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Ecotoxicological Risks in a Brackish Lake Ecosystem During Climate Change Scenarios: A Comprehensive Review on Lake Tudakul

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ABSTRACT

Climate change and anthropogenic pressures increasingly threaten the ecological integrity of inland water bodies, particularly saline lakes due to their unique hydrological and biological features. This review focuses on Lake Tudakul, one of Uzbekistan's largest saline lakes and a Ramsar-listed wetland, assessing its vulnerability under future climate scenarios. The study integrates climate scenario modeling (RCP4.5 and RCP8.5) with standardized ecotoxicological bioassays—Microtox®, MARA, algal growth inhibition, Lemna minor, and Daphnia magna toxicity tests—to evaluate combined effects of rising temperatures (2.0 °C and 4.5 °C) and chemical pollutants. Results reveal increased biological sensitivity to contaminants under elevated temperatures, suggesting potential synergistic impacts that may disrupt lake ecosystem structure and function. Lake Tudakul, a regional biodiversity hotspot, is exposed to agrochemical runoff, increasing salinity, and microplastic pollution, threatening aquatic organisms and ecological services. The accumulation and trophic transfer of pollutants—such as heavy metals, persistent organic compounds, and micro(nano)plastics—pose risks to food webs, public health, and water safety. These stressors may also increase the likelihood of harmful algal blooms and cyanotoxin outbreaks. The study emphasizes the urgent need for early-warning systems, adaptive

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management, and transboundary cooperation to mitigate ecological risks. Lake Tudakul exemplifies the vulnerability of semi-arid lakes under compounding climate and human pressures, highlighting the importance of integrative, ecosystem-based strategies to safeguard biodiversity and freshwater resources.

Keywords: Lake Tudakul; Climate Change; Ecotoxicology; Central Asia; RCP Scenarios

1. Introduction

Lakes around the world are being affected by climate change, including changes in their physicochemical and biological characteristics, as well as interactions among internal compartments and with surrounding watersheds [1]. The ecological responses of lakes to climate change are expected to become more pronounced in the future, with continued global warming, increased evapotranspiration, altered patterns of rain and drought, and disrupted or amplified climate teleconnections [2]. The continued ability of lakes to provide habitat for thousands of aquatic species and ecosystem services to society is threatened as they diminish in size, become more saline, and/or experience highly altered thermal properties. At least one of the factors occurring with climate change—warming of lake water—is known to have synergistic effects with nutrient enrichment, stimulating blooms of toxic algae in eutrophic lakes and altering food-web structure [3,4]. Likewise, complex interactions occur when other physicochemical properties are altered. Changes in salinity affect composition and diversity of the various biota and alter trophic structure and dynamics [4]. Changes in thermal stratification or duration of ice cover affect fishes and, in turn, alter the top-down control of plankton. This can have cascading effects on the food web [1]. Other synergistic and/or complex effects likely exist and are yet to be documented as we continue to learn more about the responses of different kinds of lakes to a warming Earth.

Impacts of climate change on lakes are important because lakes play a critical role in the landscape, providing nesting habitat for birds, foraging areas and water sources for many terrestrial animals, and serving as sources of oxygen and sinks for carbon and nitrogen gases [5]. For the human population, lakes are a major source of drinking water, irrigation water, recreational opportunities, and fisheries resources, and they can have major cultural and economic significance. Despite this, it is remarkable that in many nations, funds are being directed away from the careful assessment of changes in lakes in response to climate change. This is happening at a time when quantification of the rates of change is most needed to help understand processes and possible tipping points, and to identify measures to increase resilience [5].

The impact of human activities throughout Central Asia has increased significantly over the last century. In the case of Uzbekistan, long-distance atmospheric transport of pollutants from urban and agricultural sources creates substantial pollution pressure on freshwater resources. Nitrogen and sulfur emissions from inorganic fertilizers and pesticides lead to acid accumulation and severe acidification in freshwaters, threatening organisms adapted to neutral or slightly alkaline conditions [6]. Although some lakes have shown signs of recovery, the persistence of pollutants such as heavy metals, persistent organic pollutants (POPs), and micro(nano)plastics continues to pose a growing threat [7]. These contaminants accumulate in the water column and sediments, often biomagnifying through the food web and leading to significant ecotoxicological effects [7]. The oligotrophic nature and low temperatures of these lakes further aggravate the issue, as contaminants tend to persist longer than in more nutrient-rich, metabolically active aquatic systems [6]. While direct contamination sources are minimal in remote high-altitude environments, atmospheric deposition results in diffuse and unpredictable pollution patterns [6].

Crucially, climate change is expected to modify the dynamics of pollutant transport, distribution, and toxicity [8]. Rising temperatures may also alter the chemical reactivity and bioavailability of contaminants, potentially intensifying their toxicity [9]. Research has further demonstrated that contaminant exposure can disrupt the ability of organisms to regulate their metabolic rates in response to temperature fluctuations, leading to synergistic effects that further challenge their survival [10]. This underscores the growing significance of climate-induced changes in pollutant behavior, particularly in lake ecosystems where species are already vulnerable to environmental stressors. Another critical concern is the intensification of UV radiation exposure due to climate change [11]. With thinning ozone layers, UV-sensitive organisms, such as phytoplankton, are experiencing increased physiological stress [12]. This effect cascades through the food web, impacting zooplankton, fish, and other aquatic species that rely on phytoplankton as a primary food source.

This study is grounded in the theoretical framework of climate-ecotoxicology, which explores the synergistic interactions between climate-induced abiotic stressors (e.g., rising temperature, UV radiation, salinity) and chemical pollutants (e.g., heavy metals, POPs, microplastics) on biological systems. In the context of Central Asia, where climate change is exacerbated by legacy pollution from agricultural and industrial activities, this framework provides a basis for understanding the vulnerability of lake ecosystems such as Lake Tudakul. These ecosystems face unique challenges due to their closed hydrology, high evaporation rates, and shallow morphology, which amplify the effects of both warming and pollution. The economic implications are significant: Lake Tudakul supports local fisheries, recreation, and irrigation, and any degradation in ecological quality can directly translate into biodiversity loss, reduced fish yield, compromised tourism potential, and water insecurity. Causality in this context is likely bidirectional; for instance, climate change intensifies pollutant toxicity, which in turn weakens biotic resilience, thereby accelerating ecosystem collapse.

2. Importance of Lake Tudakul Basin

Lake Tudakul, a natural water body formed in 1952 from floodwaters of the Zarafshan and Amu Darya rivers, is located in the Qiziltepa district of Navoi region, approximately 26 km east of Bukhara city and just east of the Kuyimozor Reservoir (**Figure 1**). Situated in the heart of the desert, it spans about 22,000 hectares and holds an estimated 2 billion cubic meters of water. Its maximum depth reaches 17 meters, with an average between 5 and 7 meters [13]. As one of the most extensive wetlands in Uzbekistan, Tudakul is a brackish lake entirely within the Navoi region and has been registered under the Ramsar Convention by the Uzbekistan State Committee of Nature Protection. Its shoreline features diverse geology: steep slopes define the northwestern and northeastern edges, while the eastern shore gently merges into a wavelike plain that connects to nearby hills. The surrounding vegetation is primarily desert flora.

Figure 1. Lake Tudakul Basin.

The lake is replenished by excess water from the Zarafshan River via an intermediate channel and by additional input from the Amu-Bukhoro canal network, which is fed by the Amu Darya River. Supplementary channels also contribute flow to the lower canal system. Outflow from Tudakul is directed to the Kuyimozor Reservoir through a discharge canal [13].

Lake Tudakul attracts attention with its rich biodiversity. The surrounding area hosts various species such as goitered gazelles, foxes, wild cats, hares, swans, pelicans, gulls, and eagles, several of which are listed in the Red Book of Uzbekistan. Aquatic biodiversity surveys have recorded 186 species of phytoplankton, 15 zooplankton species, and 9 macrozoobenthos species [13]. The lake's ichthyofauna includes approximately 29 species, 22 of which belong to the Cyprinidae family. Among these, 16 introduced alien species dominate the fish community, including 10 originating from the Far Eastern fauna [13].

In addition to its ecological value, Tudakul is considered a recreational destination, with 22 private enterprises offering accommodations for up to 1,282 guests. Its proximity to Navoi, Samarkand, and Bukhara enhances its significance for both fishing and tourism. The lake also serves as an irrigation water source for surrounding agricultural lands. However, agrochemicals primarily enter the system through discharges from the Zarafshan and Amu Darya rivers. River inflows, fishing, aquaculture, and tourism are key anthropogenic activities contributing to pollution pressure [13].

Microplastic pollution has been reported in sections of the Zarafshan River flowing through the Samarkand and Navoi regions of Uzbekistan. Surface water sampling revealed microplastic concentrations of 3.22 ± 1.64 particles/m³, with particle diameters ranging from 0.15 to 3.00 mm [14]. Assessing environmental risks remains difficult, as data on microplastic pollution in Central Asia's freshwater ecosystems are still fragmentary. A separate study by Barinova and Mamanazarova (2021) reported the presence of nutrients, heavy metals, and phenols in the Zarafshan River, originating from multiple sources along its Navoi branch [15].

Unlike earlier studies, which primarily focused on the chemical composition or hydrological variability of saline lakes in arid zones [15], this study uniquely integrates empirical ecotoxicological test data with simulated climate scenarios (RCP4.5 and RCP8.5), providing an innovative approach to quantify synergistic stressors on aquatic life. This represents a step forward in regional climate impact studies, where empirical bioassay data remain scarce. We build upon frameworks such as those proposed by Havens and Jeppesen (2018) and incorporate thermochemical stress interactions outlined by Kazmi et al. (2022) [5,9], contextualizing our findings within a multi-trophic risk assessment framework.

3. Climate Scenarios and Ecotoxicological Tools

There are several different climate emission scenarios that can help us understand and predict the potential impacts of climate change. These scenarios are based on various assumptions about how human activities, such as burning fossil fuels, will affect the concentration of greenhouse gases in the atmosphere. The IPCC has developed a set of scenarios known as Representative Concentration Pathways (RCPs) to help understand the potential impacts of different levels of greenhouse gas emissions on the climate (**Table 1**) [11,16,17].

Table 1. Climate Scenarios [17].

Scenarios	Explanation
RCP2.6	Represents a low-emissions scenario in which greenhouse gas concentrations stabilize at around 430 ppm CO_2 equivalent (CO_2^e) by the end of the century. This scenario aims to limit global warming to 2 °C and below the pre-industrial levels.
RCP4.5	Represents a medium emissions scenario where greenhouse gas concentrations stabilize around 540 ppm CO_2^e by the end of the century. This scenario is also consistent with the goal of limiting global warming to below 2 °C, but requires more significant emissions reductions than RCP2.6
RCP6	Represents a scenario that falls between the medium and high emissions scenarios, where greenhouse gas concentrations stabilize around 630 ppm CO_2^e by the end of the century. It is not consistent with the goal of limiting global warming to below 2 °C, but would still result in lower warming levels than the highest emissions pathway (RCP8.5).
RCP8.5	Represents a high-emissions scenario in which greenhouse gas concentrations continue to rise throughout the century, reaching approximately 935 ppm CO_2^e by 2,100. This scenario is not consistent with the goal of limiting global warming to below 2 °C and would result in the highest levels of warming among the RCPs.

The Central Asia basin is one of the climate change hotspots, where the effects of global warming are evident as a result of changes in greenhouse gas concentrations in the atmosphere [18]. Future climate projections have been carried out for the RCP4.5 and RCP8.5 scenarios. The projections of these models predict that the average temperatures in the last decade of the 21st century will increase by 2.0 °C, 2.5 °C, 3.4 °C, and 4.5 °C, respectively, compared to the 1970–2000 reference temperatures for the RCP4.5 medium emission scenario, and by 4.5 °C, 4.3 °C, and 5.9 °C for the RCP8.5 high emission scenario [17]. Therefore, this review discusses ecotoxicological tests used to assess ecological risks in freshwater systems, based on the most optimistic temperature projections for medium and high emission scenarios.

The useful ecotoxicological tools in assessing the ecological status of freshwater ecosystems are acute toxicity tests such as Microtox®, MARA-Test, Lemna sp., and Daphnia sp. tests. These tools can also be used in the ecotoxicological risk assessment of Lake Tudakul under different climate change scenarios.

Microtox®, a micro-scale biomonitoring tool in ecotoxicology, is used to detect toxicity and predict the effective concentration range for other toxicity tests. The toxicity test is performed in accordance with the basic test protocols defined by the manufacturer (Microbics Corporation, 1992) with five concentrations and one control. Luminescent bacteria (*Aliivibrio fischeri* NRRL B-11177), used as a test organism for biomonitoring the toxic effects of environmental samples, are measured with the Microtox® FX analyzer. Phenol (organic) and zinc sulfate ($ZnSO_4$•$7H_2O$, inorganic), which are reference toxicants, are used as positive controls to test the fluorescence behavior of bacteria. After 15 and 30 min of incubation, the concentration that blocks 50% of the fluorescence (EC_{50}) is taken as the effect criterion and compared with the control. A portable Microtox® FX device is used to measure toxicity instantly during sampling. In this way, preliminary data are obtained for the MARA test to be performed when the samples are brought to the laboratory and the effect of the sample waiting time on toxicity is also determined.

MARA-Test (Microbial Assay for Risk Assessment) is a microbial biosensor test widely used for toxicity assessment in environmental samples. It determines toxicity by analyzing the growth rates of different microorganisms (*Bacillus subtilis*, *Escherichia coli*, *Pseudomonas aeruginosa*, *Micrococcus luteus*, *Enterococcus faecalis*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, *Acinetobacter baylyi*, *Citrobacter freundii*, *Arthrobacter globiformis*, *Salmonella enterica*, *Streptomyces coelicolor* and *Saccharomyces cerevisiae*, a yeast species). Following sampling, the lyophilized bacteria in the MARA panel are rehydrated in sterile growth medium (Luria Bertani Broth) and incubated at 30 °C for 2–3 hours for activation of the organisms. Different MARA microorganisms are added to each well using a 96-well microplate. The water sample and the control medium to be tested are added to the wells and negative control wells (wells containing only microorganisms and medium) are prepared. The microplates are placed in the incubator and incubated at 30 °C for 24–48 hours and bacterial growth is evaluated by determining the absorbance values at OD_{600} nm with a spectrophotometer. It is expected that the growth rate of microorganisms decreases in samples containing toxic substances; growth inhibition is observed in sensitive bacteria and resistant bacteria continue to grow. If 50% growth inhibition (IC*50* value) is detected, the sample is considered toxic [19]. Various agents known to be toxic to microorganisms are used as positive controls during the MARA test application: Potassium Dichromate ($K_2Cr_2O_7$) [heavy metal toxicity, 1–10 mg/L], Sodium Dodecyl Sulfate (SDS) [detergent and surfactant toxicity, 5–20 mg/L], Copper Sulfate ($CuSO_4$) [heavy metal sensitivity, 0.5–5 mg/L], chlorhexidine [antibiotic and biocide testing, 10–50 mg/L] and phenol (toxicity of organic chemicals, 10–100 mg/L). Storage conditions of the samples are very important for the toxicity analysis of the samples taken from the lake to give accurate results. Improper storage may result in the growth of microorganisms or the deterioration of contaminants in the sample.

The standard freshwater algae toxicity test is Growth Inhibition Test commonly used for aquatic toxicology testing and toxicity screening of surface waters and sediment pore waters (OECD 201, Algaltoxkit F). The test is a 72h bioassay based on growth inhibition of the freshwater microalgae, *Pseudokirchneriella subcapitata* (former names: *Selenastrum capricornutum* and *Raphidocelis subcapitata*). After 72 hours, effective concentrations (EC_{10}, EC_{20}, EC_{50}), No Observed Effect Concentration (NOEC) and

Lowest Observed Effect Concentration (LOEC) are calculated based on cell count per mL. The test is carried out in a static system using at least five concentrations of the test substance and one untreated control (three replicates per concentration or control), with an adequate initial biomass concentration expressed in cells/mL per replicate. A limit test and/or range-finding test is conducted before the definitive test. The limit test is carried out with one concentration (100 mg/L or at the solubility limit) of the test substance and one untreated control (with at least six replicates per concentration or control), with an adequate initial biomass concentration expressed in cells/mL per replicate.

The test is conducted using *Lemna minor*, a freshwater macrophyte (OECD 201). Carried out as a static test over 7 days, it evaluates the vegetative growth of *L. minor*. The test is performed in containers containing 100 mL of test solution under 4000 to 4500 lux light conditions at a standard temperature of 25 °C, and at higher temperatures of 2.0 °C and 4.5 °C above this value, based on the medium and high emission scenarios. Three replicates, each containing two 3-leaf plants, are prepared for each treatment and control group. At the end of the test, the number of leaves and dry weight are measured. The concentration values (EC) causing percentage inhibition of growth rate are taken as the effect criterion.

The Daphnia toxicity test is a standard pelagic invertebrate procedure widely used in ecological risk assessment of surface waters. The acute toxicity assay is conducted in 50 mL glass beakers with five concentrations of *D.* magna neonates (24 h old) and one control group, each in duplicate, for 48 hours (10 organisms per group). The experiment is performed under a static system with a 16-hour light/8-hour dark cycle at a standard temperature of 20 °C and at two elevated temperatures, 22 °C and 24.5 °C, which correspond to 2.0 °C and 4.5 °C above the standard, respectively, based on medium and high emission scenarios. At the end of the exposure, lethal concentration (LC) and effective concentration (EC) values are calculated based on mortality and immobility as effect criteria.

The strengths and limitations of the bioassays are summarized in **Table 2**.

Table 3 provides a comparison of similar studies conducted worldwide, focusing specifically on ecotoxicological research in lake ecosystems under climate change scenarios.

In summary, these studies demonstrate that the combination of climate change-driven temperature increases and pre-existing environmental contaminants can significantly influence the ecotoxicological responses in aquatic ecosystems such as Lake Tudakul. The application of standardized bioassays—such as Microtox®, MARA, algal growth inhibition, *Lemna minor*, and *Daphnia magna* tests—provides a comprehensive approach to detect sublethal and lethal toxic effects across multiple trophic levels and biological complexity. These tools enable detection of interactive stress effects, including increased chemical toxicity at elevated temperatures, reduced organism growth, inhibited metabolic activity, and shifts in species sensitivity. Such experimental designs not only reveal ecological risks from rising global temperatures and pollutant mixtures but also validate a methodological framework for ecological risk assessment under realistic climate change scenarios. The findings emphasize the importance of integrating climate projections into ecotoxicological testing protocols and highlight the need for continued, integrative monitoring of vulnerable freshwater ecosystems amid accelerating environmental change.

Table 2. Summary of Bioassays with Corresponding Stressors and Target Organisms.

Test Method	Target Stressors	Target Organisms	Strengths	Limitations
Microtox®	Heavy metals, organics	*Aliivibrio fischeri*	Rapid, sensitive, field-applicable	Limited ecological representativeness
MARA	Broad-spectrum pollutants	11 bacteria + 1 yeast species	High microbial diversity representation	Not organism-specific for higher trophic levels
Algaltoxkit F	Nutrients, metals, toxins	*Pseudokirchneriella subcapitata*	Ecologically relevant to primary producers	Needs culture maintenance, longer test duration
Lemna minor test	Eutrophication, herbicides, metals	*Lemna minor*	Macrophyte relevance, suitable for plant toxicity	Affected by light/temperature sensitivity
Daphnia magna test	Pesticides, metals, organics	*Daphnia magna*	Widely accepted, reflects food web dynamics	Moderate temperature control required

Table 3. Ecotoxicological Risk Studies Based on Climate Change Scenarios.

Study Area	Region	Climate Scenarios	Tests	Pollutants	Key Findings
Lake Erie	ABD-Canada	RCP8.5	Phytoplankton tests, fish embryo tests	Phosphorus, pesticides	Increase in algal blooms and toxic effects with increasing temperature
Lake Geneva (Léman)	Switzerland - France	RCP4.5, RCP8.5	Mesocosm experiment, zooplankton tests	Microplastics, UV, temperature	Synergistic toxic effects detected with UV radiation
Great Slave Lake	Canada Arctic	SRES A2 (previous version of IPCC)	Metal bioconcentration analysis	Hg, Cd, Pb	Cold-adapted species are more sensitive to temperature increases
Lake Taihu	China	RCP6	Algae and fish toxicity tests	Eutrophication, pesticides	Cyanobacteria dominance and oxidative stress response of fish increase
Lake Biwa	Japan	RCP4.5	*Daphnia magna*, algae tests	Nitrogen load, metals	Climate-induced eutrophication found to put pressure on zooplankton biomass
Lake Victoria	East Africa	RCP8.5	Phytoplankton and macroinvertebrate tests	Nutrient loads from agricultural origin	Increase in temperature and nutrients, decrease in oxygen, decrease in fish population
High Mountain Lakes (Alps)	Europe	RCP4.5, UV projections	DNA damage, pigment analyses	UV, POPs, micropollutants	UV radiation increases phototoxicity; decreases diversity in plankton

4. Ecotoxicological Risks on Aquatic Organisms Under Climate Change Effects

Climate change is causing vegetation to shift upward at high altitudes, which alters soil organic matter pools and increases the input of allochthonous materials into lakes [20]. This process boosts nutrient loading through soil erosion and decomposition, raising dissolved organic carbon and nitrogen concentrations in the water [21]. Such changes can affect pH and oxygen availability, influencing the physiology and metabolic functions of aquatic organisms [22]. Rising temperatures speed up metabolic rates, benefiting thermophilic species while displacing cold-adapted taxa [23–25]. Warmer waters also increase algal metabolic activity, potentially shifting biofilm communities toward cyanobacteria dominance [26,27]. The ecophysiology of macroinvertebrates is expected to be significantly affected by rising temperatures, affecting metabolic rates, life cycle duration, and species composition [28–30]. Thermophilic species may thrive at the expense of cold-adapted taxa, leading to biodiversity loss and functional shifts in ecosystem processes such as grazing and predation [31]. Additionally, rising temperatures accelerate metabolic rates and oxygen consumption in fish [32], while amphibians may experience a mismatch between larval development timing and food availability [33]. Higher water temperatures can also promote the growth of opportunistic pathogens, such as Carnobacterium spp., increasing infectious disease outbreaks in fish populations [7]. In fact, thermal stress can weaken fish immune systems, making them more vulnerable to such pathogens [7].

Increased UV radiation damages DNA, disrupts physiological processes, and interacts with pollutants to amplify toxic effects [12,34,35]. Some species, such as high-altitude fish, have developed photoprotective adaptations, including increased melanin production [36], while zooplankton reduce UV exposure by migrating vertically [37,38]. UV-induced stress causes algal cell damage, impairing primary production [39]. Amphibians are particularly vulnerable, as UV exposure exacerbates oxidative stress and raises the incidence of developmental anomalies [39,40].

Contaminants reduce microbial diversity in biofilms, lowering primary productivity and altering nutrient cycling [41]. Zooplankton accumulate pollutants, resulting in physiological impairments [42]. Macroinvertebrates experience developmental abnormalities and reproductive disruptions [43,44]. Fish and amphibians suffer endocrine and immune dysfunctions due to pollutant exposure [7,45].

Heavy metals impair photosynthesis in algae and bioaccumulate through the food chain, affecting both invertebrates and vertebrates [41]. Eutrophication driven by nitrogen deposition promotes cyanobacterial blooms, which deplete oxygen and favor generalist species over specialists [46,47]. Fish accumulate pollutants that increase oxidative stress and susceptibility to disease [7]. Amphibians experience endocrine disruption that impairs reproduction and development [48,49].

5. Human Health Implications of Ecotoxicological Changes in Freshwaters

Although lakes are not typically viewed as direct human health risk sources, their alterations can cause significant indirect impacts. A major concern is the transport of contaminants from these ecosystems to downstream water supplies, especially where alpine waters feed drinking water sources [7]. Trace metals, POPs, and emerging contaminants accumulate in lake sediments and biota and can eventually enter broader freshwater networks [7]. The introduction of micro(nano)plastics and related toxicants further complicates risk assessments, as these pollutants can carry chemical and biological agents such as bacteria and antibiotic-resistant genes [7,50]. Climate change-driven changes in water temperature and nutrients may also encourage cyanotoxin-producing cyanobacterial blooms, increasing human health risks [51]. Recreational exposure is another concern since lakes attract hikers, anglers, and outdoor enthusiasts who may come into contact with contaminated water. Although direct human consumption of fish from these lakes may be limited, biomagnification of toxic substances within the food web underscores the importance of ongoing ecotoxicological monitoring [52].

6. Conclusions

This review emphasizes the multifaceted and interconnected effects of climate change and human activities on the ecological health of Lake Tudakul, one of Uzbekistan's most important brackish wetlands. The lake, a key reservoir of biodiversity and a crucial socio-economic asset, faces mounting threats from climate-driven factors such as rising temperatures, changes in precipitation patterns, and increased ultraviolet (UV) radiation. These environmental shifts are likely to amplify the toxicity, bioavailability, and mobility of pollutants—including heavy metals, POPs, and micro(nano)plastics—already introduced via agricultural runoff and atmospheric deposition. Climate warming scenarios modeled under RCP4.5 and RCP8.5 indicate significant ecological risks, especially when temperature rises of 2.0 **°C** to 4.5 **°C** coincide with existing chemical contamination. Such combined thermal and chemical stressors may trigger cascading impacts across multiple trophic levels, affecting microbial populations, phytoplankton, zooplankton, macroinvertebrates, and fish, and potentially disrupting food web structure and ecosystem functions.

Climate change and human activities are increasingly threatening the ecological stability of inland waters worldwide, with saline and brackish lakes especially vulnerable due to their unique hydrological and biological features. This review examines the ecological impacts of climate change on Lake Tudakul, one of Uzbekistan's largest saline lakes, by combining climate scenario modeling with standardized ecotoxicological assessment methods. Lake Tudakul, a Ramsar-listed wetland, faces both natural and human-induced stressors. The study's innovation lies in applying multiple standardized bioassays (Microtox®, MARA, algal growth inhibition, Lemna minor, and Daphnia magna) under future warming scenarios (+2.0 **°C** and +4.5 **°C**) to evaluate the combined effects of climate change and chemical pollutants on aquatic organisms. Findings highlight increased biological sensitivity to contaminants, threatening ecosystem structure and function, with serious implications for water safety, biodiversity, and regional economies. This work emphasizes the urgent need for early-warning systems and adaptive management policies to mitigate ecotoxicological risks under climate warming.

By applying various standardized ecotoxicological test systems—including Microtox®, MARA, algae growth inhibition, *Lemna minor*, and *Daphnia magna* bioassays—this study demonstrated the feasibility of quantifying interactive stressors. These tools provide a robust framework for early detection and risk assessment of toxicological threats under realistic future climate scenarios. Importantly, the research highlights the ecological vulnerability of Lake Tudakul's endemic and introduced species, many of which may lack the physiological or behavioral capacity to adapt to combined environmental pressures. The results support the hypothesis that thermophilic and opportunistic taxa could replace cold-adapted and sensitive species, resulting in biodiversity loss, biotic homogenization, and ecosystem simplification. Additionally, increased eutrophication and UV-induced photodamage may impair primary production and nutrient cycling, further destabilizing the ecosystem.

Human health implications, though indirect, are nevertheless significant. Contaminants originating from Lake Tudakul—including antibiotic-resistant pathogens associated with microplastics or toxins from cyanobacterial blooms—can be transported downstream, threatening the safety of drinking water, recreational users, and aquatic food webs. These risks underscore the importance of proactive policy responses, integrated monitoring systems, and targeted public education to protect both environmental and human well-being. Given Lake Tudakul's designation as a Ramsar site and its hydrological connection to major water systems such as the Amu Darya and Zarafshan rivers, regionally coordinated conservation efforts are urgently required to prevent cascading ecological and public health consequences.

Finally, Lake Tudakul exemplifies how climate change intersects with legacy pollution and land-use pressures in Central Asia, highlighting the need for holistic and interdisciplinary approaches in ecological monitoring. The methodology and findings presented in this study offer a valuable framework for future research and environmental management in similarly vulnerable lake systems globally. Sustained investment in ecotoxicological monitoring, adaptive ecosystem management, and cross-border collaboration will be critical to mitigating the complex and compounding threats facing saline lake ecosystems in an era of rapid climate change.

Overall, this study advances both theoretical understanding and practical application in ecotoxicology by situating localized ecological degradation—such as that observed in Lake Tudakul—within the broader context of climate change. By applying standardized bioassays under simulated warming scenarios, it provides a replicable methodological model for assessing ecological risk in similarly vulnerable aquatic systems. The findings emphasize the importance of incorporating environmental science into regional planning and water resource management, particularly in climate-sensitive regions such as Central Asia.

Author Contributions

Conceptualization, T.M., F.S., E.E.O., A.E. and N.M.N.; formal analysis, F.S., E.E.O. and A.E.; investigation, D.N. (Dilfuza Nurmanova), N.S., D.N. (Dilora Nabieva) and N.M.N.; data curation, N.M.N. and E.E.O.; writing—original draft, T.M. and F.S.; writing—review and editing, D.N. (Dilora Nabieva), N.S., F.S., E.E.O., A.E. and N.M.N.; visualization, A.E. and N.S.; supervision and project administration, F.S. and N.M.N. All authors have read and agreed to the published version of the manuscript.

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All data supporting the reported results are provided within the manuscript. Additional data can be made available upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Jackson, L.J., Lauridsen, T.L., Søndergaard, M., et al., 2007. A comparison of shallow Danish and Canadian lakes and implications for climate change. Freshwater Biology. 52(9), 1782–1792.

[2] Intergovernmental Panel on Climate Change (IPCC), 2014. Climate Change 2013 – The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge, UK.

[3] Havens, K.E., Paerl, H.W., 2015. Climate change at

a crossroad for control of harmful algal blooms. Environmental Science & Technology. 49(21), 12605–12606. DOI: https://doi.org/10.1021/acs.est.5b03990

[4] Jeppesen, E., Meerhoff, M., Davidson, T.A., et al., 2014. Climate change impacts on lakes: An integrated ecological perspective based on a multi-faceted approach, with special focus on shallow lakes. Journal of Limnology. 73, 88–111.

[5] Havens, K., Jeppesen, E., 2018. Ecological Responses of Lakes to Climate Change. Water. 10(7), 917. DOI: https://doi.org/10.3390/w10070917

[6] Kopacek, J., Brahney, J., Kana, J., et al., 2024. The concentration of organic nitrogen in mountain lakes is increasing as a result of reduced acid deposition and climate change. Science of the Total Environment. 950, 175363.

[7] Pastorino, P., Barcelo, D., Prearo, M., 2024. Alps at risk: high-mountain lakes as reservoirs of persistent and emerging contaminants. Journal of Contaminant Hydrology. 264, 104361.

[8] Borgå, K., McKinney, M.A., Routti, H., et al., 2022. The influence of global climate change on accumulation and toxicity of persistent organic pollutants and chemicals of emerging concern in Arctic food webs. Environmental Science: Processes & Impacts. 24(10), 1544–1576.

[9] Kazmi, S.S.U.H., Wang, Y.Y.L., Cai, Y.E., et al., 2022. Temperature effects in single or combined with chemicals to the aquatic organisms: an overview of thermo-chemical stress. Ecological Indicators. 143, 109354.

[10] Grunst, M.L., Grunst, A.S., Gremillet, D., et al., 2023. Combined threats of climate change and contaminant exposure through the lens of bioenergetics. Global Change Biology. 29(18), 5139–5168.

[11] Medina-Sanchez, J.M., Cabrerizo, M.J., Gonzalez-Olalla, J.M., et al., 2022. High mountain lakes as remote sensors of global change. In: Zamora, R., Oliva, M. (eds.). The Landscape of the Sierra Nevada: A Unique Laboratory of Global Processes in Spain. Springer International Publishing: Cham, Switzerland. pp. 261–278.

[12] Tartarotti, B., Sommaruga, R., Saul, N., 2022. Phenotypic and molecular responses of copepods to UV radiation stress in a clear versus a glacially turbid lake. Freshwater Biology. 67(8), 1456–1467.

[13] Khakimova, R., Mullabaev, N., Sobirov, J., et al., 2021. Ecological state of Tudakul reservoir in Uzbekistan and estimation of fish capture in last decades. E3S Web of Conferences. 258, 08029. DOI: https://doi.org/10.1051/e3sconf/202125808029

[14] Khusanov, A., Sabirov, O., Frank, Y., et al., 2025. Microplastic pollution of the Zrafshan river tributary in Samarkand and Navoi regions of the Republic of Uzbekistan. Green Analytical Chemistry. 12, 100200. DOI: https://doi.org/10.1016/j.greeac.2024.100200

[15] Barinova, S., Mamanazarova, K., 2021. Diatom Algae-Indicators of Water Quality in the Lower Zarafshan River, Uzbekistan. Water. 13(3), 358. DOI: https://doi.org/10.3390/w13030358

[16] Van Vuuren, D.P., et al., 2011. The Representative Concentration Pathways: An Overview. Climatic Change. 109(1), 5–31. DOI: https://doi.org/10.1007/s10584-011-0148-z

[17] Ünal, Y., 2023. Global Climate Projections and Climate Change In Türkiye. İklim Değişikliği ve Türkiye İklim Ölçüm Ağı. 29–48. DOI: https://doi.org/10.53478/TUBA.978-625-8352-56-6.ch02

[18] Diffenbaugh, N.S., Giorgi, F., 2012. Climate change hotspots in the CMIP5 global climate model ensemble. Climatic Change. 114(3), 813–822. DOI: https://doi.org/10.1007/s10584-012-0570-x

[19] Fai, P.B., Grant, A., 2010. An assessment of the potential of the microbial assay for risk assessment (MARA) for ecotoxicological testing. Ecotoxicology. 19(8), 1626–1633.

[20] Kuefner, W., Hofmann, A.M., Geist, J., et al., 2021. Algal community change in Mountain Lakes of the Alps reveals effects of climate warming and shifting Treelines. Journal of Phycology. 57(4), 1266–1283.

[21] Yousaf, A., Khalid, N., Aqeel, M., et al., 2021. Nitrogen dynamics in wetland systems and its impact on biodiversity. Nitrogen. 2(2), 196–217.

[22] Small, K., Kopf, R.K., Watts, R.J., et al., 2014. Hypoxia, blackwater and fish kills: experimental lethal oxygen thresholds in juvenile predatory lowland river fishes. PLoS ONE. 9(4), e94524.

[23] Cremona, F., Agasild, H., Haberman, J., et al., 2020. How warming and other stressors affect zooplankton abundance, biomass and community composition in shallow eutrophic lakes. Climate Change. 159(4), 565–580.

[24] Iskın, U., Filiz, N., Cao, Y., et al., 2020. Impact of nutrients, temperatures, and a heat wave on zooplankton community structure: an experimental approach. Water. 12(12), 3416.

[25] Wang, L., Shen, H., Wu, Z., et al., 2020. Warming affects crustacean grazing pressure on phytoplankton by altering the vertical distribution in a stratified lake. Science of the Total Environment. 734, 139195.

[26] Crenier, C., Sanchez-Thirion, K., Bec, A., et al., 2019. Interactive impacts of silver and phosphorus on auto-

trophic biofilm elemental and biochemical quality for a macroinvertebrate consumer. Frontiers in Microbiology. 10, 732.

[27] Sentenac, H., Loyau, A., Zoccarato, L., et al., 2023. Biofilm community composition is changing in remote mountain lakes with a relative increase in potentially toxigenic algae. Water Research. 245, 120547.

[28] Bonacina, L., Fasano, F., Mezzanotte, V., et al., 2023. Effects of water temperature on freshwater macroinvertebrates: a systematic review. Biological Reviews. 98(1), 191–221.

[29] Peng, K., Dong, R., Qin, B., et al., 2023. Macroinvertebrate response to internal nutrient loading increases in shallow eutrophic lakes. Biology. 12(9), 1247.

[30] Yang, P., Jiang, X., Xie, Z., et al., 2024. Eutrophication is better indicated by functional traits than taxonomic composition of macroinvertebrate assemblages in floodplain lakes. Biodiversity and Conservation. 33(14), 4257–4274.

[31] Perilli, S., Pastorino, P., Bertoli, M., et al., 2020. Changes in midge assemblages (Diptera Chironomidae) in an alpine lake from the Italian Western Alps: the role and importance of fish introduction. Hydrobiologia. 847(11), 2393–2415.

[32] Jutfelt, F., 2020. Metabolic adaptation to warm water in fish. Functional Ecology. 34(6), 1138–1141.

[33] Arrighi, J.M., Lencer, E.S., Jukar, A., et al., 2013. Daily temperature fluctuations unpredictably influence developmental rate and morphology at a critical early larval stage in a frog. BMC Ecology. 13(1), 18.

[34] Bullejos, F.J., Carrillo, P., Argaiz, M.V., et al., 2010. Roles of phosphorus and ultraviolet radiation in the strength of phytoplankton-zooplankton coupling in a Mediterranean high mountain lake. Limnology and Oceanography. 55(6), 2549–2562.

[35] Dur, G., Won, E.J., Han, J., et al., 2021. An individual-based model for evaluating post-exposure effects of UV-B radiation on zooplankton reproduction. Ecological Modelling. 441, 109379.

[36] Gu, H., Li, S., Wang, H., et al., 2022. Interspecific differences and ecological correlations of ultraviolet radiation tolerance in low- and high-altitude fishes. Frontiers in Marine Science. 9, 1035140.

[37] Fernandez, C.E., Campero, M., Bianco, G., et al., 2020. Local adaptation to UV radiation in zooplankton: a behavioral and physiological approach. Ecosphere. 11(4), e03081.

[38] Bandara, K., Varpe, Ø., Wijewardene, L., et al., 2021. Two hundred years of zooplankton vertical migration research. Biological Reviews. 96(4), 1547–1589.

[39] Alton, L.A., Franklin, C.E., 2017. Drivers of amphibian declines: effects of ultraviolet radiation and interactions with other environmental factors. Climate Change Responses. 4(1), 6.

[40] Franco-Belussi, L., Fanali, L.Z., De Oliveira, C., 2018. UV-B affects the immune system and promotes nuclear abnormalities in pigmented and non-pigmented bullfrog tadpoles. Journal of Photochemistry and Photobiology B: Biology. 180, 109–117.

[41] Qiu, Y.W., Zeng, E.Y., Qiu, H., et al., 2017. Bioconcentration of polybrominated diphenyl ethers and organochlorine pesticides in algae is an important contaminant route to higher trophic levels. Science of the Total Environment. 579, 1885–1893.

[42] Miner, K.R., Blais, J., Bogdal, C., et al., 2017. Legacy organochlorine pollutants in glacial watersheds: a review. Environmental Science: Processes & Impacts. 19(12), 1474–1483.

[43] O'Donnell, J.A., Carey, M.P., Koch, J.C., et al., 2024. Metal mobilization from thawing permafrost to aquatic ecosystems is driving rusting of Arctic streams. Communications Earth & Environment. 5(1), 268.

[44] Yun, X., Lewis, A.J., Stevens-King, G., et al., 2023. Bioaccumulation of per- and polyfluoroalkyl substances by freshwater benthic macroinvertebrates: impact of species and sediment organic carbon content. Science of the Total Environment. 866, 161208.

[45] Hossack, B.R., Davenport, J.M., Mattison, C.K., et al., 2025. Methylmercury in subarctic amphibians: environmental gradients, bioaccumulation, and estimated flux. Environmental Toxicology and Chemistry. 44(3), 698–709.

[46] Ho, J.C., Michalak, A.M., 2020. Exploring temperature and precipitation impacts on harmful algal blooms across continental US lakes. Limnology and Oceanography. 65(5), 992–1009.

[47] Reinl, K.L., Brookes, J.D., Carey, C.C., et al., 2021. Cyanobacterial blooms in oligotrophic lakes: shifting the high-nutrient paradigm. Freshwater Biology. 66(9), 1846–1859.

[48] Burgos-Aceves, M.A., Faggio, C., Betancourt-Lozano, M., et al., 2022. Ecotoxicological perspectives of microplastic pollution in amphibians. Journal of Toxicology and Environmental Health, Part B. 25(8), 405–421.

[49] Burgos-Aceves, M.A., Ilizaliturri-Hernández, C.A., Faggio, C., 2024. Fate and transportation of pharmaceutical residues and PPCPs in the aquatic system: physiological effects and hazards. In: Garg, V. K., Pandey, A., Kataria, N., et al. (eds.). Pharmaceuticals in Aquatic Environments. CRC Press: Boca Raton, Florida, USA. pp. 31–52.

[50] Tumwesigye, E., Nnadozie, C.F., Akamagwuna, F.C., et al., 2023. Microplastics as vectors of chemical contaminants and biological agents in freshwater ecosystems: current knowledge status and future perspectives. Environmental Pollution. 330, 121829.

[51] Mez, K., Hanselmann, K., Preisig, H.R., 1998. Environmental conditions in high mountain lakes containing toxic benthic cyanobacteria. Hydrobiologia. 368(1), 1–15.

[52] Daly, G.L., Wania, F., 2005. Organic contaminants in mountains. Environmental Science & Technology. 39(2), 385–398.