



**REVIEW**

# Climate Change and Aquatic Phytoremediation of Contaminants: Exploring the Future of Contaminant Removal

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## ABSTRACT

Climate change, driven by anthropogenic activities, profoundly impacts ecosystems worldwide, particularly aquatic environments. This review explores the multifaceted effects of climate change on the phytoremediation capabilities of aquatic plants, focusing on the physiological responses to key environmental factors such as temperature, carbon dioxide (CO<sub>2</sub>) and ozone (O<sub>3</sub>) levels, pH, salinity, and light intensity. As global temperatures rise, moderate increases can enhance photosynthesis and biomass production, boosting the plants' ability to absorb and detoxify contaminants, such as metals, pharmaceuticals, and nutrients. However, extreme temperatures and salinity levels impose stress, disrupting metabolic processes and reducing phytoremediation efficiency. Elevated CO<sub>2</sub> levels generally stimulate growth and nutrient uptake, enhancing phytoremediation, but can also lead to nutrient imbalances and water acidification, complicating these benefits. Conversely, increased O<sub>3</sub> levels cause oxidative stress, damaging plant tissues and undermining phytoremediation efforts. This review also highlights the critical role of light intensity and pH in regulating plant growth and contaminant uptake. Optimal light conditions and moderate pH changes can significantly enhance phytoremediation, while reduced light due to increased water turbidity and extreme pH fluctuations pose significant challenges. The interplay between these factors and the microbial communities associated with aquatic plants is explored, revealing complex interactions that influence overall remediation efficiency. By synthesizing current research, this review provides a comprehensive understanding of how climate change influences the physiological processes of aquatic plants and their phytoremediation capacity. The findings underscore the need for adaptive management strategies to harness the benefits of phytoremediation in mitigating water pollution under changing climatic conditions. This review calls for further research into the synergistic and antagonistic interactions between climate variables to develop resilient phytoremediation systems that effectively address environmental contaminants in a warming world.

## KEYWORDS

CO<sub>2</sub>; light; macrophytes; ozone; salinization; temperature; turbidity; water

## 1 Introduction

Climate change, driven primarily by anthropogenic greenhouse gas emissions, reshapes ecosystems worldwide, significantly impacting plant physiology and phytoremediation capabilities. Predictions indicate that by the end of the 21st century, global surface temperatures could rise by 1.5°C to 5.7°C,



with the most likely increase being around 2°C to 4°C under moderate emission scenarios [1]. Additionally, atmospheric CO<sub>2</sub> concentrations are projected to increase from the current 400 to over 700 ppm, while light intensity and duration will fluctuate due to changes in cloud cover and solar radiation [1]. These shifts in environmental conditions have cascading effects on the physiological processes of aquatic plants, particularly those involved in the phytoremediation of contaminants such as metals, pharmaceuticals, and nutrients and their ability to remediate ecological contaminants.

Higher temperatures accelerate evaporation rates, leading to the salinization of water bodies [2,3], which imposes osmotic stress on aquatic plants. These plants must adjust their physiological mechanisms to cope with higher salt concentrations [4], diverting resources away from phytoremediation processes and potentially reducing their efficiency in contaminant uptake. Changes in light intensity and duration due to climate alterations can disrupt photosynthesis. Increased water turbidity from extreme weather events limits light penetration, reducing the growth and biomass of submerged plants [5] and directly affecting their capacity to absorb and process contaminants. Similarly, increased ozone (O<sub>3</sub>) levels are detrimental, causing oxidative stress and damaging cellular components, undermining the plants' overall health [5] and phytoremediation abilities. In contrast, elevated atmospheric CO<sub>2</sub> levels can stimulate plant growth by enhancing photosynthesis [5], resulting in better removal of water contaminants by plants.

Climate change also alters pH and water chemistry [6], affecting the solubility and bioavailability of nutrients [5] and pollutants. Plants must adapt their metabolic pathways to these shifts, which can hinder their efficiency in removing contaminants from the water. Furthermore, nutrient dynamics within aquatic ecosystems are changing. Higher temperatures accelerate organic matter decomposition, releasing nutrients like nitrogen and phosphorus more rapidly, while extreme weather events can lead to nutrient runoff [7]. These nutrient imbalances affect plant health and phytoremediation potential [7].

The frequency and severity of extreme climatic events, such as floods and droughts, are increasing [1], causing significant abiotic stress and physical damage to plants. This disruption can diminish their growth and capacity to mitigate pollutants. Moreover, climate change impacts the interaction between plants and their associated microbiomes. Temperature, humidity, and water chemistry shifts can destabilize these microbial communities [8], crucial in supporting plant health and enhancing phytoremediation processes. Phenological changes, such as alterations in the timing of flowering and growth cycles, are another consequence of climate change [9,10]. These shifts can desynchronize plant activities with environmental conditions, reducing their ability to absorb and detoxify pollutants optimally. Additionally, climate change may facilitate the invasion of non-native species [7], which can outcompete local aquatic plants for resources, thereby reducing the effectiveness of native plants in phytoremediation and altering the overall dynamics of the ecosystem. Furthermore, the environmental changes induced by climate change can affect the intrinsic physiological mechanisms [7] that enable plants to tolerate specific contaminants. These alterations could recalibrate plants' tolerance and uptake capabilities, leading to beneficial or detrimental outcomes. Enhanced tolerance and uptake could improve phytoremediation effectiveness, whereas reduced tolerance might impair the plant's ability to detoxify its environment.

The field of phytoremediation has seen substantial growth. A search on Google Scholar using the terms "Soil and Phytoremediation" or "Water and Phytoremediation" yielded over 25,000 publications since 2020, reflecting the substantial growth in this field. However, while phytoremediation in soil has been extensively studied, with the majority of these publications focused on soil, research related to water phytoremediation has been comparatively less represented [11,12], particularly in the context of the compounded effects of climate change on these processes. While individual studies have explored the impact of temperature, CO<sub>2</sub> levels, or salinity on plant physiology, few have integrated these factors to examine their combined effects on phytoremediation efficiency under changing climatic conditions. This study addresses this gap by analyzing how climate change influences aquatic macrophytes' physiological and biochemical

responses. The novelty of this work lies in its comprehensive approach to understanding the interplay between various climate variables—such as temperature, CO<sub>2</sub> and O<sub>3</sub> levels, pH, salinity, and light intensity—and their collective impact on the efficiency of phytoremediation. By synthesizing current research across these domains, this study offers new insights into the complex interactions that can enhance or diminish aquatic plants' phytoremediation capabilities under changing climatic conditions. Understanding these interactions is crucial for developing sustainable environmental management practices that can mitigate the negative impacts of climate change on water quality and ecosystem health. The findings underscore the urgent need for adaptive strategies to preserve and enhance phytoremediation efficiency as the climate changes. This study offers novel insights into the complex interactions between climate variables and plant functions by examining the cellular and biochemical mechanisms affected by climate change.

## 2 Aquatic Phytoremediation

As the world faces the profound impacts of climate change, the need for innovative and sustainable solutions to address environmental challenges has become increasingly pressing. One such challenge is the growing threat of water pollution, exacerbated by the changing climate [13]. Eutrophication, the excessive enrichment of water bodies with nutrients, and other pollution pose significant risks to aquatic ecosystems and human health [14]. In this context, the role of aquatic phytoremediation, the use of aquatic plants to remove contaminants from water, has gained significant attention as a promising approach to address water quality issues [14]. Phytoremediation offers a sustainable and cost-effective alternative to conventional water treatment methods, making it an attractive option for communities and regions with limited resources. This method provides a high level of remediation without compromising the physical and chemical integrity of the environment. Moreover, it offers the potential for further extraction of contaminants from the plant biomass [15].

Aquatic macrophytes, or aquatic plants, have been the focus of significant research in phytoremediation, as they have demonstrated the ability to remove a wide range of contaminants from water bodies [15,16]. Species such as *Eichhornia crassipes*, *Elodea canadensis*, *Azolla filiculoides*, *Lemna minor*, *L. gibba*, *Myriophyllum spicatum*, *Pistia stratiotes*, and *Salvinia molesta* have shown promising results in this regard [15–21]. For instance, Buta et al. [22] demonstrated that *E. crassipes*, *L. minor*, and *P. stratiotes* have high phytoremediation potential for removing nitrogen species, phosphorus (P), iron (Fe), and chromium (Cr) from wastewater. After just one week of contact, these plants removed up to 99% of Cr, 97% of lithium (Li), 100% of ammoniacal nitrogen (NH<sub>3</sub>), 95% of P, and 96% of Fe. Similarly, *E. canadensis* removed up to 66% of Cr [23], 66.16% of arsenic (As) [24], 23% of enrofloxacin (Enro), and 30% of glyphosate [21] within only a few hours of exposure to contaminated water. *S. molesta* also demonstrates high efficacy in removing metals, particularly copper (Cu) and Cr (>50% removal), and to a lesser extent, zinc (Zn), lead (Pb), nickel (Ni), and cobalt (Co) [25]. Additionally, it can accumulate mercury (Hg), with bioconcentration factors reaching 856 [26], and reclaim more than 58% of ciprofloxacin (Cipro) from the medium after only 96 h of exposure [27].

As the effects of climate change continue to manifest, the importance of developing effective and sustainable solutions to address water pollution will only grow. Exploring aquatic phytoremediation as a tool for contaminant removal presents an opportunity to enhance water quality, promote ecosystem health, and foster resilient communities in the face of a changing climate. However, the successful implementation of phytoremediation is not without its challenges. The presence of multiple types of contaminants and climatic and hydrological conditions can limit the growth and effectiveness of the plants [16,28]. For instance, the presence of glyphosate in water can increase *E. canadensis*' capacity to remove Enro by up to 700% due to the stimulation of the plant's metabolism of the antibiotic. Conversely, the presence of Enro in water decreased the plant's capacity to remediate glyphosate by up to

50% [21]. Factors such as temperature, pH, light, and salinity can all impact the ability of aquatic plants to remove pollutants effectively [29]. Therefore, it is essential to understand the effect of climate change on the remediation capacity of plants.

### 3 Temperature and Its Effects on Aquatic Plant Physiology and Phytoremediation

#### 3.1 Effects of Temperature on Aquatic Plant Physiology

Temperature is a crucial factor affecting the physiological processes of aquatic plants. It influences respiration, photosynthesis, nitrogen metabolism, and oxidative metabolism. These processes are fundamental for plant growth, energy production, and stress responses, directly linking to the plant's ability to tolerate and remediate environmental contaminants.

As temperatures rise, respiration rates generally increase to an optimum point, enhancing metabolic activity and energy production and facilitating greater uptake and detoxification of contaminants. For example, a temperature increase of 2.5°C is expected to boost respiration and primary production by 31% and 28%, respectively [30], and rising temperatures could even increase potential species richness in certain lake types [31]. However, temperatures exceeding the optimal range can lead to increased respiration that surpasses photosynthesis, resulting in a net loss of carbon and energy [32] (Table 1). Excessive temperatures can cause Rubisco deactivation and reduce chloroplast electron transport rates, co-limiting photosynthesis [33]. This imbalance impairs growth and reduces phytoremediation efficiency. Similarly, optimal temperatures enhance enzymatic activities involved in the Calvin cycle, leading to increased photosynthetic rates and biomass production (Table 1), critical for phytoremediation. However, temperatures above the optimum range can cause photoinhibition and damage to photosystem II, reducing the efficiency of light energy conversion and carbon fixation [34]. Elevated temperatures can also accelerate nitrogen uptake and assimilation [35,36], enhancing plants' growth and detoxification abilities. However, extreme temperatures can disrupt nitrogen metabolism [35], accumulating toxic ammonium and reducing the synthesis of essential proteins and enzymes. Moreover, increased temperatures can indirectly affect plant nutrition by altering nutrient cycles. For instance, Kramer et al. [37] observed that temperatures from 29°C to 30°C promote cyanobacterial growth but suppress nitrogen fixation rates in lake communities. Temperature increases are also predicted to accelerate litter decomposition rates, potentially impacting carbon sequestration and affecting plant nutrition [38]. Temperature-induced oxidative stress is another significant challenge for aquatic plants. Elevated temperatures may increase the production of reactive oxygen species (ROS), causing oxidative damage to cellular components [39]. However, some plants counteract this by upregulating antioxidant enzymes, which may improve the plants' tolerance and contaminant-removal capacity [40].

Aquatic plants have evolved various mechanisms to adapt to temperature fluctuations, such as changes in membrane fluidity, enzyme activity, and gene expression [41]. These adaptations enable some species to thrive in a broader range of temperature conditions, enhancing their effectiveness in phytoremediation under varying climatic conditions. For instance, an increase in temperature from 20°C to 30°C favored the harmful effects of the antibiotic Cipro on the mitochondrial activity of *Ricciocarpus natans*. However, it also enhanced the activity of antioxidant enzymes, preventing Cipro-induced oxidative stress and resulting in increased uptake of Cipro by the plants [42]. Similarly, in response to rising temperatures, aquatic plants modify pigment and membrane lipid composition, increasing membrane fluidity and, thus, cell permeability to water contaminants [43]. Understanding the complex interplay between temperature and plant physiology is crucial for designing and optimizing aquatic phytoremediation systems that can effectively remove contaminants in a changing climate.

**Table 1:** Physiological changes in aquatic plants under climate change scenarios

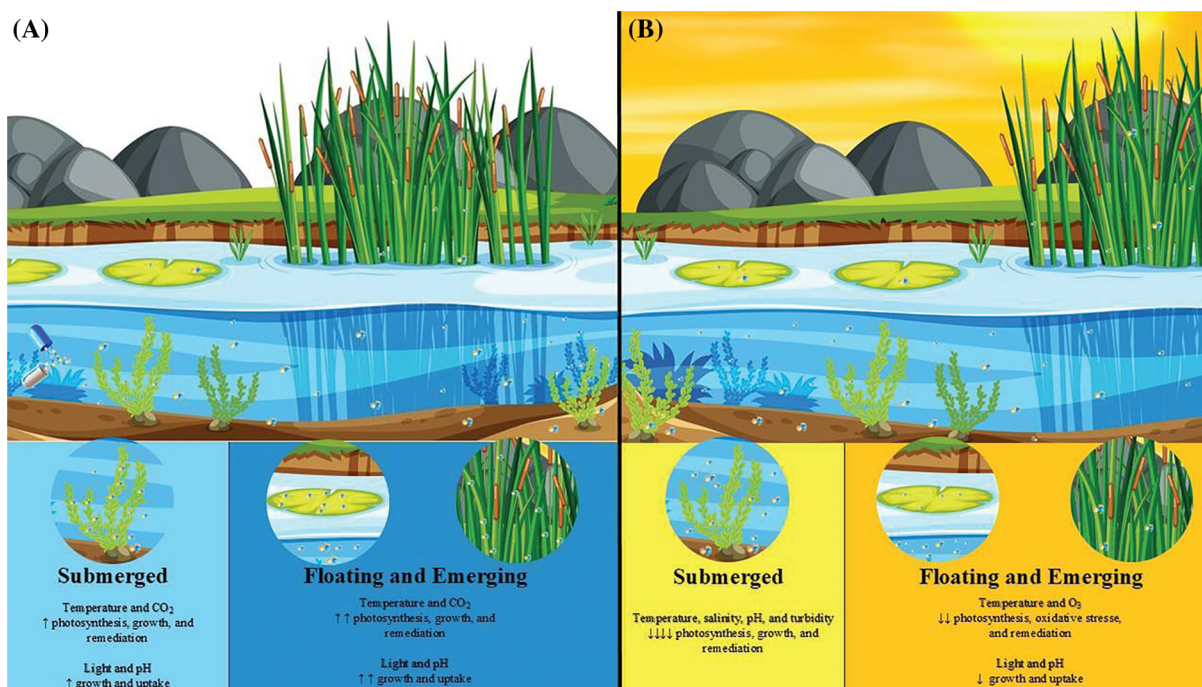
Climate change factor	Physiological process	Effect	References
Increased temperature	Photosynthesis	Optimal at moderate increase; reduced efficiency and photoinhibition at high temperatures	[34]
	Respiration	Increased rates up to an optimum, leading to energy imbalances at higher temperatures	[32]
	Nitrogen metabolism	Enhanced uptake and assimilation up to an optimum; disrupted at extreme temperatures	[35]
	Oxidative stress	Increased ROS production, requiring upregulation of antioxidant enzymes	[40]
	Biomass and growth	Enhanced growth up to an optimum; reduced under extreme conditions	[44]
Elevated CO <sub>2</sub>	Photosynthesis	Enhanced photosynthesis due to CO <sub>2</sub> fertilization effect	[45]
	Growth and biomass	Increased carbon fixation and biomass production	[45]
	Nutrient uptake	Potential imbalances in nutrient uptake, such as reduced iron and magnesium availability	[46]
	Microbial interactions	Enhanced microbial activity related to CO <sub>2</sub> assimilation and carbon decomposition	[47]
Elevated O <sub>3</sub>	Oxidative stress	Increased ROS production and cellular damage, impairing photosynthesis and growth	[48]
	Microbial biomass	Reduced microbial biomass and nutrient inputs to the rhizosphere	[49]
Increased salinity	Ion balance	Osmotic stress, altered ion uptake mechanisms, potential for enhanced or reduced contaminant uptake	[4,50]
	Antioxidant enzyme activity	Heightened activities to mitigate oxidative damage from contaminants	[4]
Changes in pH	Nutrient availability	Altered nutrient uptake and metal solubility; potential for toxic accumulations	[46]
	Rhizosphere microbiome	It affects microbial composition and activity, influencing nutrient cycling and contaminant degradation	[51]
Extreme weather events	Water availability	Drought conditions concentrate pollutants; flooding disperses contaminants	[52,53]
	Growth and stability	Physical damage and abiotic stress reducing growth and phytoremediation capacity	[54]

### 3.2 Secondary Effects of Temperature Changes

Temperature changes have several secondary effects on the aquatic environment, which can further influence aquatic plants' physiology and phytoremediation capabilities. For instance, increased temperatures accelerate evaporation rates, leading to higher water salinity. Elevated salinity levels impose osmotic stress on aquatic plants, disrupting ion balance and water uptake mechanisms [4] (Table 1). This



osmotic stress can alter the plants' physiological pathways, potentially enhancing their tolerance and uptake of specific contaminants, such as metals and pharmaceuticals (Fig. 1). For instance, heightened antioxidant enzyme activities under osmotic stress may improve the phytoremediation capacity of plants by mitigating oxidative damage from contaminants [55]. However, increased salinity can also result in decreased remediation ability by aquatic plants, as seen for metals (Cu, Zn, cadmium (Cd), and Pb) in *E. canadensis* and *Potamogeton natans* [50].



**Figure 1:** This figure illustrates the effects of moderate climate change (A) and extreme climate conditions (B) on submerged, floating, and emerging aquatic plants, highlighting the variations in their physiological responses and phytoremediation capacities. Moderate climate change (A): Mild increases in temperature and CO<sub>2</sub> levels, along with improved light and pH conditions, enhance photosynthesis, growth, and remediation capabilities. Floating and emerging macrophytes exhibit more excellent positive responses compared to submerged species. Extreme conditions (B): Under extreme conditions characterized by rising temperatures, increased salinity, elevated O<sub>3</sub> concentrations, pH fluctuations, and higher water turbidity, photosynthesis, growth, and remediation capabilities are reduced. Submerged species are particularly vulnerable to these stressors than floating and emerging macrophytes

Changes in precipitation patterns and water availability due to rising temperatures can also affect hydrological regimes, impacting the distribution and concentration of contaminants in aquatic environments [52,53]. Increases in rainfall and extreme weather events can lead to higher contaminant loads in waterways, and the interactive effects between rising contaminant concentrations and temperature in water are difficult to predict. For instance, increased temperature and nitrogen loading have significantly boosted cyanobacterial growth rates in lakes. However, this also impairs nitrogen fixation, contributing to nitrogen limitation in these ecosystems, which can profoundly affect plant communities, including the phytoremediation capacities of macrophytes. Nutrients such as nitrogen, phosphorus, and sulfur are crucial for a plant's ability to cope with contaminants, modulating their phytoremediation capacity [56,57]. Fluctuating water levels can lead to drought and flooding, each presenting unique

challenges and opportunities for phytoremediation. Drought conditions might concentrate pollutants, increasing the burden on plants, while flooding can disperse contaminants, potentially reducing their bioavailability but increasing the spatial extent of contamination. Moreover, increasing temperatures are closely linked to rising sea levels, contributing to the salinization of coastal and freshwater environments [58]. This salinization exacerbates osmotic stress on aquatic ecosystems, further influencing plant's capacity for phytoremediation.

Climate-induced shifts in pest and disease patterns may also lead to increased use of pesticides and herbicides, contributing to higher levels of these contaminants in water bodies [59,60]. The emerging threat of insect pests driven by rising global temperatures is a clear example of this issue. A study on the sweet potato whitefly (*Bemisia tabaci*) in the southeastern United States found that warmer temperatures were associated with earlier and more abundant whitefly activity, particularly in areas with higher insecticide use [61]. The study suggests that frequent insecticide applications, driven by these climate-induced pest outbreaks, may disrupt biological control mechanisms, resulting in even more persistent pest problems. This creates a potential feedback loop, or "pesticide treadmill," where increased temperatures and pest abundance lead to further pesticide use, exacerbating the contamination of water bodies as global climate change accelerates [62]. These chemicals can interact with the physiological responses of aquatic plants, affecting their growth and contaminant uptake capacities. For example, certain pesticides can inhibit or enhance specific metabolic pathways involved in phytoremediation, complicating predictions of plant performance under climate change scenarios. In *E. canadensis*, Roundup (a glyphosate-based herbicide) inhibits the activity of cytochrome P450, thereby decreasing the metabolism and uptake of the antibiotic Enro by plants. However, the presence of Enro in water increased glyphosate uptake and toxicity [21].

### 3.3 Case Studies and Comparative Analyses

Studies have explored the impacts of temperature on the phytoremediation capabilities of aquatic plants. Huynh et al. [44] investigated the removal of trace elements (Cd, As, Pb, Zn, and Cu) by water hyacinth (*Eichornia crassipes*) under different temperature regimes. Their findings showed that temperatures exceeding 33°C stifle plant development and decrease trace element-removal capacity. Similarly, Haris et al. [63] observed that temperature significantly affects the remediation capacity of water hyacinth, with optimal nutrient removal occurring at 30°C. Higher temperatures increased phosphorus release from organic matter, reducing the plant's remediation efficiency. In contrast, increasing temperature from 11°C to 32°C enhanced the cyanide metabolism rate of weeping willows (*Eleocharis acicularis*), an emergent macrophyte, by 46% for every 10°C increase due to higher enzyme activity without causing increased cyanide accumulation or toxicity [64]. However, higher temperatures also improved the remediation capacity of *E. acicularis* for As-contaminated leachate. The absorption of As by *E. acicularis* was higher at an average temperature of 20.5°C (0.8% of total As absorbed) compared to 4.2°C (0.3% of total As absorbed) [65].

Fritioff et al. [50] observed increased metal (Cu, Zn, Cd, Pb) accumulation in *E. canadensis* and *P. natans* when the temperature was raised from 5°C to 20°C. Additionally, the Cu-remediation capacity of *Typha latifolia* improved with increasing temperatures from 18°C to 32°C [66]. A recent review by Pang et al. [67] reported that the metal-remediation capacity of macrophytes generally increases with temperature up to an optimal range of 20°C–30°C. Beyond 30°C, remediation capacity can decrease due to plant stress, with maximum removal observed around 25°C–30°C for the metals studied. Similarly, increased temperature (from 20°C to 30°C) favored ciprofloxacin (Cipro) uptake by *Ricciocarpus natans* [42]. However, increased temperature (from 12°C to 28°C) had little effect on the bioaccumulation of the herbicide isoproturon in freshwater macrophytes *Egeria densa* and *Ludwigia natans*. Still, it increased the herbicide burden in *E. densa* [68].

Temperature increases can also enhance selenium (Se) accumulation by giant reed (*Arundo donax*) by altering microbial activity, affecting selenium's mobility, bioavailability, and volatility [69]. Indeed,

temperature increases can modulate microbial activity in bioremediation, impacting the efficacy of natural biodegradation or the injection of biological materials [70]. For example, higher summer temperatures were associated with increased Pb and Co remediation capacity of *Pistia stratiotes*, likely due to lower dissolved oxygen levels and bacterial abundance, compared to lower winter remediation capacity [71]. Weirich et al. [72] observed increased nitrogen removal efficiency by *P. stratiotes* and *E. crassipes* during summer. Additionally, constructed wetlands planted with aquatic macrophytes showed increased denitrification rates as water temperatures rose from 12°C to around 26°C [73]. Temperature also influences the remediation capacity of both *T. domingensis* and *Pontederia parviflora*. Temperatures above 20°C, in the mesophilic range, allowed for optimal microbial and plant metabolism, leading to high removal efficiencies for chemical oxygen demand (COD) and suspended solids. Conversely, temperatures below 20°C, in the psychrophilic range, reduced the metabolism of microorganisms and aquatic plants, leading to lower remediation capacity. Large temperature fluctuations, with drops of over 10°C in a single day, negatively impacted the stability and performance of these systems [54].

Climate change can also influence the distribution and prevalence of aquatic plant species, affecting their availability and suitability for phytoremediation. Studies have shown that certain floating species, such as *L. minor*, exhibit greater tolerance to high temperatures than other morphotypes of macrophytes [29]. Increased temperatures and freshwater salinization favor the growth of floating macrophytes and phytoplankton [74] while decreasing the metal remediation capacity of submerged macrophytes like *E. canadensis* [50]. However, the metal (Mn and Fe) removal capacity of phytoplanktonic species such as *Synechococcus elongatus* (Cyanobacteria) and *Chlorococcum infusionum* (Chlorophyta) remains unaffected under these conditions [75]. These findings suggest that floating macrophytes, such as duckweed species, may be more suitable for phytoremediation under warmer and more saline conditions. Nevertheless, compared to submerged macrophytes, floating plants have proven to be less effective in removing some contaminants, such as the antibiotic erythromycin [76], which could result in lower overall effectiveness of phytoremediation programs. A potential solution is the use of mixed cultures of floating macrophytes. For example, more excellent growth rates were observed for both *L. minor* and *S. molesta* when grown together in water contaminated with the antibiotics Cipro and sulfamethoxazole (Sulfa), compared to systems with each plant growing separately. This co-culture approach resulted in more excellent removal of Cipro and Sulfa in the mixed system [77].

In summary, temperature impacts on aquatic phytoremediation are multifaceted and require a comprehensive understanding of plant physiology, environmental interactions, and system-level optimization (Fig. 1; Table 2).

**Table 2:** Effects of rising temperatures on the phytoremediation capabilities of various aquatic plant species

Plant species	Contaminant	Impact of temperature on reclamation	Reference
<i>Eichornia crassipes</i>	Cd, As, Pb, Zn, Cu	↓ under temperatures $\geq 33^{\circ}\text{C}$	[44]
<i>Eichornia crassipes</i>	P	↓ under temperatures $> 30^{\circ}\text{C}$	[63]
<i>Eleocharis acicularis</i>	Cyanide	↑ from 11°C to 32°C	[64]
<i>Eleocharis acicularis</i>	As	↑ with average temperature of 20.5°C vs. 4.2°C	[65]
<i>Elodea canadensis</i> and <i>Potamogeton natans</i>	Cu, Zn, Cd, Pb	↑ from 5°C to 20°C	[50]

(Continued)



Table 2 (continued)			
Plant species	Contaminant	Impact of temperature on reclamation	Reference
<i>Typha latifolia</i>	Cu	↑ from 18°C to 32°C	[66]
-	Metals	↑ up to an optimal range of 20°C–30°C	[67]
<i>Ricciocarpus natans</i>	Ciprofloxacin	↑ from 20°C to 30°C	[42]
<i>Egeria densa and Ludwigia natans</i>	Isoproturon	→ from 12°C to 28°C	[68]
<i>Arundo donax</i>	Se	↑ with rising temperatures (not specified)	[69]
<i>Pistia stratiotes</i>	Pb, Co	↑ during summer temperatures (38.1°C vs. 8.2°C)	[71]
<i>Pistia stratiotes and Eichornia crassipes</i>	N	↑ during summer temperatures (~30°C vs. 25°C)	[72]
-	Various	↑ from 12°C to 26°C	[73]
<i>Typha domingensis and Pontederia parviflora</i>	COD and suspended solids	↑/↓ above and below 20°C, respectively	[54]
<i>Elodea canadensis</i>	Cu, Zn, Cd, and Pb	↓ with rising temperatures (5°C to 20°C) and salinity (0, 0.5, and 5‰)	[50]

Note: In the plant species column, - indicates no specific species; symbols ↑, ↓, and → represent an increase, a decrease, and no significant change, respectively. COD stands for chemical oxygen demand.

## 4 Light Intensity and Its Effects on Aquatic Plant Physiology and Phytoremediation

### 4.1 Effects of Light Intensity on Aquatic Plant Physiology

Light is a fundamental factor affecting the physiological processes of aquatic plants. Changes in light conditions due to climate alterations can significantly impact these processes [7]. Light intensity directly influences photosynthetic rates and the growth patterns of aquatic plants (Table 1). Optimal light conditions enhance the efficiency of photosystem II and the Calvin cycle, leading to increased carbon fixation and biomass production [78], which are essential for phytoremediation. Conversely, low light conditions can lead to etiolation, reduced growth rates, and lower biomass [78], compromising phytoremediation efficiency. Moreover, reduced light penetration due to increased water turbidity from extreme weather events can limit photosynthesis [79], reducing the energy available for growth and contaminant uptake, especially in submerged plants [80]. Underwater darkening can also alter the ecological dynamics of ecosystems, particularly impacting plants with notable phytoremediation capacities. For example, a study conducted in East China examined the effects of light attenuation on the growth and photosynthetic traits of native phytoremediator plants like water thyme (*Hydrilla verticillata*) and Eurasian watermilfoil (*Myriophyllum spicatum*) compared to the invasive Carolina fanwort (*Cabomba caroliniana*). The study found that while light attenuation inhibits the growth of native submerged plants, it facilitates the growth of invasive species like *C. caroliniana*, which exhibited superior growth and photosynthetic traits under low underwater light conditions [80]. Using native species in phytoremediation programs is crucial to avoid introducing exotic species with potential ecological impacts. Changes in light conditions will affect the success of these programs, particularly in environments susceptible to underwater darkening.

On the other hand, excessive light intensity can also induce stress responses, such as the production of ROS [81,82], which can damage plant tissues and compromise their phytoremediation capabilities [55]. Light intensity can also affect the plant's accumulation and distribution of contaminants by affecting their

growth. Higher light levels may stimulate the production of chelating compounds, such as phytochelatins and metallothioneins, which can sequester and compartmentalize metals, enhancing their removal from the environment [83]. For instance, higher light intensities in the terrestrial metal hyperaccumulator plant *Noccaea caerulescens* increased biomass production and metal accumulation, improving phytoremediation efficiency [84]. However, caution is necessary, as hyperaccumulators may mobilize metals but only accumulate some, potentially increasing the risk of metal leaching [84].

Aquatic plants have developed various adaptive strategies to cope with fluctuations in light intensity. Some species, such as water hyacinth and duckweed, exhibit a high degree of phenotypic plasticity, allowing them to acclimate to a wide range of light conditions [83]. Other plants may allocate resources to specific physiological processes, such as increased production of light-harvesting pigments or antioxidant enzymes, to mitigate the effects of excessive or limited light [85].

#### 4.2 Secondary Effects of Light Intensity Changes

Increased water turbidity, a consequence of climate-induced extreme weather events [3], reduces light penetration in aquatic environments. As discussed above, this reduced light availability affects photosynthesis and growth, decreasing phytoremediation efficiency. Turbidity also impacts the distribution of pollutants, potentially increasing their bioavailability in the water column [86] (Table 1). Climate change can also alter seasonal light patterns, affecting the timing and duration of light availability [87]. These changes can disrupt the phenology of aquatic plants, such as flowering and growth cycles, leading to mismatches between peak light availability and periods of active growth. Such disruptions can reduce phytoremediation efficiency, as plants may not be in their optimal growth phase when contaminants are most prevalent.

Understanding the relationship between light intensity, biomass production, and phytoremediation is crucial for developing effective strategies to enhance the removal of contaminants from aquatic environments. By optimizing light conditions and selecting plant species with high phenotypic plasticity or other adaptive traits, we can improve the efficiency of phytoremediation systems, making them more resilient to the impacts of climate change.

#### 4.3 Case Studies and Comparative Analyses

Light significantly influences the growth and physiology of aquatic macrophytes, which in turn impacts their phytoremediation capabilities. Photosynthetic rates increase with light intensity up to a certain point, beyond which photoprotective mechanisms are activated to prevent damage [88]. Light-induced changes in the cellular redox environment play a crucial role in metabolic regulation, affecting various pathways, including carbon, nitrogen, and secondary metabolism [89], all of which are intrinsically involved in the phytoremediation capacity of macrophytes [55]. For instance, under low-light conditions, such as those caused by increased turbidity due to climate events, biomass production is reduced, and nutrient uptake in submerged species is adversely affected [90]. In submerged macrophytes like *Potamogeton crispus*, shaded conditions (42% and 11% of full sunlight) lead to reduced tissue soluble protein, soluble carbohydrates (SC) contents, and the SC/free amino acid (FAA) ratio, while increasing FAA concentrations, and promoting the activity of antioxidant enzymes, such as superoxide dismutase and guaiacol peroxidase. This results in aggravated carbon and nitrogen consumption and oxidative stress, disrupting the plant's capacity for nutrient removal and contributing to the decline of submerged macrophytes in eutrophic lakes [91]. Conversely, intermediate light levels (around 30%–50% shade) are optimal for the phytoremediation potential of *M. aquaticum*, as this light regime promotes the greatest plant biomass and growth [92]. Light availability also affects the toxicity of herbicides to aquatic plants. For example, the herbicide atrazine decreased shoot length in *E. canadensis* grown under low-light conditions. Still, not biomass, while under optimal light conditions, atrazine significantly decreased both

shoot length and biomass [93]. In *Lemna* sp. and *Spirogyra* sp., increases in light intensity have been shown to enhance the plant's ability to remove pharmaceuticals and endocrine-disrupting chemicals from wastewater. The highest removal efficiencies were achieved in uncovered planted systems [94]. Similarly, increased light intensity enhanced the removal of diclofenac and Sulfa in wetlands. However, this enhancement was attributed to the photodegradation of the contaminants [95] rather than improved plant performance. Many organic pollutants, including pharmaceuticals, are particularly susceptible to photodegradation [96,97]. Therefore, even moderate increases in light intensity could potentially enhance remediation by facilitating the cleavage of these molecules. However, this process may also lead to the generation of intermediary metabolites, which could exhibit a higher level of toxicity to plants compared to their parent compounds [98], thereby compromising the plant's performance in contaminant uptake.

Despite its importance, there are relatively few studies on the effect of light on the remediation capacity of macrophytes. It appears that changes in the light environment due to climate change predominantly affect submerged species of macrophytes due to increased water turbidity and decreased light availability. In contrast, floating and emerging plants seem tolerant to increased light intensity and regimes (Fig. 1). Understanding these light-dependent mechanisms is crucial for improving phytoremediation strategies and deserves more attention in future research.

## 5 CO<sub>2</sub> and O<sub>3</sub> Levels, and pH Fluctuations and Their Effects on Plant Physiology and Phytoremediation

The delicate balance of CO<sub>2</sub>, O<sub>3</sub>, and pH levels in aquatic ecosystems profoundly impacts the health and functioning of aquatic plants, which are vital for phytoremediation efforts (Table 1). Increased CO<sub>2</sub> levels can enhance photosynthesis through the CO<sub>2</sub> fertilization effect, leading to higher carbon fixation rates and growth [45]. Zhang et al. [99] demonstrated that dissolved inorganic carbon enhances primary production in submerged macrophytes, suggesting a co-limitation of carbon alongside traditional nutrients. The authors also found that CO<sub>2</sub> fertilization accounted for over half of the biomass increase in northern extra-tropical forests. Similarly, Haverd et al. [100] highlighted a global CO<sub>2</sub> fertilization effect, estimating a 30% increase in photosynthesis since 1900. This increased growth can improve the plants' capacity to uptake and sequester contaminants, essential for phytoremediation efforts. However, while CO<sub>2</sub> fertilization generally promotes growth, several factors can complicate these dynamics. For instance, vapor pressure deficit (VPD) can mitigate these benefits, as Li et al. [101] noted that VPD could offset up to 68.21% of the CO<sub>2</sub> fertilization effect.

Several macrophytes have demonstrated phenotypic adaptations to varying partial pressures of CO<sub>2</sub> (pCO<sub>2</sub>), indicating that they can maintain normal function in fluctuating CO<sub>2</sub> environments [102]. Since most macrophytes can utilize either free CO<sub>2</sub> or bicarbonate (HCO<sub>3</sub><sup>-</sup>), they may exhibit stable responses to changes in pCO<sub>2</sub> as long as one of these carbon forms is available. Consequently, they may be less vulnerable to climate-induced changes in pCO<sub>2</sub> levels than other more sensitive taxonomic groups [102]. However, excessive CO<sub>2</sub> can also lead to imbalances in nutrient uptake, potentially affecting the plants' overall health and phytoremediation efficiency. For instance, while CO<sub>2</sub> enrichment boosts photosynthesis and biomass production [45], it can also significantly reduce tissue concentrations of essential nutrients such as Fe and Mg [46]. These deficiencies impair the plants' physiological functions, reducing their ability to tolerate and remediate contaminants effectively. Elevated CO<sub>2</sub> levels can reduce iron solubility in water, leading to Fe deficiency, critical for chlorophyll production and photosynthesis. Similarly, CO<sub>2</sub>-induced Mg imbalances can impair chlorophyll synthesis and enzyme function, ultimately reducing the plant's growth and phytoremediation capabilities [46].

Increasing CO<sub>2</sub> levels also drive water acidification, disrupting plant physiology and remediation capacities since pH is a critical factor influencing nutrient availability, metal solubility, and overall plant health [103]. Ocean acidification is expected to drop 0.3–0.4 pH units in the surface ocean by 2100 if

anthropogenic CO<sub>2</sub> emissions continue at the current rate [104]. From 1982 to 2021, global surface ocean pH declined by  $-0.0166 \pm 0.0010$  per decade, with regional variations [105]. Even if atmospheric CO<sub>2</sub> levels were reduced, the recovery of ocean acidification would take decades to centuries [106]. Freshwater ecosystems are similarly impacted. For instance, if increasing atmospheric pCO<sub>2</sub> is the only forcing factor, pH in the Laurentian Great Lakes will decline at the same rate and magnitude as the surface ocean through 2100 [104]. Additionally, lakes in the northeastern USA are experiencing pH decreases, potentially increasing aluminum toxicity for fish [107].

As acidification progresses, plants must invest additional energy to maintain their acid-base balance and metabolic processes, affecting their growth, reproduction, and remediation capacities [45]. At optimal pH levels (typically around neutral), nutrient uptake is maximized, supporting healthy development and phytoremediation. However, extreme pH levels (either acidic or alkaline) can reduce nutrient availability and increase the solubility of toxic metals [108], posing challenges to plant health and contaminant uptake. pH changes can also influence the speciation and interaction of multiple contaminants [108,109], affecting their bioavailability and plant uptake [108]. Additionally, pH alterations can impact the composition and activity of the rhizosphere microbiome, which plays a vital role in nutrient cycling and contaminant degradation [51]. Optimal pH supports a diverse and active microbial community, enhancing phytoremediation, while extreme pH conditions can disrupt microbial activity and reduce contaminant degradation.

Elevated O<sub>3</sub> levels cause oxidative stress in plants, producing ROS that damage cellular components [110,111]. This oxidative stress can impair photosynthesis, respiration, and overall plant growth. While plants upregulate antioxidant enzymes to counteract oxidative stress, chronic O<sub>3</sub> exposure can overwhelm these defenses, reducing the plant's capacity to tolerate and remediate contaminants. Additionally, O<sub>3</sub> can significantly alter the composition and activity of the plant-associated microbiome, which is crucial in supporting plant health and enhancing phytoremediation [48]. CO<sub>2</sub> and O<sub>3</sub> levels can influence the plant-associated microbiome, with elevated CO<sub>2</sub> potentially stimulating microbial activity, thereby enhancing nutrient and contaminant uptake [48]. However, high O<sub>3</sub> levels can disrupt beneficial microbial communities, reducing phytoremediation efficiency. Elevated O<sub>3</sub> levels have been shown to reduce phyllospheric bacterial diversity [112] and alter fungal community composition in plants [113]. Moreover, O<sub>3</sub> exposure exacerbates plant disease severity by altering microbial co-occurrence networks [114]. Understanding the complex interplay between CO<sub>2</sub>, O<sub>3</sub>, and pH levels and their effects on aquatic plant physiology is crucial for optimizing phytoremediation strategies. By managing these environmental factors, we can enhance the resilience and effectiveness of phytoremediation systems in mitigating water pollution.

### 5.1 Case Studies and Comparative Analyses

Elevated CO<sub>2</sub> levels have been shown to increase the phytoremediation efficiency of *Noccaea caerulescens* by enhancing biomass production and metal accumulation and reducing oxidative damage [115]. Similarly, CO<sub>2</sub> enrichment stimulates the accumulation of sediment-derived minerals like Al, Fe, P, and N in the submerged macrophyte *Vallisneria americana*, with the effects being more pronounced at a lower pH of 5 compared to a higher pH of 7.3 [116]. This suggests that CO<sub>2</sub> levels, in combination with pH, can significantly influence the nutrient uptake and overall health of aquatic plants.

In soil environments, elevated CO<sub>2</sub> generally enhances rhizoremediation and phytoextraction of metals by increasing biomass and microbial activity in the rhizosphere, while elevated O<sub>3</sub> has the opposite effect [48]. High O<sub>3</sub> levels decrease the inputs of assimilates to the rhizosphere, negatively impacting decomposition processes, rhizoremediation, and metal phytoextraction efficiency. Elevated O<sub>3</sub> also adversely affects microbial biomass, reducing the effectiveness of phytoremediation [48]. Increased CO<sub>2</sub> significantly enhances the abundance of bacterial and functional genes related to CO<sub>2</sub> assimilation and

carbon decomposition, promoting photoautotrophy, hydrocarbon degradation, and cellulolysis [47]. However, elevated CO<sub>2</sub> levels reduce the abundance of chemoautotrophic bacteria, including nitrifying bacteria. Culturing *E. crassipes* under elevated CO<sub>2</sub> conditions decreases photosynthetic bacteria. Still, it increases bacteria involved in complex carbon decomposition due to root exudates. These interactions can decrease bacterial diversity and the abundance of CO<sub>2</sub>-assimilating, nitrifying, and certain carbon-degrading bacteria with denitrifying properties. Consequently, the interactions between aquatic plants and the bacterial community in eutrophic waters under elevated CO<sub>2</sub> can benefit the environment and help mitigate the greenhouse effect [47]. Conversely, rising concentrations of CO<sub>2</sub> and O<sub>3</sub> have been shown to decrease the removal of polycyclic aromatic hydrocarbon (PAH) pollutants in grassland soils. This reduction in PAH degradation is linked to shifts in soil microbial community structure, specifically a reduction in gram-positive bacteria essential for soil enzyme production and PAH degradation [49]. These findings highlight the complex interplay between CO<sub>2</sub>, O<sub>3</sub>, and pH levels and their effects on phytoremediation. While elevated CO<sub>2</sub> can enhance biomass production and microbial activity, thus improving phytoremediation efficiency, elevated O<sub>3</sub> can negate these benefits by reducing microbial biomass and nutrient inputs to the rhizosphere. Additionally, changes in pH due to increased CO<sub>2</sub> levels can further complicate these interactions, affecting nutrient availability and metal solubility.

Aquatic macrophytes respond differently to environmental factors such as CO<sub>2</sub>, O<sub>3</sub>, and pH. Floating and emerging macrophytes are most resilient to elevated CO<sub>2</sub>, showing notable enhancements in photosynthesis and biomass production [117]. This is attributed to their superior carbonic anhydrase activity, which is related to their higher carbonic anhydrase activity and bolsters their phytoremediation capacity in scenarios of increased CO<sub>2</sub>. In contrast, water acidification may adversely affect submerged macrophytes [117]. These plants are highly sensitive to pH fluctuations; optimal pH levels facilitate healthy growth and nutrient uptake, while extreme pH levels can decrease nutrient availability and enhance the solubility of toxic metals, thereby compromising phytoremediation efficiency. Emergent macrophytes can tolerate a broader range of pH levels than submerged types [118]. However, extreme pH levels can still affect nutrient availability and microbial activity, potentially reducing their effectiveness. Floating macrophytes are generally less sensitive to pH fluctuations than submerged types [117]. They may tolerate a broader range of pH levels, maintaining phytoremediation capabilities even under varying conditions. However, extreme pH levels can still impact nutrient uptake and microbial interactions. Regarding O<sub>3</sub>, submerged macrophytes are generally less affected by elevated O<sub>3</sub>, as atmospheric O<sub>3</sub> does not readily dissolve in water, meaning their phytoremediation capacity is not significantly impacted. On the other hand, emergent macrophytes are more exposed to atmospheric O<sub>3</sub>, which can cause oxidative stress, reduce photosynthesis, and impair growth. Chronic exposure to high O<sub>3</sub> levels can decrease phytoremediation efficiency by damaging plant tissues and reducing assimilated inputs to the rhizosphere. Floating macrophytes are directly exposed to atmospheric O<sub>3</sub>, which can cause oxidative damage and impair growth. While they exhibit high phenotypic plasticity and can adapt to varying O<sub>3</sub> levels, chronic exposure may still reduce their effectiveness in phytoremediation (Fig. 1).

Despite the growing body of research on terrestrial systems, there is a notable lack of information regarding the impacts of CO<sub>2</sub>, O<sub>3</sub>, and pH fluctuations on aquatic phytoremediation. However, possible scenarios can be inferred. For instance, pharmaceuticals can be cleaved by ozonation and pH changes [119,120]. Thus, increased atmospheric CO<sub>2</sub> (leading to water acidification) and higher O<sub>3</sub> levels could enhance the degradation of organic contaminants, potentially aiding in their removal from water bodies. This suggests that elevated CO<sub>2</sub> and O<sub>3</sub> may affect plant health and growth; they could also contribute to the breakdown of certain pollutants, offering a mixed but potentially beneficial impact on phytoremediation in aquatic environments.



## 6 Prediction of the Overall Effect of Climate Changes

The overall effect of climate change on the phytoremediation capacity of aquatic plants is complex and multifaceted. Based on current research, several predictions can be made. First, under moderate climate change, aquatic plants are likely to enhance their growth and uptake of contaminants. Mild temperature and CO<sub>2</sub> levels increase are expected to improve photosynthesis and development, boosting the plant's ability to absorb and sequester contaminants. Additionally, optimal light conditions and moderate pH changes can further enhance these capabilities, making phytoremediation more efficient under such conditions. However, the situation changes drastically under extreme climate conditions. Extreme temperatures, high salinity, elevated O<sub>3</sub> levels, and severe pH fluctuations can induce significant stress in aquatic plants. This stress reduces growth and, consequently, the capacity for phytoremediation. Moreover, the increased frequency and intensity of extreme weather events, such as droughts and floods, can disrupt water availability and oxygen levels, compromising the effectiveness of phytoremediation.

The interactions between various climate factors also play a crucial role. There is a delicate balance between synergistic effects, such as CO<sub>2</sub> fertilization and moderate temperature increases, and antagonistic effects, such as oxidative stress from elevated O<sub>3</sub> levels and extreme temperatures. This balance will ultimately determine the net impact on phytoremediation. Plants with robust adaptation and resilience strategies, including enhanced antioxidant defenses and metabolic adjustments, will be better equipped to mitigate the negative consequences of climate change and take advantage of any positive effects. Overall, the future of phytoremediation in the context of climate change will depend on the interplay of these various factors and the ability of aquatic plants to adapt to the changing environment.

## 7 Conclusion and Future Perspectives

The analysis presented in this review highlights the significant impacts of climate change on the phytoremediation capabilities of aquatic plants. The analysis presented in this review highlights the significant effects of climate change on the phytoremediation capabilities of aquatic plants. With fewer studies exploring phytoremediation in water compared to soil, it is evident that the aquatic dimension of this technology remains underexplored, particularly in the context of the complex interactions between climate variables. The multifaceted impacts of increased CO<sub>2</sub> and O<sub>3</sub> levels, temperature fluctuations, and pH changes pose significant challenges and opportunities for utilizing aquatic macrophytes in environmental remediation. Moderate climate changes, such as slight temperature and CO<sub>2</sub> level increases, can enhance photosynthesis, growth, and contaminant uptake, thereby improving phytoremediation efficiency. However, extreme conditions, including high temperatures, elevated salinity, and severe pH fluctuations, can induce stress in aquatic plants, reducing their growth and remediation capacities. Moreover, the interactions between these various climate factors can synergize or antagonize the plants' phytoremediation abilities. The balance of these effects will depend on the plants' inherent adaptive and resilience mechanisms, such as antioxidant defenses and metabolic adjustments.

Given the complexity of these interactions, future research should focus on understanding the detailed physiological and biochemical responses of different macrophyte morphotypes under varying climate scenarios. This knowledge is crucial for developing adaptive management strategies to optimize phytoremediation efforts in the face of ongoing climatic shifts. Additionally, investigating the long-term effects of climate-induced changes on the microbial communities associated with aquatic plants, which play a crucial role in supporting phytoremediation, is essential for enhancing the resilience of these systems. Continued research and innovation are necessary to ensure the effectiveness of phytoremediation practices in a rapidly changing world. Developing resilient phytoremediation systems that can adapt to and thrive under extreme climate conditions will be vital for enhancing water quality, promoting ecosystem health, and ensuring the sustainability of these practices. By addressing these challenges, we

can better harness the potential of aquatic macrophytes to mitigate the environmental impacts of climate change and contribute to preserving global water resources.

The findings of this review have practical implications for managing water bodies and developing sustainable environmental remediation practices. By identifying the specific conditions under which phytoremediation is most effective, this study provides a foundation for designing adaptive management strategies that can be implemented to mitigate the impacts of climate change on water quality and ecosystem health. Future research should continue to build on these findings, focusing on translating scientific insights into practical applications that can enhance the resilience and effectiveness of phytoremediation systems in a warming world.

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