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Impact Of Climate Change On Harmful Algal Blooms In Marine Ecosystems And Mitigation.

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ABSTRACT

Due to climatic changes, the marine planktonic system is affected worldwide, potentially causing a rise in the severity and intensity of harmful algal blooms. However, the lack of fundamental knowledge about the mechanisms behind harmful algal blooms, forecasting their future prevalence is challenging.

There are viable concerns about the factors that influence the extension and initiation of HABs. To know the processes that control the growth of HABs, it is necessary to answer fundamental questions about the occurrence, extent, intensity, and timing in each system. In the past few years, harmful algal blooms coming from the unrestricted proliferation of algae occur often throughout the world's coastal water, causing significant ecological damage, toxic contamination of aquatic life, major economic losses due to decreasing tourism, and in some cases even human fatality. In many countries, according to numerous studies it is reported that algal blooms caused immense economic loss has their impact on fish and shellfish culture.

Therefore, Understanding the correlation between rising water temperatures, nutrient cycling, and the emergence of harmful algal blooms is paramount due to their devastating consequences. The occurrence of bloom will depend upon numerous factors such as nutrient input, upwelling of water, flow condition, water condition (PH, turbidity), temperature and local ecology interaction of organisms within and with the environment.

These blooms can inflict lasting damage on marine ecosystems, disrupt nutrient cycles, endanger aquatic life, compromise water quality, and pose a threat to human health and economies that depend on coastal resources. Exploring this connection is crucial for making reliable decisions on variations due to climatic changes, resource management, and environmental conservation initiatives. This guarantees that our oceans remain robust and preserves the welfare of both ecosystems and communities. Several factors influence the level of eutrophication of water bodies' flow rate, retention time, pollutant concentration, and standing or flowing system, fast Moving water bodies require more concentration of phosphorus and nitrogen inflow aid to prevail in eutrophic condition, while gradually moving water bodies are more vulnerable to the effect of enrichment due to higher detention time.

This study examines the influence of climate change on Harmful Algal Blooms (HABs), including changes in temperature, stratification, light availability, ocean acidification, and nutrient inputs. It aims to fill research gaps in HAB initiation and growth, recognizing their significant consequences on ecosystems and human health. Additionally, it investigates the influence of flow rate, retention time, pollutant concentration, and water system type on eutrophication, offering insights for mitigation and management.

1 INTRODUCTION

Harmful algal blooms (HABs) pose a serious threat to aquatic habitats and human health. The rapid global spread of HABs is a warning sign for the degradation of the ecosystem. Climate change forced the alteration of environmental parameters that lead to challenged conditions in aquatic ecosystems, which are favourable for the occurrence, persistence, and distribution of HAB**s** (Kazmi et al. 2022). Algae and cyanobacteria are simple organisms that live in the water. Algae and cyanobacteria can rapidly grow out of control, or "bloom," when water is warm, slow-moving, and full of nutrients. Blooms can occur in freshwater, marine water, and brackish water. Blooms can look like foam, scum, mats, or paint over the water surface. A bloom can change the colour of the water to green, blue, brown, red, or another colour. Some algal blooms may not be visible (Sukenik and Kaplan 2021)**.** Climate change is posing a significant impact on coastal water, such as warming, acidification, and reduction in oxygen levels in water bodies. During last few decades, there is an increase in harmful algal blooms (HABs), which have had a detrimental effect on ecosystems, tourism, recreation, public health, fisheries, and aquaculture (Song et al., 2021). HABs grow rapidly and accumulate over the water surface, in the presence of nutrients under suitable climate and hydrology conditions. Higher concentration of algae leads to a decrease in the transparency of water and dissolved oxygen (DO), a harmful impact on the water especially when it releases algal toxin into the water. The algae blooming of global waterways is rising due to the massive amounts of industrial and domestic sewage that contain nutrients like phosphorus and nitrogen directly discharged into lakes, rivers, reservoirs, and the ocean because of population growth, and rapid industrial and agricultural development. In addition, the amount and severity of HABs in lakes worldwide have been rising due to climate change. These findings suggested that HABs are becoming more widespread as both eutrophication and climate change are global problems (Sha et al. 2021). A comprehensive overview of HAB studies conducted over the last 3 decades and elaborated on the developments in these major hotspots (Lake Erie in the Laurentian Great Lake of North America and Lake Chaohu) research throughout that time, and the potential for freshwater and ocean algae blooms to kill aquatic life. Further, they discuss the favourable conditions for nutrient growth such as hydrology and the impact of climate change on the growth of harmful algal blooms. Also, discuss the important role of eutrophication and climate change, which harms human health and the ecology of that area (Sha et al. 2021)(Mitsch 2017)(Yindong et al. 2021a). Human activities have led to overconsumption of nutrients, causing "cultural eutrophication." This surplus leads to overgrowth of harmful phytoplankton or "blooms." Nutrient over-enrichment due to rising temperatures and the occurrence of frequent extreme hydrological events whether droughts or storms leads to eutrophication and increased harmful algal bloom. To fight Harmful Algal Blooms (HABs), it's essential to view the freshwater-to-marine continuum as a single, interconnected system. This requires a comprehensive approach that connects watersheds to the coastal ocean and encompasses the interactions between various waterbodies (Paerl et al. 2018). Human activities have led to nutrient overconsumption causing harmful algal blooms (HABs). Rising temperatures and extreme hydrological events exacerbate the problem. A comprehensive approach that connects watersheds to the coastal ocean and focuses on controlling nitrogen and phosphate locally is needed. Water flows downstream, carrying nutrients from various point sources, which accumulate in still water bodies, leading to HABs. The interconnectivity of watersheds and the direct impact upstream activities have on downstream water quality must be understood. Mitigation of HABs must focus on controlling the load of dual nutrients (nitrogen and phosphorus) at the source itself (Paerl et al. 2018).

1.1 Harmful Algal Blooms (HABs)

Harmful Algal Blooms (HABs) are a naturally occurring phenomenon that is characterized by the growth and proliferation of microscopic algae and phytoplankton. Cyanobacteria, a type of blue-green algae, are also sometimes the cause behind these harmful blooms. Macroalgae or seaweed are also known to cause harmful blooms in some cases.

HAB events occur due to the rapid proliferation of toxic or harmful microalgae over the surface of the sea or within the seawater column. Even small concentrations of species with highly toxic plankton accumulate as a substrate at the bottom and cause various problems.

The occurrence of HABs in coastal ecosystems is common, but it can also affect open-ocean, brackish, and freshwater ecosystems. The term "HABs" is used by researchers to define the bloom that leads the injury to human health, impacting socioeconomic aspects and various components of aquatic ecosystems.

The impacts of HABs can be significant, ranging from public health risks to tourism and fisheries impacts, and often require scientific and regulatory attention. As awareness about danger and its impact is increased, significant advancement has been made in HABs research and management (Anderson et al. 2012).

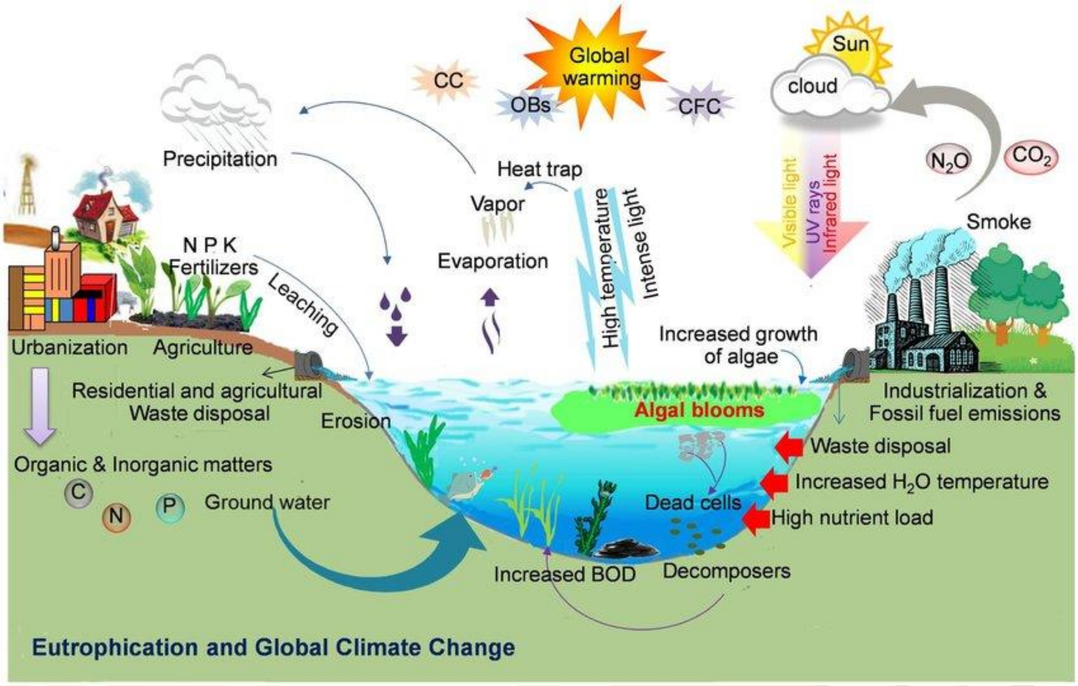

Figure 1. Occurrence of harmful algal bloom. (Source: (Rastogi et al. 2015))

1.2 Factors Leading to HABs

HABs are influenced by a complex and interacting set of biotic and abiotic factors, which include nutrient enrichment, water temperature, solar radiation, hydrological and climatic alterations, trophic interactions, and disease. Nutrients, particularly nitrogen (N) and phosphorus (P), life-sustaining elements needed by primary producers, are often the key contributors to the initiation, development, and maintenance of HABs.

Hydrologic modifications and climate change enable HABs to reach larger magnitudes and persist longer when accompanied by excessive nutrient loading. Contemporary HAB problems must be addressed on land−water−air interactive scales that link watersheds to the coastal ocean since it is increasingly recognized that to combat these threats, we need to treat the freshwater-to-marine continuum as one interconnected system. Excessive N-loading from the Mississippi River may shift coastal waters further offshore to P-limitation, leading to an expanding zone of eutrophication as the excess N is transported further offshore (Paerl et al. 2018).

1.3 Global Rise in HABs

According to various studies it is found that occurrence and impact or harmful algal blooms HABs is increasing across the globe. The factors contributing to this increase are multiple, complex, and varied, although some have been well-documented. The global rise in HABs is attributed primarily to changes in climate, usually characterized by rising sea temperatures, stronger storms, altered wind patterns, changing ocean currents, and sea level rise. Availability of nutrients such as nitrogen and phosphorus are increased from various anthropogenic points and non-point sources are also contributing to the rise of harmful algal blooms. Excessive fishing and other biological factors impacting food webs can also cause changes in microalgae (terrestrial plants) and HAB formation. Due to the negative impact on human health, environment, and economics, the growth of HABs is a serious concern. To better understand and address the issue regular monitoring, research, management is necessary (Anderson et al. 2012). The marine ecosystem is affected by climate change in various ways, which include variations in temperature, nutrient supply, and acidity of water bodies. These changes can alter species distribution and timing of the life cycle and increase harmful algal blooms (HABs). The changes may have a serious indication for marine ecosystems, including fisheries, biodiversity, and other services (Gobler 2020). The increase in harmful algal blooms (HABs) across the globe is directly linked to the increase in nutrient loads. Therefore, it is important to prioritize reducing nutrient loads to effectively handle the issue of HABs on both regional and global levels. Immediate action is required to address the challenge posed by climate change globally, due to the delay this situation will bring (Paerl et al. 2018). The impact of harmful algal blooms (HABs) on marine and freshwater ecosystems. It also states that Harmful algal blooms (HABs) are detrimental to the ecosystem. Recent studies show that global changes may be promoting a rise in select cyanobacteria in nutrient-poor northern lakes and harmful algal blooms are a climate change affecting the water warming, acidification, and other environmental stressor in marine and freshwater ecosystems. Therefore, it can be concluded that harmful algal blooms (HABs) have a significant impact on marine ecosystems(Yindong et al. 2021a).

2 IMPACT OF CLIMATE CHANGE ON COASTAL WATERS & HABS.

Climate change is having a significant impact on marine waters, leading to a rise in the occurrence of harmful algal blooms (HABs). Warming of surface seawater is the primary impact of climate change, which boosts the growth and reproduction rate of phytoplankton leading to an increase in the likelihood of HABs events. Climate change may also lead to an alteration of water circulation patterns ultimately which favours the growth of harmful algal blooms. The ocean water across the world is being affected by human-induced climate change, and factors such as acidification, and warming are impacting various marine ecosystems. These are interconnected factors and interact with other human activities, making them important aspects of the problem. To reduce the impact and mitigate potential damage it is necessary to reduce the emission of greenhouse gas emission. Acidification can cause a decrease in the production and accumulation of calcium carbonate shell-forming organisms. These types of phytoplankton species are crucial food resources for shellfish and other marine organisms. As a result, the reduction in the availability of these species may ultimately affect the whole marine food web.

Climate change can alter the precipitation pattern, Strom, and erosion in coastal regions, and enhance the nutrient delivery and cycling from land-based sources, resulting in excess availability of nutrients in coastal water. The growth of harmful algal blooms is promoted due to the excess availability of nutrients, which can lead to threats to aquatic life, contaminate seafood and adversely impact tourism and recreational activities. Excess nutrient availability can promote the growth of algal blooms, which can lead to hypoxia or anoxic conditions in coastal waters, deplete fish stocks, contaminate seafood, and adversely impact tourism and recreational activities.

To mitigate the impact of climate change on coastal water and harmful algal blooms various majors are being taken. These strategies include reduction in greenhouse gas emissions promoting land use practices that are more sustainable, and implementing effective coastal water management strategies, other factors such as nutrient loading, ocean acidification, and temperature while predicting and managing HABs (Anderson et al. 2012). Climate change accelerates the global spread of harmful cyanobacteria blooms. It allows the blooms to grow on a large scale and remain for a longer time when excess nutrients are present. Therefore, it is critical to address the issue of mitigating cyanobacterial, HABs in aquatic ecosystems that are affected by climate change and anthropogenic nutrients (Paerl et al. 2018). Studies suggest that global warming and its effect on water temperature can alter the overall functioning of aquatic ecosystems and create an environment conducive to certain phytoplankton species, leading to losses in aquatic biodiversity. Eutrophication and water temperatures, and their interactions, are believed to be crucial factors driving harmful algal blooms (HABs) occurrences. Freshwater lakes in China are suffering from both serious eutrophication and rapid warming, and studies have recorded continuous increases in surface water temperatures in these lakes over the past decades (Yindong et al. 2021a).

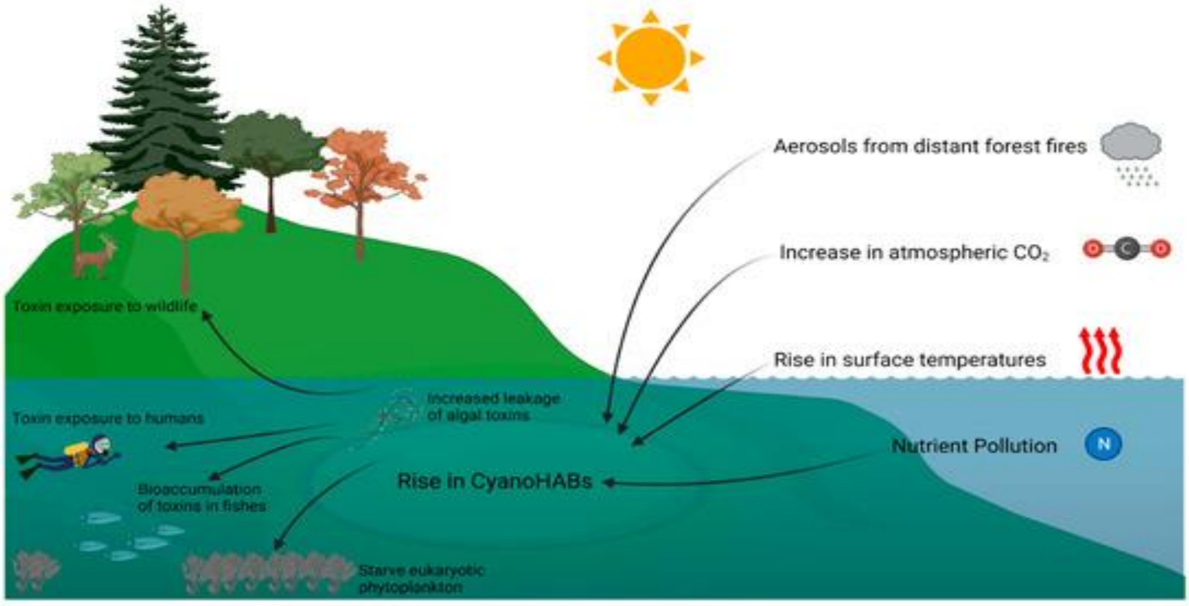

Figure 2. Impact of climate change on coastal water and HABs (**Source:** (Moore et al. 2008))

2.1 Marine Ecosystem

A marine ecosystem refers to a collection of living and non-living things that exist in a marine environment such as oceans, estuaries, and salt marshes. These ecosystems consist of a variety of organisms, including plankton, phytoplankton, seaweeds, seagrasses, invertebrates, fish, birds, and mammals.
Marine ecosystems are altered by various abiotic factors such as temperature, salinity, light penetration, and nutrient availability, which all play an important role in shaping the structure of the ecosystem. Biotic factors such as predation, competition for resources and mutualism also influence the interactions among species within marine ecosystems, altering food webs and affecting population dynamics.

Marine ecosystems contribute to the Earth's carbon cycle and climate regulation by absorbing and releasing CO2 and other gases, storing carbon in the form of organic matter, and maintaining global ocean temperatures. Additionally, these ecosystems provide important ecosystem services such as regulating climate, nutrient and element cycling, air and water purification, food provision, recreation, and culture, and supporting commercial and subsistence fishing.

However, human activities, such as overfishing, habitat loss, pollution, and climate change, have caused significant stress to these ecosystems, negatively impacting the health and resilience of these systems. Therefore, conservation efforts that aim to protect and restore marine ecosystems, and reduce the impact of anthropogenic stressors, are essential for the preservation of both the ecological and socio-economic services that these ecosystems provide.

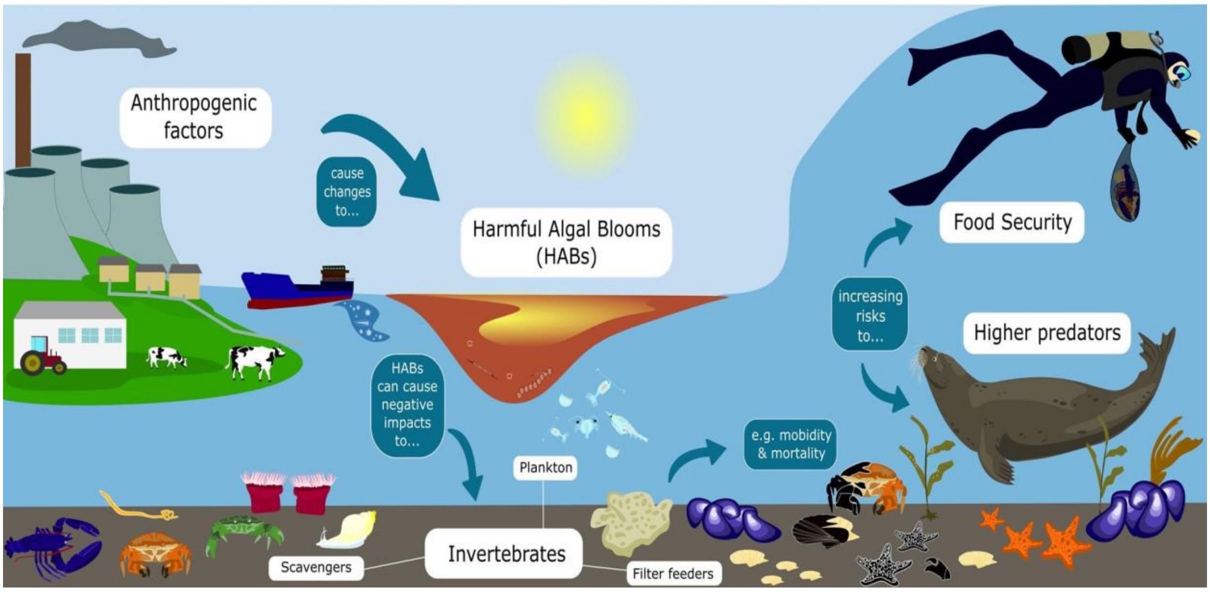

Figure: 3. Impact of HABs (Harmful Algal Bloom) on marine ecosystem. (Source: (Turner et al. 2021))

2.2 Impacts of HABs on Marine Ecosystems

HABs can have negative impacts on marine ecosystems, food webs, and fisheries. The ecological damages can include toxin-related mortalities of higher trophic levels, including mammals, birds, and various invertebrates, such as clams, oysters, and scallops. HABs can also reduce light penetration and cause oxygen depletion, which negatively affects marine life and can trigger larger-scale ecosystem changes, including hypoxia, anoxic and water column sulphide accumulation, eutrophication, and expansion of the niches occupied by phytoplankton. Changes in food-web dynamics and negative impacts on fisheries production can follow in the aftermath of these events. A broad understanding of how human-induced propagule sources and other factors contribute to the success of invasive algal species provides opportunities for effective, integrated management strategies aimed at preventing the spread and establishment of harmful algal species across regions (Paerl et al. 2018).

2.3 Effects of HABs on water quality

HABs can impact water quality in various ways, such as increasing the turbidity, color, and odor of water, reducing its clarity, impairing its taste and safety, and depleting its oxygen levels. HABs can also lead to the production of toxins that can have severe impacts on the health of humans, domestic animals, and aquatic organisms. Moreover, the decomposition of HABs can result in unpleasant odors and taste, promote the development of anoxic zones and hypoxia, and contribute to greenhouse gas emissions. Therefore, HABs can have significant negative consequences for water supply, fisheries, recreation, tourism, and property values, highlighting the need for effective management strategies (Paerl et al. 2018) HABs, or harmful algal blooms, can negatively impact the physiology and feeding behaviour of resident bivalves, and recent ocean warming has caused bloom-favorable conditions for several HABs to become established earlier and persist longer.

2.4 Effects of HABs on human health

HABs can cause acute and chronic patterns of illness in humans, and the toxins produced by the microalgae causing HABs can be ingested through contaminated seafood, direct skin contact, or inhalation of airborne toxins.

Acute symptoms of HABs exposure include gastrointestinal upset, nausea, vomiting, diarrhea, abdominal pain, and dizziness. Most of the studies on HABs and human health involve acute poisonings from contaminated seafood. These symptoms can range from mild to severe, depending on the type of toxin and the amount consumed. Saxitoxins, for example, can cause paralytic shellfish poisoning, leading to respiratory and heart failure, and, in some extreme cases, death.

Chronic exposure can lead to respiratory problems, neurological issues, and even death. HABs can also cause skin rashes, respiratory irritation, and eye discomfort. Long-term exposure to HAB toxins can also lead to chronic respiratory illnesses such as bronchitis or asthma. In addition, some studies suggest that exposure to HAB toxins may increase the risk of liver cancer and neurodegenerative diseases such as Alzheimer's disease. HABs can affect people in various ways, depending on different factors such as age, health status, and type of exposure. Understanding the burden of disease from exposure and the effects of HABs requires transdisciplinary work across environmental/marine sciences, toxicology, and public health and the use of more advanced epidemiological methods and mathematical modelling. The toxic effects of HABs can resemble those of infectious disease, including norovirus, or other chemical exposures, and so are often underdiagnosed. Similarly, as these illnesses can be mild and self-limiting, there is significant under-reporting to public health authorities, and therefore, the evidence presented in this review is likely to represent a small proportion of all actual illnesses (Young et al. 2020).

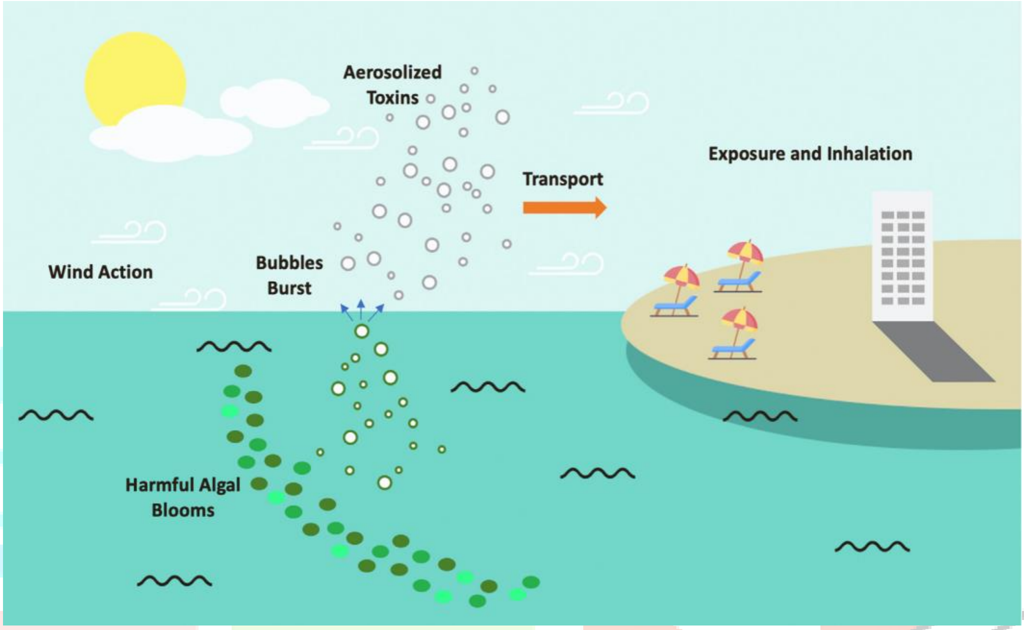

Figure: 4. Effects of HABs on human health, (Source: (Lim et al., 2023))

3 MITIGATION STRATEGIES

Mitigating Harmful Algal Blooms (HABs) involves a multifaceted approach that encompasses both preventive measures and reactive strategies. Nutrient management, particularly the reduction of nitrogen and phosphorus inputs from agricultural runoff and wastewater discharges, is a fundamental preventive measure. Implementing and enforcing regulations and best management practices to control nutrient loading into water bodies play a crucial role. Early detection and monitoring of HABs using advanced technologies and satellite imagery enable timely responses. Additionally, the development of predictive models for HAB occurrence assists in proactive management. Physical control methods, such as the use of algaecides, can be applied in localized areas, but their effectiveness may vary. Furthermore, public awareness campaigns and outreach initiatives are essential for educating communities about the environmental and health risks associated with HABs. The integration of these strategies into a comprehensive and adaptive management framework is key to addressing the complex and dynamic nature of harmful algal blooms. There are various mitigation strategies to control or mitigate harmful algal blooms that involve the combination of proactive measures and reactive interventions.

Nutrient management: control the nutrient input from sources by implementing best management practices to reduce runoff from non-point sources such as agriculture, urban area, and industries, which include vegetation, application of fertilizer and crop cover (Anderson et al. 2002). The construction of a floating wetland will also act as a natural filter to reduce the nutrient load of water before it reaches the coastal water bodies, different plant species may be used in a constructed wetland to uproot the nutrients present in water (Mitsch et al. 2015).

Water quality monitoring: implementation of a regular monitoring system, which is used to detect harmful algal blooms in earlier stages will allow local authorities to respond timely to take appropriate action to minimize the impacts of harmful algal blooms (Doucette et al. 2009). Remote sensing and satellite imagery technologies play an important role in monitoring the quality of water and detecting algal bloom across the large spital scale, by sensing the colour of the ocean on the coast (Gower and King 2011)

Physical and chemical control: Through mechanical mixing devices the vertical columns of water are mixed which allows atmospheric oxygen to be mixed in water and prevents the accumulation of algae (Hudnell and Dortch n.d.). Modified clay (MC) is also used to mitigate harmful algal blooms, which provides an environmentally friendly method of HAB mitigation due to its flocculation properties. Factors which influence the efficiency are water current, water exchange rate and size of the water body to explore the potential of MC with other HABs mitigating techniques to increase efficiency (Song et al. 2021b).

4 LITERATURE REVIEW

Climate change is having an extensive environmental and ecological impact on the world's oceans. The top layer of the ocean is warmer than the deeper water because it is exposed to atmospheric conditions and responds quickly to the outer atmosphere. Between 1971 and 2010, the worldwide average rise in temperature in the top layer of 75 m of the ocean was 0.11 °C per decade; at 700 m depth, it dropped to 0.015 °C per decade. With the rise in global temperatures, the top layer of the ocean is undergoing significant changes. These changes affect the penetration of light underwater, upwelling frequency and intensity, thermohaline overturning, nutrient cycling, precipitation, and storms. Phytoplankton, including harmful algal bloom present in the upper layer, are the first to respond to the ocean changes happening in the top layer. Due to short life spans and rapid generation, HABs are sensitive to changes in water characteristics (Trainer et al. 2020). Climate change is having significant impacts on coastal waters, including warming, acidification, and deoxygenation. Harmful algal blooms (HABs) have also increased over the past few decades, negatively impacting public health, recreation, tourism, fishery, aquaculture, and ecosystems. The United Nations' Intergovernmental Panel on Climate Change's (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) linked HABs to climate change, showing that they have expanded and increased in frequency since the 1980s. The report attributes this partly to ocean warming, marine heatwaves, oxygen loss, eutrophication, and pollution. HABs have negative impacts on food security, tourism, local economy, and human health. Human activity, including climate change, is promoting global trends in HABs, but individual events are driven by local, regional, and global drivers (Song et al. 2021a). The impact of climate change on eutrophic lakes, which are characterized by high nutrient concentrations and often suffer from harmful algal blooms. The authors use modelling results to predict that as surface water temperatures increase, the seasonal fluctuations of internal nutrient loadings in the lake may intensify, leading to stronger impacts in regulating nutrient concentrations and water limitations. This could make it difficult to achieve nutrient control targets throughout the year. Additionally, the article predicts that with warmer surface waters, algal blooms may last longer and start earlier in the year. Overall, the article emphasizes the importance of considering internal nutrient cycling in the restoration of eutrophic lakes in the future(Yindong et al. 2021a). The increase in frequency and intensity of HABs has been linked to rising temperatures on the surface of the sea caused by climate change, which creates favourable conditions for the growth and distribution of harmful algal species(Tewari 2022). Due to the increase in carbon dioxide level, ocean water is becoming acidic, and impact on aquatic organisms. Acidification of the ocean is favourable for the growth of harmful algal bloom HABs which gives them an edge over other species (Gobler et al. 2017)**.** Due to global warming alterations of precipitation patterns are also increasing the nutrient input into the water bodies raising HABs. Excess nutrients may enter the ocean because of increased rainfall and runoff, accelerating the development of HABs (Paerl et al. 2018). Harmful algal blooms (HABs) can cause oxygen depletion in affected areas, leading to "dead zones" that harm marine life. Some HAB species produce toxins that can kill fish, mammals, and other organisms (Griffith and Gobler 2020a). Human activities cause nutrient overconsumption and harmful algal blooms (HABs). Rising temperatures and hydrological events worsen the problem. To mitigate HABs, control nitrogen and phosphate locally, and understand the impact of upstream activities on downstream water quality (Paerl et al. 2018).

(Moore et al. 2008)

Analyse the relationship between specific large-scale climate variability patterns, marine conditions, and harmful algae. HABs create various health issues in humans such as gastrointestinal, respiratory, and neurological illnesses. Due to climate change the severity and frequency of the HABs may increase and lead to severe and frequent health problems. Surface temperature is increasing due to climate changes, and it impacts rainfall and evaporation trends, altering the PH vertical mixing of water. HAB's cab damages the ecosystem and leads to economic losses in fisheries and the recreational industry.
More research is required to create effective strategies to mitigate the effect of the changing climate on these systems and gain a deeper understanding of the intricate connection between climate, HAB and human health. A multidisciplinary approach is required for the research.

(Carey et al. 2013)

He studied the optimization watershed management practices to improve the quality of water from point and non-point sources. Various point and non-point sources which carry nutrients from urban watersheds to the water bodies. Nitrogen (N) and phosphorus (P) come from various sources in urbanized watersheds, including stormwater runoff, atmospheric deposition, and wastewater treatment systems.
Nutrient transport in urban watersheds can be enhanced due to natural hydrological routes being affected due to impermeable surfaces, stormwater management projects and artificial drainage systems. The issue of nutrients in urban watersheds is not completely known, and further research is needed to address the water quality impacts. Various point and non-point sources are identified that contribute to nutrient input to surface and groundwater.
Stable isotopes can be used to trace pollutants, but distinguishing sources can be difficult. This paper studies the effect of nutrients on water systems and aquatic populations, particularly focused on urban areas, and proposes strategies for reducing their impact. It also discusses factors which affect the nutrient cycle and lawn management practices which help in long-term retention.

(Davidson et al. 2014)

They are highlighting areas of uncertainty and ongoing research. Complex challenges are associated with certain causes and effects in this context, given the complexity of coastal ecosystems and the many factors that can affect the growth and distribution of harmful algal blooms. There is increasing evidence that anthropogenic activities, such as agriculture, aquaculture, and urbanization, contribute to harmful algal bloom in coastal areas. Harmful algal blooms can cause significant damage to marine ecosystems and human health, including killing of fish, shellfish poisoning, and respiratory problems. The regulation of nutrients from point or non-point sources is a potentially feasible response to the problem of harmful algal blooms and could have significant economic and environmental benefits. More research is required to determine the economic cost associated with harmful algal blooms and the development of various effective mitigation strategies. Determine the relation between HABs and anthropogenic nutrient enrichment. Negative impact of HABs on human health. Insufficient evidence that only organic nutrients are responsible for HABs.

(Gkelis et al. 2014)

Sample of water and plankton were collected two from offshore and two from inshore, and various parameters temperature, ammonia, nitrite, nitrate, DO, PH, and soluble reactive phosphorus concentration were analysed. The presence of plankton and identification of cyanobacteria were found by using microscopic and molecular analysis of various parameters such as PH, temperature and nutrient cycle in Lake Pamvotis change during the whole year.
In offshore stations, there is a significant decrease in DO during the summer season. Lake is witnessing eutrophication due to the presence of high concentrations of reactive phosphorous and nitrogen. Cyanobacteria are the primary reason behind bloom-forming phytoplankton in lakes. The growth rate of cyanobacteria

increases with an increase in temperature. Physical, biological, and chemical parameters as well as microcystin concentration were analysed at stations over the lake, soluble reactive phosphorus conc., PH, dissolved oxygen, nitrite, nitrate, ammonia, and water temperature show a strong seasonal cycle. Statistical methods are used for comparing the mean of samples from all stations and identifying correlations between variables.

(Paerl et al. 2016)

The strategy includes control of anthropogenic point and non-point source nutrient input reductions, increasing flushing rates, mechanically enhanced vertical mixing, using ultrasound waves to control algal growth, nutrient removal through upstream wetland development, application of algaecides, encouraging the growth of aquatic vegetation for nutrient attenuation and removal, and dredging and capping of bottom sediments to reduce sediment-water column nutrient regeneration. The latter strategy includes manipulating food webs to encourage the filtering and consumption of CyanoHABs.

Address both nitrogen and phosphorus nutrients to control CyanoHABs. In freshwater, limiting Phosphorus inputs alone may accelerate the eutrophication of coastal and estuarine waters that are sensitive to Nitrogen. Controlling non-point nutrient sources is difficult due to the diffuse nature of the nutrient sources. Due to the diffuse nature of nutrients, non-point sources are difficult to control. Agricultural and other major nutrient sources may require a regional focus because nutrients have been confined in wetlands and tributaries. Non-point nitrogen and phosphorus loading are rising due to an increase in the use of fertilizer, animal waste discharge, soil erosion and disturbance, agricultural emission, and septic systems due to the increasing human population. Various mitigation techniques are suggested such as Point and non-point source nutrient input reductions, increasing flushing rates (decreasing water residence times), Mechanically-enhanced vertical mixing, manipulating food webs to encourage filtering and consumption of CyanoHABs, utilizing ultrasound waves to control algal growth, Nutrient removal through upstream wetland development, chemical treatment, Encourage growth of submersed and emergent aquatic vegetation for nutrient removal and dredging and capping of bottom sediments to reduce sediment-water column nutrient regeneration.

(West et al. 2017)

Water quality, nutrient concentrations, and algal biomass were assessed over 10 weeks. This study was conducted in 30 plastic tanks in a rooftop research compound at Bangor University, Wales

Five treatments examined:

- FCWs planted with Phragmites australis, Juncus effusus, and Iris pseudacorus
- Unplanted FCW
- Control system
- Tanks filled with 70 L of tap water, were vigorously mixed to remove dissolved chlorine gas.
- Two-day equilibration period
- Three replicates per trophic state/treatment combination

ANOVA (Analysis of variance) revealed no significant differences in pH between treatments for the mesotrophic system for the time points analysed, suggesting similar biogeochemical controls on PH. No significant differences between plant species were observed at either trophic level, again suggesting similar controlling factors. Rapid nutrient reduction observed in the planted treatments system, with direct nutrient uptake possibly responsible, further research on plant-microbial interactions is needed along with the role that higher dissolved oxygen levels play in the rhizosphere of planted FCW treatments.

FCWs were found to limit algal bloom formation and the associated effects on water chemistry and planted FCWs consistently performed better than the unplanted treatments. Higher DOC levels in the rhizosphere may enhance denitrification and nitrate removal efficiency, but where FCW are employed in reservoir applications the drawbacks of high DOC levels in drinking water sources, including increased treatment costs and potential disinfection byproduct formation, should be considered.

A study was conducted to analyse the quality of water and algal biomass in 30 plastic ponds (Floating constructed wetlands) to treat algal bloom. Algal bloom formation was limited in planted FCWs, outperforming unplanted treatments. However, higher dissolved organic carbon (DOC) levels in the rhizosphere may enhance denitrification, but drawbacks such as increased treatment costs and disinfection byproduct formation should be considered in reservoir applications.

(Paerl et al. 2018)

Studied various water systems.

- Headwater Streams
- Riverine Systems
- Lakes And Reservoirs
- The Transit to Estuarine and Coastal Waters

Discuss various mitigation techniques, physical, chemical, and biological such as Dredging, Hydrological flushing, Ultrasonic cell disruption techniques, and Chemical treatments such as the use of flocculating agents and algaecides. The faster growth rate of CyanoHABs is expected under warm water, extreme climatic conditions and increased nutrient demand which leads to an increase in BOD.
Within the Southern California Bight (CA), where point sources dominate nutrient inputs, 92% of total terrestrial N loading to coastal waters is from wastewater effluent discharged directly into coastal waters via outfall pipes. To reduce nutrient load water bodies/targets should be treated as connected and not treat each water body as a closed system. Install flashboard riser in drainage ditches to increase the retention time to enhance the nitrogen processing, which reduces the Nitrogen export to downstream water. The Article addresses the rise of HABs in freshwater-to-marine ecosystems due to enteropathogenic activity. Climate change and nutrient over-enrichment are the major reasons for an increase in eutrophication and HABs globally. To control HABs for a long time the only solution is to reduce the nitrogen and phosphorous input.

(Griffith & Gobler, 2020)

Coastal ecosystems are the host to a diverse array of aquatic life. Discussed interactions between HABs and acidification. Due to changes in climate marine and freshwater ecosystems are warming, deoxygenating, and acidifying. The impact of HABs on the ecosystem is intensifying in parallel with these changes. Various eutrophic habitats that have HABs are already experiencing environmental stressors. Incorporating HAB species into experiments and monitoring programs where the effects of multiple climate change stressors are considered will provide a more ecologically relevant perspective of the structure and function of marine ecosystems in future, climate-altered systems. Due to changes in climate HABs are occurring frequent and intense in coastal water as well as in freshwater ecosystems. Aquatic habitat which is already rich in nutrients are more vulnerable to climate change and harmful algal blooms. To examine the combined effect of HABs and climate change, and develop the mitigation strategies integrated approach is needed.

(Gobler 2020)

The impact of Harmful algal blooms on human health, recreational activities, tourism, fishery, aquaculture, and the ecosystem all have risen over the past few decades. The extent to which climate change is intensifying these HABs is not clear, but there is lot of research on this topic this century alone. The range and frequency of HABs increased in coastal areas since the 1980s due to non-climatic drivers' nutrient runoff and climatic driver's marine heatwave, ocean warming, deoxygenation, eutrophication, and pollution. HAB's being promoted due to human activity. Identifies specific drivers within coastal waters, like increased riverine nutrient run-off and pollution. The extent to which climate change is intensifying these HABs is not clear, but there has been research that indicates the adverse impacts of HABs on public health, recreation, tourism, fishery, aquaculture, and ecosystems have all increased over the past several decades.

(Pal et al. 2020)

Overview of HABs organisms that impact the growth of cyanobacteria, species-specific interactions, and mechanisms for mitigation of HABs. Also discussed were the limitations and feasibility of extrapolating laboratory results to the field. Provide an overview of Biotic control of HABs. Discuss how various organisms (bacteria, protozoa, and zooplankton) impact the growth of cyanobacteria in HABs. Describe various mechanisms for mitigation of HABs such as competition, predation, and parasitism. limitations and feasibility concerns of biotic control approaches, such as variations in laboratory versus field results and species-specific interactions. Focused on the biotic control of Harmful Algal Blooms (HABs) by selected microbial species. Also discusses the effects of HABs on human health, aquatic ecosystems and water bodies and highlights the demand for successful and economic mitigation techniques. variations in laboratory versus field results and species-specific interactions.

(Young et al. 2020)

HABs clinical syndromes were classified as “acute” or “chronic”. Identify the Gap in the evidence base, including lack of surveillance and epidemiological studies, and limited use of toxin measurement in human samples. The study found that exposure to HABs can lead to a range of illnesses in humans, including respiratory, gastrointestinal, and neurological symptoms, as well as skin rashes. The authors emphasize that the severity and type of symptoms that arise from exposure to HABs can vary widely based on multiple factors, including the type of toxin produced by the algae, the route of exposure, and individual susceptibility. The article highlights the need for further research to examine the mechanisms underlying the toxic effects of HABs and the factors that contribute to variations in health outcomes. HABs exposure can lead to acute illness in humans. Evidence of association between marine HABs and observed human health was mapped. A total of 380 studies were included, 57.9% related to Ciguatera poisoning, and most studies (63.7%) were based on anecdotal evidence and case reports. Only (8.4%) of studies used human specimens to confirm the illness.

(Song et al. 2021b)

The harmful algal bloom mitigation method involves the use of modified clay (MC). MC provides an environmentally friendly method of HAB mitigation due to its flocculation properties. The flocculation efficiency of natural clay is limited, which results in a large dosage requirement. MC can alter nutrient cycling and reduce algal toxins in water bodies. Modified clay (MC) is used to reduce harmful algal cell density from water by coagulation and sedimentation. MC is used to reduce the nutrient load of sediment during red tide/ HABs, which can help to prevent the reoccurrence of HABs. The efficiency of MC depends upon the level of exposure to sunlight, which indicates it is a time-specific application. Factors which influence the efficiency are water current, water exchange rate and size of the water body to explore the potential of MC with other HABs mitigating techniques to increase efficiency. Use of MC for the control of HABs in closed water or region. However, for HABs control in the open sea, the effect of MC is insignificant because of the low dosage of MC and better water exchange.

(Yindong et al. 2021b)

Process-based water quality model (Environmental Fluid Dynamics Code, EFDC) used to perform an analysis of internal nutrient cycling and growth of phytoplankton. (Lake Chaohu)

A monthly nutrient monitoring data set was used to reveal a seasonal pattern of nutrient concentration. Contributions from internal loadings on seasonal nutrient variations were quantified. Restoration of the eutrophic lake is a challenge due to lake warming induced by climate change. Due to lake warming, stronger seasonal fluctuations of internal loading create beneficial conditions for a longer duration of cyanobacteria blooms in the year ultimately leading to the occurrence of HABs. Opposite to the seasonal variations of water temperatures, the higher concentrations of N species occurred in spring and winter, while lower values were observed in summer and autumn. This study examines the impact of lake water warming on the internal nutrient cycling of eutrophic lakes using Lake Chaohu, China, as a case study.

The study suggests that lake warming intensifies the seasonal pattern of internal nutrient cycling, potentially contributing to the increased occurrence of harmful algal blooms. The findings provide valuable information for water managers in the restoration of eutrophic lakes under climate change.

(Tewari 2022)

In this study the impact of climate change is categories as direct and indirect impact, such as temperature variation, ice coverage, precipitation, and runoff. Also discuss the potential solution and various mitigation strategies to reduce the effect of HABs. Variation in climate directly influence the harmful algal blooms by rising temperature, intensifying bloom, climate change impacts on lake temperature, precipitation and runoff, and lake ice coverage can influence the frequency, formation, and toxicity of HABs. It is observed that temperature of few lakes is rising. This increase in temperature is not restricted up to surface, but temperature of subsurface is also increasing and winter season is shortening. Climate change leads to heat wave which tends to increase in warmer period of surface water. lakes are experiencing increase in stratification in future climate, stratifying period of lake is becoming longer which impact on the lake ecosystem. Studied about various possible solution and strategies to mitigate the affect of climate change on HABs. There is a research gap between mitigation strategies and HABs Due to improvements in technology, there is potential for early detection of HABs. More research should be conducted to model molecular changes of HABs and their impact on aquatic ecosystems.

5 FUTURE SCOPE

Further research should be focused on understanding how climate change will affect harmful algal blooms and communities in coastal areas. Advancement in the prediction of HABs, and formulation of plans that will help to minimize the impact on coastal ecosystems, animals, and human communities. Focus on developing sophisticated predictive models which integrate oceanographic variables, climate change data, and history of occurrence of HABs, for accurate prediction and monitoring of harmful algal blooms. Need for more studies on microbial characteristics of Harmful algal blooms to understand their biological activity or production of cyanobacterial toxins in water under extreme climatic conditions.

To develop the most effective management and mitigation strategies for harmful algal blooms under different climate scenarios, and how can we implement them at a global scale.

Further investigations on cyanobacterial ecology and cyanotoxin production to understand the environmental factors that influence bloom formation and toxin production. Further research should explore the potential of combining MC (Modified Clay) with other HABs mitigation techniques, such as the use of algaecides or biological control methods, to improve the overall effectiveness of HABs control. To develop solution strategies to mitigate public health and socioeconomic impacts and enhance socio-ecological system resilience to future HABs. Advances in technology, such as omics techniques including transcriptomics, metabolomics, genomics, and proteomics, have provided new insights into HAB formation and toxin production, and may be leveraged to improve predictions on how climate change will impact the dynamics of HABs.

6 CONCLUSION

The impact of climate change on water quality, and how it is intensifying the expansion of harmful algal blooms (HABs)are studied and how climate-related variables, including rising water temperatures, shifts in hydrology, and disruptions in the nutrient cycle, stand as a primary driver behind the growing of HABs. The temperature rise caused by anthropogenic activities poses a serious threat to human health, aquatic ecosystems, and economic sectors such as the fishery industry. As the result of climate change and eutrophication continues in a coastal region, the growth of harmful algal blooms (HABs) is a concern for aquatic ecosystems. To know the impact of HABs on aquatic life, it is critical to incorporate them into experiments and monitoring alongside other climate change stressors. While potential mitigation measures such as biotic control, watershed management, and innovative techniques like modified clay and floated constructed wetlands have been proposed, their practical implementation faces challenges. The review emphasizes the need for multidisciplinary research and systematic data synthesis, consistently emphasizing the importance of considering socioeconomic implications. Further interdisciplinary research will help to understand the impact of harmful algal blooms due to climate change on water quality, human health, socioeconomic, and aquatic ecosystems. Due to the complications in the blooms, it is required to characterise the HABs carefully and more focused on the biological characteristics of the bloom to understand the production of cyanobacteria toxins in the water.

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