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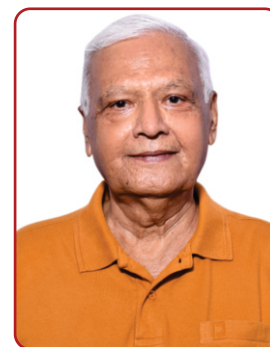
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Ecotoxicological consequences of climate change - unforeseen threat to planetary health

Professor Emeritus S. V. S. Rana*Advisor, Journal of Environmental Biology, Lucknow-226 022, India*

Centre of Excellence in Toxicology, Chaudhary Charan Singh University, Meerut-250 004, India

Email: sureshvs_rana@yahoo.comORCID: <https://orcid.org/0000-0003-3929-300X>

Several examples of ecotoxicological episodes are aptly available in literature. Each of these disasters have resulted in the widespread damage to natural resources, wild life, humans and ecosystems. Minamata episode-1956; Bhopal gas tragedy- 1984; London Smog-1952; DDT ecosystem impact- 1960s; Chernobyl disaster- 1986; Exxon Valdez accident-1989 and Fukushima disaster-2011 are few incidences. In addition, global warming, increased carbon dioxide and methane emissions, wild fires and melting of polar ice are a big threat to all major biomes.

Climate change and its consequences on structure and function of ecosystem(s) now warrant a strategic management and planning. Climate change can be defined as "significant shifts in global or regional weather patterns caused by anthropogenic activities like burning of fossil fuels culminating into rising temperatures, melting of ice, sea level rise and increase in the frequency and severity of extreme weather conditions". Greenhouse gases viz. CO₂ and CH₄ trap solar heat forming a blanket around the Earth. According to NASA and IPCC, currently Earth is heating at an unprecedented rate. The year 2024 was declared as the warmest year by WMO. Experts argue that climate change is altering the ecotoxicological landscape serving as "threat multiplier". It makes ecosystem(s) more vulnerable to toxic hazards. In terrestrial ecosystems, climate change may manifest into altered species distribution, phenology, disturbed food webs, loss of biodiversity, damage to ecosystem functions and increased risk to communicable and non-communicable diseases as well.

In this section we discuss how rising temperatures, shifting precipitation trends and ocean acidification alter the behavior, transport, bioavailability and toxicity of environmental poisons, *i.e.* toxic elements, pesticides, persistent organic pollutants, biotoxins and emerging pollutants leading to enhanced, often synergistic risks to planetary health.

Significant changes in soil health have been attributed to climate change. Parameters like soil erosion, loss of soil organic matter, permafrost thaw, acidification, salinization of soil, nutrient cycle disruption, carbon loss, changes in microbial communities and plant soil relationships have exhibited noteworthy effects (Nigussie, 2024). Most important the effects of climate change can be demonstrated on carbon cycle. Global CO₂ emissions have recorded high, with total emissions of 38.11 billion metric tons (IEA Global Energy Review, 2026). Due to continued rise in fossil fuel emissions, driven by coal and oil demand, achieving the target of 1.5°C decrease in global temperature by 2050, seems increasingly difficult to meet (Crippa, 2025). Climate change can disrupt oxygen cycle primarily by inducing ocean acidification, deoxygenation and reducing atmospheric oxygen levels. A 2% decrease in ocean oxygen levels over the past 50 years, has been registered. This is about 10 times faster than the increase in CO₂. The combination of warmer, less oxygenated waters, and increased algal blooms severely damage marine biodiversity and fisheries (Anderson *et al.*, 2025). Organisms stressed by climate change find difficult to detoxify contaminants.

The effects of climate change on hydrologic cycle can lead to intense and erratic precipitation, higher flood risks in some areas and drought in others, reduced snow fall/earlier melting of ice and erratic monsoon patterns. It might affect the distribution and toxicity of heavy metals, persistent organic pollutants (POPs) and pesticides (Pathak, 2022). Moreover, the adaptive response of aquatic biota to climate change may affect eco-toxicological outcomes. Warming waters, ocean acidification, change in water currents can cause decline in the fish population and threaten food security. Shift in population may affect fish physiology, behavior, reproduction, productivity and loss of habitat leading to ecosystem instability, altered food webs and economic hardships (Brander, 2010).

Ecotoxicological disasters like Minamata and Itai Itai had widespread effects on human and environmental health. Recent studies have reported that global warming, increased precipitation and acidification of waters alter the mobility and bio-accumulation of toxic elements viz. Hg, Cd, As, and Pb in different ecosystems and exacerbate their toxicity. Rising temperatures and altered precipitation (flood/drought) mobilize already trapped elements from soil, snow and sediments into aquatic systems. Higher temperatures directly amplify toxic effects of metals in aquatic species and affect their growth, fertility and fecundity. While, lower pH of water can increase the bioavailability of elements like Pb and Cd, higher temperatures can promote methylation of elements like arsenic and mercury. Climate change induced changes in trophic structure of ecosystems may enhance bioaccumulation and biomagnification of toxic metals in food chains. Contrarily, low temperature in Arctic regions can release metals from permafrost leading to enhanced metal pollution. Cohesively, climatic factors may further increase the impact of toxic elements on the environment and human health (Xiao *et al.* 2024). Further increase in CO₂ would transform heavy metals in acidified waters to more toxic forms, increasing their bioavailability and risks to aquatic life, ultimately to humans through bioaccumulation in food webs (Alum, 2023).

Climate factors together with pesticide form a synergistic relationship. Higher temperatures accelerate chemical degradation of pesticides and enhance their evaporation leading to increased inhalation risks for man and animals. Accelerated reduction and detoxification of pesticides may lead to increased mortality even in non-target populations. Contrarily, higher precipitation may result in runoff into water bodies, while drier conditions make pesticides persistent and accelerates evaporation of others. Increased pest pressure due to changing climates necessitates frequent pesticide application leading to enhanced residual concentration in crops. In estuarine systems, increase in salinity may promote pesticides toxicity.

Persistent organic pollutants (POPs) are carbon based toxic substances that may exist in the environment for years, bioaccumulate in the fatty tissues of organisms, travel long distances and are often used as pesticides, industrial chemicals or industrial byproducts. They include DDT, lindane, dieldrin, endosulfan, polychlorinated biphenyls (PCBs), dioxins and furans, waterproof clothing, non-stick cookware and carpet treatment. Fragile ecosystems like Arctic and Antarctic systems, are known to accumulate POPs. Melting glaciers may change their course, behavior and toxicity through increased mobility, bioavailability and release from reservoirs like melting ice and thawing permafrost. Higher temperatures and increased precipitation both can enhance volatilization and transport of POPs from soil and water enhancing their concentration in atmosphere and transport to higher latitudes. Climate change may alter the bioavailability and bioaccumulation of POPs through altered food web (Borga *et al.*, 2022).

Several bacteria, fungi, plants and animals are known to secrete/produce poisonous substances called biotoxins. They are classified as microbial toxins, saxitoxins, fish toxins and natural toxins. Their inhalation, ingestion or absorption may cause severe illness or death in humans. Climate change may enhance the toxicity of biotoxins (Berry, 2021). European waters were found to be contaminated with tetrodotoxin (fish, Octopus), ciguatoxin (Dinoflagellates) and palytoxin (corals) raising issues of food safety (Estevez *et al.*, 2019). Climate factors are affecting the growth of cyanobacteria that produce cyanotoxins including microcystins, cylindrospermopsin, anatoxins and saxitoxins (Melaram *et al.*, 2024). Human exposure to these toxins may occur through drinking contaminated water, swimming in algal blooms or eating contaminated fish. Consequent health effects may include skin irritation, headache, damage to liver and respiratory system. Emerging and unregulated pollutants viz. pharmaceuticals, microplastics, endocrine disruptors, personal care products, perfluoroalkyl substances (PFASs), and biological pollutants are considered as emerging pollutants (Xiao, 2017). Melting of permafrost can release PFASs. Plants can absorb these chemicals and pose health risks to humans (Gander, 2022). There's an urgent need for suitable analytical methods and novel treatment technologies for biosafety against emerging pollutants (Tang *et al.*, 2019).

Negative effects of climate change on major ecosystems thus include elevated global temperatures, altered precipitation patterns, increased frequency of droughts, sea level rise, melting of ice and an increased risk of natural disasters. Societal and environmental systems respond to these threats through suitable mitigation or adaptation mechanisms. Most important amongst these challenges is the food security for humans. Not only the staple crop yields *i.e.* wheat, rice and maize in both tropical and temperate regions are being affected, the productivity of marine and fresh water ecosystems in terms of fisheries is also decreasing. Climate change may decrease the global fish community biomass by as much as 30% by 2100 (Carrozza *et al.*, 2017). The cracks in marine food chain alter the distribution, productivity and species composition of global fish production (Fabry *et al.*, 2008). Fragile ecosystems viz. estuaries, coral reefs, mangroves and sea grass beds too have exhibited negative effects of climate change. In brief, institutional management strategies are immediately required to ensure human food security and nutritional demands.

Environmental disasters necessitate invention of regulatory mechanisms aimed at ecosafety. Climate change has attracted significant attention at inter-government level and is being monitored by agencies viz. Inter-governmental Panel on Climate Change (IPCC); UN Framework on Climate Change (UNFCCC), World Health Organization (WHO); World Meteorological Organization (WMO) and United Nations Environmental Program (UNEP). Climate change is affecting all major ecosystems including human beings. The risks are unevenly distributed but are greater for disadvantaged populations. WHO claims climate change to be the major threat to life on our planet in 21st century. Moreover, extreme weather events pose public health problems *i.e.* transmission of infectious and zoonotic diseases (Alum *et al.*, 2024). World economic forum has estimated 14.5 million more deaths due to climate change by 2050. Increase in drought in certain regions would cause 3.2 million deaths from malnutrition. If these conditions prevail for rest of the century, over 9 million climate related deaths would occur annually by 2100.

Recently, a meeting of Conference of Parties 30 (COP 30), was held at Belem, Brazil from 10 – 21 November 2025. It focused on implementation of Paris Agreement, setting new goals on climate change for 2035 with emphasis on tropic forest conservation. The next meeting of COP-31 is to be held in November 2026 at Antalya, Turkiye, which would focus on enhancing the global climate action with strong emphasis on climate justice. In September 2015, UN General Assembly had adopted seventeen sustainable development goals for 2030. Amongst these, goal # 3 demonstrated on good health and well being while goal # 13 emphasized on combating climate change and its effects. During COP23 held at Bonn, Germany in December 2023, extensive discussion was held on climate change and human health. It proposed reduction in climate related morbidity and mortality in vulnerable communities. However, application of toxicological tools to improve understanding of the relationship between climate change and health has not been deliberated.

Based on the above information, it can be concluded that immediate adoptive measures and climate justice needs to be executed. Standard ecotoxicological tests should to be incorporated with climate stress assessment. It is advised that long term monitoring of ecosystems should be performed to track the combined effect of climate change and emerging contaminants like PFAS and micro/nanoplastics. Concept of green toxicology that integrates safety assessments into the design of new chemicals and materials early in their development needs to be introduced in all management practices. It is expected that nature based solutions will help in increasing the resilience of ecosystems. Awareness on climate related toxicological hazards amongst public, industry and policy makers will yield significant dividends. Monitoring and surveillance of climate sensitive toxins in highly vulnerable areas should be conducted at regular intervals. Employing tools of predictive toxicology, artificial intelligence and machine learning will aid in predicting the impact of climate change on the organisms and develop early warning systems.

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