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Distribution and Impact of Harmful Algae Blooms (HABs) in Background of Global Climate Change

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Abstract: Harmful algal blooms (HABs) are increasingly recognized as a critical global environmental challenge, particularly in the context of climate change. This paper synthesizes the current understanding of HABs' global distribution, key environmental drivers, ecological and economic impacts, and advancements in monitoring technologies. Recent data indicate significant regional clustering of HAB events, especially in coastal regions of Europe, Asia, and North America. The study highlights how climate change exacerbates HABs through rising ocean temperatures, increased precipitation leading to nutrient runoff, and ocean acidification caused by elevated CO_2 levels, which enhance the growth and toxicity of harmful algal species. The consequences of HABs are severe and multifaceted, including mass marine organism mortality, bioaccumulation of toxins, threats to public health via contaminated seafood, and substantial economic losses in fisheries and tourism. The paper also explores evolving monitoring methods, such as molecular diagnostics, AI-assisted remote sensing, and IoT-integrated water quality sensors. It highlights the importance of international cooperation, standardized data collection, and proactive policy development to mitigate future impacts. Overall, the study provides a comprehensive perspective on HABs in the background of growing climate change and calls for approaches to effectively manage their ecological and societal risks.

Keywords: Harmful Algal Blooms (HABs), Climate Change, Ocean Algal

1. Introduction

Harmful algal blooms (HABs) refer to excessive overgrowth of harmful algae, particularly species that produce toxins or otherwise disrupt aquatic ecosystems. Human observations of algal bloom events can be traced back over a thousand years, with some of the earliest references appearing in biblical texts that described water discoloration and widespread fish mortality as natural phenomena [1]. The species responsible for HABs are taxonomically diverse, comprising both prokaryotic and eukaryotic organisms. Among prokaryotes, all morphological groups of cyanobacteria (e.g. *Lyngbya wollei*) are associated with HABs. Eukaryotic contributors include certain species of diatoms (e.g. *Didymosphenia geminata*), haptophytes (e.g. *Prymnesium parvum*), chrysophytes, chlorophytes (e.g. *Cladophora glomerata*), Dinoflagellates, Rhaphidophytes (e.g. *Gonyostomum ssemens*) andeuglenophytes also occasionally involved [2].

HABs can lead to a range of adverse impacts, including seafood biotoxin, water discoloration, animal or plant mortalities, foam and mucilage production. By 2019, HAB events associated with seafood biotoxins represented approximately 48% of all documented cases [3]. The toxins produced

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by these harmful algal species that are detrimental to other organisms and water conditions, including Saxitoxins, Tetrodotoxin, Spirolides, Brevetoxins, Gymnodimine, Okadaic acid, Pectenotoxins, Ciguatoxins, Yessotoxins, Azaspiracid, Hemolysins, Domoic Acid, Anatoxins, Mueggelone, Cylindrospermopsin, Microcystins and Nodularins [4].

In the present day, HABs as a significant global environmental issue, drawing continued scientific and public attention. The impact of HABs listed above extends beyond marine ecology, affecting fisheries, human health, tourism, and coastal economies. In the context of global climate change, environmental challenges are increasingly linked with climate-related issues. The heightened focus on the ecological and economic consequences of climate change across scientific and policy domains has positioned algal blooms as an essential and unavoidable area of research. Studying HAB dynamics in climate change background is critical to the conservation of marine biodiversity, food security, and public health. Despite growing scientific interest and necessity, there is limited consistency in monitoring methods and a significant lack of standardized and comprehensive international frameworks for the reporting and management of HAB events. Consequently, a globalized research perspective is especially critical in the current context. Nonetheless, existing studies in this field are limited to regional scales.

This article analyzes the key environmental driving factors including temperature, rainfall, and acidification in the current distribution of red tide events, evaluates the ecological and economic impacts, and discusses emerging monitoring technologies and international management strategies. This article aims to integrate the current status of the global phenomenon of HABs, the association between climate change and factors, the ecological and economic impacts, and the current technological developments, providing the latest global perspective for current research and providing background and inspiration for future research and the development of effective management strategies.

2. Global status review of HABs

2.1. Case description

According to the database provided by the IOC-UNESCO Harmful Algae Information System (Figure 1), in the past 5 years, global Harmful Algal Blooms (HABs) have exhibited significant regional clustering [5]. According to reports, most incidents occurred in coastal waters, with the most intense reports occurring along the Western European coastline. In Asian, HABs events are primarily reported along the southeastern coast of China, as well as in Japan and the Philippines, with the Philippines having the highest reported density of red tide. In North America, HABs outbreaks have been observed along the east coast of the U.S. and the coastal regions of California. For instance, in March 2025, a record-breaking large-scale HAB event was detected from the Aleutian Islands to the waters of California and has significantly impacted local fisheries and marine ecosystems [6]. There have also been notable concentrations of HABs events reports along the eastern coast of Australia and in the central South Atlantic. In contrast, fewer HABs events have been reported in the offshore waters of Africa, South Asia and the polar regions.

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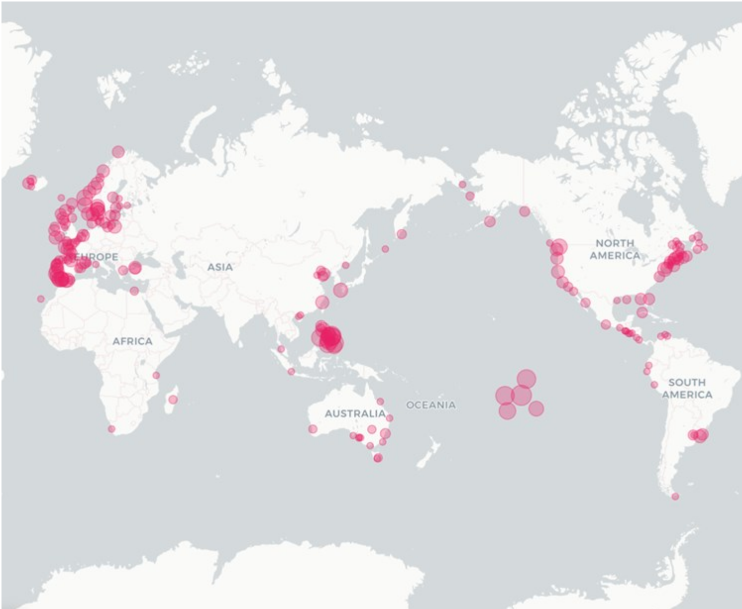

Figure 1: The global HAB events reports distribution since 2020 [5]

At present, there is debate within the academic community regarding the trends in HABs events reports. According to data provided by the IOC-UNESCO Harmful Algae Information System website, the number of HABs reports remained relatively stable prior to 2020, with 2020 marking the highest report number in the past five years [5]. However, according to the visualization data provided by NASA, there was no significant decline in several HABs event report occurrences between 2020 and 2023 [7]. A study published in 2021 suggested that there is no significant global trend in the occurrence of HABs events [8].

Moreover, due to variations in detection capability and research investment across different regions and periods, discrepancies in reporting accuracy exist, which may hinder a comprehensive understanding of global HABs trends. Nevertheless, when assessed in the context of real-world conditions, HABs remain a global concern. Their distribution is closely linked to their underlying causes and impacts, highlighting the need for continued advancement in monitoring technologies to observe and analyze their occurrences in order to mitigate more severe ecological and societal consequences.

2.2. Global impact

The wide-range impacts of HABs have attracted public attention, one of the most pressing concerns is the detrimental effect of HABs on marine ecosystems. The toxins produced by HABs associated with algae can have severe consequences for marine organisms. High concentrations can lead directly to mortality, and Prolonged exposure to these harmful algal toxins may result in a range of sublethal effects, including immunosuppression, developmental abnormalities, and the onset of various diseases [4]. The process of bioaccumulation can further exacerbate the long-term effects of HABs. Algal toxins accumulate through the food chains, and the toxin concentration increases at higher trophic levels, potentially leading to more severe and long-term impacts on marine organisms, including top predators.

Due to the harmful impact of algal toxins on marine organisms, the marine fisheries sector has suffered significant effects. One of the most direct consequences is the mass mortality of farmed fish and shellfish. The large-scale fish kills associated with HABs have been estimated to cause economic losses of up to $ 8 billion per year [9]. In addition, HAB toxins may also lead to direct threats to

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human health through the consumption of contaminated seafood. According to existing reports data collected, several HAB-related toxins have been identified, highlighting the growing risk to public health and underscoring the need for enhanced monitoring and risk management strategies [5].

Another significant detrimental effect of HABs is the disruption to the tourism industry of coastal regions. HAB events often degrade the aesthetic quality of marine environments, primarily through discoloration of the water and unpleasant odour. Moreover, the toxins produced by harmful algae can also pose direct health risks to tourists. For example, the 2018 red tide event in Florida, characterized by a massive bloom of Karenia brevis, resulted in an estimated $2.7 billion in economic losses to the local tourism sector [10].

2.3. Factors

Considering the global distribution of HABs events reports, occurrences of HABs associated with climate conditions, especially temperature. Reports of HAB events are more densely concentrated in tropical and subtropical regions compared to polar areas, indicating a correlation between HAB occurrences and climate. As global warming intensifies, the rising ocean temperatures could expand the optimal temperature range for harmful algae, potentially exacerbating HAB phenomena and facilitating their poleward expansion.

Extreme rainfall events are also associated with intensive HABs events. In some coastal regions, the explosive growth of certain algal species is associated with nutrient enrichment. For example, the increase in Pseudo-nitzschia in the northern Gulf of Mexico has been positively correlated with the flux of nutrients discharged into marine waters by the Mississippi River [11]. This correlation suggests that HAB events can be influenced by riverine inputs. Increasing precipitation will lead to higher nutrients flowing into the ocean, thereby promoting large-scale HABs events. As global climate change and extreme weather events become more frequent, the HABs led by river runoff have emerged as an important environmental issue.

In the context of global climate change, ocean acidification driven by increasing concentrations of atmospheric carbon dioxide (CO2) has also become a critical environmental concern. Ocean acidification has also been considered as associated with the occurrence HABs events. Research has shown that when the partial pressure of CO2 in seawater exceeds 600μatm, there is a significant increase of HABs-associated species *Vicicitus globosus*. Furthermore, when CO2 level rises above 800μatm, it triggers the occurrence of HAB events [12].

2.4. Existing detection and monitoring method

To effectively study and manage the status of global HABs events occurrences, the research and application of HAB monitoring technologies has become a notable area of inquiry. Detection methods for HABs generally fall into two main categories: species detection and toxin detection. Traditional species detection relies on the manual quantification of algal abundance in water samples, a process that is often labor-intensive and dependent on expert analysis. Toxin detection focuses on identifying HABs associated toxins using various techniques, including chemical analytical methods, in vitro assays, and in vivo assays [13]. A current focal point in technological development is the detection of specific molecular markers associated with HAB-related algal species. Certain emerging technologies that integrate multiple data analysis approaches are also being actively developed. Current methods often combine molecular, chemical, and remote sensing data with advanced computational techniques—such as machine learning and statistical modeling—to improve the accuracy, timeliness, and spatial resolution of HABs detection. For example, a novel species detection technique has been developed that combines hyperspectral imaging with deep learning technology to enable effective prediction of HAB events [14]. Monitoring water quality conditions is another

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important approach for detecting and forecasting HABs. A water quality sensing technology that integrates Internet of Things (IoT) capabilities with PETG 3D printing has been developed to enable early warning of potential HAB events [15]. With the advancement of artificial intelligence (AI), detection methods incorporating AI technologies have emerged as another significant area of interest. For example, an AI model developed using freely available remote sensing data has enabled low-cost prediction of HAB events in the Persian Gulf and the Gulf of Oman [16].

As discussed above, although the trends in HAB occurrences remain a debate within the scientific community, it is clear that HABs pose significant ecological and societal threats. With the advancement of various monitoring technologies, approaches that balance economic feasibility with high sensitivity are increasingly being implemented in practice. Governments around the world have a responsibility to control and address HABs issues, including regulating nutrient discharge via river runoff and enhancing marine ecosystem restoration efforts. Furthermore, international cooperation is essential in establishing mechanisms for information sharing and coordinated cross-border responses will be crucial in managing the global impacts of HABs.

2.5. Future development forecast and targeted governance measure

As ocean temperatures continue to rise, the thermal conditions that support the growth of harmful algal species are likely to keep expanding to higher latitudes. Moreover, increased extreme weather events—especially heavy rainfall—will likely aggravate nutrient runoff from rivers into coastal waters. Ocean acidification, driven by elevated atmospheric CO_2 levels, may also selectively benefit certain HAB species, enhancing their growth rates and toxin production. Overall, if current trends continue, HABs are likely to become more frequent, widespread, and disruptive. To prevent further deterioration, the development of effective management strategies has become one of the most critical research priorities at this stage. Effectively addressing the challenges posed by HABs requires a multi-faceted and collaborative approach that integrates policy, science, and community action. First, regional governments have a responsibility to address the root causes of HAB-related issues through targeted solutions. For instance, mitigating river eutrophication by promoting sustainable agricultural practices and enhancing soil conservation efforts. International cooperation is also crucial in addressing the root causes of HABs. Addressing ocean acidification and rising water temperatures requires long-term and globally coordinated planning and management efforts. Second, investments in advanced detection technologies are essential. Governments should prioritize the research and implementation of new detection technologies to enable a rapid and effective response to HAB events. As previously mentioned, a lack of standardized data collection due to disparities in research investment across regions remains an issue that must be addressed to advance effective global HAB management. Strengthened international collaboration is essential for the establishment of globally standardized systems for monitoring and reporting HABs.

3. Conclusion

In the context of global climate change, the emergence of harmful algal blooms (HAMs) in the oceans represents a significant global environmental issue. This review has presented the global review of HAB occurrence, ecological and economic impact and current advancements in monitoring technology. Over the past five years, HABs events have shown clear regional clustering, with particularly high occurrences in coastal areas of Europe, Asia, and North America. Although there remains debate over the data trends observed in HAB reporting, the extensive distribution and significant environmental consequences of HABs have highlighted sustained scientific investigation and public concern. Climate change has intensified certain factors that contribute to large-scale HABs. For example, rising global temperatures have broadened the spread range where conditions are

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optimal for the growth of harmful algal species. Extreme rainfall events increase nutrient runoff from rivers promoting the growth of harmful algal species. Rising atmospheric CO_2 concentrations contribute to ocean acidification, which has been shown to enhance the growth potential of certain harmful algal species. The consequences of HABs are multifaceted. Marine ecosystems are facing severe threats from algal toxins that cause mass mortality and long-term sublethal effects on aquatic species. Certain algal toxins also cause public health risks, further leading to economic losses in the aquaculture and tourism industry. In the monitoring and prediction of HAB events, certain new technologies are continually being developed and implemented currently. Current detection technologies—including molecular methods, remote sensing, and AI-based tools are developing new directions for more efficient HABs control and monitoring. Policy attention and international cooperation are also critical means of mitigating the ecological and economic impacts of HABs. This paper highlights the global distribution and climate-related drivers, their ecological and socioeconomic impacts and current monitoring technologies development, and contribute to a more comprehensive global perspective for further research.

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