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Toxic Climatescapes: Mapping the Next Generation of Environmental Risks

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Abstract
Climate change is accelerating the release, distribution, and toxicity of numerous environmental contaminants, posing new risks to human and ecological health. This review synthesizes recent evidence (2017–2024) on the interaction between climate-related factors and contaminants such as heavy metals, PFAS, microplastics, biotoxins, and endocrine disrupting compounds. A comparative account, based on literature data, maps how temperature rise, altered precipitation, permafrost thaw, and extreme events influence contaminant mobility and hazard profiles. The findings highlight emerging toxins, shifts in exposure pathways, and compounded health threats, emphasizing the need for integrated climate toxicology risk frameworks. Addressing these risks requires targeted monitoring, improved public health preparedness, and proactive policy responses.

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Introduction

Similar to many of today's global crises, climate change is driving significant transformations in our environmental systems, impacting more than just temperature increases and extreme weather events. Climate change is now altering the distribution, concentration, and toxicity of environmental contaminants, creating previously unrecognized toxicological risks.[1] Rising temperatures, melting glaciers, and shifts in precipitation patterns are releasing contaminants that have been long sequestered in soils, sediments, and ice into the environment, while simultaneously unleashing additional toxins due to these same changing conditions.[2] These toxicants include heavy metals, persistent organic pollutants, and biotoxins from harmful algal blooms.[3] The changing climate may amplify or alter the toxicological effects of these contaminants.

The evolving toxicological landscape presents significant public health and environmental

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challenges that demand novel approaches to understanding, monitoring, and mitigating these risks. Vulnerable populations, particularly those along coastlines, in low income areas, and among Indigenous communities are at heightened risk of exposure. Furthermore, ecosystems are increasingly burdened by a multitude of environmental stressors.[4] Climate change is escalating the incidence of exposure to diverse biotoxins from microorganisms, plants, and animals, while simultaneously facilitating the release and spread of hazardous pollutants.[13] This includes the mobilization of heavy metals, persistent organic pollutants, and air pollutants, which are becoming more bioavailable, thereby intensifying their harmful effects on human health.[42] Rising temperatures are expected to increase the toxicity of pollutants and elevate tropospheric ozone levels. Additionally, climate change may influence the trajectory of persistent organic pollutants through changes in food webs, lipid dynamics, and organic carbon cycling.[5]

The concept of "climate toxicity" has emerged in the field of oncology, highlighting the increased cancer risk from environmental carcinogens and the ecological consequences of cancer treatments.[6] As extreme climate events become more frequent, there is an urgent need for innovative frameworks to assess and manage chemical stressors that protect both human health and ecosystems. Despite some progress, significant challenges remain in applying environmental toxicological insights to the context of global climate change.[7] Therefore, understanding the multifaceted impacts of climate change on human health and ecosystems is more critical than ever in the field of toxicology.

Traditional toxicological models, which often assess chemicals in isolation under stable conditions, are insufficient for capturing the complex interactions between chemicals and the dynamic exposure patterns induced by climate change. An adaptive toxicology framework is urgently needed to address the interconnectedness of climate and toxicity, and how these forces interact to create new environmental threats. This commentary advocates for interdisciplinary collaboration, regulatory policy revisions, and proactive public health strategies to confront these emerging environmental hazards.

Methodology

This study adopted a systematic literature review approach, adapted from established environmental toxicology research methodologies.[1] Literature was retrieved from Scopus, Web of Science, and Science Direct databases between 2017 and 2024 using keywords such as polycyclic aromatic hydrocarbons (PAHs), poly and perfluoroalkyl substances (PFAS), Chronic obstructive pulmonary disease (COPD), climate toxicity, and Endocrine-disrupting compounds. The inclusion criteria focused on peer-reviewed studies addressing chemical contaminants whose behaviour or toxicity is influenced by climate change, as well as their ecological or human health impacts.[16,20] Only articles providing empirical data, systematic reviews, or significant conceptual contributions were included. Titles and abstracts were screened for relevance, with duplicates removed prior to full-text review.

Discussion

The Emergence of Novel Environmental Toxins

Climate change is accelerating the release and spread of various environmental toxins, including heavy metals, organic pollutants, algal toxins, and industrial chemicals.[8] These blooms, driven by Cyanobacteria, produce cyanotoxins biotoxins that can cause serious human health issues, including acute poisoning, liver damage, and neurodegeneration. The contamination of drinking water by cyanotoxins is becoming an increasingly critical concern in urban areas worldwide, demanding expanded research and monitoring efforts.[9]

Marine biotoxins, especially paralytic shellfish toxins like saxitoxin, pose significant health risks and economic challenges. Biotoxins are categorized into marine (e.g., phycotoxins), bacterial (e.g., endotoxins and exotoxins), fungal (e.g., mycotoxins like aflatoxins), and plant toxins (e.g., alkaloids and ricin), each causing distinct clinical symptoms, ranging from gastrointestinal to neurological effects.[10] Shellfish and finfish are major vectors of these toxins, presenting widespread public health hazards. Furthermore, Prior studies have documented the growing incidence of marine and freshwater biotoxins as a result of climate change with rising temperatures and changing environmental conditions, fostering the spread of harmful microalgae and Cyanobacteria into new regions.[11,13] For example, toxins like tetrodotoxin, ciguatoxin, and palytoxin have emerged in European waters, creating food safety monitoring challenges.[12,14] Similarly, climate change is affecting the growth of cyanotoxins such as microcystins, nodularin, and cylindrospermopsin in freshwater ecosystems.[15] These trends are alarming, as existing regulatory frameworks and monitoring systems often fail to account for many novel toxins, leaving them unregulated and potentially entering markets without adequate oversight. Furthermore, the absence of chronic toxicity studies, a limited understanding of toxin generation mechanisms, and difficulties in detecting and quantifying these biotoxins further complicate the issue.[14]

Research has also highlighted growing concerns over emerging pollutants (EPs) in the environment including pharmaceuticals, endocrine disruptors, “poly and perfluoroalkyl substances (PFAS)”, and biological pollutants.[16-18] Climate change is exacerbating PFAS emissions, while the degradation of microplastics is contributing to greenhouse gas emissions, thus further intensifying climate change. The warming of the planet is also causing the release of PFAS stored in permafrost, altering their global movement. PFAS are highly persistent and bio accumulative, with exposure occurring through air, water, food, and consumer products.[17] Plants can absorb these chemicals, which can disrupt ecosystem functioning and pose significant health risks to humans. PFAS exposure has been linked to a range of adverse health effects, including reproductive, metabolic, and endocrine system disturbances.[6,18] Environmental pollutants, even in minute quantities, present considerable risks to both ecological and human health, as they persist in air, water, soil, and biological tissues. According to advances in analytical methods, have facilitated the identification of numerous novel PFAS compounds with 455 new compounds discovered between 2009 and 2017.[19] To address the challenges posed by emerging pollutants, improved detection methods, toxicity assessments, and novel treatment technologies are essential.[20] Understanding the prevalence, ecological fate, and bio-toxicity of these pollutants is critical for advancing scientific research and developing effective environmental management strategies.[21]

Climate-Driven Changes in Chemical Toxicity

Climate change is interacting with environmental chemical toxicity in complex ways. Climate related stresses, such as rising temperatures and altered pH levels, can heighten organism’s susceptibility to chemical toxicity. Conversely, chemical exposures may impair an organism' ability to adapt to changing environmental conditions.[22] Synergistic interactions between climate change and chemical pollutants are often more common than additive or antagonistic effects.[23] For example, elevated temperatures have been shown to increase freshwater snails’ sensitivity to cadmium, with effects ranging from additive to synergistic depending on the organism's life stage and pollutant concentration.[24] These complex interactions complicate predictions of toxicological outcomes under future climatic scenarios, highlighting the need for more robust methodologies in environmental risk assessment

Climate change is not only affecting the toxicity of existing chemicals but is also facilitating the emergence of new toxins. Changes in climate conditions can enhance the inherent toxicity of chemicals by altering their chemical transformations, interactions with biological systems, and environmental persistence. Notable examples include ozone and air pollutants, polycyclic aromatic hydrocarbons (PAHs), pesticides, heavy metals, and microplastics. Rising temperatures and increased sunlight can exacerbate respiratory diseases, oxidative stress, and mutagenic potential. Similarly, acidification increases the solubility, reactivity, and toxicity of metals in aquatic environments. Higher temperatures also accelerate plastic degradation, leading to the release of endocrine disrupting compounds.25 Temperature, pH, and salinity changes influence the chemical transformation and bioavailability of pollutants, thus modifying their toxicological effects. For instance, rising temperatures can enhance the volatility of pesticides and industrial chemicals, releasing them into the atmosphere and increasing inhalation risks for human populations.[31]

Recent studies have highlighted the environmental risks associated with rising temperatures that liberate compounds from permafrost and sediments. Many "dormant chemicals," such as heavy metals and organic pollutants, can be released from thawing permafrost posing significant threats to ecosystems.[16] In Siberian permafrost, for instance, increased mercury levels have been linked to higher organic carbon levels and specific types of sediment.[27] As the climate warms, the concentrations of methylmercury in Arctic permafrost may increase with the potential to affect both local and global ecosystems.[26] Similarly, rising temperatures in the Arctic Ocean could destabilize methane hydrates in continental margin sediments, releasing methane into the atmosphere and exacerbating ocean acidification and oxygen depletion.[28] These chemical releases, caused by melting permafrost and warming oceans, present significant environmental challenges and require further research to mitigate their impacts.

Additionally, rising CO2 levels may transform heavy metals in acidified waters into more toxic forms, increasing their bioavailability and the associated risks to aquatic life, which can ultimately be transmitted through food webs to humans.[29] Key heavy metals affected by these processes include cadmium, lead, mercury, arsenic, copper, and zinc. Changes in precipitation patterns due to climate change may also influence the distribution and toxicity of persistent organic pollutants and pesticides.[31]

Moreover, the adaptive responses of organisms to climate-driven stressors may affect toxicological outcomes. It is well established that environmental stress weakens an organism's immune system and detoxification capacity, making it more susceptible to toxins. Likewise, exposure to chemicals may impair an organism's ability to cope with adverse climate conditions.[32] Interestingly climate change is also influencing the bioactive components of medicinal plants, reducing their therapeutic potential. For example, under elevated soil salinity, *Aloe barbadensis* miller (Aloe vera plant) experiences a reduction in phenolic content and antioxidant activity, while drought stress diminishes the flavonoid content in Vitis *vinifera*, *Lavandula angustifolia*, and *Artemisia tridentata*.[33] Similarly, "St. John's wort" (*Hypericum perforatum*) exhibits alterations in the concentration of its active compounds under stress conditions, potentially affecting its pharmacological efficacy.[34]

Given these complex overlaps between chemical exposure, biological responses, and environmental stressors, a more sophisticated approach to toxicological risk assessment is necessary to better understand the cumulative effects of climate change on both human health and ecosystems

Implications for Human and Ecological Health

Vulnerable populations are disproportionately affected by the toxicological risks exacerbated by climate change. Indigenous coastal and riverine communities, who rely on local seafood and traditional subsistence practices, are particularly at risk due to the bioaccumulation of toxins in fish and marine mammals. Seafood can contain a range of harmful substances, including heavy metals such as mercury, lead, and arsenic persistent organic pollutants like PCBs and PFAS, harmful algal toxins such as domoic acid, saxitoxins, and ciguatoxins, as well as microplastics carrying bisphenols, phthalates, and other heavy metals. These contaminants tend to bioaccumulate and bio magnify, raising global concerns about seafood safety.[35,38]

In addition, the increased volatility of chemical pollutants in industrialized areas is likely to exacerbate the risks for low-income communities, where exposure to airborne contaminants is already more prevalent.[1] Children, the elderly, and individuals with pre existing health conditions are especially vulnerable, as is the case in high density urban areas. For instance, higher levels of airborne pollutants such as those from industrial and biomass sources coupled with poor ventilation in urban environments can worsen respiratory conditions like asthma and chronic obstructive pulmonary disease (COPD) in already vulnerable populations.

Recent studies highlight the significant impact of climate change on both human and ecological health.[37] Predict that rising temperatures will contribute to increased heat-related morbidity and mortality, intensify extreme weather events, and exacerbate vector-borne diseases. Furthermore, climate change is influencing the dynamics of infectious diseases, including zoonotic infections as increased rainfall facilitates the spread of pathogens.[36] Ecological disruptions, such as deforestation and changes in land use, have also been linked to the emergence of diseases like malaria.[29,30] As such, immediate action is required to reduce emissions, implement adaptation strategies, and promote climate justice.

There is also a pressing need for research on the long-term effects of early-life exposure to climate enhanced toxins, such as lead and methyl mercury, to better understand the neuro developmental consequences for future generations. These toxins have the potential to significantly impact public health outcomes making it crucial to explore their effects on the developing brain and how they may shape health outcomes across the lifespan.[39]

A Call for Adaptive Toxicology and Regulatory Frameworks

Recent literature emphasizes the need for a paradigm shift in toxicology toward more adaptable and contemporary methodologies. Given the complex toxicological risks posed by a changing climate, an adaptive approach to both toxicology and environmental regulation is essential. Traditional toxicology, which is typically conducted under controlled conditions and focuses on individual chemicals, may not adequately address the synergistic and dynamic effects that result from climate driven exposures. To fully capture the range of climate related toxicological risks, a systems level approach is required one that integrates environmental science, epidemiology, and toxicology.[40]

Adaptive regulatory frameworks capable of responding rapidly to emerging threats are crucial. Policymakers must recognize this need and prioritize the development of such frameworks. This could involve establishing new standards for environmental quality that take into account the climate-induced effects on chemical persistence, bioavailability, and toxicity. Additionally, enhancing monitoring and surveillance efforts to track climate-sensitive toxins in the most vulnerable regions is paramount.

In this context, the growing role of artificial intelligence in toxicology has gained attention.[41,42] Highlighted the potential of AI to improve chemical hazard assessments, stressing the importance of its responsible development. Building upon advancements in predictive toxicology, such as machine learning and AI, will enhance our ability to forecast the impacts of climate change on organisms. Moreover, these tools can be instrumental in developing early warning systems that help mitigate the risks posed by emerging climate-driven toxins.

Recommendations for Policymakers and Regulators

- Strengthen environmental policies to address emerging climate-induced toxins
- Enhance air and water quality standards to mitigate contamination from heavy metals and biotoxins.
- Implement early warning systems for harmful algal blooms and pollutant surges
- Support the development of climate-adaptive toxicology frameworks in public health policies through interdisciplinary approaches that integrate toxicology, climate science, and public health.
- Improve detection methods for novel environmental toxins, including POPs and PFAS
- Investigate long-term exposure risks of climate-enhanced pollutants on human and ecological health
- Expand monitoring programs to track toxin exposure in vulnerable populations
- Educate communities about climate-related toxicological risks and preventive measures enhance medical preparedness for toxin-related health issues
- Adopt sustainable practices to reduce industrial emissions and pollutant discharge
- Invest in cleaner technologies to minimize chemical contamination and climate
- Ensure corporate responsibility in managing environmental waste
- Advocate for policy changes that prioritize environmental health reduce exposure risks by staying informed on air and water quality alerts
- Adopt sustainable habits to reduce chemical pollution and support eco-friendly industries.

Conclusion

Climate change is amplifying the risks posed by a diverse range of environmental contaminants, from heavy metals and PFAS to microplastics, biotoxins, and endocrine-disrupting compounds. This review highlights how climate drivers such as rising temperatures, altered precipitation patterns, thawing permafrost, and extreme weather events are reshaping contaminant mobility, bioavailability, and toxicity.

The evidence underscores the urgent need for integrated monitoring systems, predictive climate toxicology models, and targeted public health preparedness strategies. Strengthening interdisciplinary collaboration between environmental scientists, toxicologists, epidemiologists, and policymakers will be essential for effective risk mitigation.

Future research should focus on filling data gaps for under studied contaminants, developing early warning systems for climate driven pollution events, and assessing cumulative exposures from multiple interacting hazards. Proactive policy frameworks and adaptive management strategies will be critical to safeguard ecosystems and human health in the face of accelerating climate change.

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Data Availability Statement
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Ethics Statement
This review uses only publicly available literature and involves no human or animal studies. All sources are cited, and the work complies with the ethical publishing standards of Current World Environment and COPE guidelines. No conflicts of interest exist.

Informed Consent Statement
This study did not involve human participants, and therefore, informed consent was not required.

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Author Contributions
- **Annem Srinivas Reddy:** Conceptualization, Methodology, Writing – Original Draft, Supervision
- **Rama Vemula:** Data Collection, Analysis, Writing – Review & Editing

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