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REVIEW

Interactive Effects of Climate Change and Contaminants in Aquatic Ecosystems on Environmental-Human Health

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Abstract

Purpose of the Review Climate change is intensifying the pressures on aquatic ecosystems by altering the dynamics of contaminants, with cascading effects on ecological and human health. This review synthesizes recent evidence on how rising temperatures, altered precipitation patterns, and extreme weather events influence chemical and microbial contaminant dynamics in aquatic environments.

Recent Findings Key findings reveal that elevated temperatures enhance phosphorus pollution and algal blooms, increase heavy metal release from sediments, and promote the mobilization of organic pollutants. Concurrently, climate change exacerbates microbial contamination by facilitating the spread of waterborne microbial contaminants, especially posing more pressure to antimicrobial resistance-related contaminants through temperature-driven horizontal gene transfer and extreme precipitation events. Complex interactions between chemical and microbial contaminants like heavy metals co-selecting for antibiotic resistance further amplify risks. The compounded effects of climate change and contaminants threaten water quality, ecosystem resilience, and public health, particularly through increased toxicant exposure via seafood and waterborne disease outbreaks. Despite growing recognition of these interactions, critical gaps remain in understanding their synergistic mechanisms, especially in data-scarce regions.

Summary This review highlights the urgent need for integrated monitoring, predictive modeling, and adaptive policies under a One Health framework to mitigate the multifaceted impacts of climate-driven contamination. Future research should prioritize real-world assessments of temperature effects, urban overflow dynamics during extreme weather, and the socio-behavioral dimensions of contaminant spread to inform effective mitigation strategies.

Keywords Climate change · Aquatic ecosystems · Chemical contaminants · Microbial contaminants · Ecosystem resilience

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Introduction

Aquatic ecosystems are vital and vulnerable components of the Earth, providing crucial ecological services, such as water resources, carbon sequestration, and habitat for biodiversity [1]. The aquatic ecosystems mainly include riverine, lake, and marine ecosystems. However, the aquatic ecosystems are increasingly threatened by the dual pressures of climate change and environmental contamination [2]. Climate change, driven by anthropogenic activities, alters the physiochemical properties of aquatic environments [3], while environmental contaminants, ranging from chemical and microbial contaminants, exacerbate the stress on the aquatic environment [3]. The interplay between these two stressors is emerging as a critical area of research, as their combined effects can lead to enhanced bioaccumulation and toxicity,

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with far-reaching consequences for ecosystem health and human well-being [4].

Climate change manifests in aquatic ecosystems through rising temperatures, water acidification, and an increase in the frequency and intensity of extreme weather events [5]. Global surface temperatures are projected to increase by 1.5 °C to 4.5 °C by the end of the century if no actionable interventions are implemented [6]. Global warming is particularly pronounced in aquatic systems, where it disrupts thermal stratification, alters species distributions, and accelerates metabolic rates in organisms [7]. Concurrently, ocean acidification, driven by the absorption of atmospheric CO_2, is reducing pH levels and affecting the solubility and bioavailability of chemical contaminants [8]. Extreme weather events, such as hurricanes, floods, and droughts, further compound these effects by mobilizing contaminants and altering hydrological regimes [9].

Contaminants, on the other hand, introduce additional pressures on aquatic ecosystems. Chemical contaminants, including heavy metals, pesticides, and pharmaceuticals, are pervasive in aquatic environments due to agricultural runoff, industrial discharges, and urban wastewater [10]. After entering the aquatic environment, persistent chemical contaminants may be bioaccumulated through food webs, leading to toxic effects at higher trophic levels [11]. Microbial contaminants, such as pathogenic bacteria and antimicrobial resistance genes, pose additional risks by compromising ecological and human health [12]. The spread of antimicrobial resistance, in particular, is a growing concern, as it undermines the effectiveness of antibiotics and complicates the management of infectious diseases under the One Health framework [13].

The interaction between climate change and contaminants in the aquatic environments is complex and multifaceted [14]. Climate change can influence the fate, transport, and toxicity of contaminants [15], while the presence of contaminants in the aquatic environment can modulate the resilience of ecosystems to climatic stressors. For example, rising temperatures can increase the solubility and bioavailability of chemical contaminants, enhancing their accumulation in the food web [16]. Similarly, pH changes in ocean acidification can affect the speciation of heavy metals and the adsorption of organic pollutants onto microplastics, potentially increasing their toxicity [17]. At the same time, contaminants can exacerbate the effects of climate change by impairing the physiological and reproductive capacities of organisms, reducing their ability to cope with thermal stress or acidification.

Despite the growing recognition of these interactions, significant gaps remain in our understanding of their ecological and human health implications. Most studies to date have focused on the individual effects of climate change or contaminants, with limited attention to their synergistic or antagonistic interactions. This review seeks to address this gap by synthesizing recent literature on the interactive effects of climate change and contaminants in aquatic ecosystems, with a focus on bioaccumulation and toxicity. The review was organized according to Fig. 1. By integrating findings from the past 5 years, this review aims to (1) evaluate climate-driven changes in chemical contaminant dynamics, (2) assess climate-microbial contaminant interactions, and (3) discuss integrated implications for ecosystems and human health.

Climate Change on Environmental Chemical Contaminants

Climate change is significantly altering the dynamics of chemical contaminants in aquatic ecosystems, with profound implications for water quality and ecological health. Elevated temperatures and altered precipitation patterns influence phosphorus pollution and exacerbate algal blooms, while higher temperatures can enhance the release of heavy metals from sediments. Additionally, extreme weather events, such as intense storms and floods, promote the mobilization of organic pollutants into water bodies. These interconnected processes underscore the growing threat of climate-driven contamination in aquatic systems. A summary of the impacts of climate change on chemical pollutants, including their pathways and ecological consequences, is presented in Table 1 and Fig. 2.

Temperature and Precipitation on Phosphorus Pollution and Algal Bloom

Hydrological changes caused by climate change may release more nutrients from land into the aquatic environments [18, 19], leading to intensifying potential algal blooms [20]. Zhi et al. [21] used deep learning to reconstruct phosphorus (P) trends in 430 US rivers (1980–2019), revealing widespread declines in concentrations but an overall increase in P loss due to rising river discharge, highlighting challenges in controlling agricultural non-point sources and climate-driven hydrological changes. Hou et al. [22] deployed 2.91 million Landsat images (1982–2019) to create a global algal bloom database, revealing blooms in 21,878 lakes (8.8%) worldwide, with increasing frequency, especially in Asia and Africa, highlighting the growing threat to water quality under the changing climatic environment and increasing nutrient loading from land to the surface water. In addition to the freshwater system, Dai et al. [23] mapped daily coastal algal blooms (2003–2020) using global satellite data, revealing a significant global increase in bloom extent (+13.2%)

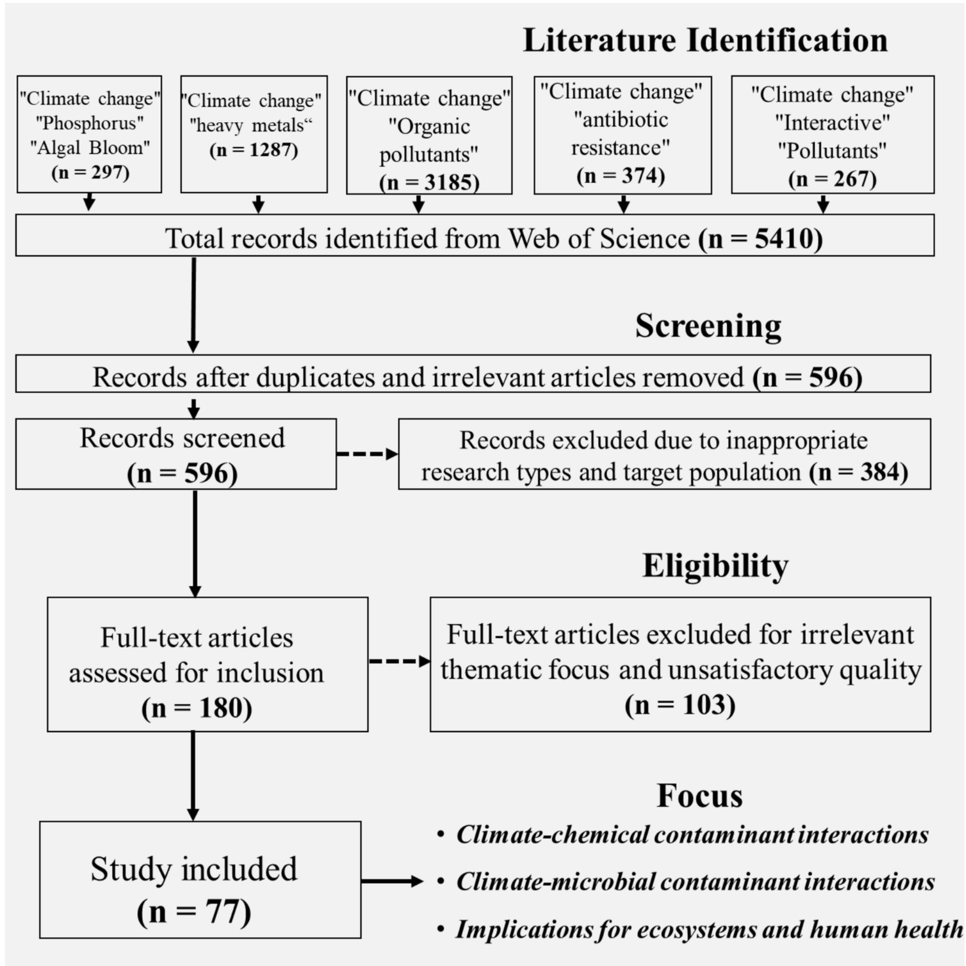

Fig. 1 Flowchart of literature search and analysis methodology

and frequency (+59.2%), driven by ocean circulation and rising sea surface temperatures, with implications for fisheries and ecosystem management.

High Temperature Increasing Heavy Metal Release

The mobility and toxicity of heavy metals in aquatic ecosystems are significantly affected by climate change [24, 25]. Zhao et al. [26] examined how pH, temperature, and salinity influence Cu and Zn fractions in Lake sediments using control experiments. They found lower pH and higher temperature and salinity can increase heavy metal release under future climate change environments, with varying effects on metal speciation which may increase the uptake of heavy metals to higher trophic levels. Mok et al. [27] used macroanalysis of 7922 studies (1979–2021) to examine the link between climate change and heavy metal pollution in coastal regions. Their analysis highlights an increasing research focus on heavy metal contamination, ecological quality, and ocean acidification under a climate change environment. Compared the lab-based findings and large-scale field observations, laboratory studies often isolate individual drivers (e.g., pH or temperature), while real-world systems are shaped by complex, interacting stressors such as fluctuating redox conditions, hydrological variability, and biological processes. Macro-scale analyses, on the other hand, offer broad patterns but lack the resolution to capture process-level dynamics. Recently, Zitoun et al. [28] reviewed and discussed how climate change and human activities alter trace element cycling in coastal systems, emphasizing the need for more data, especially in the Global South, to address challenges in modeling and understanding multi-stressor effects. They identified significant uncertainties in how combined effects of climate events (e.g., heatwaves and storms) and anthropogenic activities (e.g., land-use change and pollution) modulate metal fluxes and toxicity. Despite general agreement that warming and acidification increase metal mobility, inconsistencies remain regarding the dominant drivers and their interactions across different ecosystems. In addition, the long-term impacts of climate-induced changes in metal speciation on trophic transfer and ecosystem health are poorly understood. Addressing these knowledge gaps requires integrated research approaches that combine

Table 1 Impact of climate change on environmental chemical contaminants

Subtype	Study type	Geographic Scope	Climate driver	Key findings	Ref
Phosphorus	Modeling (deep learning)	430 US rivers (1980–2019)	Climate-driven hydrological changes	Widespread declines in concentrations but an overall increase in phosphorus loss due to rising river discharge	[21]
Algal bloom	Landsat images	A global algal bloom database from 2.91 million Landsat images (1982–2019)	Changing climatic environment and increasing nutrient loading	Revealing algal blooms in 21,878 lakes (8.8%) worldwide, with increasing frequency, especially in Asia and Africa	[22]
Algal bloom	Global satellite data	Mapped daily coastal algal blooms (2003–2020)	Rising sea surface temperatures	A significant global increase in bloom extent (+13.2%) and frequency (+59.2%)	[23]
Heavy metals	Field scale	Global coastal systems	Diverse factors	Climate events are releasing more contaminants and makes metals in the ocean more toxic	[28]
POPs	Field scale	Urban stormwater runoff	Extreme stormwater	Persistent chemicals and pharmaceuticals flux despite regulatory bans	[30]
Atrazine, caffeine, triclocarban, and seven antibiotics	Field scale	Mid-Atlantic region of the USA	High precipitation and temperature	Heavy rainfall and higher temperatures generally increased the detection and concentration of contaminants, with long-term high temperatures potentially leading to degradation of these compounds	[31]

laboratory experiments, long-term field monitoring, and predictive modeling. The development of global water and Earth system models offers a promising avenue to simulate metal transport and transformation under future climate scenarios and to explore potential feedback mechanisms across spatial and temporal scales.

Extreme Weather Promoting Organic Pollution

Climate change also plays a crucial role in the environmental fate and toxicity of organic contaminants, including antibiotics, persistent organic pollutants (POPs), pesticides, and pharmaceuticals and personal care products (PPCPs). Changes in hydrological patterns causing extreme weather, such as intensified rainfall and storm surges, increase the mobilization of organic contaminants from terrestrial sources to aquatic ecosystems [29]. Breedveld et al. [30] studied the impact of urbanization and extreme weather events on contaminant runoff in an urban river, revealing episodic contaminant fluxes to the inner Oslo fjord, with a notable decrease in polycyclic aromatic hydrocarbons levels since the 1980 s and persistent chemicals and pharmaceuticals flux despite regulatory bans. Zhu et al. [31] investigated the impact of extreme weather events, particularly high precipitation and temperature, on the distribution of emerging contaminants in surface waters from the Mid-Atlantic region, finding that heavy rainfall and higher temperatures generally increased the detection and concentration of contaminants, with long-term high temperatures potentially leading to degradation of these compounds.

It should be noted that climate change affects both environmental processes in the aquatic systems and the fate of contaminants. Heavy stormwater and extreme weather events have significant impacts on the water cycle and contaminant dynamics in aquatic ecosystems. First, climate change alters hydrological processes, leading to increased inputs of onshore pollutants (such as first flush and combined sewer overflows) into aquatic systems [32]. Additionally, the redistribution and transformation of pollutants can occur during wet-dry transition events [33]. Second, the biogeochemical behavior of contaminants in aquatic environments is influenced by climate change. For example, the adsorption and desorption of pollutants can be affected by hydrodynamic conditions, thereby enhancing their mobility. Moreover,

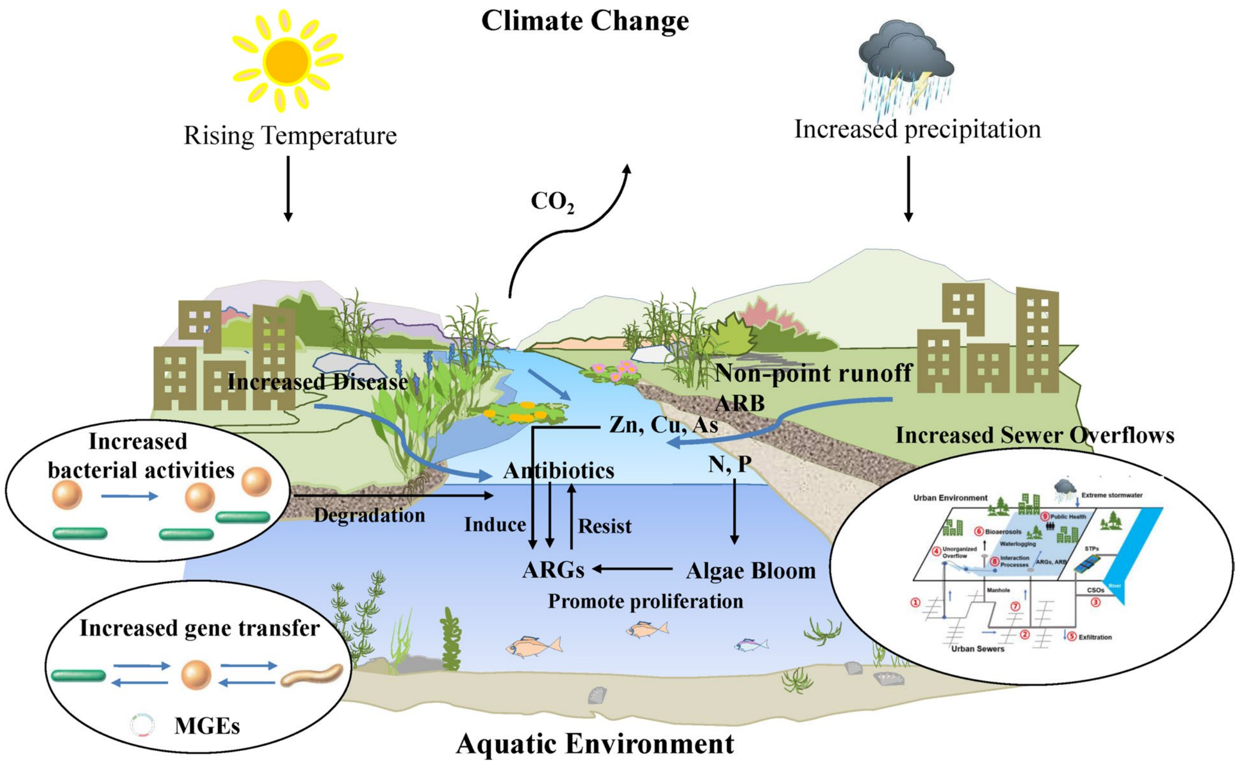

Fig. 2 Illustration of compound effects between climate change and contaminants in the aquatic ecosystems

intense stormwater events may resuspend sediments in river or lake systems, significantly altering sedimentation–resuspension dynamics and the sediment–water interface [34]. The extent to which contaminants are mobilized depends strongly on compound-specific properties and environmental thresholds. For example, compounds with low octanol–water partition coefficients (K_{ow}) and high solubility tend to remain in dissolved form and are easily mobilized during high-flow events [35]. In contrast, hydrophobic contaminants with higher K_{ow} values, like PAHs and some pesticides, are more likely to sorb particles and be transported through sediment-bound processes [36]. Sorption–desorption dynamics are further modulated by temperature, pH, and sediment characteristics, all of which are sensitive to climate change. These findings highlight the need to move beyond descriptive accounts and adopt a mechanistic understanding of contaminant fate under climate change. Future research should focus on linking hydrological thresholds and regional conditions with contaminant-specific behaviors, using predictive tools that integrate partitioning theory, degradation kinetics, and multi-compartment modeling frameworks.

Climate Change on Environmental Microbial Contaminants

Climate change also influences microbial contaminant dynamics, affecting the survival, distribution, and virulence of pathogenic microorganisms. Elevated temperatures have been linked to the increased prevalence of waterborne diseases caused by bacteria such as *Vibrio cholerae*, which thrive in warmer marine environments. Rising temperatures also enhance the survival and persistence of fecal indicator bacteria such as *Enterococcus* and *Escherichia coli*, raising concerns about water quality and human health risks. Extreme weather events, including floods and hurricanes, exacerbate microbial contamination by increasing the transport of pathogens from terrestrial sources to aquatic environments. Heavy rainfall can overwhelm wastewater treatment systems, as has been observed recently in the global climate change, leading to the discharge of untreated sewage into water bodies [37]. This could enhance the spread of antibiotic-resistant bacteria and other microbial pathogens, heightening the risk of disease outbreaks. Ocean acidification, another consequence of climate change, may also affect microbial communities by altering competition dynamics and pathogen virulence.

These interactions are synthesized in Fig. 2, which illustrates two major climate-driven feedback loops. In the rising

Table 2 Impact of climate change on environmental microbial contaminants

Subtype	Study type	Geographic scope	Climate driver	Key findings	Ref
ARGs, pathogens	Field scale	USA	Temperature rising	A 10 °C temperature increase was associated with 4.2%, 2.7%, and 2.2% antibiotic resistance increase for the human pathogenic bacteria (HPB) of *Escherichia coli*, *Staphylococcus aureus*, and *Klebsiella pneumoniae*	[37]
ARGs, pathogens	Field scale	28 provinces/regions of China (2005–2019)	Temperature rising	A 1 °C increase in ambient temperature can contribute to 1.14- and 1.06-fold increase in carbapenem-resistant *K. pneumoniae* (CRKP) and *Pseudomonas aeruginosa* (CRPA) prevalence, respectively	[38]
ARGs	Field scale	28 European countries (2000–2016)	Temperature rising	A 10 °C warm ambient temperature experienced more rapid antibiotic resistance increases for all antibiotic classes	[39]
ARGs, pathogens	Field scale	USA	Extreme stormwater	Pathogenic indicator bacteria and ARGs were elevated in indoors	[52]
Algal bloom and ARGs	Field scale	Four eutrophicated lakes in China	Interactive effects	When aquatic temperature increasing from 16 to 36 °C, cyanobacteria-associated antibiotic resistance increased 3–295 folds	[42]

temperature loop, increased temperatures accelerate microbial metabolism and environmental degradation, enhancing the release of heavy metals (e.g., Zn, Cu, and As) and residual antibiotics. This promotes algal blooms, microbial proliferation, and the spread of antibiotic resistance. In parallel, the increased precipitation loop highlights how storm-driven runoff and sewer overflows mobilize contaminants and nutrients, further triggering eutrophication and pathogen growth. Both loops reinforce each other and are amplified by mobile genetic elements (MGEs) which facilitate the horizontal transfer of antibiotic resistance genes across microbial populations in aquatic systems. The interplay between climate change and microbial contaminants, particularly antimicrobial resistance (AMR) and pathogens, is a critical area of concern. Antimicrobial resistance is a kind of trait when microorganisms (such as bacteria, viruses, fungi, and parasites) evolve to resist the effects of antimicrobial drugs (like antibiotics, antivirals, and antifungals) that were originally effective against them [38]. The bioactive pollutants, such as antibiotic resistance genes (ARGs) and antibiotic-resistant bacteria (ARB), pose potential risks to public health [12, 39]. While AMR and climate change have been considered two major threats to human society. Moreover, they exhibit interactive links revealed by recent publications. Compound effects of climate and AMR may make the situation worse, as discussed below [40–42].

Increased Temperature Stimulating Horizontal Transfer of ARGs

One of the direct consequences of climate change is rising temperatures, which is the most concerned factor addressed by researchers regarding the topic of links between climate change and antibiotic resistance. It is evident that increasing temperature can lead to the increased transfer and dissemination of ARGs (Table 2) [43–46]. A 10 °C temperature increase was associated with 4.2%, 2.7%, and 2.2% antibiotic resistance increase for the human pathogenic bacteria (HPB) of *Escherichia coli*, *Staphylococcus aureus*, and *Klebsiella pneumoniae* across the USA [43]. A survey in 28 provinces/regions of China over the period from 2005 to 2019 indicated that a 1 °C increase in ambient temperature can contribute to a 1.14- and 1.06-fold increase in carbapenem-resistant *K. pneumoniae* (CRKP) and *Pseudomonas aeruginosa* (CRPA) prevalence, respectively [44]. Across 28 European countries, evidence of a long-term (over 17 years (2000–2016)) effect of temperature on ARG rate increase was found in over 4 million tested isolates [45]. A 10 °C warm ambient temperature experienced more rapid antibiotic resistance increases for all antibiotic classes. Ambient temperature may significantly impact the growth rates of ARB and help explain geographic variations [45]. When aquatic temperature increased from 16 to 36 °C, cyanobacteria-associated antibiotic resistance increased 3–295 folds [47]. These findings highlight that temperature increases stimulate the spreading of AMR.

The potential mechanisms, such as stimulation of horizontal gene transfer (HGT), stress induced by heat shock response, and regulation of microbial communities, can be involved in these phenomena. Numerous previous studies have demonstrated that horizontal transfer frequencies of ARGs are increased along with temperature-increasing [41, 48]. First of all, HGT is achieved via mobile genetic elements (MGEs), while emerging MGEs, vectors of resistance genes, are originated from central latitudes [49]. For instance, the transfer of conjugative IncP-1 Plasmid *pKJK5* to wild *Escherichia coli* strains was increased from the temperature of 9 to 25 °C [48]. Temperature can promote bacterial acquisition of extracellular agents.

As one of the environmental stresses, temperature triggers heat shock response in bacteria and exhibits potentially similar physiological effects of antibiotics [41, 50]. It has been demonstrated that temperature induces and selects for mutations of ARGs. Cellular response to temperature stress may share the same functions (such as protection and DNA repairment) with cellular response to antibiotics. As a result, mutations that resist temperature stress can also grant resistance to antibiotics, and the reverse is true. For example, over hundreds of generations culture of *E. coli* under high-temperature stress (42 °C), 12 out of 115 experimental strains developed rifampicin resistance genes, even though the bacteria were never exposed to any antibiotics in the experiments [51]. This might be attributed to temperature and rifampicin targeting the same selection site (RNA polymerase) which transcribes DNA into RNA and regulates gene expression. Mutations in the RNA polymerase active site altered gene expression in a way that was beneficial under high-temperature stress [41, 51]. Temperature may accelerate adaptive evolution by promoting mutagenesis and generating a greater supply of mutations. Moreover, higher temperatures may drive the selection for enhanced biofilm formation, resulting in enhancement of tolerance to antibiotics [41].

Rising temperatures have already impacted and will continue to influence the range, distribution, and community composition, as well as the physiological and ecosystem functions of microorganisms, and indirectly affect the dynamics of antibiotic resistance in the environment. For instance, an experiment of soil antibiotic resistance in plantation and natural forest ecosystems over a 5-year simulated climate warming showed that 15 ARGs (including aminoglycoside, beta-lactam, multidrug, sulfonamide, and tetracycline) were significantly enriched in the warm group, which is mainly ascribed to community compositions of bacteria, fungi, and protists [52].

Temperature is also related to a natural freeze–thaw cycle (FTC), commonly occurring in terrestrial ecosystems of high-latitude environments. However, their frequency has increased due to global climate change. Recent evidence demonstrated that FTC enhanced by climate change also facilitates antibiotic resistance dissemination [53]. Notably, rising temperature can significantly change hydrological process in cryosphere and permafrost. The runoff formed by freeze brings ARGs and bacteria into nearby aquatic systems. This input source can be frequently occurred under global climate change. Over 50% of resistance genes were enriched after FTC treatment [53]. This finding highlights the need for temperature-related phenomena.

Precipitation Driving AMR Spreading

Global climate change can cause the increasing frequency of stormwater and extreme weather events [40], contributing to spreading AMR broadly across the environment. High precipitation rates and extreme stormwater enhance the flush effects of agricultural and urban surfaces, driving pollutants into rivers and lakes. Previous studies have verified that stormwater runoff promotes the dissemination of antibiotic resistance [54]. Mechanistically, the transport of AMR contaminants involves surface wash-off, soil erosion, and saturation-excess runoff, particularly during intense storms or prolonged rainfall. Infiltration processes in soil–water interactions may temporarily retain ARGs in the vadose zone, but during heavy precipitation events, saturation and preferential flow can accelerate their transport to groundwater or facilitate lateral movement into surface waters [55]. In agricultural soils, especially those receiving manure or biosolids, rainfall can dislodge bound ARGs and promote their release into drainage networks [56]. Similarly, urban impervious surfaces lack this buffering capacity, rapidly channeling contaminants into storm drains [57]. Moreover, urban sewers, one of the hotspots and reservoirs of ARGs [58], can drive the expansion of ARGs via CSOs [32, 59]. Because CSOs occur much more frequently under heavy stormwater. The CSOs can dramatically bring bioactive pollutants onto the ground and promote the spreading of AMR at the urban scale, even posing direct exposure to the public. Moreover, extreme stormwater events can cause urban flooding and waterlogging, and the interaction between CSOs and flooding may drive the migration of ARGs and ARBs over a long distance. A survey regarding AMR after a hurricane in the USA indicated that pathogenic indicator bacteria and ARGs were elevated indoors [60]. To better understand these processes, future studies should integrate fate and transport modeling to quantify ARG fluxes under varying hydrological scenarios and land use conditions.

Controversial Effects of Elevated CO_2 on ARGs

Elevated CO_2 is the primary contributor to global climate change while it also shows stimulating effects for antibiotic resistance dissemination, as revealed by recent literature [61–63]. Higher CO_2 concentrations may affect membrane permeability, intracellular leakage, carbon transfer efficiency, and biofilm formation, potentially influencing the horizontal transfer of resistance genes [61]. In a survey related to Hg-contaminated soil, the relative abundances of targeted ARGs and pathogens were increased under the pressure of elevated CO_2 level [61]. However, controversial effects of elevated CO_2 have also been observed. For example, increased CO_2 levels reduced the spread of aminoglycoside and vancomycin resistance genes in sulfadiazine-contaminated soil [64].

The contradictory findings related to the effects of CO_2 on ARG dynamics depend on multiple factors, including CO_2 concentration, bacterial species, and environmental conditions. Low CO_2 can stimulate bacteria growth, increasing gene transfer. However, high CO_2 disrupts bacterial metabolisms, reducing conjugation efficiency [65]. Additionally, bacteria exhibit species-specific responses. For example, *P. aeruginosa* may increase biofilm formation and ARG transfer under the stress of CO_2 [61] while other microorganisms may reduce biofilm and transduction of resistance genes. Environmental factors, such as pH value, exhibit contradictory effects on gene transfer under the pressure of CO_2 [65]. The effects of elevated CO_2 level on the dissemination of ARGs in the environment need more research efforts and take complex environmental factors into account.

Implications for Ecosystems and Human Health

Interactive Between Chemical and Microbial Contaminants Under Climate Change

Climate change drives many more chemical and microbial contaminants into the aquatic systems, resulting in the deterioration of water quality and threats to human beings. While the compound effects between these two kinds of contaminants can make the situation much more complicated. High concentration levels of both heavy metals and antibiotics in the aquatic systems can stimulate and co-select ARGs [66, 67]. Heavy metals like Cu, Zn, and As are commonly detected in water and sediments. Prolonged exposure to these metals can select for multidrug-resistant (MDR) bacteria, such as *Klebsiella pneumoniae* and *Acinetobacter baumannii* [66, 67]. Under climate change, heavy metal and antibiotic pollution in rivers, lakes, and sediments is linked to increased ARG abundance. In addition, PPCPs in water can also stimulate the proliferation of resistance genes [68]. Moreover, compound effects between algal bloom and antibiotic resistance have been observed recently [47]. A field survey conducted in four eutrophic lakes in China revealed that 62% of the 528 tested antibiotic combinations exhibited antagonistic interactions, which were highly conserved across cyanobacterial species. These findings suggest that complex interactive links between different types of contaminants can be caused by global climate change.

Implications for Ecosystems and Human Health

The implications of climate change and the presence of contaminant mixtures on human health are significant and concerning. One major issue is the increased exposure to toxicants through the consumption of seafood. Many aquatic species, particularly those of commercial value such as fish and shellfish, accumulate various contaminants, including heavy metals and persistent organic contaminants [69]. Chronic exposure to these contaminants can result in long-term health conditions such as neurological disorders, cancers, and reproductive complications, with vulnerable groups, including pregnant women, infants, and immunocompromised individuals, being especially at risk [70]. Additionally, climate-induced changes in ocean temperature, salinity, and acidity can influence the bioaccumulation and biomagnification of toxic substances within marine organisms, further heightening the risks to human health [11].

Another pressing concern is the elevated risk of waterborne disease outbreaks under changing climatic environment [12]. Climate change can increase the occurring rates of epidemic disease. Climate-induced changes can contaminate water sources, facilitating the spread of pathogens like *Vibrio cholerae*, the causative agent of cholera. Additionally, warmer temperatures can promote the proliferation of foodborne pathogens and antibiotic-resistant pathogens [71]. The relative abundance of supercarriers including human pathogens with multiple ARGs and virulence factors can be increased by soil warming [72]. Notably, the AMR surveillances across USA, China, and European countries indicated that antibiotic-resistant pathogens were more prevalent along with temperature increase (Table 2). These pathogens include CRKP and CRPA, both of which are listed as critical priority pathogens by the World Health Organization (WHO). The alarming fact that climate change promotes the prevalence of critical pathogens poses a serious public health risk. In addition, increasing epidemic disease leads to more consumable of antibiotics and indirectly results the dissemination of AMR [73, 74]. These interconnected dynamics highlight the need for a One Health approach, which recognizes the interdependence of environmental, animal, and human health. For example, ARGs originating from livestock or aquaculture may enter aquatic ecosystems via runoff or wastewater discharge, where they are further propagated under warmer, nutrient-rich conditions [75]. These resistant genes can then re-enter human populations through water, food, or direct contact, creating a transboundary health threat [76]. Wildlife may serve as both reservoirs and amplifiers of resistant pathogens, linking ecosystems and public health outcomes more tightly than ever before [77].

The interplay between climate change, contaminants, and ecosystems presents a multifaceted issue with far-reaching consequences for both environmental and human health. Addressing these challenges calls for a paradigm shift in environmental management and policy development. To safeguard ecosystems and human populations, there is an urgent need for adaptive and integrated strategies, for example leveraging real-time monitoring, predictive modeling, and early warning systems to address the multifaceted risks posed by climate change and complex contaminant mixtures. By prioritizing research, improving monitoring capacities, and developing flexible regulatory frameworks, we can better prepare for the uncertainties of a rapidly changing world.

Conclusions

Climate change can contribute many more contaminants into the aquatic ecosystems and increase the algal bloom frequency and dissemination level of antibiotic resistance. Multiple factors related to temperature, precipitation, epidemic, and CO_2 contribute to this phenomenon, and interactions among them may also exist. The increased species and concentrations of chemical contaminants may exert selective pressure on aquatic microorganisms and promote the transfer of microbial contaminants (such as ARGs). Moreover, the compounding effects of climate change and contaminants may cause the two serious issues much worse. Increased temperature and frequencies of extreme weather can accelerate the horizontal transfer of ARGs to human pathogenic bacteria, posing severe health issues to human beings over the globe. Integrative environmental management and policy development are urgently needed to tackle the compounding effects.

Future Prospects

Future prospects regarding links between climate change and contaminants on environment-human health can be listed as follows:

(1) One Health surveillance in data-scarce regions: A major research gap exists in low- and middle-income countries, which are disproportionately vulnerable to climate-driven contaminant risks but underrepresented in data. Establishing integrated One Health surveillance systems linking environmental, animal, and human health monitoring is vital. Leveraging remote sensing, machine learning, and portable diagnostic tools will help capture real-time changes in contaminant dynamics and improve early warning systems.

(2) Real-world assessment of temperature impacts: Temperature is the primary factor that attracts the most attention from researchers. However, recent studies focused on temperature conditions in lab conditions. Future studies should better profile the effects of temperature rise at environmental conditions under climate change. Complex links between temperature and antibiotic resistance should be comprehensively considered.

(3) Extreme weather events induced overflows in urban water systems: One of the most alarming issues is that climate change induces more extreme events and CSOs. However, the interaction between sewer overflows and urban waterlogging or flooding is generally neglected. Much more efforts are needed to profile the source-flow-sink process of ARGs and ARB in urban sewer systems and interaction dynamics between CSOs as well as unorganized overflows (such as manhole overflows) and waterlogging. Establishing precise models to predict the fate of ARGs and ARB during and after waterlogging to protect the public from resistant pathogens exposure.

(4) Climate-Influenced toxicity and bioaccumulation: Future research should focus on enhancing our understanding of how climate change affects the distribution, toxicity, and bioaccumulation of contaminants across different ecosystems. Additionally, the development of innovative monitoring techniques and more sensitive detection methods will be critical for reducing both human and environmental exposure to toxicants.

(5) Integrating behavioral and societal changes: Climate change may also change behavioral and social aspects across humans and animals, thus indirectly affects the dynamics of both chemical and microbial pollutants [43]. In the future, attention should be paid to the behavioral and social changes of humans and animals, and the fundamental mechanism of their effects on the fate of chemical and microbial pollutants.

Author Contribution K.Y., S.M., and X.T. prepared the first draft of the manuscript. Y.C. and P.J. validated the data and literature review. All authors reviewed and edited the content, contributing to refining the manuscript. X.T. supervised the writing and conceptualization of the study.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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