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Review of Harmful Algal Blooms in the Kenyan Major Freshwater Lakes: Impacts on Local Community Livelihoods and Sustainable Mitigation Strategies

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Abstract

Harmful algal blooms (HABs) have emerged as a major environmental and socio-economic challenge in Kenya's freshwater ecosystems, particularly in lakes such as Victoria, Naivasha, and Baringo. These blooms, driven by nutrient enrichment, climate change, and land-use changes, threaten water quality, biodiversity, and the livelihoods of dependent communities. This review aims to synthesize existing literature on the causes, impacts, and mitigation of HABs in Kenya's freshwater ecosystems, with a focus on their implications for community livelihoods and ecosystem sustainability. A systematic review approach was employed, drawing on peer-reviewed journal articles, government and NGO reports, and regional case studies published between 2003 and 2025. The analysis categorizes findings into four key themes: (1) Freshwater lakes affected by HABs in Kenya (2) Causes and contributing factors of HABs in the Kenyan Freshwater Lakes including nutrient enrichment and climate change; (3) ecological and socio-economic impacts, particularly on fisheries, aquaculture, and public health; and (4) mitigation and, management strategies, highlighting both policy frameworks and community-based interventions. The findings reveal that while Kenya has made strides in freshwater management, challenges persist due to inadequate monitoring, weak enforcement of water quality regulations, and limited community awareness. Sustainable solutions are critical for long-term management. Eco-friendly agricultural practices, constructed wetlands for wastewater treatment, and community-based monitoring programs offer promising approaches. Combining scientific research with traditional knowledge could enhance resilience and adaptive strategies. The review recommends improved policy coordination, investment in green technologies such as bioremediation, and enhanced public education to reduce nutrient loading. Overall, this paper underscores the urgent need for a multidisciplinary approach to address HABs in Kenya's freshwater ecosystems. By linking ecological health to community well-being, the review contributes to the broader discourse on sustainable freshwater resource management in sub-Saharan Africa.

Keywords: Harmful algal blooms, freshwater ecosystems, cyanotoxins, livelihoods, mitigation strategies, Kenya

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Introduction

Algal blooms are a natural phenomenon that occurs when populations of algae rapidly increase in water reservoirs. These blooms can occur in various environments, such as oceans, bays, and freshwater systems. Algal blooms can be harmless or harmful, depending on the species involved and the environmental factors that trigger them. Because of their autotrophic way of life, they have colonized a variety of habitats, from the predictable, flexible, and advantageous niches, such as freshwater lakes and rivers, to the harsh, unfavorable environments, such as hot springs and deserts (Igwaran et al., 2024). Harmful algal blooms (HABs) are complicated phenomena that are usually caused by a complex web of interactions between various environmental elements rather than a single environmental source. Toxin-producing algae are caused by species such as cyanobacteria or dinoflagellates. Cyanobacteria, a form of photosynthetic bacteria commonly referred to as blue-green algae, frequently induce algal blooms in freshwater and, on occasion, in marine environments (NOAA, 2025).

Globally, HABs have increased due to climate change, eutrophication, and land-use changes (Woolway et al., 2021) affecting freshwater and marine ecosystems across all continents (Paerl & Otten, 2016; Chorus & Welker, 2021). Several factors, including temperature, nutrient availability, light intensity and duration, bio-physiological and chemical traits, ecology, and episodic hydrological events (droughts and floods) are responsible for bloom formation (Kimambo et al., 2019). In many parts of the world, HABs disrupt drinking water supplies, impair fisheries, and reduce ecosystem resilience, posing serious challenges to sustainable water management (Anderson et al., 2021). Cyanobacteria is a recognized phenomenon, and several incidences have been reported in more than 25 countries, including India, Italy, Germany, Netherlands, Sweden, Greece, USA, China, Madagascar, Algeria, Ghana, Ethiopia, Zimbabwe, Botswana, Egypt, Cameroon, Mozambique, Uganda, Sudan, Kenya, Senegal, Burkina Faso, Lesotho, Morocco, Nigeria, South Africa, Tanzania and Tunisia (Ndlela et al., 2016). For example, Lake Erie, the North American Great Lake is the 11th largest lakes by surface area and is plagued by toxic harmful algal blooms; it is a temperate system dominated by agricultural nutrient pollution (African Center for Aquatic Research and Education, 2022).

In Africa, major freshwater bodies such as Lake Victoria, Lake Tanganyika, and Lake Malawi have experienced frequent HAB outbreaks (Sitoki et al., 2012). The growth of a Microcystis cyanobacterial bloom in Lake Loskop, South Africa, during the midsummer peak rainy season was associated with elevated nutrient concentrations, notably 0.7 mg/l orthophosphate and 17 mg/l nitrogen (Elidrissi et al., 2024). Elidrissi also reported that in March 2009, when temperatures ranged from 21 to 26 °C, Lake Nhambavale in Mozambique recorded a high total MCs content (7.89µg/L). In 2012, Stoyneva-Gärtner et al in their study illustrates that in contrast, Lake Edward has a wide variety of cyanobacteria taxa, including a sizable percentage of heterocytous forms, and the input from the hypereutrophic Kazinga Channel does not seem to provide an inoculum to Lake Edward, which has a different microflora, Lake George and its connection to Lake Edward, the Kazinga Channel, are essentially dominated by colo-Nial coccoid cyanobacteria. These outbreaks not only degrade aquatic habitats but also endanger the livelihoods of millions who depend on inland waters for fisheries, drinking water, and irrigation. Freshwater ecosystems in Kenya include lakes, rivers, reservoirs, and wetlands. These freshwater bodies are essential for biodiversity, livelihoods, and economic activities such as agriculture, fisheries, and tourism (Chorus & Welker, 2021). Major freshwater lakes include Lake Victoria, Lake Naivasha, and Lake Baringo (Sitoki et al., 2012), which play a critical role in providing potable water, supporting fisheries, and sustaining biodiversity. All the subsistence communities around these water bodies depend directly on near-shore water (Mbonde et al. 2015). However, increasing incidences of harmful algal blooms (HABs) pose significant threats to these aquatic environments, affecting their ecological integrity, economic value, and public health (Paerl & Otten, 2016). The dominant cyanobacteria HABs in Kenyan freshwater bodies include *Microcystis spp.*, *Anabaena spp.*, and *Dolichospermum spp.*, which are capable of producing toxins which can produce toxins with severe ecological and health implications (Ndlela et al., 2016; Pawlik-Skowrońska et al., 2022). Lake Victoria has experienced massive cyanobacterial blooms, primarily due to eutrophication and rising water temperatures (Mutebi et al., 2022). Similarly, Lake Naivasha has witnessed recurrent algal proliferation linked to agricultural runoff and inadequate wastewater treatment (Harper et al., 2011).

The ecological and socio-economic impacts of these HABs include fish kills, biodiversity loss, and contamination of drinking water sources (Ndlela et al., 2016). The HABs decrease primary productivity by limiting light penetration contributing to a loss of fish production through “productivity-nutrient continuum.” The process would be reinforced by oxygen depletion of the deeper waters causing fish kills, and biodiversity loss (Sitoki et al., 2013). Fishing is one of the risk activities for developing health problems associated with HABs, due to the frequency of water contact and use during fishing (Mchau et al., 2019). In addition, human health is at risk due to the potential contamination of drinking water and fish stocks, leading to conditions such as gastroenteritis and liver damage (Chorus & Welker, 2021).

Researchers, decision-makers, and local communities are very concerned about the growing incidence and severity of HABs in Kenya's freshwater lakes (Sitoki et al., 2012). Although several localized studies have investigated HAB dynamics in individual Kenyan lakes, there remains a critical gap in synthesizing their ecological and socio-economic impacts at the national scale. Specifically, there is limited integration of scientific findings on HAB drivers, community livelihood implications, and the sustainability of existing mitigation strategies. Effective mitigation solutions are needed because climate change is worsening the situation by changing precipitation patterns and raising water temperatures (Woolway et al., 2021). Therefore, sustainable watershed management techniques, increased monitoring, and regulatory enforcement are necessary to address concerns about HABs. Tropical HABs persist throughout the seasons, making control more difficult than in temperate settings (Roegner et al., 2021).

In this review, we attempt to fill the gap by providing a thorough examination of the prevalence, causes, and effects of HABs in the context of the frequent occurrence of algal blooms documented in freshwater lakes in Kenya. It highlights recent advancements, points out knowledge gaps, and makes recommendations to help management in the future. It outlines current mitigating techniques and offers suggestions for efficient algal bloom management and control. To sustainably manage Kenya's freshwater resource, addressing the HAB issue requires a multidisciplinary strategy that includes scientific research, policy measures, and community engagement.

Methodology

This review employed a systematic literature review approach to collect, evaluate, and synthesize existing research on harmful algal blooms (HABs) in Kenya's freshwater ecosystems. Relevant literature published between 2003 and 2025 was retrieved from peer-reviewed journals, government and NGO reports, and academic databases such as Scopus, Web of Science, and Google Scholar. Search terms included "harmful algal blooms," "cyanobacteria," "eutrophication," "Kenya," "Lake Victoria," "Lake Naivasha," "Lake Baringo," and "freshwater ecosystems."

Inclusion criteria focused on studies addressing HAB drivers, ecological and socio-economic impacts, and mitigation or management strategies. Data were synthesized thematically, allowing for cross-lake comparisons of causes, impacts, and management responses. This approach enabled the identification of common patterns, region-specific challenges, and knowledge gaps in Kenya's HAB research landscape. Freshwater Lakes Affected by HABs in Kenya.

Findings and Discussion

Causes and Contributing Factors of HABs in the Kenyan Freshwater Lakes

1. Nutrient Enrichment and Eutrophication

Excess nutrient input from agricultural runoff, sewage discharge, industrial waste, and erosion from deforested catchments accelerates algal growth (Fiorella et al. 2017; Hart LN et al., 2025), leading to eutrophication. The enrichment of water bodies with nutrients and minerals, particularly phosphorus (P) and/or nitrogen (N), typically above their thresholds, is known as eutrophication (Igwaran et al., 2024). A large portion of this nutrient increase can be attributed to heavy rainfall, the allochthonous fluvial nutrient inputs from agricultural, and urban areas in the catchment (Sitoki et al., 2012), sewage discharge, and deforestation to the lake has persistently led to algal bloom, especially in Winam Gulf, Lake Victoria (Zepernick et al., 2024). Soaps and detergents used within the basin also directly contribute to eutrophication (Odada et al., 2006). Odada et al (2006) also added that nutrient loads account for about 90% of the phosphorus and 94% of the nitrogen input into the lake and are associated mainly with atmospheric deposition and land runoff.

Excess nutrients stimulate the growth of phytoplankton, especially cyanobacteria, which can outcompete other algae due to their buoyancy regulation and nitrogen-fixation capabilities (Paerl et al., 2016). Nitrogen enrichment can exacerbate bloom severity and toxin production, especially in nitrogen-limited systems (Paerl et al., 2011). Metagenomic analyses reveal that Dolichospermum employs nitrogen fixation to thrive in nitrogen-limited environments, while Microcystis produces hepatotoxic microcystins (Hart LN et al., 2025). Phosphorus has traditionally been considered the limiting nutrient in freshwater systems. Schindler et al. (2008) demonstrated through long-term whole-lake experiments that phosphorus input alone is sufficient to trigger cyanobacterial blooms. Micronutrients such as silicon and iron are also vital for growth; yet, some may not be limiting factors but rather stimulatory. For instance, *Microcystis spp.* possesses iron-binding molecules known as siderophores, which bind ferric ions to create soluble iron-siderophore complexes that mimic Fe^{2+} (Nwankwegu et al., 2019).

The phytoplankton community in Winam gulf, Lake Victoria, changed from a diatom flora to one dominated by cyanobacteria, and increased macronutrient concentrations (Sitoki et al., 2013). The increase in nutrient content led to shifts in the diatom community from the dominance of *Aulacoseira* to the supremacy of *Nitzschia* and from the dominance of green algae (Chlorophyta) and large diatoms (Bacillariophyta) to the dominance of cyanobacteria (Olokotum et al., 2020). Both western Lake Erie and Kisumu Bay, Nyanza Gulf, Lake Victoria are similar in that they are shallow systems that experience heavy nutrient pollution, which results in annual Microcystis-dominated toxic harmful algal blooms (African Center for Aquatic Research and Education, 2022).

(i) Agricultural Runoff

The primary anthropogenic drivers of HABs in freshwater ecosystems include excessive nutrient loading from agricultural runoff, industrial discharge, and sewage discharge (Fiorella et al. 2017). One of the ways excessive nutrients enter water is through agricultural runoff (from animal manure and chemical fertilizers that get washed from farms by rain). Recent research indicates that fish in Lake Victoria exhibit varying concentrations of organochlorine pesticide residues, which reflect the transfer of agrochemical residues from agricultural lands within the catchment area via rivers to the lake. Kisumu Bay, Lake Victoria, is a tropical system that receives a mixture of urban and agricultural nutrient pollution (African Center for Aquatic Research and Education, 2022). The transformation of Lake Naivasha from eutrophic to hypereutrophic status due to increased fertilizer imports is evident, as phosphorus contents have risen about threefold compared to measurements taken in a 2002 research (Onyango et al., 2024).

Significant amounts of nitrogen and phosphorus are added to the soil by the use of synthetic fertilizers. Cereal crops require high nitrogen and phosphorus, leading to increased nutrient runoff when fertilizers are over-applied or applied improperly. In contrast, legume crops reduce nitrogen runoff but still risk phosphorus loss (Lan et al., 2024). Excess nutrients that are not absorbed by crops are vulnerable to being washed away by irrigation or rainfall; this runoff can eventually reach coastal marine environments through drainage systems, rivers, and streams (Lan et al., 2024). For instance, due to poor farming practices on the Turgen hills surrounding Lake Baringo, whenever it rains, flash floods occur from inflowing rivers driven by altered land cover in the Lake catchment, which has increased erosion and sediment transport to the lake (Ochuka et al., 2019).

Agrochemical runoff from floriculture and intensive agriculture has contributed to algal blooms, leading to oxygen depletion and fish mortality. The declining water quality threatens the sustainability of the lake’s commercial fisheries and biodiversity (Harper et al., 2011). The use of agrochemicals has increased in the lake basin where large-scale farms of coffee, tea, cotton, rice, maize, sugar, and tobacco are located, and their effluents are drained through wetlands before reaching the lake (Odada et al., 2006). For example, in Lake Naivasha, the 50 km^2 surrounding the lake is home to a flourishing horticultural industry (Onyango et al., 2024), particularly floriculture (Jimoh et al., 2007), which raises the possibility of applying N and P fertilizers. The surrounding watershed has experienced rapid agricultural growth due to the displacement of local small-scale businesses by large-scale international farming operations (Zepernick et al., 2024). According to a study by Onyango et al. (2024), the Lake Naivasha catchment's population density exceeds 600 persons per km^2, necessitating smaller land holdings and increased nutrient and pesticide application for smallholder farmers. Agriculture in the Lake Naivasha catchment is diverse, including horticulture, animal rearing, and crop production. This affects the possible movement of pesticides and nutrients from land to water, as well as the condition of the rivers and lakes' ecosystems (Onyango et al., 2024). The possibility of excessive nutrient and pesticide runoff or leakage from agricultural fields into neighboring water bodies is unavoidable, given the higher nutrients and pesticides levels observed compared to earlier research and the increased land use for crops (Onyango et al., 2024). Elidrissi et al. (2024) reported that cyanobacteria co-occur with other cyanotoxins, such as MCs, ATX in Lake Naivasha, Kenya, and NOD and MCs in Lake Victoria.

(ii) Industrial Pollution

Wastewater discharge, septic leaks, and industrial waste runoff contribute to nutrient loads, playing a crucial role in the development of HABs. Major sectors from which untreated effluent is derived include beer-brewing, pulp and paper production, fish processing, agro-processing, and abattoirs, which discharge raw/untreated waste into rivers and lakes (Odada et al., 2006; Nyamweya et al., 2023). There will likely be further degradation of the water quality due to the ongoing global population growth and human demand on water bodies (Igwaran et al., 2024). The shift from small-scale to large-scale industrial production, and from small to large farms (Odada et al., 2006).

Uncontrolled disposal of mining tailings, industrial wastes, expired pesticides, medical waste, petrol station wastes, bunkering wastes, and banned substances like DDT into lakes is a significant issue (Odada et al., 2006).

2. Climate Change

Climate change has significantly contributed to the increasing growth rate, frequency, and intensity of HABs in Kenya's freshwater ecosystems, threatening aquaculture productivity and sustainability (Rolton et al., 2022).

(i) Rising Water Temperature

CyanoHABs, which develop in warm, stagnant water, are anticipated to escalate in intensity and duration as a result of climate change-induced increases in water temperature (U.S. Environmental Protection Agency, 2025).

Rising temperatures increase the stratification of the water column, which reduces vertical mixing (Winder & Sommer, 2012). This leads to the formation of nutrient-rich surface layers where algae can proliferate. Reduced mixing also means lower turbulence, which favors the growth of harmful algal species that thrive in stable, calm water conditions (Huisman et al., 2004). A greater degree of water column stratification in Lake Victoria is caused by seasons with the least amount of rainfall; under stratifying conditions, buoyant cyanobacteria have a selective advantage over non-motile algae (Okello & Kurmayer 2011). Additionally, stratification of lakes during warm seasons enhances surface stability and creates low-turbulence zones that benefit buoyant cyanobacteria (Paerl & Huisman, 2008).

Elevated temperatures enhance the growth rates of harmful algal species, prolong bloom duration, and increase toxin production (O'Neil et al., 2012), leading to severe ecological and public health risks (Woolway et al., 2021). The growth of cyanobacteria is favored due to their higher thermal tolerance compared to other phytoplankton. The cumulative effects of these on Lake Baringo's thermal stratification and mixing regimes further concentrate nutrients in the photic zone, thereby creating a more conducive environment for cyanobacterial dominance and subsequent bloom development (Feng et al., 2024). Some harmful algae produce more toxins at higher temperatures. For example, cyanobacteria such as *Alexandrium spp*. and *Cylindrospermopsis raciborskii* are known to increase their toxin production in warmer waters (Paerl & Huisman, 2008). This makes blooms not only more frequent but also more dangerous to aquatic life and humans (Gobler et al., 2017).

Rising temperatures enable harmful algal species to expand their range towards the poles, colonizing new areas that were previously too cold. This geographical shift increases the occurrence of HABs in regions that were not historically affected (Moore et al., 2008). On the other hand, warmer waters also create favorable conditions for the invasion of harmful algal species into new ecosystems, where they may encounter fewer predators or competitors, leading to more severe blooms (O'Neil et al., 2012). Rising water temperatures, create optimal conditions for the proliferation of cyanobacterial genera, thereby exacerbating the frequency and intensity of harmful algal blooms in Lake Naivasha.
Alternatively, in some higher latitude regions, stronger stratification may isolate phytoplankton cells in a relatively calm, upper ocean layer with elevated nutrients. This regime might favor diatoms over dinoflagellates, given the more rapid growth rates of diatoms exposed to high nutrient levels (Gobler et al., 2017). Reduced mixing and tidal occurrences facilitate both hypoxia and anoxia in freshwater ecosystems, both of which significantly promote the proliferation of cyanobacterial harmful algal blooms (cyanoHABs) (Nwankwegu et al., 2019).

(ii) Effects of extreme hydrological events on nutrient cycling

Extreme hydrological events, such as droughts, storms, and floods, also influence the occurrence of HABs. Droughts reduce water levels, leading to higher concentrations of nutrients and increased water residence time, which enhances bloom formation (Chorus & Welker, 2021). Intense rainfall and flooding affect nutrient runoff dynamics from agricultural lands and urban areas (Ndlela et al., 2016), increasing nitrogen and phosphorus inputs into the freshwater systems, which further promote HAB development (Mutebi et al., 2022; Igwaran et al., 2024).

Climate change and hydrologic changes, when combined with high nutrient loads, help HABs achieve ideal magnitude and amplitude with long-term dominance (Nwankwegu et al., 2019). Storms and floods can introduce additional nutrients and potentially disrupt existing ecosystems, creating conditions more conducive to bloom formation (Paerl & Huisman, 2009).

More frequent droughts can concentrate pollutants resulting in episodic elevations of nutrient concentrations, promoting stratification and bloom production in slowly replenishing lotic systems (Nwankwegu et al., 2019).

(iii) Increased Carbon Dioxide

Climate change may cause water to become more acidic, which increases dissolved CO_2 and promotes photosynthesis in cyanobacteria (Igwaran et al., 2024). Atmospheric carbon dioxide (CO_2) concentrations have risen from 275 to 400 parts per million (ppm) since the beginning of the industrial revolution, and climate change predictions indicate that atmospheric CO_2 levels will continue to rise, reaching about 950 ppm by the year 2100 (Elidrissi et al., 2024). Algae, especially cyanoHABs, which can float to the top and use the extra carbon dioxide, can develop more quickly in environments with higher carbon dioxide levels (U.S. Environmental Protection Agency, 2025). Algal species competition and grazing creatures are impacted by this increase in water acidity. The abilities of freshwater cyanobacteria to produce a variety of hepatotoxic and neurotoxic compounds have made them widely known (Okello & Kurmayer 2011). Because of their effective carbon-concentrating mechanism at a higher pH, cyanobacteria are better competitors (Okello et al., 2010).

3. Land Use Changes and Deforestation

The East African Community, comprising seven sovereign states to a greater extent, is characterized by eutrophic water bodies, which have unfortunately been subjected to severe land use charges and pollution pressure, which may result in a rise in cyanobacteria instances (Omara et al., 2023).

(i) Deforestation Effects on Sedimentation and Nutrient Flow

Deforestation and urban expansion have led to increased soil erosion and nutrient runoff into freshwater ecosystems (Harper et al., 2011). Deforested watersheds contribute higher sediment loads, altering light penetration and nutrient cycling, which favor HAB development. Unsustainable land management practices, including deforestation and overgrazing in the Lake Baringo basin, exacerbate soil erosion, leading to increased sediment and nutrient loading into the lake, thereby promoting algal proliferation and increasing turbidity (Paerl et al., 2018; Onyango et al., 2024).

Increased soil erosion and nutrient runoff are the results of unsustainable land-use practices; Burning forests and increased dust from soil erosion are blamed for the high atmospheric nutrient loading (Odada et al., 2006). The combustion of fossil fuels, deforestation, and land development contribute to increasing atmospheric carbon dioxide levels. This promotes detrimental algal blooms, as cyanobacteria may utilize carbon dioxide which is available not just at the water's surface but also dissolved inside the water. As algae die and sink to the bottom of a freshwater body, they break down and release carbon that had been stored, giving cyanobacteria more fuel to proliferate (NRDC, 2019).

(ii) Urbanization

Over time, Kenya's population has increased, and land use resources have increased by approximately 75% of Kenyans work in agriculture, while only 20% of the country's land is arable (Ochuka et al., 2019). There is a rapid growth of urban and peri-urban which are largely unplanned; many buildings are erected without authorization within the wetlands. Lakes are becoming increasingly contaminated due to population growth, poorly planned development along riverbanks, and excessive use of various agrochemicals in the surrounding regions of watersheds (Madzivanzira et al., 2023). Wastewater disposal is increasingly problematic in African nations since significant amounts of municipal waste and industrial effluent, both containing very high nutrient levels, are generated due to increased industrialization and urbanization (Madzivanzira et al., 2023). In Lake Victoria basin, untreated wastewater discharged into rivers and the lake from industrial operations, including the pulp and paper industry, food processing, textiles, sugarcane processing, alcohol distilleries, and other informal sectors, could be a source of pollution (Nyamweya et al., 2023). Untreated urban wastewater and fish cage aquaculture in Lake Victoria, release nutrient-rich effluents that exacerbate eutrophication (Mbonde et al., 2015). Continuous increase in wastewater discharge, mostly from the East and South-east sides of the gulf, further increased trophic conditions across the gulf (Sitoki et al., 2012).

Increased settlements around Lake Naivasha have amplified nutrient runoff, particularly phosphorus and nitrogen, into the lake, creating an ideal environment for cyanobacterial blooms (Onyango et al., 2024). This nutrient enrichment from urban sources exacerbates eutrophication, fostering the proliferation of CyanoHABs that detrimentally alter the aquatic food web and degrade critical fish habitats (Paerl et al., 2018; Gobler et al., 2024).

4. Socio-Economic and Ecological Impacts of HABs

(i) Impact on Fisheries and Aquaculture

Fish kills

HABs contribute to fish kills, habitat degradation, and reduced fish stock, negatively affecting fisheries and aquaculture industries (Paerl & Otten, 2016). Some HABs produce potent toxins that directly harm fish by damaging gills, disrupting neurological functions, or causing other physiological harm (Oh et al., 2023). For example, the dinoflagellate *Karenia mikimotoi* can cause severe gill damage, abnormal fish behavior, and ultimately death, even in waters with high dissolved oxygen (Oh et al., 2023). These toxins produced by HABs compromise fish health, leading to economic losses among communities dependent on fishing as a primary livelihood (Ndlela et al., 2016). HABs are the poisoning of shellfish and fish, which can lead to severe health effects when consumed by humans.

Karenia spp. (e.g., *K. brevisulcata, K. selliformis*) has caused major fish and shellfish mortalities in NZ due to toxins like brevetoxins and gymnodimine (Rolton et al., 2022). *Alexandrium spp.* (e.g., *A. pacificum, A. minutum*) cause sublethal effects on shellfish (e.g., reduced byssus production, paralysis) and have potential neurotoxic effects on fish (Rolton et al., 2022). *Pseudo-nitzschia spp.* produces domoic acid, which can accumulate in shellfish and affect feeding behavior and immunity (Rolton et al., 2022).

The effects of eutrophication include extensive phytoplankton blooms, which resulted to massive fish kills, and near-shore belts of water hyacinth *Eichhornia crassipes* were observed in Lake Victoria (Sitoki et al., 2012). Due to the cascading effects of the loss of phytoplanktivorous species, the nearly total extinction of the endemic fishes, particularly the phyto- and zooplanktivorous haplochromines, had a significant ecological impact and most likely exacerbated the eutrophication process (Sitoki et al., 2013).

Habitat Degradation

Non-toxic HABs disrupt ecosystems, fisheries resources, and recreational facilities, often due to the high biomass of accumulated algae, which can create noxious scums and foam, shade other phytoplankton and seagrass beds, and cause faunal mortalities through decay and oxygen depletion (Anderson et al., 2017). Oxygen deficiency (hypoxia) exerts a dual impact: on a macro scale, it restricts species distribution in the aquatic environment and compels alterations in behavior; on a micro scale, it induces physiological changes that affect lifecycle performance, reproductive capacity, growth potential, and susceptibility to diseases (Madzivanzira et al., 2023). The presence of harmful algal blooms increases oxygen depletion (resulting from bacterial degradation of dead algal biomass), further degrading the water quality (Igwaran et al., 2024), causing the loss of ecologically and economically important species.

Harmful algal blooms, particularly cyanobacteria change the energy flow of the food webs in aquatic environments, affecting the aquatic ecosystem's health and causing biodiversity loss (Paerl & Otten, 2016). The depletion of herbivorous fish species that graze on algae has disrupted ecological balance, enabling algal blooms to flourish unchecked (Mbonde et al., 2015). Overfishing in Lake Victoria, for instance, has reduced populations of algae-feeding fish, further exacerbating bloom formation. Zooplanktons, which typically control algal growth, may inadvertently promote HABs by shunting nutrients toward toxin-producing species under nutrient-stressed conditions (Mitra & Flynn, 2006). This creates a feedback loop where HABs outcompete non-toxic algae, leading to persistent blooms.

High concentrations of phytoplankton and particulate matter (dense algal blooms) reduce light penetration in the water column, which impacts photosynthetic organisms like benthic algae (Lan et al., 2024). This habitat degradation extends to the accumulation of cyanotoxins within the aquatic food web, posing a chronic threat to higher trophic levels and potentially impacting the overall ecological stability of Lake Naivasha (Musa et al., 2022; Igwaran et al., 2024). Blooms prevent light penetration, which affects fish migratory and food sources and further reduces fish populations (Obuya et al., 2023). The mass proliferation of harmful algal blooms not only increases turbidity in eutrophic lakes but also inhibits the establishment and growth of aquatic macrophytes, thereby harming the underwater ecosystem for many species of fish and invertebrates (Paerl & Huisman 2012). Dense surface blooms of cyanobacteria may increase water temperatures by absorbing light intensively through their photosynthetic and photoprotective pigments.

The transparency of the water also declined, partly due to the increased algal blooms and partly due to silt carried in by the rivers, and this has been implicated in the decline of the haplochromines by interfering with their mating behaviour, which is highly dependent on visual cues (Sitoki et al., 2013).

Economic Losses for Fisherfolk

HABs disrupt fish stocks and deter exports, jeopardizing food security and incomes. The harmful algal blooms cause substantial damage by reducing fish stocks, limiting harvests, leading to significant losses in the fishing sector, and causing considerable economic repercussions (Madzivanzira et al., 2023). Fish kills in Winam Gulf, Lake Victoria and Lake Naivasha, for instance, have led to reduced fish catches and income losses among artisanal fishers (Harper et al., 2011). Declining fish stocks have forced many small-scale fishers to seek alternative livelihoods, thereby impacting food security and economic stability in the region. Fishermen and households who rely directly on fishing for their livelihoods and protein suffer financial losses due to biofouling of fishing gear and boats, which reduces their efficiency (Obuya et al., 2023). Declining fish availability also forces traders particularly women who dominate post-harvest handling to travel farther or pay higher prices, thereby reducing profit margins and food security.

HABs cause lakes, reservoirs, and rivers to become unsightly, and at times, dangerous, reducing tourism, recreation, commercial fishing, and property values and increasing water quality monitoring, management, and treatment costs (NRDC, 2019).

(ii) Public Health Risks

Consumption of contaminated water and disease outbreaks

Cyanobacteria such as *Microcystis aeruginosa* and *Anabaena flos-aquae*, commonly recorded in Kenyan freshwatervlakes, produce potent toxins including microcystins and anatoxins. According to Roegner et al (2021), 50% of households rely solely on contaminated lake water, lacking alternatives like boreholes or treated supplies. There is several human health effects linked to direct exposure to toxigenic HABs through skin contact and direct consumption, mainly from contaminated, untreated or treated water (Olokotum et al., 2022). Consuming crops irrigated with water contaminated with cyanotoixins is an additional pathway for human exposure to cyanotoxins (Madzivanzira et al., 2023).

Toxins from cyanobacteria and airborne phytoplankton can cause dermatitis, rhinitis, asthma, allergies, and bronchitis (Igwaran et al., 2024). Additionally, fisher populations may experience skin irritation from lipopolysaccharides and other substances, unpleasant odor and taste compounds, and direct gastrointestinal impacts from unintentional oral consumption while bathing or recreation (Roegner et al., 2021). The toxins produced by these algae can cause liver damage, neurotoxicity, and gastroenteritis in humans and animals (Mbonde et al., 2015; Chorus & Welker, 2021). A great diversity of cyanobacterial species has been documented in Lake Victoria dominated by *Microcystis spp.* in Winam Gulf (Sitoki et al., 2012; Olokotum et al., 2020; Obuya et al., 2023). The blooms have led to fish kills, hypoxia, and contamination of drinking water, affecting millions of people reliant on the lake for water and livelihood (Sitoki et al., 2012).

Cyanotoxins released by HABs pose serious health risks to humans through contaminated drinking water, recreational exposure, and bioaccumulation in aquatic organisms (Sitoki et al., 2012). Major cyanobacterial species responsible for HABs in Kenya *include Microcystis spp.*, *Anabaena spp.*, *Microcystis aeruginosa*, *Anabaena flos-aquae*, *Dolichospermum spp.*, and *Cylindrospermopsis raciborskii*

(Sitoki et al., 2012; Paerl & Otten, 2016). They produce potent toxins like cyclic hepatotoxic peptides (microcystins, nodularins), dermatoxic, cytotoxic, genotoxic, or neurotoxic alkaloids, polyketides, and amino acids (lyngbyatoxin-a, cylindrospermopsins, anatoxins, saxitoxins, aetokthonotoxin, lipopolysaccharides (endotoxins), guanitoxin, beta-N-methylamino-L-alanine, and aplysiatoxins microcystins, anatoxins, and cylindrospermopsin (Codd et al., 2005; Roegner et.al., 2021; Omara et al., 2023). The toxins produced by these algae can cause liver damage, neurotoxicity, and gastroenteritis in humans and animals (Chorus & Welker, 2021).

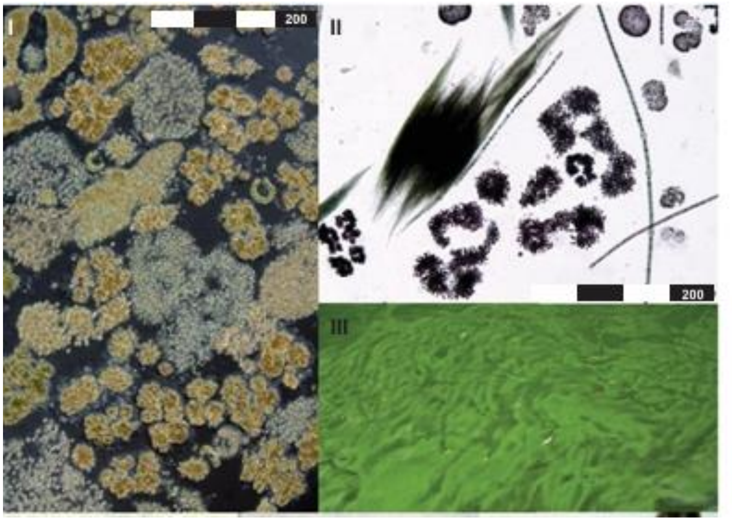
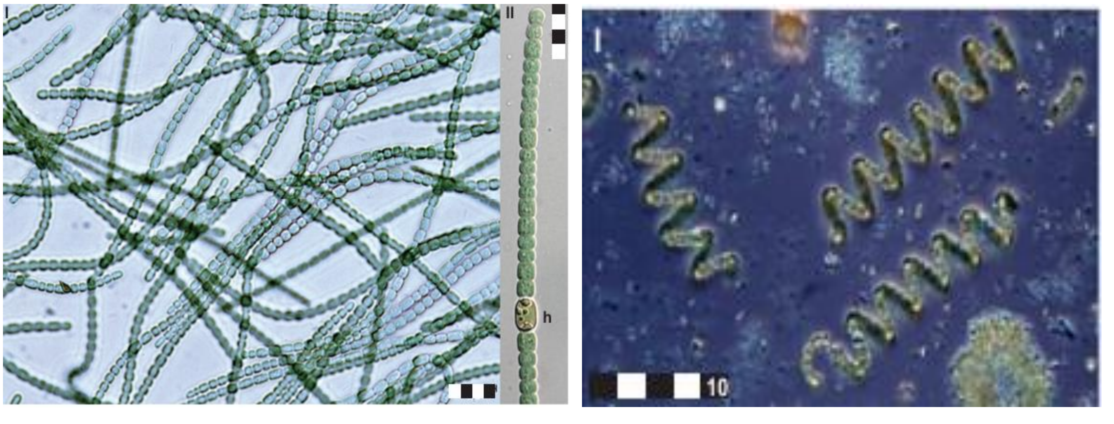


Figure 1: *Microcystis sp.* (I) natural sample; (II) typical plankton community consisting of *Aphanizomenon flosaquae* fascicles, Microcystis colonies and *Dolichospermum sp.* trichomes; (III) *Microcystis sp*. surface bloom (Chorus & Welker 2021)



A B

Figure 2: (A). *Anabaena sp.* (B). *Dolichospermum sp.* (Chorus & Welker, 2021).

Microcystins, cyanobacterial toxins, have been detected in studies at levels exceeding the World Health Organization's (WHO) recommended threshold of 1.0 µg/L for drinking water (Roegner et al., 2023). Cyanotoxins resistant to environmental degradation and normal removal methods represent an even greater threat to human health. For example, boiling does not destroy or denature microcystins because they are known to remain stable even at high temperatures (Roegner et al., 2021). Water treatment facilities in Kenyan riparian counties that border the Lake Victoria basin employ a combination of physical, chemical, and biological methods to lower pollutants which has proven to be difficult to remove persistent cyanotoxins like anatoxin and saxitoxin completely, and people frequently turn to collecting untreated lake water directly because of the inconsistent water delivery from treatment facilities to household taps (Obuya et al., 2023).

Toxins affecting livestock and human populations

Human exposure to cyanobacteria toxins can cause several health problems, such as rashes, blistering mouth, conjunctivitis, flu-like symptoms, hives, fever, eye, ear, and skin irritation, visual abnormalities, hepatic failure, and death (Igwaran et al., 2024). Cyanobacterial toxins are classified as hepatotoxins, neurotoxins, cytotoxins, and dermatoxins (irritant dermal toxin) based on the symptoms observed in humans and other vertebrates (Sahoo et al., 2024).

Microcystin produces hepatotoxins that inhibit eukaryotic protein phosphatases in humans. Concentrations of microcystin can have variable consequences for humans, livestock and wildlife on the African continent (Olokotum et al, 2022). Their consumption has been linked to acute side effects such as nausea, diarrhea, and irritations of the skin, eyes, and throat. At the same time, long-term exposure to MCs causes hepatic necrosis, stunted growth, reduced reproduction capacity, and, ultimately, mortality in both humans and fish (Omara et al, 2023). Nearshore HABs provide long-term exposure to MCs, which poses a serious health risk, especially for small children, the elderly, and people with weakened immune systems (Roegner et al., 2021). There have been reports of elevated levels of microcystin in the gut contents of small sun-dried fishes called *Rastineobola argentea*, commonly known as "dagaa," that are given whole to individuals as meals (Fiorella et al. 2017; Roegner et al., 2021).

Anabaena flos-aquae produces anatoxin-a and saxitoxin that lead to neurotoxicity and imitation of the neurotransmitter acetylcholine (Mchau et al., 2019), which can be lethal if consumed by tainted water or dried algal crusts or accidentally swallowed causing burning, tingling, respiratory paralysis, and dysrhythmia (Omara et al, 2023). When anatoxin-a binds to nAchRs, it has an affinity more than 20 times that of acetylcholine and has the same effect as microcystin; that is, it causes a conformational effect on the receptor, opening the channel pore to allow ions (Ca2+ and Na+) to enter the neuron (Omara et al, 2023). A study conducted in 2000, 2002, and 2004 on the mass deaths of Flamingos in three soda lakes (Embakaai Crater, Lake Natron, and Lake Manyara in the Arusha Region) found that cyanobacterial toxins (Anatoxin-a and Microcystins) were the cause (Kimambo et al., 2019).

Cylindrospermopsin produced from *Cylindrospermopsis raciborskii* and *Anabaena spp*. is known to target T lymphocytes, neutrophils, vascular endothelium, the liver, kidneys, heart, spleen, ovary, eye, and lung (Omara et al, 2023). The Cylindrospermopsin toxins are hepatotoxic, cytotoxic, and neurotoxic, which can inhibit glutathione synthesis, protein synthesis, and cytochrome P450 in humans (Mchau et al., 2019).

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(iii) Economic and Livelihood Consequences

Harmful algal blooms have negative economic repercussions through the shutdown of water-related enterprises, a decline in tourism, and higher water treatment expenses. Lake Victoria's fishery employs 200,000 people and contributes 8% of global inland fish harvests (Fiorella et al., 2017). With excessive biomass, anoxia, and odor from algal blooms, the need for water treatment can lead to economic losses (Igwaran et al., 2024), thereby causing damage due to interruptions in water services. The presence of HABs can adversely affect the aesthetics of nearby properties.

The medical costs associated with HABs' intoxication and allelopathy, such as the price of hospitalization and transportation, as well as a notable reduction in everyday productivity (Nwankwegu et al., 2019).

Tourism Sector Disruptions

HABs disrupt local economies by reducing tourism revenue, increasing water treatment costs, and threatening food security (Harper et al., 2011).

A rapid decrease in beach tourists' leisure activities, complete fish harvesting, and fishing closures for recreational fishermen have been shown to have adverse impacts on society, including disturbances to social and cultural customs and financial losses to tourism sectors (Nwankwegu et al., 2019). These eventually disrupt the tourism sector as there is reduced number of tourists visiting the sites. In Lake Naivasha, for example, episodes of algal discoloration and foul odors have coincided with sharp declines in recreational tourism and birdwatching activities, reducing revenue for hotels and tour operators. The economic ripple effects extend to sectors such as floriculture and irrigation agriculture that depend on clean freshwater sources.

Decreases in fishery catch set millions of people's food security at risk in addition to causing financial losses (Obuya et al., 2023).

Reduced Agricultural Productivity Due to Water Contamination

Toxins and biomass from HAB can contaminate groundwater supplies, which can then carry these materials into agricultural soils possibly, deteriorating soil quality (Newton et al., 2023). Communities relying on freshwater resources for agriculture and domestic use (Nyamweya et al., 2023) face additional burdens due to water contamination and loss of aquatic biodiversity (Chorus & Welker, 2021).

In Lake Naivasha, intensive agricultural and floricultural activities contribute to high nitrogen and phosphorus loading through fertilizer runoff, creating conditions favorable for cyanobacterial dominance (Harper et al., 2011). This nutrient influx reduces water transparency and oxygen availability, threatening the floriculture industry that relies on clean water for irrigation and export compliance standards.

Through toxin absorption, HABs can concentrate in edible crop tissue, impeding photosynthesis, seedling development, and sucrose metabolism (Newton et al., 2023). This can eventually cause risk to both humans and animals.

5. Mitigation and Management Strategies

Efforts to mitigate cyanobacteria in Lake Victoria have been implemented, including reducing fertilizer inputs to the lake, monitoring for cyanobacteria, and developing strategies to manage blooms once they occur (Obuya et al., 2023).

(i) Policy and Regulatory Frameworks

Effective management of HABs requires strong policy frameworks and regulatory measures at national and regional levels. Policies such as the Water Act of Kenya and environmental protection laws should enforce stricter regulations on nutrient pollution, industrial discharges, and land-use practices (Odada et al., 2006). Governments and environmental agencies should strengthen water-quality monitoring programs and implement pollution-control measures to mitigate the effects of HABs.

Local municipalities should purchase sound sewage treatment systems that effectively reduce nutrient loads to aquatic habitats. Another option is to employ artificial wetlands, which are made to treat wastewater by creating a shallow dip in the ground with a flat bottom (Madzivanzira et al., 2023). Constructed wetlands provide an economical and efficient solution, demonstrating efficacy in treating municipal, industrial, agricultural, and household wastewater.

(ii) Community-Based Mitigation Approaches

Engaging local communities in the management of freshwater ecosystems is crucial in reducing HAB occurrences. Developing community-led solutions such as decentralized water treatment systems and alternative livelihood programs can empower local populations to address water quality challenges while enhancing their economic resilience

a) Sustainable agricultural practices to reduce nutrient runoff: By emphasizing the use of natural inputs and biological processes, organic farming lessens reliance on synthetic fertilizers that contain phosphorus (P) and nitrogen (N), which are the leading causes of nutrient runoff into aquatic systems. Organic farming improves soil structure and increases its capacity to hold nutrients by using techniques like crop rotation, cover crops, and the application of organic manure. This reduces the amount of N and P that runs off into the marine environment (Lan et al., 2024). The transformation of agriculture to organic farming methods, together with the use of innovative nitrogen and phosphate fertilizers and mixed organo-mineral fertilizers, plays a significant role in tackling the environmental concerns provided by conventional farming (Lan et al., 2024). Using controlled-release fertilizers, establishing vegetative buffer zones, and using precision farming methods can reduce the amount of surplus nutrients entering water bodies, reducing the development of HAB (Newton et al., 2023).
b) Riparian buffer restoration and conservation efforts: Community-led initiatives, such as riparian buffer zone restoration, sustainable agricultural practices, and pollution awareness campaigns, can help minimize nutrient runoff and improve water quality (Harper et al., 2011). For example, initiatives around Lake Naivasha promoting riparian vegetation restoration and buffer strips have reduced runoff in localized areas (Harper et al., 2011). High (relatively low-cost, co-benefits for soil conservation and biodiversity), but requires land tenure clarity and incentives for farmers. Implementation success is mixed and heavily depends on community buy-in and enforcement.
c) Public awareness and capacity-building programs: Local fishermen and farmers should be educated on best practices that

reduce nutrient inputs into lakes. Also, citizens can effectively participate in reducing deforestation and planting more trees, which could help reduce the effects of climate change (Madzivanzira et al., 2023).

(iii)Technological and Scientific Approaches

a) *Implementing real-time water quality testing and HAB forecasting, especially in high-risk zones like Winam Gulf:*

An ideal monitoring system could provide early notice of upcoming harmful occurrences and enhance predictive capability in both the short and the long term by enabling real-time, highly automated, and accurate bloom identification. Satellite and in-situ monitoring enable timely detection of blooms and targeting of responses; regional programs (Lake Victoria monitoring) show value but funding and technical continuity are limiting factors in Kenya (Nyamweya et al.,2023).

b) *Use of algicidal bacteria and natural predators*

This approach show promise in trials, but require local validation for scale, and socio-ecological contexts. Reserving herbivorous zooplankton by lowering the numbers of their possible predators, such as zooplanktivorous and piscivorous fish, effectively aids in reducing the growth and proliferation of HABs. Large populations of phytoplankton can be directly consumed by filter feeders like tilapia and daphnia, but this ability is restricted to a small number of grazers in aquatic environments (Nwankwegu et al., 2019). Algaecidal Streptomyces U3 effectively eliminates harmful algae *Heterosigma akashiwo* in three days in the laboratory, but its fast-growing nature makes it unreliable as a biocontrol measure in freshwater-marine environments (Nwankwegu et al., 2019).

c) *Wastewater Treatment Innovations*

For treating surface water, coagulation, clarification, and rapid sand filtration are effective in eliminating cyanobacterial cells but only partially in removing free (dissolved) cyanotoxins (Olokotum et al., 2022). Advanced water treatments and filtration techniques that reduce or eliminate HAB and their toxins include ultraviolet (UV)-C irradiation, ozonation, and activated carbon (Newton et al., 2023), providing economical methods and improvements in water safety and quality. Centralized treatment reliably removes nutrients but is expensive to expand; decentralized options (including constructed wetlands) can be cost-effective for peri-urban communities.

d) *Use of constructed wetlands for nutrient filtration*

Riparian buffers have high-efficiency N and P removal (≥75% removal efficiency) through optimization in anaerobic-anoxic-aerobic constructed wetland, leading to water quality improvement beyond nutrient strategies (Nwankwegu et al., 2019).

Multiple Kenyan pilot studies and reviews report that constructed wetlands (surface and subsurface types) can substantially reduce organic load, suspended solids and nitrogen; phosphorus removal is more variable and depends on design, plant species, substrate and hydraulic retention time. For example, a constructed wetland used to treat flower-farm effluent at Lake Naivasha demonstrates technical feasibility under tropical conditions. These projects show good pollutant reduction but also highlight operational and design challenges.

Land scarcity near cities, competing land uses, seasonal hydraulic variability, maintenance needs (desludging, vegetation management), and limited local technical capacity can reduce constructed wetlands effectiveness and sustainability if these factors are not planned for.

(iv)Role of Research, Education, and Stakeholder Collaboration

Importance of continuous monitoring and predictive modeling: Sustained efforts in HAB monitoring and research are vital to mitigate their adverse effects and safeguard ecological and human health effectively.

Integration of Indigenous knowledge with scientific solutions: Integrating HAB management into national climate adaptation plans, given projections of intensified blooms under warming. Addressing the impacts of climate change on HABs requires integrated watershed management, climate adaptation strategies, and enhanced monitoring of freshwater ecosystems to predict and mitigate future outbreaks (Paerl & Otten, 2016). In Lake Victoria, integrated water quality monitoring under the LVEMP II program has provided valuable data but lacks consistent implementation due to funding gaps (Odada et al., 2006). Integrating remote sensing and in situ data is essential for accurately assessing the taxonomic richness of phytoplankton.

6. Challenges and Knowledge Gaps in HABs Management

(i) Monitoring and Data Collection Challenges

Many freshwater bodies in Kenya lack continuous monitoring programs, leading to gaps in data on HAB occurrences, species composition, and toxicity levels (Sitoki et al., 2012). Insufficient data hampers the ability to predict bloom events and implement early-warning systems (Ndlela et al., 2016). Evaluation of the threats to the environment and human health is challenging due to the absence of standardized monitoring protocols for HAB-related pollutants of rising concern (Igwaran et al., 2024). The lack of widely accessible, analytically standardized methods for assessing toxins naturally results in nonroutine surface water monitoring.

Advanced monitoring technologies such as satellite imaging and remote sensing are costly and require technical expertise (Paerl & Otten, 2016). Within county-level water resource departments, research institutions, and many stakeholders lack the financial and technical capacity to implement high-tech solutions for HAB management (Mbonde et al., 2015). Without sustained funding, even well-intentioned initiatives fail to establish robust datasets, leaving policymakers with insufficient evidence for intervention design (Paerl & Otten, 2016).

(ii) Policy and Governance Gaps

These financial constraints are, in turn, a reflection of weak policy enforcement and fragmented governance structures across the water and environmental sectors (Njiru et al., 2014). Also, the lack of data and continuity reflects deeper policy and institutional weaknesses. Kenya's Water Act of 2016 was designed to streamline water governance by establishing the Water Resources Authority (WRA) and devolving management to catchment-level structures. However, the Act does not explicitly address nutrient pollution, eutrophication, or HAB management, focusing primarily on water allocation, use, and conservation. As a result, there is no clear regulatory framework or guidance for monitoring algal toxins, controlling agricultural nutrient runoff, or coordinating multi-agency responses to HABs. Weak inter-agency collaboration among the WRA, NEMA, and county governments further complicates enforcement and accountability (Njiru et al., 2014). The absence of clear mandates often leads to overlapping roles or neglected responsibilities, allowing effluent discharge and agricultural runoff to persist unchecked (Nyamweya et al., 2023). Although regulations exist to control water pollution and nutrient enrichment, enforcement remains a significant challenge (Odada et al., 2006). Inadequate resources, institutional weaknesses, and a lack of political will contribute to ineffective policy implementation.

Local communities around Lake Victoria, Naivasha, and Baringo, that are dependent on fisheries and freshwater resources, lack awareness of HAB risks and mitigation measures. Without adequate education and engagement, communities may continue practices that contribute to eutrophication and HAB proliferation (Harper et al., 2011). Many riparian communities remain unaware of the health risks associated with algal toxins or the role of land-use practices in exacerbating blooms. This socioeconomic gap reinforces both the governance and technical challenges: without public pressure or informed community participation, policy reforms remain superficial and monitoring programs struggle to collect reliable citizen data.

Climate change and limited adaptation capacity intensify these interconnected challenges. While climate change is recognized as a driver of HABs, the specific impacts of changing temperatures, precipitation patterns, and extreme weather events on bloom dynamics require further investigation (Woolway et al., 2021). Yet, climate adaptation programs rarely integrate HAB monitoring or management strategies, illustrating another policy coordination gap. More research is needed to develop climate-resilient mitigation strategies (Mutebi et al., 2022.

(iii) Socio-Economic and Cultural Barriers

Lack of financial support for installing recycling facilities in urban areas is one of the barriers. This limits their ability to adopt environmentally sound practices, such as improved sanitation or the use of non-polluting fertilizers, reducing the feasibility of community-led HABs prevention strategies.

Low levels of education and environmental literacy among affected communities reduce awareness about HAB risks, their causes, and preventive measures. Many communities living around freshwater lakes may continue to pollute water bodies due to a lack of understanding of nutrient-loading sources and their consequences, thus exacerbating the problem.

Risk communication strategies often overlook local languages, customs, and modes of information dissemination. This knowledge gap in culturally sensitive communication has led to poor public responsiveness to HAB warnings.

Many HAB management programs do not fully involve local communities in the design and implementation of interventions. Ignoring local knowledge and priorities limits the sustainability and acceptability of scientific solutions, underscoring a significant knowledge-practice.

Conclusion

In this review, freshwater lakes such as Victoria, Naivasha, and Baringo have increasingly suffered from HAB events, driven by a complex interplay of anthropogenic pressures, including nutrient enrichment from agricultural runoff, industrial pollution, deforestation, and urban expansion further compounded by climate change-induced temperature rise and altered hydrological patterns.

The socio-economic and ecological consequences of HABs are extensive: they degrade water quality, reduce fish stocks, disrupt aquatic food webs, and impose significant public health risks due to toxin exposure. These effects directly threaten the livelihoods of millions who rely on freshwater bodies for food, income, and drinking water, while also undermining national development goals related to food security, public health, and sustainable water resource management.

Current mitigation efforts, though promising, remain insufficient in scope and enforcement. Addressing this issue requires a holistic, multi-stakeholder approach that combines strengthened policy frameworks, advanced scientific monitoring, community-based watershed management, and targeted public education. Integrated strategies such as sustainable farming practices, riparian buffer zone restoration, effective wastewater treatment, and real-time water quality monitoring must be scaled up.

Recommendations

To effectively address the rising threat of Harmful Algal Blooms in Kenya's freshwater ecosystems, improved intersectoral collaboration and policy integration is vital.

Effective HAB management requires coordination between environmental, agricultural, health, and water management authorities. Policies addressing water quality, land use, and public health should be harmonized and incorporated into national development plans and climate resilience strategies. For example, implementing a progressive fine structure for industries, flower farms, and municipal facilities that exceed discharge limits, while offering tax incentives or subsidies to those investing in wastewater treatment upgrades. The legal and institutional frameworks governing freshwater management must be strengthened. Relevant environmental laws and policies should be reviewed to explicitly address HABs, and adequate funding should be allocated to institutions tasked with enforcement, research, and ecosystem conservation.

Establish long-term monitoring programs and early warning systems to detect and manage the occurrence of HAB are also critical. Integrated monitoring that combines satellite-based remote sensing, field sampling, and community-based surveillance should be implemented across major lakes and reservoirs. The number of trained water quality inspectors should be increased, especially in hotspot regions such as Winam Gulf and Lake Naivasha. These officers should be equipped with portable monitoring tools and rapid toxin-testing kits Establishing centralized data platforms for real-time water quality monitoring and information sharing among stakeholders would also enable timely responses to bloom events and improve long-term trend analysis.

There is a need to strengthen nutrient management and pollution control. This can be achieved through the enforcement of environmental regulations that limit the discharge of agricultural runoff, untreated sewage, and industrial effluents into freshwater bodies. Encouraging public private partnerships for constructing and maintaining wastewater treatment and constructed wetland systems, especially around urban and peri-urban lakes. The public private partnerships can mobilize technical expertise and sustainable financing mechanisms. Promoting sustainable agricultural practices, such as precision farming, organic methods, and the restoration of riparian buffer zones, will help reduce nutrient loading, particularly nitrogen and phosphorus, which are primary drivers of eutrophication.

Community engagement and capacity building should be prioritized to foster local stewardship of freshwater resources. This includes training community members, fisher folks, and water users on HAB identification, safety measures, and sustainable lake management practices. Training local fishers and community water-user associations to collect basic water quality data and report bloom events. Integrating citizen science with institutional monitoring can improve early detection and foster local ownership. Strengthening community-based organizations and Water Resource User Associations will help ensure that local knowledge and participation are integrated into decision-making processes.

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