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The role of toxicology in climate change: Understanding the risks of novel environmental toxins

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ABSTRACT

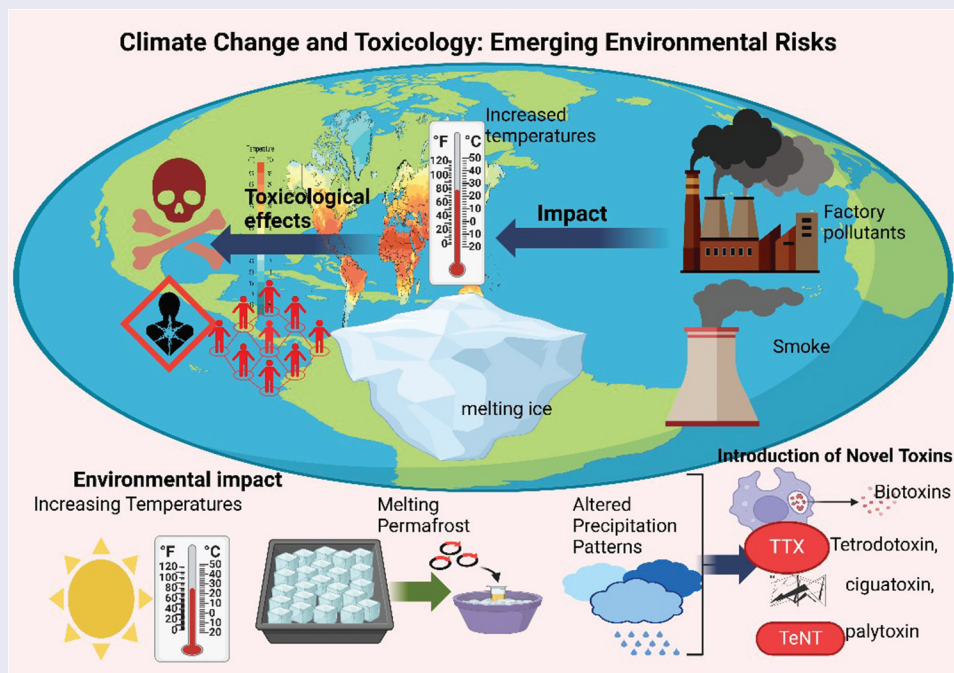
Climate crisis intensification contributes to reshaping toxicological landscapes, elevating human and ecological health hazards through environmental toxin emergence and change. Increasing temperatures, altered precipitation patterns, and melting permafrost remobilize and amplify toxins and have particularly severe effects on vulnerable populations, including coastal and indigenous communities. Assessment of the complex, climate-driven toxicological hazards requires an adaptive approach to toxicology that couples interdisciplinary and systems-level strategies. This commentary focuses on how climate change alters the toxicological landscape by redistributing and transforming contaminants such as heavy metals, persistent organic pollutants, and biotoxins as well as introducing novel environmental toxins, and heightening health risks for vulnerable populations. This study used data published in 2017–2024 from reliable scientific databases like Scopus, Web of Science, and ScienceDirect. The study emphasizes the need for adaptive toxicology frameworks to assess and mitigate climate-induced hazards, advocating for interdisciplinary collaboration and policy reform to promote proactive solutions.

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Climate change; toxicology; environmental contaminants; heavy metals; adaptive toxicology; vulnerable populations



1. Introduction

Similar to many contemporary global crises, climate change leads to profound alterations in our environmental systems, extending beyond mere temperature increases and severe weather events. Climate change is

now also changing the distribution, concentration, and toxicity of environmental contaminants and, in turn, presents previously unrecognized toxicological risks (Wang et al., 2023). Rising temperatures cause glaciers to melt and change precipitation patterns, releasing

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contaminants that have long been sequestered in soils, sediments, and ice into the environment and unleashing other toxins in reaction to those same changing conditions (Li & Xu, 2023). Some of the chemicals that can cause toxic effects are heavy metals, persistent organic pollutants, and biotoxins from harmful algal blooms (Igwaran et al., 2024). Changes in the climate may make these effects stronger or change how they work.

The evolving toxicological landscape presents major public health and environmental challenges that require new ways of understanding, monitoring, and reducing these risks. Exposure risks are increased for vulnerable populations, especially along coasts, in low-income and indigenous communities, and ecosystems are challenged to adapt to the cumulative burden of multiple environmental stressors (Johnston & Cushing, 2020). Climate change is elevating the incidence and risk of exposure to diverse biotoxins from microorganisms, flora, and fauna while also facilitating the mobilization and dissemination of hazardous environmental pollutants (Berry, 2021). It changes how dangerous substances like heavy metals, persistent organic pollutants, and air pollutants are made and spread, which makes them more bioavailable and increases their harmful effects on human health (Geng & Li, 2022). Increasing temperatures are anticipated to elevate the toxicity of pollutants and augment tropospheric ozone levels. Climate change may also influence the trajectory of persistent organic pollutants via modifications in food webs, lipid dynamics, and organic carbon cycling (Nadal et al., 2015). Alterations in precipitation might influence the volatilisation and deposition of persistent organic pollutants and pesticides, thereby exacerbating air pollution in metropolitan regions experiencing less rainfall. The dispersion of heavy metals, hydrocarbons, and pesticides is affected by climatic variations, especially alterations in precipitation and temperature (El Baz & El Baz, 0000). The notion of ‘climate toxicity’ has arisen in oncology, focusing on the heightened cancer risk from environmental carcinogens and the ecological consequences of cancer therapies (Weadick et al., 2023).

With a rising incidence of extreme climate events, there is an urgent need for innovative frameworks for evaluating and controlling chemical stressors to safeguard human health and ecosystems efficiently. Notwithstanding advancements, considerable obstacles persist in applying environmental toxicological insights to the framework of global climate change (Wilson, 2023). Given these challenges, the contribution to understanding the multifaceted impacts of climate change on human health and ecosystems is more important than ever for toxicology. Traditional toxicological frameworks, however, which tend to consider chemicals

in isolation and under stable conditions, may not sufficiently depict the interplay of chemicals and the dynamic and changing exposure patterns resulting from climate change. An adaptive toxicology paradigm is urgently needed that addresses the intertwined relationship between climate and toxicity and how the two interact to create emerging threats to our environment. This commentary calls for involvement from multiple disciplines, revisions in regulatory policy, and proactive public health stewardship to combat these environmental threats.

2. The emergence of novel environmental toxins

Climate changes are intensifying the emission and dispersion of various environmental toxins, including heavy metals, organic pollutants, algae toxins, and industrial products. For instance, rising temperatures and changed precipitation patterns mobilize toxic heavy metals such as mercury, cadmium, and arsenic, which leach from soils and sediments into water systems (Bolan et al., 2024). Additionally, thawing permafrost and melting glaciers are remobilizing industrial pollutants that have long resided in soil and ice, thereby reintroducing them to ecosystems and food chains. In addition, increased agricultural activity and shifting climate patterns are causing algal blooms in both freshwater and marine ecosystems (Wang et al., 2023). Blooms from these organisms commonly produce cyanotoxins, a category of biotoxins whose levels have the potential to cause serious human health effects, ranging from acute poisoning to chronic disease, including liver damage and neurodegeneration. Contamination by cyanotoxins in drinking water is becoming an important issue for urban centers around the globe, requiring expanded toxicological research and monitoring (Igwaran et al., 2024). Marine biotoxins, especially paralytic shellfish toxins such as saxitoxin, present significant health hazards and economic difficulties. Biotoxins are typically classified into marine (e.g. phycotoxins), bacterial (e.g. endotoxins and exotoxins), fungal (e.g. mycotoxins such as aflatoxins), and plant categories (e.g. alkaloids and ricin), each eliciting specific clinical manifestations that vary from gastrointestinal to neurological symptoms (Parak et al., 2024). Marine shellfish and finfish are prevalent vectors of these toxins, presenting considerable public health hazards globally. Microplastics may carry cyanobacterial toxins, especially microcystins, which can increase the concentration of toxins by up to 28 times when they move from water to plastic (Pestana et al., 2021; Tumwesigye

et al., 2023). Prior research emphasizes the rising incidence of marine and freshwater biotoxins attributable to climate change. Increasing temperatures and modified environmental circumstances are facilitating the proliferation of harmful microalgae and cyanobacteria in novel areas (Berry, 2021). This has resulted in the presence of toxins such as tetrodotoxin, ciguatera toxin, and palytoxin in European waters, creating issues for food safety monitoring (Estevez et al., 2019). In freshwater ecosystems, climate change is affecting the growth of cyanotoxins like microcystins, nodularin, and cylindrospermopsin (Melaram et al., 2024). These tendencies are alarming because existing regulation and monitoring initiatives exclude numerous novel toxins, potentially allowing their entry into the market. More so, the lack of chronic toxicity studies, inadequate understanding of toxin generation mechanisms, and analytical challenges in detecting and quantifying these biotoxins exacerbate the problem (Estevez et al., 2019). Some research has highlighted the increasing apprehension regarding emerging pollutants (EPs) in the environment. These encompass pharmaceuticals, endocrine disruptors, poly- and perfluoroalkyl substances (PFASs), and biological pollutants (Xiao, 2017). Climate change is amplifying PFAS emissions, whereas the degradation of microplastics contributes to greenhouse gas emissions, hence intensifying climate change. The melting of permafrost caused by global warming could release PFAS that have been stored, which could change how they move around the world. PFAS are extremely persistent and bioaccumulative, with exposure arising from multiple sources such as air, food, water, and consumer products (Gander, 2022). Plants can absorb these chemicals, which can influence their role in ecosystems and pose health risks to humans. Research has linked PFAS exposure to detrimental health consequences on reproduction, metabolism, endocrine function, and other organ systems (Adu et al., 2023). Environmental pollutants present considerable hazards to ecological and human health, frequently remaining in air, water, soil, and biological tissues even in minimal quantities. According to Xiao (Xiao, 2017), advanced analytical methods have facilitated the identification of several novel PFASs, resulting in the discovery of 455 new compounds from 2009 to 2017. Enhanced detection methods, toxicity evaluations, and novel treatment technologies are necessary to tackle the issues presented by emerging pollutants (Tang et al., 2019). Comprehending the prevalence, ecological destiny, and biotoxicity of these pollutants

is essential for numerous scientific fields and environmental management approaches (Falandysz et al., 2024).

3. Climate-driven changes in chemical toxicity

There is an interaction between climate change and chemical toxicity in the environment. Climate-related stresses, such as elevated temperatures and modified pH levels, might increase organisms' vulnerability to chemical toxicity. On the other hand, chemical exposures can hinder organisms' capacity to adapt to fluctuating environmental conditions (Noyes & Lema, 2015). Synergistic impacts between climate change and chemical pollution are more prevalent than additive or antagonistic interactions (Cabral et al., 2019). Elevated temperatures have been demonstrated to enhance sensitivity to cadmium in freshwater snails, with effects varying from additive to synergistic based on life stage and pollutant concentration (Kimberly & Salice, 2013). These interactions present difficulties in forecasting toxicological outcomes under prospective climatic scenarios and underscore the necessity for more comprehensive methodologies in environmental risk assessment (Cabral et al., 2019; Noyes & Lema, 2015).

Climate change is affecting the toxicity of existing chemicals as well as the introduction of new toxins. Climate change can increase the inherent toxicity of chemicals by altering their chemical transformations, interactions with biological systems, and environmental persistence. Key examples include ozone and air pollutants, polycyclic aromatic hydrocarbons (PAHs), pesticides, heavy metals, and microplastics. Rising temperatures and stronger sunlight can exacerbate respiratory diseases, oxidative stress, and mutagenic potential. Acidification increases metal solubility, reactivity, and toxicity to aquatic organisms. Higher temperatures also accelerate plastic degradation, leading to endocrine-disrupting compounds (Yang et al., 2024). Changes in temperature, pH, and salinity influence the chemical transformation and bioavailability of pollutants, thereby influencing their toxicological profiles. For instance, rising temperatures can increase the volatility of pesticides and industrial chemicals, leading to their release into the atmosphere and potential inhalation exposure in human populations (Pathak et al., 2022). Recent studies underscore the environmental hazards linked to

rising temperatures that liberate compounds from permafrost and sediments. Different ‘dormant chemicals’, such as heavy metals and organic compounds, can be released from thawing permafrost, potentially affecting ecosystems (Jiao et al., 2024). More mercury has been found in deep layers of Siberian permafrost, which is a big problem. This is linked to higher levels of organic carbon and different types of sediment (Rutkowski et al., 2021). Climate warming and thawing may elevate methylmercury concentrations, with Arctic permafrost acting as a possible source of mercury (Ignatavičius et al., 2022). Also, rising temperatures in the Arctic Ocean could make methane hydrates in continental margin sediments less stable, which could let methane escape into the water and the air (Ruppel & Kessler, 2017). This may intensify ocean acidification and oxygen depletion. Melting permafrost and rising ocean temperatures release these chemicals into the air. This causes a lot of problems for the environment and needs more research to understand and fix. Similarly, scientists predict that increases in CO₂ will transform heavy metals in acidified waters into more toxic forms, increasing their bioavailability and risk to aquatic life, and ultimately to humans through their bioaccumulation in food webs (Alum & Department of Biochemistry, 2023). Key heavy metals affected include cadmium, lead, mercury, arsenic, copper, and zinc. Climate-induced changes in precipitation patterns may influence the distribution and toxicity of persistent organic pollutants and pesticides (Pathak et al., 2022). Furthermore, the adaptive responses of organisms to climate-driven stressors may influence toxicological outcomes. It is well known that organisms experiencing environmental stress are more susceptible to toxins due to their weakened immune system and lowered detoxification capabilities. Similarly, chemical exposure may impair an organism’s ability to withstand adverse climate conditions (Jomova et al., 2023). Again, it has been reported that climate change can impact negatively on bioactive components of medicinal plants thereby lowering their therapeutic potentials (Alum, 2024). For instance, Sharma et al (Sharma, 2024). discovered that aloe vera diminished phenolic content and antioxidant activity under conditions of elevated soil salinity, whereas drought stress led to a reduction in flavonoids in *Vitis vinifera*, *Lavandula angustifolia*, and *Artemisia tridentata*. Likewise, St. John’s Wort (*Hypericum perforatum*) exhibited alterations in the concentration of its active compounds under stress

conditions, which may affect the plant’s pharmacological efficacy (Nicolussi et al., 2020). The overlap of chemical exposure with biological response and environmental conditions in the human body requires a more sophisticated form of toxicological risk assessment.

4. Implications for human and ecological health

Vulnerable populations are most likely to experience the health effects of these climate-exacerbated toxicological risks. Coastal and riverine indigenous communities, who rely on local seafood and traditional subsistence practices, may be particularly vulnerable to the bioaccumulation of toxins in fish and marine mammals. Seafood contains various toxins, including heavy metals like mercury, lead, and arsenic, persistent organic pollutants like PCBs, PFAS, harmful algal toxins like domoic acid, saxitoxins, and ciguatoxins, and microplastics containing bisphenols, phthalates, and heavy metals. These contaminants bioaccumulate and biomagnify, making seafood safety a global concern (Orji et al., 2021). Moreover, the increased volatility of chemical contaminants in industrialized areas is likely to make the presence of airborne pollutants even more risky for low-income communities (Wang et al., 2024). Children, the elderly, and people with pre-existing health conditions are also at elevated risk, just like in other high-density areas. For example, increasing pollution levels of airborne pollutants, industrial and biomass pollution, greater exposure and poor ventilation in urban areas may worsen asthma and chronic obstructive pulmonary disease (COPD) due to already compromised respiratory system (Wang et al., 2024).

Recent studies underscore the profound effects of climate change on human and ecological well-being. Byg and Shah (Byg & Shah, 2024) predict that projected rising temperatures will increase heat-related morbidity and death, intensify extreme weather events, and intensify vector-borne diseases. Climate change influences infectious diseases including zoonotic infections since increased rainfall correlates favorably with pathogens escalation (Rupasinghe et al., 2022). Ecological disturbances, such as deforestation and alterations in land use, have been associated with the introduction of diseases including malaria (Alum et al., 2024). Therefore, immediate measures are required to reduce emissions, execute adaptation methods, and advance climate justice. Furthermore, there is a need to conduct research on early life exposure to climate-enhanced toxins like lead and methylmercury to better understand the long-term neurodevelopmental consequences, which could potentially impact public health outcomes for future generations (Basu et al., 2023).

5. A call for adaptive toxicology and regulatory frameworks

Recent literature advocates for a change in perspective in toxicology toward more flexible and contemporary methodologies. An adaptive approach to toxicology and environmental regulation is necessary to face the intricate toxicological risk problems associated with a changing climate. Traditional toxicology, often conducted under controlled conditions and focusing on individual chemicals, may not be sufficient to assess the synergistic and dynamic effects resulting from climate-driven exposures. Capturing the full spectrum of climate-related toxicological risks instead requires a systems-level approach that incorporates environmental science, epidemiology, and toxicology (Fawzy et al., 2020). Adaptive regulatory frameworks, capable of rapid response to emerging threats, are necessary for this purpose, and policymakers must understand this. This could include new standards of environmental quality that account for climate-based effects on chemical persistence, bioavailability, and toxicity. Furthermore, we should enhance the effectiveness of monitoring and surveillance of climate-sensitive toxins in the most vulnerable areas. Recently, Hartung (Hartung, 2023) examined the growing significance of artificial intelligence in toxicology, underscoring its capacity to improve chemical hazard assessment and stressing the necessity for responsible development. Building on the developments of predictive toxicology (e.g. machine learning and artificial intelligence) will allow us to improve the prediction of the impacts of climate change on organisms and develop early warning systems.

6. Conclusion

The intersection of climate change and toxicology is a critical, but underexplored, niche in environmental health science. Climate change is reshaping the toxicological landscape by altering the distribution, bioavailability, and toxicity of environmental contaminants, including heavy metals, persistent organic pollutants, and biotoxins. These changes pose heightened risks to human and ecological health, particularly for vulnerable populations in coastal, low-income, and indigenous communities. Traditional toxicology frameworks are insufficient to address the complexities of climate-driven toxin exposure, necessitating an adaptive, interdisciplinary approach that integrates toxicology, climate science, and public health. Strengthening environmental regulations, enhancing monitoring efforts, and fostering collaboration among policymakers, researchers, healthcare providers, and industries are critical to mitigating emerging toxicological threats. Proactive research and policy adaptation

are essential to safeguard human and environmental health in the face of an evolving climate crisis.

7. Recommendations for stakeholders

Collaboration and proactive measures across diverse sectors is essential to mitigate the growing risks of climate-induced toxicological threats:

7.1. For policymakers and regulators

- (i) Strengthen environmental policies to regulate emerging climate-induced toxins.
- (ii) Enhance air and water quality standards to mitigate heavy metal and biotoxin contamination.
- (iii) Implement early warning systems for harmful algal blooms and pollutant surges.
- (iv) Support climate-adaptive toxicology frameworks in public health policies.

7.2. For researchers and scientists

- (i) Develop interdisciplinary approaches integrating toxicology, climate science, and public health.
- (ii) Improve detection methods for novel environmental toxins, including persistent organic pollutants (POPs) and PFAS.
- (iii) Investigate long-term exposure risks of climate-enhanced pollutants on human and ecological health.

7.3. For public health authorities and healthcare providers

- (i) Expand monitoring programs to track toxin exposure in vulnerable populations.
- (ii) Educate communities about climate-related toxicological risks and preventive measures.
- (iii) Enhance medical preparedness for toxin-related health issues, including seafood-borne illnesses and respiratory diseases from air pollution.

7.4. For industry and private sector

- (i) Adopt sustainable practices to reduce industrial emissions and pollutant discharge.
- (ii) Invest in cleaner technologies that minimize chemical contamination and climate impact.
- (iii) Ensure corporate responsibility in managing environmental waste and hazardous materials.

7.5. For communities and individuals

- (i) Advocate for policy changes that prioritize environmental health.
- (ii) Reduce exposure risks by staying informed on air and water quality alerts.
- (iii) Adopt sustainable habits such as reducing plastic use and supporting eco-friendly industries.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

Additional data that support the findings of this study are available from the author upon reasonable request.

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