index.php/SES

Climate Change and Emerging Contaminants: Changing Environmental Fate, Exposure Pathways, and Ecological Risks

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ARTICLE INFORMATION

Submitted: June 07, 2026
Accepted: September 25, 2026
Published: October 14, 2026
Volume: 2
Issue: 1

KEYWORDS

Climate change; emerging contaminants; environmental fate; contaminant transport; exposure pathways; ecological risks.

ABSTRACT

Climate change is increasingly reshaping the environmental fate, transport, transformation, and ecological impacts of emerging contaminants, creating complex challenges for environmental protection and ecosystem sustainability. Emerging contaminants, including pharmaceuticals, personal care products, pesticides, microplastics, per- and polyfluoroalkyl substances (PFAS), and endocrine-disrupting chemicals, occur in aquatic, terrestrial, and atmospheric environments, where their behavior is influenced by changing climatic conditions. This study examines the interactions between climate change and emerging contaminants, focusing on how rising temperatures, altered precipitation patterns, floods, droughts, sea-level rise, and extreme weather events influence contaminant persistence, mobility, bioavailability, and distribution. It also explores changing exposure pathways, including surface runoff, groundwater infiltration, atmospheric deposition, sediment resuspension, and food-web transfer, which may increase the exposure of aquatic organisms, terrestrial wildlife, and human populations. Climate-driven changes in hydrological processes and ecosystem conditions can alter contaminant degradation rates, chemical interactions, and biological uptake, potentially intensifying toxicity and disrupting ecological relationships. Furthermore, the combined effects of climate stressors and chemical pollution may produce cumulative and synergistic risks that are not adequately captured by conventional environmental risk assessment approaches. The study highlights the need for integrated monitoring systems, climate-informed contaminant modeling, improved regulatory frameworks, and interdisciplinary risk assessment strategies that account for interactions between environmental change and chemical pollution. It concludes that understanding the dynamic relationship between climate change and emerging contaminants is essential for anticipating future ecological risks, strengthening environmental management, and developing adaptive pollution-control strategies that protect ecosystem resilience under changing climatic conditions.

1. Introduction

Climate change and environmental pollution are among the most significant and interconnected challenges confronting contemporary environmental science. Rising global temperatures, changing precipitation patterns, increasing frequency and intensity of extreme weather events, sea-level rise, and alterations in hydrological cycles are transforming the physical, chemical, and biological processes that regulate environmental quality. At the same time, the widespread production and use of emerging contaminants, including pharmaceuticals, personal care products, pesticides, per- and polyfluoroalkyl substances (PFAS), microplastics, nanomaterials, industrial chemicals, and endocrine-disrupting compounds, have introduced additional pressures on terrestrial, freshwater, marine, and atmospheric systems (Tong, 2025). Although climate change and chemical pollution are frequently examined as distinct environmental problems, their interactions have important implications for contaminant persistence, transport, transformation, bioavailability, and ecological toxicity. Understanding these interactions is therefore essential for assessing environmental risks under changing climatic conditions and developing effective strategies for pollution prevention, ecosystem protection, and sustainable environmental management.

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Emerging contaminants comprise a diverse group of chemical and particulate substances that are increasingly detected in environmental matrices or are receiving greater scientific and regulatory attention because of improved analytical capabilities and growing evidence of their potential adverse effects. These substances originate from multiple sources, including municipal wastewater, pharmaceutical manufacturing, agricultural runoff, industrial discharge, plastic degradation, landfill leachate, and urban stormwater. Their environmental behavior varies according to their chemical structure, solubility, volatility, persistence, and interactions with organic matter, sediments, soil minerals, and biological organisms. Some contaminants degrade relatively rapidly under favorable environmental conditions, whereas others persist for extended periods, accumulate in sediments, or undergo transformation into products that may retain or develop toxic properties (Ogayemi, 2026). Conventional wastewater treatment and environmental remediation technologies may not completely eliminate many of these substances, allowing their continued release into ecosystems. Consequently, emerging contaminants present complex environmental challenges, particularly when their distribution and behavior are influenced by climatic changes that alter environmental conditions and ecosystem functioning.

Climate change can modify the environmental fate of contaminants through several interconnected mechanisms. Increasing temperatures can influence chemical reaction rates, volatilization, microbial degradation, and the metabolic activities of organisms involved in contaminant transformation. However, the direction and magnitude of these effects depend on contaminant-specific properties and local environmental conditions. Higher temperatures may accelerate the degradation of some compounds while increasing the persistence, mobility, or biological availability of others. Changes in precipitation intensity and frequency can affect contaminant dilution, runoff, leaching, erosion, and transport from terrestrial environments into rivers, lakes, estuaries, and coastal waters (Borgå, 2022). Heavy rainfall and flooding may mobilize pollutants accumulated in agricultural soils, industrial sites, wastewater systems, and urban surfaces, resulting in short-term increases in environmental concentrations. Conversely, prolonged drought can reduce water availability and dilution capacity, concentrating contaminants in aquatic environments and increasing exposure risks for aquatic organisms. These processes demonstrate that climate change does not influence contaminant behavior uniformly; rather, it modifies the environmental conditions under which contaminants are released, transported, transformed, and ultimately encountered by ecological receptors.

The effects of climate change on contaminant dynamics are particularly evident in aquatic ecosystems, where temperature, water chemistry, hydrological variability, and sediment interactions collectively regulate pollutant distribution. Rising water temperatures can alter the partitioning of certain chemicals between water, sediments, and biological tissues, while changes in dissolved oxygen, pH, salinity, and dissolved organic carbon can influence contaminant speciation, mobility, and bioavailability. In freshwater systems, altered river flows and reduced water levels may affect contaminant concentrations, sediment resuspension, and the efficiency of natural attenuation processes. In coastal and marine environments, sea-level rise, saltwater intrusion, storm surges, and changing ocean conditions can redistribute contaminants and affect their interactions with sediments and organisms (Hung, 2022). Furthermore, flooding and extreme weather events can overwhelm wastewater treatment infrastructure, increase the release of untreated or partially treated wastewater, and transport plastic debris and associated chemical additives across environmental boundaries. These changing conditions may create contaminant exposure patterns that differ substantially from those observed under historical climatic conditions, complicating environmental monitoring and risk assessment.

Climate-related changes in contaminant fate also extend beyond transport and persistence to include the modification of exposure pathways. Environmental exposure occurs when contaminants move from their sources through air, water, soil, sediments, and food webs before reaching organisms. Climate change can modify these pathways by changing the frequency of pollutant releases, the connectivity between environmental compartments, and the duration and intensity of contact between contaminants and biological receptors. For example, intense rainfall can facilitate the transfer of pesticides, pharmaceuticals, microplastics, and industrial chemicals from land into aquatic systems (Hatje, 2022). Drought conditions can increase the concentration of certain pollutants in limited water supplies, while wildfires may release previously stored contaminants into the atmosphere and redistribute them through ash deposition and subsequent runoff. Permafrost thaw and the destabilization of contaminated soils may also mobilize legacy pollutants that have remained relatively isolated under frozen conditions. Additionally, changes in temperature and seasonal biological activity can influence the timing of contaminant exposure relative to organism development, reproduction, migration, and feeding. Such changes may increase the likelihood that sensitive life stages encounter harmful concentrations, even where average environmental contaminant levels remain relatively stable.

The ecological consequences of these interactions are potentially substantial because exposure to emerging contaminants can affect organisms at multiple biological levels. Depending on their properties and exposure concentrations, contaminants may interfere with endocrine regulation, reproduction, growth, development, immune function, behavior, and metabolic processes. Microplastics and nanoplastics may also interact with organisms through ingestion, physical interference, and the transfer of associated chemical substances, although the magnitude and ecological significance of these effects vary across exposure

scenarios. Climate-related stressors can intensify some contaminant effects by reducing physiological tolerance, altering detoxification processes, or increasing organisms' energetic requirements (Armitage, 2011). For instance, elevated temperatures may increase metabolic demand while simultaneously reducing dissolved oxygen availability in aquatic habitats, potentially limiting organisms' capacity to cope with additional chemical stress. Similarly, drought, salinity changes, and food shortages may compromise physiological resilience and influence the toxicity of particular contaminants. Nevertheless, interactions between climatic stressors and chemical pollutants are not always additive or synergistic; depending on the species, contaminant, exposure conditions, and biological endpoint, their combined effects may also be antagonistic. Evaluating these interactions is therefore necessary to avoid underestimating or incorrectly characterizing ecological risks.

At the ecosystem level, climate change and emerging contaminants may jointly influence biodiversity, species interactions, nutrient cycling, primary productivity, decomposition, and the stability of ecological communities. Organisms exposed to multiple stressors may experience changes in survival, reproductive success, feeding behavior, and habitat suitability, potentially affecting population dynamics and trophic relationships. Contaminants that accumulate in organisms may be transferred through food webs, exposing predators to substances originating from distant or interconnected habitats (De Wit, 2022). Climatic changes that alter migration, feeding patterns, or the distribution of species may further modify these transfer processes. In addition, the loss or decline of sensitive species may change community composition and ecosystem functioning, while the persistence of contaminants in sediments and soils can create long-term sources of exposure even after direct pollutant releases have declined. These concerns are particularly important in ecosystems already experiencing habitat degradation, biodiversity loss, and increasing pressure from human activities. A comprehensive assessment of ecological risk must therefore consider not only the toxicity of individual contaminants but also the cumulative effects of multiple pollutants, climatic stressors, and changes in ecosystem structure and function.

Despite increasing recognition of the relationship between climate change and chemical pollution, important knowledge gaps remain. Much environmental risk assessment continues to rely on historical monitoring data, standardized laboratory tests, and exposure scenarios that may not adequately represent future climatic conditions. Traditional approaches often evaluate individual contaminants under relatively stable temperature, water chemistry, and hydrological conditions, potentially overlooking the variability and complexity of real-world environmental exposure. Moreover, contaminant monitoring is uneven across regions and environmental compartments, with important gaps in long-term datasets, mixture toxicity assessments, transformation-product identification, and evidence concerning chronic effects on non-target organisms (Clasen, 2025). Emerging analytical technologies have improved the detection of trace contaminants, but the presence of a substance does not necessarily establish its ecological significance, and the effects of many compounds at environmentally realistic concentrations remain uncertain. Additional challenges include the limited integration of climate projections into contaminant transport models, difficulties in predicting interactions among multiple stressors, and insufficient representation of ecological thresholds and sensitive biological life stages in some risk assessment frameworks. Addressing these limitations requires interdisciplinary approaches that integrate environmental chemistry, climatology, hydrology, ecotoxicology, ecology, and predictive modeling.

Against this background, examining climate change and emerging contaminants within a unified analytical framework is essential for improving understanding of environmental fate, exposure pathways, and ecological risks. Such an approach can clarify how changing climatic conditions influence contaminant release, transport, persistence, transformation, and bioavailability across interconnected environmental systems. It can also identify circumstances in which climate-related stressors alter organism sensitivity, modify contaminant transfer through food webs, or increase the vulnerability of ecological communities. Integrating climate projections with environmental monitoring, experimental ecotoxicology, and modeling approaches may further strengthen the ability to anticipate future pollution hotspots and identify ecosystems requiring priority protection (Alshamsi, 2022). This perspective is particularly relevant for environmental management because pollution control strategies designed around historical environmental conditions may become less effective as temperature regimes, hydrological patterns, and extreme weather events change.

Accordingly, this study examines the interactions between climate change and emerging contaminants, focusing on their implications for environmental fate, exposure pathways, and ecological risks. Specifically, it explores how climatic variables and extreme events influence contaminant transport, persistence, transformation, and bioavailability; evaluates the ways in which changing environmental conditions modify exposure across terrestrial, freshwater, and marine ecosystems; and discusses the potential consequences for organisms, populations, biodiversity, and ecosystem functioning (Singh, 2024). The study also considers methodological and regulatory challenges associated with assessing contaminant risks under changing climatic conditions and identifies priorities for future research, monitoring, and environmental management. By synthesizing these interconnected dimensions, the study seeks to advance a more integrated understanding of climate-sensitive contaminant dynamics and support the development of adaptive, evidence-based strategies for reducing chemical pollution and safeguarding ecological integrity in a changing global environment.

2. Methodology

2.1. Research Design

This study adopts a narrative literature review design to examine how climate change influences the environmental fate, transport, exposure pathways, and ecological risks of emerging contaminants. A review-based approach is appropriate because the interactions between climatic processes and emerging contaminants encompass multiple environmental compartments, contaminant classes, and ecological systems. The methodology integrates findings from environmental chemistry, ecotoxicology, climate science, hydrology, soil science, and environmental health to develop a comprehensive understanding of the mechanisms through which changing climatic conditions may alter contaminant behavior and ecological impacts. Particular attention is given to emerging contaminants, including pharmaceuticals and personal care products, microplastics and nanoplastics, per- and polyfluoroalkyl substances (PFAS), endocrine-disrupting chemicals, pesticides, antimicrobial-resistant microorganisms, and other contaminants of emerging concern. The review also considers the influence of increasing temperatures, altered precipitation patterns, droughts, floods, wildfires, sea-level rise, and extreme weather events on contaminant mobility, persistence, bioavailability, and toxicity.

2.2. Literature Search Strategy

Relevant scientific literature was identified through a structured search of major academic databases and scholarly search platforms, including Scopus, Web of Science, PubMed, ScienceDirect, and Google Scholar. These sources were selected to capture interdisciplinary research on climate change, environmental pollution, contaminant fate, and ecological risk assessment. The search focused on peer-reviewed journal articles, systematic reviews, experimental studies, field investigations, and relevant scientific assessments addressing the relationships between climatic variability and emerging contaminants. Search terms included combinations of the following concepts: "climate change," "emerging contaminants," "contaminants of emerging concern," "environmental fate," "contaminant transport," "bioavailability," "ecological risk," "microplastics," "PFAS," "pharmaceutical residues," "extreme weather events," "drought," "flooding," "temperature increase," and "ecosystem exposure." Boolean operators, including AND and OR, were used to combine search terms and refine the retrieval of relevant publications. For example, search combinations included "climate change AND emerging contaminants," "flooding AND contaminant transport," and "temperature increase AND environmental toxicity." Additional publications were identified by examining the reference lists of relevant articles to locate studies that might not have been retrieved through the initial database searches.

2.3. Literature Selection Criteria

The selection of literature was guided by the relevance of each publication to the central objectives of the review. Studies were considered eligible when they examined emerging contaminants in environmental systems, investigated the effects of climate-related variables on contaminant behavior, evaluated contaminant exposure pathways, or assessed ecological consequences under changing climatic conditions. Research addressing freshwater and marine environments, terrestrial ecosystems, agricultural landscapes, urban watersheds, sediments, soils, and atmospheric transport was included where it contributed to understanding the interactions between climate change and emerging contaminants. Both empirical studies and relevant conceptual or modeling investigations were considered to capture experimental evidence, observed environmental patterns, and projected future risks. Publications examining conventional pollutants were included only when their findings provided useful evidence about mechanisms relevant to emerging contaminants, such as contaminant mobilization during flooding, enhanced transport during storm events, or changes in chemical transformation under elevated temperatures.

Studies were excluded when they lacked a clear connection to the research objectives, did not provide sufficient methodological or scientific information, or focused exclusively on unrelated environmental or climatic issues. Duplicate records were removed during the screening process, and publication titles, abstracts, and, where necessary, full texts were assessed for relevance. Greater emphasis was placed on peer-reviewed research and credible scientific assessments, particularly studies that provided direct experimental, observational, or modeling evidence. Earlier foundational publications were retained when they established important principles concerning contaminant persistence, transport, bioaccumulation, or ecotoxicity. This approach allowed the review to incorporate both recent developments and established scientific knowledge without relying exclusively on publication date as a measure of relevance.

2.4. Data Extraction and Organization

Information from the selected publications was extracted and organized according to the principal themes of the study. The extracted information included contaminant categories, environmental media, climatic variables, mechanisms of contaminant transformation and transport, exposure pathways, ecological receptors, and reported environmental effects. Where available, the review also considered the study setting, research design, analytical techniques, modeling approaches, and major limitations identified by the original authors. This information provided a basis for comparing findings across different environmental contexts and identifying areas of agreement, uncertainty, and inconsistency within the literature.

The extracted evidence was organized around five interconnected dimensions: climate-related drivers, environmental fate and transport, exposure pathways, ecological responses, and implications for environmental risk assessment. Climate-related drivers included rising temperatures, changes in precipitation intensity and seasonality, drought, flooding, wildfire activity, and sea-level rise. Environmental fate and transport encompassed contaminant degradation, persistence, sorption and desorption, dissolution, volatilization, sedimentation, remobilization, and movement between environmental compartments. Exposure-related information focused on the transfer of contaminants through water, soil, sediment, air, food webs, and biological tissues. Ecological response data included toxicity, reproductive and developmental effects, physiological stress, microbial community changes, bioaccumulation, and potential disruptions to ecosystem structure and functioning. Organizing the evidence in this manner facilitated the examination of climate change as a modifying factor that can influence several stages of contaminant behavior rather than as an isolated environmental pressure.

2.5. Thematic Analysis and Evidence Synthesis

A qualitative thematic synthesis was used to integrate the findings from the selected literature. The analysis involved identifying recurring concepts, comparing reported mechanisms, and examining relationships between climatic conditions and contaminant behavior across environmental settings. The first analytical theme concerned the influence of climate change on the physical and chemical properties of environmental systems, including temperature-dependent reaction rates, changes in water chemistry, soil moisture variability, and alterations in hydrological processes. The second theme examined how these changes affect contaminant persistence, degradation, partitioning, mobility, and distribution across environmental compartments. The third theme focused on exposure pathways, particularly the redistribution of contaminants during floods, the concentration of pollutants under drought conditions, the transport of particle-associated contaminants during storm events, and the transfer of contaminants through aquatic and terrestrial food webs.

The fourth theme addressed ecological consequences, including changes in organism exposure, contaminant bioavailability, toxicity, and the potential for combined stress from chemical pollution and climatic extremes. The final theme examined implications for environmental monitoring, ecological risk assessment, and pollution management under future climate scenarios. Findings were compared across contaminant groups and ecosystem types to distinguish broadly applicable mechanisms from effects that depend on specific chemical properties, environmental conditions, and biological characteristics. Particular attention was paid to evidence indicating that climate-related changes may increase contaminant risks in some circumstances while reducing or redistributing them in others. This comparative approach avoided assuming that warming or extreme weather produces uniform effects across all contaminants and ecosystems.

2.6. Assessment of Evidence Quality and Uncertainty

The strength and limitations of the available evidence were considered during the synthesis. Greater interpretive weight was assigned to studies with clearly described methods, appropriate analytical procedures, relevant environmental measurements, and transparent reporting of results. Experimental studies were examined for their relevance to realistic environmental conditions, while field investigations were considered in relation to site-specific characteristics and the potential influence of confounding factors. Modeling studies were evaluated according to the clarity of their assumptions, the climatic scenarios considered, and the extent to which their outputs were supported by observational or experimental evidence. Findings from laboratory experiments were not automatically treated as equivalent to effects observed in natural ecosystems, particularly where exposure concentrations, exposure duration, or environmental conditions differed substantially.

The review also recognized important sources of uncertainty, including differences in contaminant detection methods, limited long-term monitoring, inconsistent definitions of emerging contaminants, geographic imbalances in available research, and difficulties separating climatic influences from other environmental pressures. Additional uncertainty may arise from interactions among temperature, pH, salinity, dissolved organic matter, oxygen availability, and hydrological conditions. The behavior of complex contaminant mixtures and the ecological consequences of simultaneous exposure to pollutants and climate-related stressors were also considered. These limitations were taken into account when interpreting reported relationships and drawing broader conclusions about future ecological risks.

2.7. Methodological Limitations

As a narrative review, this study is designed to provide an integrated and critical interpretation of interdisciplinary evidence rather than a statistical aggregation of effect sizes. Differences in study designs, contaminant characteristics, climatic variables, exposure conditions, and ecological endpoints may limit direct comparisons among individual studies. Furthermore, emerging contaminants represent a rapidly expanding field, meaning that newly identified chemicals, analytical methods, and climate-related findings may not be fully represented in the available literature. The search process may also be affected by database coverage, publication bias, language restrictions, and differences in terminology across disciplines. Consequently, the findings are interpreted in relation to the scope and quality of the available evidence, and conclusions are framed cautiously where direct

empirical evidence remains limited. Despite these limitations, the interdisciplinary review approach provides a useful foundation for understanding the mechanisms connecting climate change with the environmental fate, exposure pathways, and ecological risks of emerging contaminants, while identifying priorities for future research and climate-informed environmental management.

3. Findings and Discussion

The findings of this review indicate that climate change can substantially alter the environmental fate, transport, exposure pathways, and ecological effects of emerging contaminants. Rising temperatures, changing precipitation patterns, prolonged droughts, flooding, wildfires, and sea-level rise influence the persistence, mobility, bioavailability, and distribution of contaminants across aquatic, terrestrial, and atmospheric environments (Talreja, 2025). Emerging contaminants include pharmaceuticals and personal care products, endocrine-disrupting chemicals, microplastics, per- and polyfluoroalkyl substances (PFAS), pesticides, and other chemicals whose environmental occurrence and potential effects may not be adequately addressed by conventional monitoring and regulatory systems.

The reviewed evidence suggests that climate change and chemical pollution should not be treated as independent environmental pressures. Climatic conditions may modify contaminant concentrations, degradation rates, and transport mechanisms, while chemical exposure can reduce the capacity of organisms and ecosystems to withstand heat stress, oxygen depletion, habitat degradation, and other climate-related disturbances. However, these interactions are contaminant-specific and depend on environmental conditions, chemical properties, ecosystem characteristics, and the timing and duration of exposure (Pereira, 2015). Some climatic changes may accelerate contaminant degradation, whereas others may increase persistence, remobilization, or ecological exposure. The following sections synthesize these relationships and discuss their implications for environmental protection, ecological risk assessment, and climate-responsive pollution management.

3.1. Climate Change and the Environmental Fate of Emerging Contaminants

Climate change influences the environmental fate of emerging contaminants by modifying the physical, chemical, and biological processes that determine their persistence, transformation, transport, and accumulation. Temperature, precipitation, solar radiation, soil moisture, water chemistry, and microbial activity collectively influence the movement of contaminants between water, soil, sediment, and air (Yan, 2010). Consequently, historical observations of contaminant concentrations may become less representative of future environmental conditions as climatic patterns change.

An important finding is that the relationship between climate change and contaminant fate is not uniformly positive or negative. Higher temperatures may accelerate the degradation of certain biodegradable chemicals, while simultaneously increasing the persistence or mobility of other substances through changes in sorption, volatilization, chemical transformation, and biological activity. Similarly, heavy rainfall can dilute contaminants in some circumstances but increase their transport into rivers, groundwater, and coastal environments in others (Hiranmai, 2023). These contrasting responses demonstrate the importance of assessing contaminant fate within specific climatic and environmental contexts.

3.1.1. Effects of Rising Temperatures on Contaminant Persistence and Degradation

Rising environmental temperatures influence the persistence and degradation of emerging contaminants by changing chemical reaction rates, microbial metabolism, photochemical processes, and interactions between contaminants and environmental media. For many biodegradable organic compounds, increasing temperature can accelerate microbial transformation when suitable microorganisms, oxygen, moisture, and nutrients are available. Pharmaceuticals entering wastewater treatment systems, for example, may undergo faster biodegradation under certain warmer conditions (Kallenborn, 2012). However, this response is not universal because temperature increases can also reduce dissolved oxygen, alter microbial community composition, and inhibit the biological processes responsible for contaminant removal.

The relationship between temperature and contaminant degradation is particularly important for wastewater treatment facilities and receiving aquatic environments. Conventional biological treatment processes depend on microbial communities that transform organic pollutants. Moderate warming may enhance some biological reactions, but excessive heat can disrupt microbial activity and reduce treatment performance. In addition, warmer water generally holds less dissolved oxygen, potentially limiting aerobic degradation and increasing the persistence of some organic contaminants (Biswas, 2018). These effects are especially relevant in shallow lakes, reservoirs, and slow-moving rivers that experience prolonged summer warming.

Temperature also affects the sorption and desorption of contaminants in soils and sediments. For certain chemicals, higher temperatures can promote desorption from sediment particles, increasing the fraction available in the water column. Other chemicals may remain strongly associated with organic matter or mineral surfaces, depending on their molecular structure and the properties of the receiving environment. Volatile contaminants may also move more readily into the atmosphere as

temperatures rise, although the magnitude of this process depends on volatility, soil moisture, surface conditions, and atmospheric transport (Maulvault, 2018). Therefore, increased temperature does not necessarily result in either greater persistence or greater mobility for all contaminants.

Evidence from broader research on global environmental change and chemical pollution supports the need to account for these multiple mechanisms. For example, the Stockholm Convention's work on persistent organic pollutants highlights the importance of long-range environmental transport and the continuing presence of chemicals that resist degradation. Climate-related changes in temperature and environmental partitioning may further complicate their distribution. Similarly, studies of pharmaceuticals in wastewater systems demonstrate that removal efficiency varies substantially across compounds and treatment conditions (Vasilachi, 2021). These observations indicate that temperature alone is insufficient to predict contaminant persistence without considering chemical-specific properties and biological responses.

An additional concern is the potential for transformation products to have different environmental characteristics from their parent compounds. A pesticide or pharmaceutical may degrade more rapidly under warmer conditions while producing intermediate compounds that remain mobile or biologically active. Accordingly, environmental assessments should evaluate both parent substances and relevant transformation products (Naidu, 2016). This is particularly important where warming coincides with drought, reduced streamflow, or declining oxygen concentrations, because these conditions can alter degradation pathways and increase the duration or intensity of exposure.

3.1.2. Changes in Hydrological Patterns and Contaminant Transport

Changes in hydrological patterns are among the most important mechanisms through which climate change alters contaminant transport. Shifts in rainfall intensity, seasonal precipitation, river discharge, groundwater recharge, evaporation, and drought frequency can influence contaminant dilution, concentration, infiltration, runoff, and movement between environmental compartments (Noyes, 2025). The consequences vary according to watershed characteristics, land use, soil permeability, contaminant solubility, and the condition of wastewater and stormwater infrastructure.

During droughts, reduced river discharge can decrease the dilution of contaminants released from wastewater treatment plants, industrial facilities, agricultural land, and urban drainage systems. Consequently, concentrations of pharmaceuticals, personal care products, pesticides, and other pollutants may increase in receiving waters even when their total discharge remains relatively stable. Low flows may also increase water residence time and intensify warming, creating conditions that affect chemical transformation and biological exposure (Nadal, 2015). These effects are particularly significant in water-scarce regions where rivers serve simultaneously as ecological habitats, irrigation sources, and domestic water supplies.

Conversely, intense precipitation can increase the movement of contaminants from land to water through surface runoff, erosion, and drainage. Agricultural chemicals may be transported into streams shortly after application, while contaminants accumulated in urban soils, roads, and drainage channels can enter rivers during storm events. In areas with combined sewer systems, heavy rainfall can overwhelm infrastructure and release inadequately treated wastewater into receiving environments (Imoobe, 2024). These events can generate short-lived but substantial contamination peaks that routine sampling programs may fail to detect.

Groundwater contamination is also influenced by changing hydrological conditions. Increased rainfall may enhance the infiltration of mobile contaminants through permeable soils, particularly where groundwater is shallow or protective soil layers are limited. Pesticides, nitrate-associated contaminants, and certain pharmaceuticals may reach groundwater under favorable transport conditions. However, the effect depends on soil structure, preferential flow pathways, aquifer properties, and the chemical's tendency to sorb or degrade (Di Guardo, 2018). In contrast, prolonged drought can reduce recharge and increase dependence on groundwater resources, potentially intensifying human and ecological exposure to existing contamination.

Hydrological change further affects contaminant exchange between rivers, wetlands, sediments, and coastal systems. Floodplains and wetlands may temporarily retain contaminants through sedimentation and sorption, but subsequent changes in water levels, oxygen conditions, or sediment chemistry can release previously accumulated substances. Sea-level rise and saltwater intrusion may also change groundwater chemistry and the behavior of some contaminants in coastal aquifers (He, 2025). Such processes are relevant for persistent chemicals and metals whose mobility can depend on salinity, pH, redox conditions, and interactions with sediment particles.

These findings are consistent with the broader conclusions of climate–water research, including the Intergovernmental Panel on Climate Change's assessments of changing hydrological extremes and the United Nations Environment Programme's work on freshwater pollution. They reinforce the view that contaminant monitoring must consider not only average concentrations but also discharge rates, seasonal variation, storm-event peaks, and the movement of pollutants between environmental

compartments (Cains, 2024). A central implication is that concentration measurements alone may provide an incomplete picture of environmental risk. Reduced flow can increase concentration while decreasing total contaminant transport, whereas floods may dilute measured concentrations while increasing the total mass of pollutants delivered downstream. Risk assessments should therefore distinguish between contaminant concentration, transported mass, duration of exposure, and the sensitivity of organisms receiving the exposure.

3.1.3. Influence of Extreme Weather Events on Contaminant Mobilization and Redistribution

Extreme weather events, including floods, hurricanes, heatwaves, droughts, and wildfires, can mobilize contaminants that have accumulated in soils, sediments, industrial sites, waste facilities, and urban environments. Unlike gradual climatic changes, these events can produce abrupt changes in contaminant distribution, leading to temporary contamination peaks and the redistribution of pollutants across large areas (Gomes, 2024). Their environmental consequences depend on event intensity, duration, antecedent environmental conditions, and the vulnerability of local infrastructure.

Flooding is a particularly important pathway for contaminant redistribution. Floodwaters can transport contaminated sediments, agricultural chemicals, microplastics, pharmaceuticals, industrial chemicals, and waste-derived pollutants into rivers, wetlands, agricultural fields, and coastal ecosystems. Flooding of wastewater treatment facilities, landfills, mining areas, or industrial storage sites may release contaminants that would otherwise remain contained (Zandaryaa, 2025). Following the event, pollutants may settle in floodplain sediments and persist beyond the immediate flood period, creating potential sources of secondary exposure.

Wildfires introduce another set of contaminant pathways. Combustion can release metals, particulate matter, and persistent organic pollutants from vegetation, buildings, plastics, and other materials. Ash and fire-affected soils may subsequently be transported by wind or rainfall into nearby water bodies. Changes in soil structure and vegetation cover can increase erosion, while the loss of plant cover reduces the capacity of landscapes to intercept runoff (Zitoun, 2024). The resulting contaminant pulse may affect water quality long after the fire has been extinguished.

Droughts can produce similar redistribution effects through different mechanisms. As soils dry, contaminants may accumulate near the surface or become associated with fine particles and organic matter. Subsequent rainfall can mobilize these accumulated substances in a concentrated first flush. In aquatic systems, drought-related reductions in water volume may expose contaminated sediments to oxygen, alter pH and redox conditions, and change the release of metals and other sediment-associated pollutants. When water levels recover, these contaminants may re-enter the water column and become available to aquatic organisms (Balbus, 2013). Heatwaves can also increase contaminant-related risks by intensifying evaporation, reducing dissolved oxygen, and stressing biological communities. In urban environments, elevated temperatures may coincide with increased stormwater runoff following intense rainfall, creating combined exposure to chemical mixtures. Extreme weather can additionally damage drinking-water and wastewater infrastructure, reducing treatment reliability and increasing the likelihood of untreated or partially treated discharges.

These mechanisms demonstrate why contaminant assessments based on normal weather conditions may underestimate risks associated with extreme events. Monitoring should include pre-event baselines, measurements during or immediately after events where feasible, and follow-up assessments to determine whether contaminants remain in sediments, soils, or biological tissues (O'Flynn, 2021). Event-based monitoring is particularly valuable for identifying pollution hotspots, evaluating infrastructure vulnerabilities, and determining whether ecological recovery is delayed by continuing chemical exposure.

3.2. Climate-Driven Changes in Emerging Contaminant Exposure Pathways

Climate change alters the pathways through which emerging contaminants reach organisms and ecosystems. The reviewed evidence indicates that changes in water availability, soil moisture, atmospheric circulation, land surface conditions, and food-web interactions can modify the intensity, duration, and distribution of chemical exposure. Contaminants may move between environmental compartments through runoff, infiltration, sediment transport, atmospheric deposition, and biological uptake. These processes create opportunities for contaminants released in one location to affect organisms and communities far beyond the original source (Tong, 2025). A significant finding is that exposure pathways are increasingly interconnected under changing climatic conditions. For example, a pesticide applied to agricultural land may be transported by heavy rainfall into surface water, accumulate in sediments, enter aquatic organisms, and subsequently reach fish-eating birds or humans through food consumption. Similarly, contaminants released during wildfires can be deposited on land or water and later redistributed by runoff. Such interactions demonstrate that the environmental risks of emerging contaminants cannot be fully understood by examining individual media or exposure routes in isolation.

3.2.1. Aquatic Exposure Pathways: Surface Water, Groundwater, and Sediments

Surface water represents a major exposure pathway for emerging contaminants because rivers, lakes, reservoirs, and coastal waters receive pollutants from wastewater discharges, agricultural runoff, industrial activities, and urban drainage. Climate change modifies these pathways through changes in water temperature, river discharge, rainfall intensity, and evaporation. During droughts, reduced dilution can increase the concentrations of contaminants entering rivers from wastewater treatment plants (Ogayemi, 2026). During floods, contaminants may be transported over larger areas and introduced into aquatic systems that previously experienced relatively limited pollution.

Pharmaceuticals and personal care products provide a useful example of these processes. Compounds such as antibiotics, analgesics, and ingredients in personal care products may enter surface waters through treated wastewater and urban runoff. During low-flow conditions, the concentration of some compounds may increase because receiving waters contain less water relative to the pollutant load. Aquatic organisms may consequently experience prolonged exposure, particularly downstream of wastewater discharge points (Borgå, 2022). However, the magnitude of the effect depends on discharge volumes, treatment efficiency, chemical degradation, and the hydrological characteristics of the receiving water body.

Groundwater presents a different but equally important exposure pathway. Mobile contaminants can infiltrate through soil and enter aquifers, where their persistence may be prolonged by limited sunlight, lower microbial activity, or restricted oxygen availability. Climate-related changes in rainfall and groundwater recharge can modify the movement of these substances. Heavy rainfall may facilitate contaminant infiltration, whereas prolonged drought may reduce recharge and increase reliance on groundwater containing existing pollutants (Hung, 2022). In coastal areas, saltwater intrusion may alter groundwater chemistry and influence the mobility of certain contaminants.

Sediments are particularly important because they can act as both sinks and secondary sources of contamination. Hydrophobic organic chemicals, some persistent pollutants, and contaminant-bearing microplastics may accumulate in sediments and become available to benthic organisms. Changes in water temperature, oxygen availability, sediment disturbance, and chemical conditions can alter the release or bioavailability of sediment-associated substances (Hatje, 2022). Floods may redistribute contaminated sediments downstream, while drought-related water-level fluctuations may expose previously submerged materials to changing environmental conditions.

The interaction between these aquatic pathways is important for understanding contaminant exposure. A chemical entering a river may become associated with suspended particles, settle into sediments, and subsequently be resuspended during high-flow events. Alternatively, dissolved contaminants may infiltrate into groundwater or enter organisms directly through gills and other biological surfaces (Armitage, 2011). These processes indicate that water-column measurements alone may underestimate the overall contamination burden of an aquatic ecosystem.

The findings support the broader argument presented by De Wit (2022), who emphasized the global challenge of organic chemical contamination in water resources, and Clasen (2025), who demonstrated the importance of freshwater ecosystem threats associated with human pressures. Under climate change, these pressures are likely to interact more dynamically, making integrated surface-water, groundwater, and sediment monitoring essential for identifying exposure hotspots and protecting freshwater biodiversity.

3.2.2. Terrestrial Exposure Pathways: Soils, Agricultural Systems, and Food Chains

Terrestrial ecosystems receive emerging contaminants through pesticide application, irrigation with reclaimed wastewater, atmospheric deposition, sewage sludge application, industrial emissions, and the disposal of contaminated materials. Climate change influences the movement of these pollutants by altering soil moisture, erosion, microbial activity, plant growth, and the frequency of runoff events (Alshamsi, 2022). These changes can affect contaminant accumulation in agricultural soils, uptake by crops, exposure of soil organisms, and transfer through terrestrial food chains.

Agricultural systems are especially vulnerable because they combine chemical inputs with climatic conditions that regulate soil and water movement. Heavy rainfall following pesticide application may transport chemicals from fields into adjacent water bodies, while prolonged dry conditions can reduce microbial degradation and increase the concentration of certain contaminants in surface soils. Subsequent rainfall may mobilize these accumulated chemicals, exposing plants, soil invertebrates, and aquatic organisms to sudden contamination pulses (Singh, 2024). The magnitude of these effects depends on pesticide properties, application timing, soil composition, vegetation cover, and local rainfall patterns.

Irrigation practices may further influence contaminant exposure. In water-scarce regions, the use of treated or partially treated wastewater can introduce pharmaceuticals, personal care product residues, and other contaminants into agricultural soils.

Repeated application may lead to accumulation of some persistent substances, although the extent of accumulation varies with treatment quality, soil conditions, degradation rates, and crop characteristics (Talreja, 2025). Under high temperatures, changes in soil moisture and microbial activity may alter the transformation of these compounds. In addition, increased irrigation demand during droughts can increase the frequency of contaminant inputs where water quality is inadequately controlled.

Contaminant uptake by plants creates potential pathways into food chains. Certain chemicals may be absorbed through roots, deposited on leaves, or retained on plant surfaces. The extent of uptake depends on chemical properties, plant species, soil characteristics, and the availability of contaminants in soil water. Chemicals that accumulate in edible plant tissues may contribute to dietary exposure, while contaminated plant material may expose herbivorous insects, livestock, and other organisms (Pereira, 2015). However, the presence of a contaminant in soil does not automatically imply significant crop uptake or food-chain transfer; bioavailability and biological processing must also be considered.

Soil organisms, including earthworms, nematodes, fungi, and beneficial microorganisms, are exposed through contact with contaminated soil and the consumption of organic matter. These organisms support decomposition, nutrient cycling, soil aggregation, and plant productivity. Yan, (2010) highlighted the ecological importance of soil biota in the context of microplastic contamination, illustrating how emerging pollutants can interact with fundamental soil processes. Climate-related changes in soil temperature and moisture may further influence these interactions by changing microbial communities, organism activity, and contaminant bioavailability.

Food-chain transfer is also relevant for persistent contaminants that accumulate in organisms. Some substances may move from soil or water into invertebrates and then into birds, mammals, or humans. The strength of this transfer depends on chemical persistence, tissue affinity, metabolic transformation, feeding behavior, and trophic position (Hiranmai, 2023). Consequently, climate-driven changes in species distributions, feeding relationships, and food availability may indirectly alter exposure patterns even when environmental contaminant concentrations remain relatively stable.

3.2.3. Atmospheric Transport, Deposition, and Human–Wildlife Exposure

The atmosphere is an important pathway for the long-distance transport of emerging contaminants. Chemicals may enter the air through industrial emissions, waste combustion, volatilization from soil and water, dust generation, and the resuspension of contaminated particles. Once airborne, contaminants can travel across landscapes and national boundaries before being deposited through rainfall, snowfall, or dry particle deposition (Kallenborn, 2012). Climate change can alter these processes by influencing atmospheric circulation, temperature, precipitation, wind patterns, and the frequency of wildfires and dust events.

Higher temperatures can increase the volatilization of certain chemicals from contaminated surfaces, although the extent of this effect depends on vapor pressure, environmental binding, and surface conditions. Persistent organic pollutants may undergo repeated cycles of volatilization, atmospheric transport, and deposition, contributing to their distribution across regions distant from their original sources (Biswas, 2018). Changes in temperature and precipitation can modify the location and timing of these processes, potentially affecting the accumulation of pollutants in colder environments and other sensitive ecosystems.

Wildfires and droughts can intensify atmospheric transport by generating smoke, ash, and contaminated dust. Combustion may release chemicals from vegetation, industrial materials, waste, and previously contaminated soils. Wind can transport these substances over considerable distances, while subsequent rainfall deposits airborne contaminants onto land and water (Maulvault, 2018). This creates a connection between atmospheric pollution, terrestrial contamination, and aquatic exposure that may persist after the original climatic event.

Atmospheric deposition also affects remote ecosystems. Pollutants transported over long distances may reach mountains, forests, lakes, and polar environments where local emission sources are limited. Deposition onto snow and ice can be followed by contaminant release during melting, potentially producing short-term exposure peaks in downstream waters. Changes in snow cover and seasonal melt timing may therefore alter the timing of pollutant delivery to aquatic habitats (Vasilachi, 2021). Humans and wildlife may be exposed to airborne contaminants through inhalation, ingestion of deposited particles, and consumption of contaminated food or water. Fine particles can carry metals and persistent organic pollutants, while airborne microplastics and other synthetic particles may be transported through atmospheric circulation. Wildlife exposure may occur through inhalation, deposition on feathers or fur, ingestion of contaminated dust, or consumption of contaminated prey. However, the relative importance of these pathways differs substantially across chemicals and species, and the ecological significance of airborne microplastic exposure remains an area of active investigation.

The work of Naidu (2016) on the global distribution of persistent organic pollutants provides a useful foundation for understanding the role of atmospheric transport and temperature-dependent environmental partitioning. Climate change adds

further complexity because atmospheric movement and deposition are influenced by changing environmental conditions. These findings support the integration of atmospheric sampling with soil, water, and biological monitoring, particularly in regions affected by wildfires, dust storms, industrial emissions, or long-range pollutant transport.

3.3. Ecological Risks and Impacts on Environmental Systems

The ecological consequences of emerging contaminants depend on exposure concentration, duration, bioavailability, chemical mixtures, species sensitivity, and ecosystem condition. Climate change can modify several of these factors simultaneously, creating conditions in which organisms encounter contaminants while experiencing heat stress, oxygen limitation, water scarcity, or habitat disturbance. Such combined pressures may affect individual survival, growth, reproduction, behavior, and the ecological relationships that sustain ecosystem functioning (Noyes, 2025). The reviewed evidence suggests that ecological risk cannot be determined solely from whether a contaminant exceeds a fixed concentration threshold. A concentration that produces limited effects under favorable environmental conditions may have greater consequences when organisms are already stressed by warming or reduced oxygen availability. Conversely, some climatic conditions may reduce exposure by increasing dilution or accelerating degradation. Ecological assessments must therefore consider the direction, magnitude, and biological significance of climate–contaminant interactions rather than assume that all combined effects are additive or synergistic.

3.3.1. Effects on Aquatic Organisms and Freshwater Ecosystems

Aquatic organisms are particularly susceptible to changes in water temperature, dissolved oxygen, flow conditions, and chemical exposure. Fish, amphibians, aquatic invertebrates, algae, and microorganisms depend on environmental conditions that regulate respiration, metabolism, reproduction, and habitat suitability. Climate change can alter these conditions while simultaneously changing the bioavailability and toxicity of emerging contaminants (Nadal, 2015). Warming can increase metabolic rates in ectothermic organisms, potentially changing their feeding behavior, growth, and contaminant uptake. In some circumstances, higher temperatures may increase the rate at which organisms absorb and process chemicals. However, uptake and accumulation are not determined by temperature alone; they also depend on chemical properties, exposure concentrations, elimination rates, and physiological responses. Consequently, warming may increase, decrease, or leave unchanged the internal concentration of particular contaminants.

Reduced dissolved oxygen presents an additional concern. Warm water generally holds less oxygen, and eutrophication can intensify oxygen depletion as organic matter decomposes. Under these conditions, fish and invertebrates may experience physiological stress while being exposed to pharmaceuticals, pesticides, endocrine-disrupting chemicals, or metals. Affected organisms may have less capacity to maintain normal physiological functions, making the ecological consequences of contamination more pronounced in susceptible species.

Endocrine-disrupting chemicals are of particular concern because they can interfere with hormonal processes involved in development and reproduction (Imoobe, 2024). Laboratory and field research has documented reproductive and developmental effects associated with certain endocrine-active substances, although outcomes depend on chemical identity, exposure level, and species. Climate-related changes in water temperature can also influence reproductive timing and developmental rates. When these processes occur together, contaminants may affect organisms during sensitive developmental periods, potentially altering recruitment and population dynamics.

Aquatic invertebrates can also experience changes in behavior, feeding, growth, and reproduction following exposure to pharmaceuticals and pesticides. Because these organisms form a major component of freshwater food webs, population-level changes can influence the availability of prey for fish and other predators (Di Guardo, 2018). Contaminant effects on algae and microbial communities may further alter primary production, decomposition, and nutrient cycling. Thus, ecological impacts can extend beyond directly exposed species to affect ecosystem processes and food-web relationships.

The study by He (2025) examined the interactive effects of elevated temperature and chemical exposure on aquatic organisms, emphasizing the importance of considering climate-related stress when assessing chemical toxicity. Their synthesis supports the conclusion that conventional toxicity tests conducted under constant temperatures may not fully represent the responses of organisms experiencing environmental warming.

3.3.2. Impacts on Terrestrial Biodiversity, Soil Organisms, and Ecosystem Functioning

Terrestrial organisms experience emerging contaminant exposure through soil contact, food consumption, inhalation, and the ingestion of contaminated water. Climate change can modify these pathways through changes in soil moisture, temperature, vegetation cover, drought intensity, and rainfall patterns. As a result, chemical exposure may influence terrestrial biodiversity and ecosystem functioning differently across agricultural landscapes, forests, grasslands, and urban environments.

Soil organisms are particularly important because they regulate decomposition, organic matter transformation, nutrient availability, and soil structure. Microorganisms and fungi contribute to nutrient cycling and the breakdown of organic compounds, while earthworms and other invertebrates influence soil aeration and aggregation (Cains, 2024). Contaminants that alter these communities can affect ecosystem functions even when direct effects on larger organisms are difficult to detect. Microplastics, for example, may change soil physical properties, influence interactions between soil organisms and organic matter, and affect water movement under some experimental conditions. The magnitude and ecological significance of these effects vary with particle characteristics, concentration, soil type, and exposure duration.

Climate change may intensify these effects by altering the environmental conditions under which soil organisms function. During drought, reduced moisture can constrain microbial activity and organic matter decomposition. When contaminants are also present, the combined effects may further disrupt nutrient cycling or delay ecological recovery. In other circumstances, warming may stimulate microbial activity and increase the degradation of some organic pollutants. These contrasting responses emphasize the importance of distinguishing between specific chemicals, soil types, and climatic conditions.

Terrestrial plants may also experience combined exposure to contaminants and climatic stress. Drought and high temperatures can alter root development, nutrient uptake, transpiration, and defense mechanisms (Gomes, 2024). Where contaminated soils or irrigation water are involved, these changes may influence chemical uptake and distribution within plant tissues. Certain contaminants may impair plant growth or physiological processes, while the effects of heat and water limitation may independently reduce plant performance. The combined outcome can affect vegetation cover, crop productivity, and the availability of habitat and food for wildlife.

Wildlife may be affected through direct exposure and changes in food availability. Pollutant accumulation in prey can expose insectivorous birds, predatory mammals, and other consumers. Climate-related shifts in species distributions and feeding patterns may change which populations encounter contaminated habitats or prey. For example, a drought that reduces the availability of uncontaminated water may concentrate wildlife around a smaller number of water sources, potentially increasing exposure where contamination is present (Zandaryaa, 2025). This is a plausible context-dependent pathway rather than a universal response across ecosystems.

Contaminant-related changes in biodiversity can have wider implications for ecosystem services. Reductions in pollinator populations may affect plant reproduction, while changes in soil organisms can influence agricultural productivity and carbon cycling. Chemical impacts on decomposers and microbial communities may alter the breakdown of organic matter and the movement of nutrients through ecosystems. These effects may be especially consequential when climate change has already reduced ecological resilience through habitat loss, fire, or water stress.

The findings are consistent with the broader ecological perspective of Zitoun (2024) on microplastics and soil systems and with the wider literature on contaminant impacts on terrestrial biodiversity. They indicate that ecological assessment should move beyond individual-organism toxicity and include soil processes, community composition, trophic interactions, and ecosystem recovery. Such an approach is necessary to determine whether combined climate and contaminant pressures produce persistent changes in ecosystem functioning.

3.3.3. Combined Effects of Climate Stressors and Emerging Contaminants on Ecological Health

A central finding of this review is that climate stressors and emerging contaminants can interact to produce ecological effects that differ from those predicted by assessing each pressure independently. These interactions may be additive, synergistic, or antagonistic. Additive effects occur when combined impacts approximate the sum of individual effects, while synergistic effects arise when the combined impact is greater than expected from the separate pressures. Antagonistic interactions occur when one pressure reduces the effect of another (Balbus, 2013). The outcome depends on chemical properties, exposure timing, environmental conditions, and the biological characteristics of the affected organisms.

Warming and chemical exposure provide a well-studied example of this complexity. Increased temperature can raise metabolic demands in fish and aquatic invertebrates, potentially reducing the energy available for growth, reproduction, and detoxification. When organisms are simultaneously exposed to pesticides or pharmaceuticals, these demands may contribute to greater physiological stress. However, higher temperatures can also accelerate the degradation of some chemicals, potentially reducing exposure (O'Flynn, 2021). The net effect must therefore be determined empirically rather than inferred from temperature alone.

Drought and pollution may also interact through reduced water availability. As river flows decline, contaminants discharged from wastewater facilities may become less diluted, while warmer water and lower oxygen levels increase physiological stress on aquatic organisms. During subsequent rainfall, accumulated contaminants may be mobilized into receiving waters. This sequence

creates a dynamic exposure pattern in which organisms experience prolonged stress followed by short-term contaminant pulses (Tong, 2025). Standard assessments that use constant contaminant concentrations may fail to capture these temporal effects.

Extreme weather can additionally interact with persistent contamination to delay ecosystem recovery. A flood may damage habitats and redistribute contaminated sediments, while the resulting chemical exposure affects organisms recolonizing the affected area. Similarly, wildfire may remove vegetation, increase erosion, and mobilize pollutants into aquatic ecosystems. The ecological consequences may extend beyond the initial disturbance if contaminants remain in sediments or soils and continue to affect reproduction, recruitment, or community composition (Ogayemi, 2026). Chemical mixtures add another dimension to these interactions. Environmental organisms are rarely exposed to a single chemical, and the composition of contaminant mixtures can change during droughts, floods, or periods of altered wastewater discharge. Some chemicals act through similar biological pathways, while others affect different physiological systems. Climate-related changes in exposure concentrations may therefore alter mixture toxicity, even if the concentration of each individual substance remains below its respective regulatory threshold.

These findings support the concept of cumulative environmental risk, in which climate-related pressures, chemical exposure, habitat alteration, and biological vulnerability are evaluated together. The IPCC's assessments of climate impacts and the European Environment Agency's work on systemic environmental risks provide a broader basis for understanding why multiple pressures can undermine ecosystem resilience. However, evidence for particular synergistic effects remains uneven across chemical classes and species, and additional research is needed to establish reliable predictive relationships (Borgå, 2022). Future assessments should prioritize realistic multiple-stressor experiments, chronic exposure studies, field-based ecological observations, and population-level indicators. Particular attention should be given to sensitive life stages, species with restricted habitats, and ecosystems already experiencing significant climatic stress. Such research would help distinguish genuine synergistic effects from additive or context-dependent responses and improve the scientific basis for environmental management.

3.4. Interactions Between Climate Change and Emerging Contaminant Classes

The reviewed literature indicates that the environmental consequences of climate change differ considerably across contaminant classes. Pharmaceuticals, endocrine-disrupting chemicals, microplastics, PFAS, persistent organic pollutants, pesticides, and metals exhibit different patterns of persistence, mobility, bioavailability, and biological activity. Consequently, the same climatic event may increase the exposure associated with one contaminant while reducing or redistributing the exposure associated with another. A major implication is that climate-responsive environmental assessment should not treat emerging contaminants as a single, homogeneous category (Hung, 2022). Instead, it should consider chemical-specific properties, environmental transformation, source characteristics, and the ecological processes through which contaminants affect organisms. Particular attention is needed for chemicals that persist for long periods, are continuously released into the environment, or can produce biological effects at relatively low concentrations.

3.4.1. Pharmaceuticals, Personal Care Products, and Endocrine-Disrupting Chemicals

Pharmaceuticals and personal care products enter the environment primarily through wastewater discharges, household activities, healthcare facilities, and the disposal of unused medicines and chemical products. Their occurrence in aquatic environments is influenced by consumption patterns, wastewater treatment performance, discharge volumes, and environmental degradation. Climate change can modify these factors through changes in water availability, treatment conditions, and the hydrological pathways connecting urban areas with receiving ecosystems (Hatje, 2022). Drought is particularly important where wastewater effluent constitutes a substantial proportion of river flow. Reduced dilution may increase the concentrations of pharmaceuticals and personal care product residues downstream of discharge points. Antibiotics, analgesics, antidepressants, and other biologically active compounds may consequently expose aquatic organisms to concentrations that vary considerably across seasons. Although treatment plants remove many contaminants to varying degrees, conventional treatment processes do not eliminate every pharmaceutical compound completely.

Higher temperatures may alter pharmaceutical degradation during wastewater treatment and after discharge. Some compounds may be removed more rapidly through temperature-dependent biological or chemical processes, whereas others may persist because of limited biodegradability, reduced oxygen availability, or changes in microbial communities (Armitage, 2011). Extreme rainfall can also reduce treatment efficiency in overloaded systems or cause untreated wastewater releases, introducing additional contaminant mixtures into aquatic environments.

Endocrine-disrupting chemicals present a distinct concern because they can interfere with hormonal signaling and biological processes associated with development, reproduction, and metabolism. Examples include certain bisphenols, alkylphenols, phthalates, and hormonally active pharmaceutical substances. Climate change may alter their exposure pathways through

temperature-dependent partitioning, runoff, wastewater discharge, and changes in the timing of biological development (De Wit, 2022). For example, fish exposed to endocrine-active substances during sensitive reproductive stages may experience effects that influence reproductive performance, although outcomes vary by compound, concentration, species, and exposure duration. Climate-driven changes in the timing of reproduction may further complicate these risks. Seasonal temperature changes can influence breeding cycles and developmental processes, potentially changing when organisms encounter endocrine-active chemicals. If contaminant exposure coincides with sensitive developmental periods, the consequences may differ from those observed under constant exposure conditions (Clasen, 2025). This possibility supports the need for seasonally resolved monitoring and toxicity testing that reflects realistic temperature fluctuations.

Research on pharmaceutical residues in the environment, including Alshamsi (2022), established the importance of understanding the ecological implications of medicines released into natural systems. Later work has expanded attention to wastewater treatment, mixture exposure, and the effects of biologically active compounds on non-target organisms. These findings, considered alongside climate-related changes in water availability and temperature, suggest that pharmaceutical pollution should be assessed through a combination of source control, improved treatment, and ecological monitoring.

Effective management requires improved pharmaceutical disposal practices, treatment technologies capable of removing persistent compounds, and routine monitoring of wastewater receiving environments. During droughts and heatwaves, authorities should consider additional sampling downstream of major discharge points (Singh, 2024). The assessment of endocrine-disrupting chemicals should also include biological indicators, such as reproductive and developmental endpoints, rather than relying exclusively on chemical concentration measurements (Ogayemi, 2026).

3.4.2. Microplastics, Per- and Polyfluoroalkyl Substances (PFAS), and Persistent Organic Pollutants

Microplastics, PFAS, and persistent organic pollutants represent important but chemically distinct contaminant groups. Microplastics are small plastic particles that may originate from the fragmentation of larger plastic products, synthetic textiles, tire wear, and industrial processes. PFAS comprise a large group of fluorinated substances characterized by highly persistent carbon–fluorine bonds in many members of the group. Persistent organic pollutants include chemicals that resist degradation and may undergo long-range transport and biological accumulation (Talreja, 2025). Although these groups differ substantially in structure and behavior, climate change can alter their distribution and exposure through shared pathways such as runoff, sediment transport, atmospheric movement, and changes in water availability.

Microplastic distribution is strongly influenced by hydrological processes. Heavy rainfall can transport plastic particles from roads, agricultural land, waste disposal sites, and urban drainage systems into rivers and coastal environments. Floods can redistribute particles already accumulated in sediments, while drought may concentrate microplastics in shrinking water bodies. Subsequent rainfall can mobilize particles that have accumulated on exposed land surfaces (Pereira, 2015). The resulting distribution depends on particle size, shape, density, surface characteristics, and interactions with suspended sediment and organic matter (Lakavath, 2025).

Temperature and ultraviolet radiation can also influence plastic weathering and fragmentation. Exposure to sunlight and environmental heat may contribute to the degradation of certain plastic materials, although fragmentation does not necessarily eliminate plastic pollution. Instead, it can generate smaller particles that may be transported differently and interact with organisms in different ways. Heatwaves, droughts, and wildfires may alter these processes, particularly where plastic waste is exposed on land (Yan, 2010). However, the extent to which climate change will alter global microplastic concentrations remains uncertain and depends on future plastic production, waste management, and environmental transport.

Microplastics may also interact with other contaminants. Their surfaces can adsorb some organic chemicals and metals, depending on polymer properties, environmental aging, and surrounding water chemistry. Nevertheless, the ecological importance of plastics as vectors of contaminants varies among environmental settings, and their role should not be assumed to exceed other exposure routes such as contaminated water, sediment, or food. Research by Hiranmai (2023) demonstrated that plastic-associated chemicals can contribute to biological exposure under experimental conditions, supporting continued investigation of particle–chemical interactions.

PFAS present a different set of challenges because many compounds resist environmental degradation and can remain in water, soil, and biological systems for extended periods. Their transport is influenced by molecular structure, chain length, functional groups, interactions with organic matter, and water chemistry. Flooding may redistribute PFAS from contaminated industrial sites, firefighting training areas, waste facilities, or affected soils. Drought can increase concentrations in some water bodies, while changes in groundwater recharge may influence the movement of mobile PFAS through aquifers (Biswas, 2018).

Not all PFAS behave identically. Some are relatively mobile in water, whereas others exhibit stronger interactions with particular environmental surfaces or accumulate differently in organisms. Consequently, a general prediction that warming or increased rainfall will always increase PFAS mobility would be inappropriate. Climate-sensitive assessment should instead evaluate compound-specific transport, source locations, groundwater vulnerability, and potential pathways into drinking-water supplies and food webs (Maulvault, 2018). Persistent organic pollutants can also be redistributed through climate-related changes in temperature and atmospheric circulation. Some compounds undergo repeated cycles of volatilization, long-range atmospheric transport, and deposition, while others accumulate in sediments or biological tissues. Changes in temperature may alter environmental partitioning, and melting snow or ice can release previously deposited contaminants into receiving waters. In aquatic food webs, persistent and bioaccumulative compounds may expose predators through contaminated prey, although the extent of biomagnification differs among substances.

The Stockholm Convention on Persistent Organic Pollutants provides an important international framework for controlling listed persistent organic pollutants, while the expanding international and national attention to PFAS reflects concerns about their persistence and potential health and ecological effects. These policy developments highlight the need to combine chemical regulation with climate-sensitive environmental monitoring (Vasilachi, 2021). For microplastics, reducing unnecessary plastic release, improving waste collection, and limiting the escape of plastic particles from wastewater and stormwater systems remain important preventive measures (Lakavath, 2025).

Collectively, these contaminant classes illustrate why environmental management must integrate persistence, mobility, source control, and climate vulnerability (Naidu, 2016). Monitoring programs should distinguish between particle-associated contaminants and dissolved chemicals, measure relevant PFAS and persistent organic pollutants individually where possible, and assess how floods, droughts, and changing temperatures alter their distribution.

3.4.3. Pesticides, Heavy Metals, and Other Emerging Chemical Contaminants

Pesticides and heavy metals present significant environmental concerns because climate change can modify both their transport and their effects on non-target organisms. Pesticides are intentionally applied to control agricultural pests, weeds, and diseases, while metals may originate from mining, industrial emissions, agricultural inputs, waste disposal, and naturally occurring geological materials. Their environmental behavior differs substantially, but both groups can be redistributed by runoff, erosion, sediment transport, and changes in soil and water chemistry (Noyes, 2025). Changing precipitation patterns may affect pesticide exposure by altering the relationship between application timing and runoff. Intense rainfall shortly after pesticide application can transport chemicals from agricultural fields into streams, ponds, and wetlands. During droughts, farmers may change pesticide application practices in response to altered pest pressures, irrigation requirements, and crop conditions. Subsequent rainfall may mobilize chemicals that accumulated during dry periods. These processes create temporal exposure patterns that cannot be adequately represented by annual average concentrations.

Temperature can influence pesticide degradation, volatilization, and toxicity. Some pesticides break down more rapidly under warmer conditions, while others may persist because degradation is limited by moisture, microbial activity, or chemical characteristics. Higher temperatures may also alter the physiological responses of aquatic and terrestrial organisms to pesticide exposure. For example, aquatic invertebrates exposed to an insecticide during a heatwave may experience a different biological response from organisms exposed under cooler conditions (Nadal, 2015). The direction and magnitude of this interaction depend on the pesticide, species, and exposure conditions.

Climate change may also influence pesticide use itself. Changes in temperature, rainfall, growing seasons, and pest distributions can alter agricultural pest pressure and the timing of chemical application. If pesticide use increases in response to emerging pest problems, contaminant inputs may rise even where the environmental fate of individual compounds remains unchanged (Imoobe, 2024). This distinction is important because climate-related pollution risks can arise through changes in both environmental processes and human behavior.

Heavy metals present additional challenges because they cannot be degraded in the same way as organic contaminants. Metals such as mercury, cadmium, lead, and arsenic may persist in soils and sediments, although their chemical forms, mobility, and biological availability can change substantially with environmental conditions (Di Guardo, 2018). Flooding can transport metal-contaminated sediments downstream, while drought and soil disturbance may expose contaminated particles to erosion and redistribution.

Changes in soil and water chemistry can alter metal mobility. For example, shifts in pH and redox conditions may change the binding of certain metals to mineral surfaces and organic matter. In flooded soils, changes in oxygen availability can alter the chemical forms of some metals, while subsequent drying and reoxygenation may modify their mobility again. Mercury presents a

particularly important case because microbial processes under suitable environmental conditions can produce methylmercury, a form that can accumulate in aquatic food webs (He, 2025). Climate-related changes in temperature, flooding, and organic matter availability may influence these processes, but the direction and magnitude of the response depend on ecosystem conditions.

Climate-driven erosion and sediment redistribution can expose aquatic organisms to metals that were previously stored in soils or sediments. The resulting ecological effects may include impaired growth, reproduction, and physiological functioning, depending on metal identity, concentration, and exposure duration. In agricultural systems, contaminated irrigation water and soils may also create pathways for metal uptake by crops and subsequent exposure through food consumption (Cains, 2024). Other chemical contaminants, including industrial additives, flame retardants, corrosion inhibitors, and certain transformation products, may exhibit comparable climate-sensitive behavior. Their risks are often difficult to characterize because environmental occurrence data, toxicity information, and standardized monitoring methods are incomplete. This uncertainty is especially important when contaminants occur as mixtures or are released during extreme weather events.

3.5. Environmental Monitoring, Risk Assessment, and Adaptation Strategies

The reviewed evidence indicates that existing environmental monitoring and risk assessment systems require greater consideration of climatic variability and extreme events. Many conventional programs were developed to evaluate pollutant concentrations under relatively stable environmental conditions or to determine compliance with fixed regulatory thresholds. Although these approaches remain important, they may fail to capture short-lived contamination peaks, changing transport pathways, mixture effects, and climate-related shifts in ecological sensitivity. An effective response requires coordinated monitoring of environmental media, climate variables, contaminant sources, and biological responses (Gomes, 2024). Risk assessment should incorporate the possibility that the same chemical may behave differently across seasons, hydrological conditions, and ecosystems. In addition, environmental policies should integrate pollution prevention, climate adaptation, wastewater infrastructure resilience, and ecosystem restoration rather than treating chemical pollution as a separate management issue.

3.5.1. Limitations of Conventional Monitoring and Ecological Risk Assessment under Changing Climatic Conditions

Conventional environmental monitoring often relies on periodic sampling, standardized laboratory analysis, and comparisons with regulatory thresholds. These methods provide valuable information about contaminant occurrence and compliance, but they may not adequately capture environmental conditions characterized by increasing climatic variability. Sampling conducted monthly or quarterly, for example, may miss a short-lived contamination peak following heavy rainfall or a period of elevated exposure during prolonged drought (Zandaryaa, 2025). A major limitation is the reliance on average concentrations. Annual or seasonal averages can conceal substantial differences between normal conditions and extreme events. A river may meet a water-quality standard during routine sampling while experiencing brief but ecologically important contamination pulses after a storm. Similarly, contaminant concentrations may increase during low-flow periods even if the annual pollutant load remains relatively stable. Consequently, assessments based solely on average concentrations can misrepresent the timing and intensity of ecological exposure (Watara, 2026).

Another limitation concerns the environmental conditions used in toxicity testing. Standard laboratory experiments often maintain relatively constant temperatures, water chemistry, and contaminant concentrations to improve experimental control. However, organisms in natural environments experience fluctuating temperatures, variable oxygen availability, changing food resources, and exposure to mixtures of chemicals. These differences may affect contaminant uptake, metabolism, and biological sensitivity (Zitoun, 2024). Laboratory results remain essential for establishing toxicity relationships, but their application to climate-stressed ecosystems requires careful consideration of environmental realism ().

Conventional assessments may also overlook indirect ecological effects. A chemical may have limited effects on the survival of an individual organism but influence feeding behavior, reproduction, predator–prey interactions, or microbial activity. Such changes can affect ecosystem functioning without producing immediate mortality. Likewise, climate-related habitat changes may influence whether exposed populations can recover from chemical stress (Balbus, 2013). Risk assessment should therefore consider population dynamics, ecosystem processes, and recovery potential in addition to individual-level toxicity.

A further challenge is the incomplete characterization of emerging contaminants and transformation products. Analytical methods may not detect all substances present in environmental samples, while toxicity information may be limited for newly identified chemicals. Mixture effects are particularly difficult to predict when organisms encounter numerous compounds alongside temperature stress, oxygen depletion, and habitat disturbance (O'Flynn, 2021). In addition, environmental monitoring capacity is unevenly distributed, and some regions lack the laboratory infrastructure, long-term datasets, or financial resources needed to assess complex climate–pollution interactions.

3.5.2. Integrated Monitoring, Predictive Modelling, and Climate-Responsive Risk Assessment

Integrated monitoring offers a practical means of addressing the limitations of conventional environmental assessment. It combines chemical measurements with climatic observations, hydrological data, ecological indicators, and information about pollutant sources. This approach enables researchers to evaluate not only where contaminants occur but also how environmental conditions influence their movement, persistence, and effects on organisms. An integrated monitoring program should include surface water, groundwater, sediments, soils, and relevant biological tissues where appropriate (Tong, 2025). Sampling should be conducted across seasons and intensified during high-risk periods, such as floods, heatwaves, droughts, and wildfire recovery. For example, a river monitoring program could measure pharmaceutical concentrations alongside water temperature, dissolved oxygen, discharge, and wastewater effluent volume. These combined observations would help distinguish changes caused by pollutant loading from those associated with reduced dilution or altered degradation.

Emerging analytical technologies can strengthen this approach. High-resolution mass spectrometry can support the identification of known and previously unrecognized chemical substances, while passive sampling can provide information about contaminant exposure over extended periods. Remote sensing can help identify land-use changes, wildfire-affected areas, flood extent, and other environmental conditions relevant to pollutant mobilization (Ogayemi, 2026). However, remote sensing generally cannot identify individual chemical contaminants directly without supporting measurements or validated indirect indicators. Its greatest value lies in connecting environmental change with targeted chemical monitoring.

Predictive modelling provides another important opportunity. Hydrological models can estimate runoff, infiltration, and contaminant movement under different rainfall scenarios, while chemical fate models can simulate degradation, sorption, volatilization, and transport. Ecological models can then evaluate how predicted exposure may affect species or ecosystem processes (Borgå, 2022). Combining these approaches can support scenario-based assessments of contaminant behavior under future climate conditions.

For example, a watershed model could estimate how an intense rainfall event might transport pesticides from agricultural fields into a freshwater lake. Chemical fate modelling could assess the persistence of those substances, while ecological risk modelling could estimate exposure for sensitive aquatic invertebrates. Such a framework would help identify vulnerable locations and determine whether additional buffer zones, improved drainage management, or event-based sampling could reduce risks (Hung, 2022). The accuracy of the predictions would depend on the quality of input data, the assumptions used, and the extent to which the models had been validated against field observations (Lakavath, 2024).

Artificial intelligence and machine learning may further support contaminant monitoring by identifying patterns in large datasets, detecting anomalous measurements, and predicting pollution hotspots. Models trained on historical chemical concentrations, weather observations, land-use characteristics, and hydrological conditions could help identify periods when contamination is more likely. Nevertheless, predictive performance should not be confused with causal understanding. Models may perform poorly when applied to climate conditions outside their training data, especially where monitoring is sparse or environmental processes are changing (Hatje, 2022). Explainability, independent validation, uncertainty analysis, and transparent data practices are therefore essential.

Climate-responsive risk assessment should combine predicted environmental exposure with information about organism sensitivity and ecological vulnerability. This involves considering not only the concentration of a chemical but also the timing and duration of exposure, the presence of other stressors, and the capacity of an ecosystem to recover. Assessments should examine multiple plausible climate scenarios and explicitly identify uncertainties in contaminant degradation, transport, and toxicity (Armitage, 2011). A further priority is the development of harmonized monitoring protocols and data-sharing arrangements. Comparable analytical methods and reporting standards would make it easier to compare results across regions, identify long-term trends, and evaluate the effectiveness of pollution control measures. Such coordination is particularly important for transboundary rivers, shared aquifers, and pollutants capable of long-range atmospheric transport.

3.5.3. Policy Responses, Pollution Mitigation, and Adaptive Environmental Management

The findings indicate that effective management of emerging contaminants under climate change requires coordinated policies addressing chemical pollution, climate adaptation, ecosystem protection, and infrastructure resilience. Traditional pollution-control measures remain necessary, but their effectiveness may decline where climatic changes alter contaminant transport, increase extreme-event frequency, or expose ecosystems to multiple simultaneous stressors (De Wit, 2022). Environmental management should therefore combine prevention at pollution sources with measures that reduce climate-related exposure and improve ecosystem recovery.

Pollution prevention is a fundamental priority. Industrial facilities, healthcare institutions, agricultural operations, and wastewater treatment plants should adopt practices that minimize the release of hazardous chemicals into the environment. For pharmaceutical pollution, this includes appropriate medicine disposal, improved wastewater treatment, and measures to reduce unnecessary chemical discharge. For agricultural contaminants, integrated pest management, appropriate pesticide application, vegetated buffer strips, and soil conservation can reduce runoff and erosion (Clasen, 2025). Improved plastic waste collection, recycling, and stormwater management can limit the release of plastic particles into aquatic and terrestrial environments.

Climate-resilient infrastructure is equally important. Wastewater treatment plants, landfills, industrial storage facilities, and hazardous-waste sites should be assessed for their vulnerability to floods, heatwaves, droughts, and other climatic hazards. Flood protection, secure chemical storage, backup treatment capacity, and emergency response plans can reduce the likelihood of contaminant releases during extreme events (Alshamsi, 2022). Where treatment facilities experience reduced efficiency during heatwaves or intense rainfall, operational adjustments and infrastructure improvements may help maintain pollution-control performance (Watara, et al., 2025).

Nature-based solutions can complement conventional infrastructure. Wetlands, riparian vegetation, floodplains, and restored river corridors can intercept some contaminants, reduce erosion, and retain suspended sediments. Vegetated agricultural buffers can reduce the movement of pesticides and sediment-bound pollutants into waterways, while wetland restoration may improve water retention and support biodiversity. Nevertheless, these systems should not be regarded as universal contaminant-removal solutions. Their effectiveness depends on pollutant properties, hydraulic conditions, ecosystem design, and maintenance (Singh, 2024). Accumulated contaminants may also be remobilized if wetlands or sediments are disturbed or exposed to changing redox conditions.

International environmental agreements provide an important foundation for managing persistent and hazardous chemicals. The Stockholm Convention addresses listed persistent organic pollutants, while the Minamata Convention on Mercury focuses on protecting human health and the environment from anthropogenic mercury emissions and releases. The Basel Convention regulates transboundary movements of hazardous wastes and their disposal (Talreja, 2025). These frameworks can support pollution prevention and international cooperation, although their effectiveness depends on national implementation, monitoring capacity, enforcement, and the extent to which emerging contaminants fall within existing regulatory coverage.

A climate-responsive regulatory approach should complement chemical-specific standards with risk-based monitoring and event-sensitive management. Authorities could establish enhanced sampling protocols for rivers downstream of wastewater treatment plants during droughts, assess industrial sites located in flood-prone areas, and prioritize groundwater monitoring where changing recharge patterns may affect contaminant movement (Pereira, 2015). Regulatory agencies should also evaluate whether existing environmental quality standards adequately reflect chronic exposure, sensitive life stages, mixture effects, and changing climatic conditions (Lakavath 2024).

The importance of adaptive management is particularly evident where scientific uncertainty remains high. Rather than relying exclusively on fixed management plans, environmental agencies should periodically update risk assessments using new monitoring results, improved toxicity data, and changing climate projections. This approach allows interventions to be adjusted when new contaminants are identified, pollution hotspots emerge, or extreme events reveal previously unrecognized vulnerabilities. Equity and institutional capacity are also important considerations. Low-income communities and regions with limited water-treatment infrastructure may face greater exposure when droughts reduce water availability or floods damage sanitation systems (Yan, 2010). In many developing regions, limited analytical facilities and inconsistent monitoring constrain the identification of contamination sources. Strengthening laboratory capacity, supporting affordable monitoring technologies, sharing environmental data, and improving access to safe water can help reduce these inequalities. International research partnerships and technical cooperation are particularly valuable where environmental problems cross national boundaries.

Finally, policy effectiveness should be evaluated through measurable environmental and ecological outcomes. Relevant indicators include reductions in contaminant concentrations and pollutant loads, improved wastewater treatment performance, reduced contamination following extreme weather events, recovery of sensitive species, and improvements in soil and freshwater ecosystem functioning (Hiranmai, 2023). Monitoring these outcomes would help distinguish policies that produce measurable environmental benefits from those that primarily increase administrative activity without reducing exposure.

Taken together, these findings support a shift from conventional pollution management toward integrated, preventive, and adaptive environmental governance. The most effective strategies are likely to combine source reduction, climate-resilient infrastructure, ecosystem-based interventions, improved monitoring, and enforceable regulatory standards (Kallenborn, 2012).

Such an approach recognizes that chemical pollution and climate change are interconnected environmental challenges requiring coordinated responses.

4. Conclusion

Climate change and emerging contaminants represent interconnected environmental challenges that are increasingly influencing contaminant fate, transport, exposure pathways, and ecological risks across terrestrial, freshwater, and marine ecosystems. This review highlights how rising temperatures, altered precipitation patterns, extreme weather events, droughts, floods, and sea-level rise can modify contaminant persistence, mobility, bioavailability, and distribution, potentially intensifying ecological exposure and disrupting ecosystem functions. Emerging contaminants, including pharmaceuticals, microplastics, per- and polyfluoroalkyl substances (PFAS), pesticides, and industrial chemicals, may interact with climate-driven environmental changes in complex ways, producing context-dependent effects on aquatic organisms, terrestrial wildlife, and biodiversity. These interactions underscore the limitations of conventional environmental risk assessments that evaluate chemical pollution and climate change independently. Addressing these challenges requires integrated monitoring systems, climate-informed risk assessment frameworks, advanced analytical technologies, and interdisciplinary research capable of identifying combined and long-term ecological effects. Furthermore, strengthening wastewater treatment, controlling contaminant emissions at their sources, improving environmental regulations, and promoting sustainable chemical management are essential for reducing pollution risks under changing climatic conditions. Future research should prioritize long-term field investigations, vulnerable ecosystems, contaminant mixtures, and the development of predictive models that account for interactions among climate variables, chemical behavior, and biological responses. Ultimately, integrating climate adaptation strategies with pollution prevention and ecosystem conservation policies will be critical to protecting environmental quality, maintaining biodiversity, and enhancing ecosystem resilience in an increasingly climate-affected world.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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Artificial Intelligence (AI) Use Disclosure: The authors declare that no artificial intelligence tools were used in the preparation of this manuscript.

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