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Harmful Algal Blooms in Malaysia: Occurrence, Preparedness, Challenges, and Recommendations

(Ledakan Alga Berbahaya di Malaysia: Kejadian, Kesiapsiagaan, Cabaran dan Cadangan)

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ABSTRACT

Harmful Algal Blooms (HABs) pose increasing environmental and economic threats to Malaysia, affecting marine ecosystems, fisheries, and public health. This study reviews HAB occurrences from 2001 to 2024, analyzing species diversity, geographical expansion, and response strategies. Findings show that *Pyrodinium bahamense*, *Alexandrium minutum*, and *Margalefidinium polykrikoides* remain the dominant species, but newly emerging harmful algae, such as *Pseudo-nitzschia* and *Gambierdiscus belizeanus*, indicate diversification of HAB species. Reports confirm a rise in HAB frequency, extending beyond previously affected regions like Sabah to Peninsular Malaysia. Malaysia's current HAB early warning system is reactive, relying on time-consuming conventional microscopy and resource-intensive molecular tools. While international advancements include satellite remote sensing, its application in Malaysia is challenged by frequent cloud cover and high costs. To improve, this review highlights the need for rapid, cost-efficient, on-site localized detection technologies like broad detection tools (biosensors). Implementing these methods will enable real-time monitoring and accurate, rapid identification of HAB events, leading to more effective and proactive management. Moreover, strengthening multi-agency collaboration, enforcing stricter pollution controls, and enhancing public awareness programs are crucial for long-term mitigation. These strategies offer a pathway toward a sustainable, technology-driven approach to HAB management in Malaysia.

Keywords: Algal species diversification; early warning systems; Harmful Algal Blooms (HABs); Malaysia; mitigation strategies

ABSTRAK

Ledakan Alga Berbahaya (LAB) semakin mengancam alam sekitar dan ekonomi Malaysia, menjejaskan ekosistem marin, perikanan dan kesihatan awam. Penyelidikan ini mengulas kejadian LAB dari tahun 2001 hingga 2024 dengan menganalisis kepelbagaian spesies, peluasan geografi dan strategi tindak balas. Keputusan menunjukkan bahawa *Pyrodinium bahamense*, *Alexandrium minutum* dan *Margalefidinium polykrikoides* kekal sebagai spesies dominan, namun kemunculan alga berbahaya baharu seperti *Pseudo-nitzschia* dan *Gambierdiscus belizeanus* menunjukkan kepelbagaian spesies LAB yang semakin meningkat. Laporan juga mengesahkan peningkatan kekerapan kejadian LAB yang kini turut berlaku di Semenanjung Malaysia, bukan lagi terhad kepada kawasan seperti Sabah sahaja. Sistem amaran awal LAB di Malaysia ketika ini bersifat reaktif, bergantung kepada teknik mikroskopik konvensional yang memakan masa dan kaedah molekul yang memerlukan sumber tinggi. Walaupun terdapat kemajuan di peringkat antarabangsa seperti penderiaan jauh satelit, penggunaannya di Malaysia terhad disebabkan oleh liputan awan yang kerap dan kos yang tinggi. Bagi meningkatkan keupayaan pemantauan, kajian ini menekankan keperluan kritikal terhadap teknologi pengesanan pantas, kos-efisien dan setempat seperti alat pengesanan menyeluruh (biosensor). Pelaksanaan kaedah ini membolehkan pemantauan masa nyata dan pengesanan kejadian LAB yang lebih cepat dan tepat, sekali gus membolehkan pengurusan yang lebih berkesan dan proaktif. Selain itu, pengukuhan kerjasama antara agensi, penguatkuasaan kawalan pencemaran yang lebih ketat dan peningkatan program kesedaran awam amat penting untuk mitigasi jangka panjang. Strategi ini menawarkan laluan ke arah pendekatan pengurusan LAB yang mampan dan dipacu teknologi di Malaysia.

Kata kunci: Kepelbagaian spesies alga; Ledakan Alga Berbahaya (LAB); Malaysia; sistem amaran awal; strategi mitigasi

INTRODUCTION

Harmful Algal Blooms (HABs) pose an escalating global threat, causing mass marine mortality, seafood contamination, and substantial economic losses in fisheries and aquaculture (Oh et al. 2023). During these events, specific microalgal species proliferate rapidly, producing toxins through specialized genetic pathways triggered by nutrient-rich or stressful environmental conditions (Wang

& Huang 2025; Wang et al. 2016). While some toxins are released naturally into the water as extracellular compounds, many remain stored inside the cell as intracellular toxins. These are released into the environment when the algae cells die naturally through autolysis or are broken down, such as by stomach acids in animals that ingest them. These toxins accumulate in seafood and may lead to severe human poisoning. Beyond chemical toxicity, HABs can physically clog fish gills, deplete dissolved oxygen, and disrupt entire aquatic food webs.

The definition of a HAB varies by regulatory body, often depending on cell density and toxin concentration. While The U.S. Environmental Protection Agency (US EPA) characterizes blooms primarily by physical indicators such as surface scums (Fristachi et al. 2008), the World Health Organization (WHO 2003) quantifies a low-risk bloom at densities exceeding 20,000 cells mL^{-1}. However, HAB thresholds are highly species-specific; for example, in the Malaysian context, *Pyrodinium bahamense* and *Margalefidinium polykrikoides* (formerly *Cochlodinium polykrikoides*) are considered potentially harmful at densities as low as 1 cells mL^{-1}, as these levels signal a potential threat to local fisheries before visible blooming occurs (Jipanin et al. 2019).

In Malaysia, HABs have frequently occurred along coastal waters, notably in Sabah with annual *P. bahamense* and *M. polykrikoides* blooms for decades (Lim, Gires & Leaw 2012). However, since 2013, HAB events have expanded geographically to Peninsular Malaysia, including Pahang, Kelantan, Johor, and Perak (Yñiguez et al. 2021). Key species like *P. bahamense*, *Alexandrium minutum*, and *M. polykrikoides* have caused paralytic shellfish poisoning (PSP) and large-scale fish kills (Razali et al. 2022; Tan et al. 2021). Despite fewer PSP human poisoning reports recently, the economic impact, especially on aquaculture, remains substantial.

Despite ongoing Department of Fisheries Malaysia (DOFM) monitoring, early detection and mitigation remain insufficient. Current programs rely on time-consuming, expertise-dependent microscopy and conventional molecular methods (Jipanin et al. 2019), often overlooking new hotspots by focusing solely on previously affected regions. Unlike some developed nations employing satellite-based detection and predictive modeling (Karen et al. 2013), Malaysia primarily relies on *in situ* sampling. This highlights a pressing need for rapid, broad-spectrum alternative monitoring tools.

This review provides a comprehensive analysis of Malaysian HAB occurrences from 2001-2024, examining trends in species diversity, geographical distribution, and impacts. It also evaluates current preparedness and compares Malaysia's management strategies internationally. By identifying challenges and opportunities, this review aims to contribute to more effective and proactive HAB management in Malaysia. Figure 1 provides an overview of the paper's content.

MATERIALS AND METHODS

STRATEGIES FOR COMPILING THE TIMELINE OF HAB EVENTS IN MALAYSIA

To construct a comprehensive timeline of HAB occurrences in Malaysia, data were gathered from scientific journals, reliable online sources, and government reports spanning from 2001 to 2024. Journals were sourced exclusively from SCOPUS using keywords such as 'Malaysia' AND 'HAB' OR 'harmful algal bloom' OR 'algal bloom' OR 'red tide'. To capture region-specific events, additional searches replaced 'Malaysia' with individual state names ('Johor', 'Penang', and 'Sabah').

One reliable online source is the Harmful Algae Event Database (HAEDAT), a meta-database containing records of HAB events internationally. The HAEDAT database for Malaysia includes events from 1991 to 2019, was accessed through (https://haedat.iode.org/). News articles from reliable media platforms such as The Star and MyNews were reviewed, along with Google searches in both English and Malay languages, to identify webpage information on HAB events. To ensure data reliability, duplicate reports from multiple sources were removed, and priority was given to peer-reviewed journals. This approach provided a structured and validated timeline of HAB occurrences across Malaysia's coastal waters.

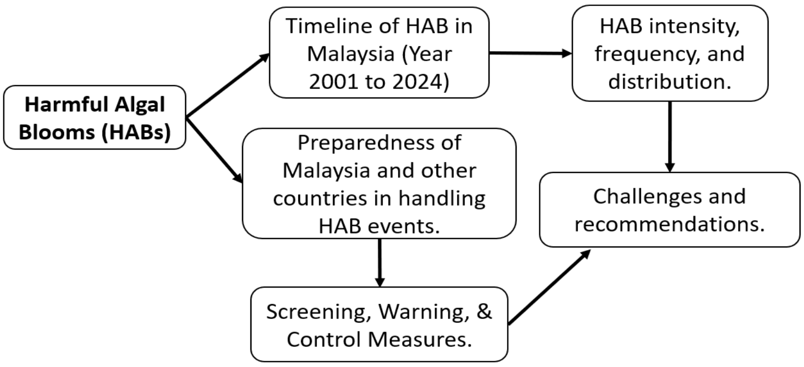

FIGURE 1. Overview of this review article

DEFINING THE SCOPE OF 'PREPAREDNESS' FOR HAB EVENTS

Preparedness in this paper refers to a country's ability to anticipate, detect, and respond to HAB events effectively. To assess Malaysia's level of preparedness, this study categorized the response framework into three key stages: Screening, Warning, and Control Measures.

Screening This initial stage involves routine monitoring of water quality and phytoplankton populations to detect potential HAB threats. Monitoring methods include microscopy, molecular tools, and bioassays for toxin detection.

Warning This stage is triggered when harmful algae or their associated toxins reach predefined threshold levels, signaling a potential risk. Different countries establish unique threshold values based on species-specific toxicity or biomass concentration. The study reviewed global HAB alert thresholds to compare Malaysia's criteria against international standards.

Control Measures This stage encompasses action taken following a confirmed HAB event, including restrictions on seafood harvesting, fish farm management interventions, and public health advisories. Furthermore, mitigation strategies to reduce or prevent HAB events are discussed in this stage.

In conducting the search on SCOPUS and Google, the keywords 'Malaysia' AND 'HAB' OR 'harmful alga* bloom' OR 'alga* bloom' OR 'red tide' AND 'management' OR 'mitigation' OR 'preparedness' were employed. For searches related to other countries, the keyword 'Malaysia' was replaced with the names of other countries. Countries were selected based on two main criteria: (I) geographical and climatic similarities such as Indonesia, Thailand, and the Philippines, and (II) the presence of structured HAB monitoring and response framework, as seen in countries like the United States, France, and Australia. This approach aims to provide a better understanding of strategies adopted by Malaysia and other nations in addressing HAB, highlighting both common practices and country-specific advancements.

RESULTS AND DISCUSSION

HAB HISTORICAL CONTEXT AND GEOGRAPHIC EXPANSION

Historically, HABs in Malaysia were concentrated in Sabah, exemplified by *P. bahamense* blooms (Table 1). Since the first major PSP event in 1976, these blooms have become a persistent threat. A synthesis by Jipanin et al. (2019) reported 3,279 HAB events in Sabah through 2017, with *P. bahamense* accounting for over half (1,752 events), particularly in Sepanggar Bay and Kota Kinabalu. Bloom concentrations in Sabah coastal waters typically range from 10-100 cells mL^{-1}, such as the 2013 outbreak which recorded a mean of approximately 34 cells mL^{-1} (Alkawri et al. 2016; Suleiman et al. 2017).

The earliest HAB case reported in Peninsular Malaysia dates to 1978 in Teluk Kumbar, Penang, involving a bloom of *Noctiluca scintillans* (Razali et al. 2022). Although reports from Peninsular Malaysia were historically less frequent than those from East Malaysia, documented HAB events in Peninsular waters have increased since the 2000s, with notable cases around and after 2013, broadly in line with global observations of expanding HAB occurrences.

TAXONOMIC DIVERSIFICATION AND EMERGING TOXIC THREATS

The synthesis of data from Tables 1 and 2 show an alarming transition from a predictable, localized problem to a complex, multi-species crisis. While historical records were primarily dominated by the dinoflagellates *P. bahamense* and *M. polykrikoides*, the last two decades have seen a significant broadening of the taxonomic spectrum. This diversification is most evident in the emergence of varied PSP vectors; where *P. bahamense* was once the sole concern, species such as *Alexandrium minutum* in Kelantan, *A. tamiyavanichii* in Pahang, and *Gymnodinium catenatum* in the Selangor and Negeri Sembilan regions have now established themselves as persistent saxitoxin producers (Bernama 2024; Lim, Gires & Leaw 2012; Mohammad-Noor et al. 2018).

The risk profile has further expanded beyond PSP to include Amnesic Shellfish Poisoning (ASP) and Ciguatera Fish Poisoning (CFP). Table 2 highlights the ubiquitous nature of domoic acid-producing *Pseudo-nitzschia* spp., which have been documented across numerous distinct coastal locations ranging from Miri in Sarawak to Port Dickson in the Peninsular Malaysia (Teng et al. 2013). This suggests a high degree of adaptability among these diatoms across varying salinities and temperatures. Simultaneously, the discovery of the benthic dinoflagellate *Gambierdiscus belizeanus* on the east coast of Sabah introduces a more insidious threat to the food chain, as ciguatera toxins accumulate in reef fish, complicating seafood safety protocols in one of Malaysia's most productive fishing zones (Leaw et al. 2011).

Furthermore, the potential emergence of the raphidophyte *Chattonella subsalsa* in the Johor Strait emphasizes the arrival of novel ichthyotoxic species that pose a direct threat to the aquaculture sector (Lum et al. 2022). The environmental impact of these blooms is no longer limited to toxicity alone; the proliferation of non-toxic but high-biomass species like *N. scintillans* and *Coscinodiscus* sp. has increasingly led to mass fish mortalities through mechanical gill damage and severe deoxygenation (Diego-McGlone et al. 2024; Tan et al. 2021). Ultimately, the historical data from Table 1 and the additional species discoveries in Table 2 were synthesized into Figure 2 to provide a visual representation of these longitudinal trends. This figure clearly illustrates the expanding ecological niche for harmful algae in Malaysia, documenting the steady rise in both species richness and occurrence frequency over the study period.

SOCIO-ECONOMIC AND PUBLIC HEALTH IMPACTS

The evolving profile of Malaysian HABs has direct consequences for food safety and fisheries management. While acute public health crises have occurred, most notably the 2013 Kota Kinabalu outbreak that resulted in four fatalities (Suleiman et al. 2017) and the 2014 Kuantan Port event involving ten hospitalizations (Mohammad-Noor et al. 2018), the nature of the impact is becoming more diverse.

Recent years from 2019 to 2024 have shown a shift toward compounded ecological threats. These include mass fish mortalities caused by deoxygenation associated with *Noctiluca scintillans* blooms in Penang (Diego-McGlone et al. 2024), as well as mussel contamination in Port Dickson linked to multi species blooms (Bernama 2024). Such complex, multi-species events represent a significant technical challenge, as the presence of diverse taxa with varying physiological traits requires multiple, distinct detection methods, thereby complicating routine surveillance. Furthermore, the detection of dangerous toxin levels in freshwater systems, such as *Microcystis* species in Tasik Aman (Aida 2024), indicates that HAB risks are now extending beyond the traditional boundary between marine and freshwater environments.

MANAGEMENT IMPLICATIONS

The complexity displayed in Tables 1 and 2 suggest that traditional monitoring may no longer suffice. The presence of varied bloom behaviors and ‘cryptic’ toxic species requires a transition toward proactive management. This includes stringent nutrient pollution controls, enhanced seafood toxicity surveillance, and the integration of modern technologies such as biosensing and satellite-based predictive modeling (Chin et al. 2022; Durán-Vinet et al. 2021). Without such interventions, the increasing prevalence of these harmful species poses an escalating risk to Malaysia’s marine ecosystems, public health, and the economic stability of the fishing industry.

SCREENING: MONITORING AND EARLY DETECTION

Malaysia’s HAB monitoring lacks uniform standardization across states, resulting in inconsistent, largely localized, and less technology-driven surveillance. This contrasts sharply with comprehensive international systems; even Cambodia reportedly relies on post-incident analysis (Table 3).

Malaysia’s HAB surveillance is limited by a reliance on labor-intensive manual sampling and centralized laboratory routing, such as the Likas Fisheries Complex, which restricts the scale and timeliness of monitoring (Jipanin et al. 2019; Lim, Gires & Leaw 2012; Mohyedin et al. 2019). This fragmented workflow is worsened by regional inconsistencies where states monitor HABs only episodically, unlike Sabah’s year-round routine. Furthermore, the system is inherently reactive because responses only trigger after cell thresholds are breached, requiring a slow, sequential notification process from state directors down to local media, which ultimately delays public health and economic protections (Jipanin et al. 2019).

These management gaps are reflected in a comparative scoring system where regional variations persist across the country (Mohyedin et al. 2019). Sabah and Kelantan achieve the highest scores (4/4 points) due to their implementation of water quality controls, prevention measures, awareness campaigns, and specialized SOPs or laboratory tools. In contrast, Johor, Pahang, and Sarawak scored the lowest at 1 to 2 points, primarily due to a lack of dedicated laboratories and comprehensive prevention strategies.

In contrast, countries like the United States utilize sophisticated, technology-driven programs, including satellite-based tracking and predictive modeling, enabling proactive, near real-time surveillance (Elizabeth et al. 2008). Satellite observations provide repeated, wide-area views essential for routinely tracking blooms across local and global waters (Shen, Xu & Guo 2012). Unlike point-based sampling, this frequent, large-scale coverage enables robust operational monitoring through integrated frameworks. For example, remote-sensing products are increasingly used to drive advanced forecasting; these range from schemes combining ocean-color data with particle-tracking (Lin et al. 2021) to AI-based early-warning systems that utilize freely available satellite streams to predict risks in regions like the Persian Gulf (Shahmiri, Seyed-Djawadi & Siadatmousavi 2025).

Other nations also employ established, diverse monitoring strategies to manage HAB risks (Fisheries 2022; Frederic 2021; Yñiguez et al. 2021). For instance, Lake Geneva (France/Switzerland) utilizes monthly microscopy-based phytoplankton analysis, triggering alerts when biomass exceeds 1000 μg L^{-1} (Frederic 2021). In Hong Kong, monitoring involves seawater discoloration checks and biotoxin testing in fish culture zones, supported by public education through posters and leaflets (Agriculture, Fisheries and Conservation Department 2022). Meanwhile, the Philippines employs a targeted approach in previously affected areas, using mouse bioassays to test shellfish for PSP (Yñiguez et al. 2021).

WARNING: THRESHOLD LEVELS AND RISK WARNINGS

In Malaysia, HAB alert thresholds and communication vary by state. Sabah has specific cell density triggers for *P. bahamense* and *M. polykrikoides*, and issues public advisories when shellfish toxin levels exceed 80 µg saxitoxin equivalents per 100 g of meat (Eong & Sulit 2017). Communication methods include radio, TV, notices, and signboards, but dissemination is often localized, with different states employing distinct strategies (Gristwood 2022; Jipanin et al. 2019). While Sabah’s infrastructure is robust, the reliance on localized dissemination through radio, TV, and physical signboards presents a critical gap in the digital age. This localized approach may fail to reach transient fishing populations or younger demographics who do not engage with traditional media, which suggests

TABLE 1. Timeline documenting reported HAB occurrences in Malaysia's coastal waters from 2001 to 2024

Years	Location	HAB Species	Bloom Concentration (cells mL^{-1})	Impact	References
2001	Tumpat, Kelantan	*Alexandrium minutum*	NR	6 hospitalised due to PSP	(Lim, Gires & Leaw 2012)
2002	Johor Bahru, Johor	*Prorocentrum minutum*	>200.0	Water discoloration	(Usup et al. 2004)
2004	Kuala Penyu, Sabah	*Pyrodinium bahamense*	11.2	PSP reported	(HAEDAT n.d.)
2004	Kota Kinabalu, Pulau Gaya, & Gayana Resort of Sabah	*Pyrodinium bahamense* & *Margalefidinium polykrikoides*	0.6 – 52.8	Water discoloration, PSP reported	(HAEDAT n.d.)
2005	Sepanggar Port, Sabah	*Pyrodinium bahamense* & *Margalefidinium polykrikoides*	11.4 – 1386.0	PSP reported	(HAEDAT n.d.)
2005	Kota Kinabalu, Sabah	*Margalefidinium polykrikoides*	6000.0	Water discoloration	(Anton et al. 2008)
2005 & 2006	Penang	-	NR	Mortality of caged fish	(Lim et al. 2014)
2006	Trayong, Sabah	*Pyrodinium bahamense*	160.0	PSP reported	(HAEDAT n.d.)
2006	Kuching, Sarawak & Kota Kinabalu, Sabah	*Margalefidinium polykrikoides*	6000.0	Water discoloration, some fish kills	(Anton et al. 2008)
2007	Pangkor, Lumut, Penang	*Neoceratium furca*	NR	Water discoloration	(Lim, Gires & Leaw 2012)
2007	Trayong, Sabah	*Pyrodinium bahamense* & *Margalefidinium polykrikoides*	NR	Water discoloration	(HAEDAT n.d.)
2007	Pulau Gaya & Karambunai, Sabah	*Pyrodinium bahamense*	7.1 – 29.5	Shellfish contamination	(HAEDAT n.d.)
2008	Kota Kinabalu, Sabah	*Margalefidinium polykrikoides*	11.5	Water discoloration	(HAEDAT n.d.)
2008	Sg Jarum Mas, Perak	*Alexandrium* sp.	NR	Water discoloration	(Roziawati & Faazaz 2011)
2009	Kota Kinabalu, Sabah	*Pyrodinium bahamense*	NR	Shellfish contamination	(Lim, Gires & Leaw 2012)
2009	Sepanggar Port, Andus Papar, Trayong, Karambunai, Sg Mengkabong, Tanjung Badak, Pulau Gaya, Pulau Manukan of Sabah	*Pyrodinium bahamense*	3.7 – 1303.9	Water discoloration, shellfish contamination	(HAEDAT n.d.)
2012	Sepanggar Port & Karambunai, Sabah	*Pyrodinium bahamense*	0.9 – 20.1	-	(HAEDAT n.d.)

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2012	Kota Kinabalu & Tanjung Aru, Sabah	*Margalefidinium polykrikoides*	420.2 – 1134.4	Water discoloration	(HAEDAT n.d.)
2013	Pulau Gaya & Kuala Mengalong, Sabah	*Pyrodinium bahamense*	251.8 – 472.8	Water discoloration, shellfish contamination	(HAEDAT n.d.)
2013	Pulau Papan, Sabah	*Pyrodinium bahamense* var *compressum*	NR	Water discoloration, potential shellfish contamination	(Daily Express 2013)
2013	Kota Kinabalu, Sabah	*Pyrodinium bahamense* var *compressum*	NR	4 deaths, 58 reports of PSP	(Suleiman et al. 2017)
2013	Coastal waters of Perak and Straits of Tebrau	*Margalefidinium polykrikoides*	2.5 – 4.7	Red discoloration, cultured finfish mortality	(Harun et al. 2015)
2013	Kuantan Port, Pahang	*Alexandrium tamiyavanichii*	>8.1	PSP reported	(Mohammad-Noor et al. 2018)
2013	Kota Kinabalu, Sabah	*Gonyaulax polygramma*	NR	Water discoloration	(Jipanin et al. 2019)
2014	Kudat, Sabah	*Noctiluca scintillans*	NR	Water discoloration, some fish kill	(Jipanin et al. 2019)
2014	Kuantan Port, Pahang	*Alexandrium tamiyavanichii*	0.8	10 hospitalised with PSP symptoms	(Mohammad-Noor et al. 2018)
2014, 2015	West Johor Strait	*Karlodinium australe*	2340.0 – 200000.0	Water discoloration, mortality of caged fishes	(Lim et al. 2014)
2015	Sungai Geting, Kelantan	*Alexandrium minutum*	23000.0	Severe water discoloration, contaminated benthic clams	(Lau et al. 2017)
2015	Kota Marudu, Sabah	*Noctiluca scintillans*	NR	Water discoloration	(Jipanin et al. 2019)
2016	Bachok, Kelantan	*Chattonella malayana*	143.0	Water discoloration, fish kill	(Lum et al. 2022)
2017	Kota Kinabalu, Sabah	*Margalefidinium polykrikoides*	NR	Water discoloration	(Jipanin et al. 2019)
2018	Miri, Sarawak	*Pseudo-nitzschia cuspidata*	2500.0	Domoic acid contamination in shellfish	(Teng et al. 2021)
2019	Teluk Bahang, Penang	*Coscinodiscus* sp.	25.0	Water discoloration, fish kill	(Tan et al. 2021)
2019	Kuala Penyu, Sabah	*Pyrodinium bahamense*	NR	Water discoloration, shellfish contamination	(Miwil 2019)

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2020	Coastal waters north of Perak and south of Penang	*Margalefidinium fulvescens*	461.0 – 622.0	Water discoloration, fish kill	(Razali et al. 2022)
2021	Sg Geting, Kelantan	*Alexandrium minutum*	NR	Shellfish contamination	(DOFM 2021)
2022	Northern Malacca Strait, Penang	*Tripos furca*	820.0	Water discoloration	(Azmi et al. 2025)
2023	Kota Kinabalu, Sabah	*Margalefidinium polykrikoides & Pyrodinium bahamense*	NR	Shellfish contamination	(Abdullah 2023)
2023	Teluk Bahang, Penang	*Noctiluca scintillans*	NR	Reduced dissolved oxygen, fish kill	(Diego-McGlone et al. 2024)
2024	Port Dickson, Negeri Sembilan	*Pyrodinium bahamense* var *compressum, Margalefidinium polykrikoides, & Gymnodinium catenatum*	NR	Contaminated mussel	(Bernama 2024)
2024	Tasik Aman, Selangor	*Microcystis sp.*	NR	Dangerous levels of toxins detected	(Aida 2024)

Note: 'NR' = 'not reported'

TABLE 2. Discoveries of other harmful algal species in Malaysia's coastal waters

Harmful algae	Toxin/Effect	Location	References
Chattonella subsalsa	Ichthyotoxicity	Johor Strait	(Lum et al. 2022)
Alexandrium taylori & *Alexandrium peruvianum*	Saxitoxin	Kuching Bay & Sarawak River, Sarawak	(Lim et al. 2005)
Alexandrium affine, Alexandrium leei, & Alexandrium tamarense	Saxitoxin	Straits of Malacca	(Usup et al. 2002)
Gymnodinium catenatum	Saxitoxin	Selangor region	(Su-Myat et al. 2012)
Pseudo-nitzschia spp.	Domoic acid	Queen Bay, Miri, Kuala Penyu, Kabong, Kota Belud, Kota Kinabalu, Kudat, Port Dickson, Sempurna, Muar, Teluk Batik, Johor, Santubong, Gerigat, Bintulu, Kuala Terengganu & Pulau Banggi	(Teng et al. 2013)
Gambierdiscus belizeanus	Ciguatera	East coast of Sabah	(Leaw et al. 2011)

a need for real-time and mobile-integrated alert systems to supplement existing notices.

For other Malaysian states such as Johor, Kelantan, and Pahang, there is a lack of localized or state-specific toxin thresholds. Instead, these regions adhere to the National Shellfish Sanitation Program (NSSP) where biotoxin testing is triggered when cell counts of high-risk species like *P. bahamense* reach the threshold of 10 cells mL^{-1} (Eong & Sulit 2017). This reliance on a centralized national framework raises concerns regarding environmental equity because states with emerging HAB risks may lack the specialized monitoring equipment found in Sabah, leading to a reactive rather than proactive safety posture. Furthermore, the 10 cells mL^{-1} trigger may be insufficient in

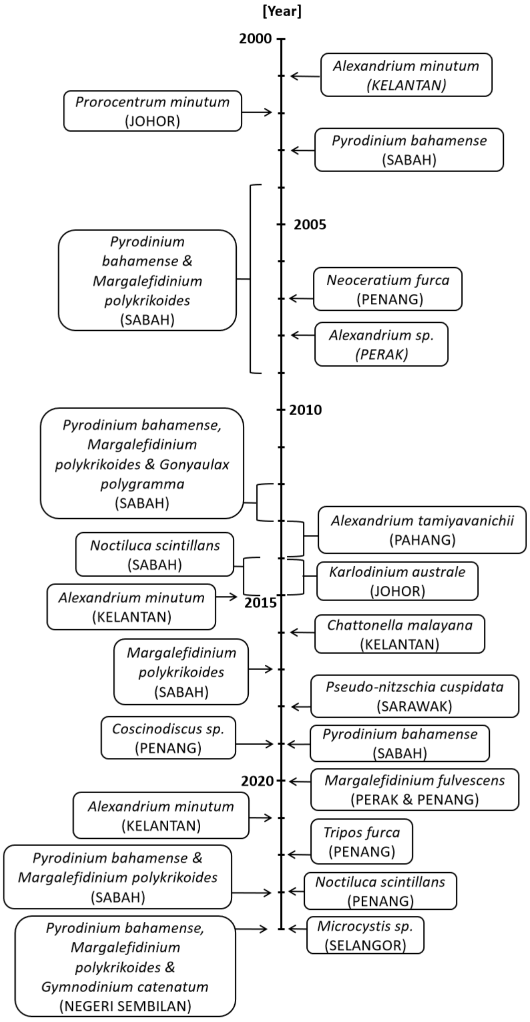

FIGURE 2. Timeline trend of reported HAB species in Malaysia. Species occurrences are indicated by the scientific name followed by the state in parentheses (for example *Alexandrium minutum* (Kelantan))

nutrient-rich waters where bloom acceleration can outpace the weekly sampling cycles typical of the NSSP. While unique state-level limits are not codified for these areas, the national framework adopts the international standard of 80 µg STX per 100 g of meat (Eong & Sulit 2017). This ensures a consistent safety standard across the country, yet it lacks the detail required to account for regional variations in shellfish consumption rates.

Toxin thresholds in other nations vary significantly based on the target matrix and the specific species involved. In Lake Geneva (France/Switzerland), an alert is triggered when phytoplankton biomass exceeds 1000 µg L^{-1} (Frederic 2021), while in the Murray River, Australia, the threshold is set at microcystin levels exceeding 10 µg L^{-1} (Biswas 2017). Regarding seafood safety, France implements toxicity thresholds of 80 µg kg^{-1} for Diarrhetic Shellfish Poisoning (DSP) and 10 mg kg^{-1} for ASP (Agúndez, Chenouf & Raux 2022). Similarly, the Philippines monitors PSP in shellfish, with an alert threshold of 0.6 µg g^{-1} (Yñiguez et al. 2021). The discrepancy in measurement units across these nations creates a significant barrier to the harmonization of international seafood trade. For Malaysian exporters, navigating these varying thresholds requires rigorous compliance with the most stringent international standards, which often needs more frequent and costly laboratory testing than what is required for domestic consumption.

CONTROL MEASURES: RESPONSE AND MITIGATION STRATEGIES

In Malaysia, HAB control primarily relies on reactive measures such as harvesting restrictions, fish stock relocation, and public health advisories communicated via various channels (Eong & Sulit 2017; Lim, Gires & Leaw 2012). However, mitigation frameworks are inconsistent across states, with some lacking defined management protocols, relying only on basic awareness or limited analysis (Mohyedin et al. 2019).

TABLE 3. Summary of preparedness of Malaysia and other countries in managing HAB events

Location/ Country	1st Stage – HAB screening (routine monitoring & early detection)	2nd Stage – HAB warning (threshold exceeded)	3rd stage – Control measures (response measures & mitigation)	References
Lake Geneva (France/ Switzerland)	Water samples collected and analyzed monthly using microscopy to detect phytoplankton	Phytoplankton biomass exceeding 1000 µg L^{-1} triggers an alert	No control measures documented	(Frederic 2021)
France	No routine screening reported	Toxicity thresholds: 80 µg kg^{-1} for DSP, 10 mg kg^{-1} for ASP in seafood	Seafood production closed, fish cages relocated, detoxification, and shifting of fishing activity to unaffected areas. Efforts to reduce anthropogenic pressures	(Agúndez, Chenouf & Raux 2022)
United States	Satellite data and transport models used for HAB tracking and short-term prediction	Threshold not specified	Closure of shellfish harvesting, application of clay flocculation, algicides, and HAB-specific pathogens for mitigation. Industry mobilization for response efforts	(Elizabeth et al. 2008)
Arkansas, United States	No routine screening reported	Threshold not specified	Public health risk assessments for cyanotoxins. Development of sampling, testing protocols, and strategies to prevent HAB events by reducing nutrient pollution	(Arkansas State Waters 2019)
Gulf of Mexico	Satellite-based HAB early warning system	Threshold not specified	Operational bulletins issued twice a week during active HAB events	(Karen et al. 2013)
Murray River, Australia	Weekly sampling of ~1,500 samples from 152 sites. Cell counting and toxin testing performed	Alert triggered when HAB concentration exceeds 50,000 cells L^{-1} or microcystins exceeding 10 µg L^{-1}	Warning signs for water users, public alerts via social media, and flushing of water bodies to disperse blooms	(Biswas 2017)
Hong Kong	Weekly, biweekly, or seasonal sampling of fish culture zones. HAB presence detected via seawater discoloration. Biotoxin testing in seafood	Threshold not specified	HAB warnings issued to marine fish farmers, distribution of educational posters and leaflets to the public	(Fisheries 2022)
Tumpat, Kelantan (Malaysia)	Routine shellfish toxicity monitoring at frequently affected sites	Threshold not specified	The Health Department bans shellfish collection for several months	(Lim, Gires & Leaw 2012)
Malaysia	Johor: Water quality and HAB species monitoring conducted twice weekly from January to March, then monthly or case based. Periodic monitoring of livestock Sabah: Water quality monitoring at 1 m and 3 m depths to predict bloom duration Kelantan: Monthly water sampling at HAB outbreak hotspots; increased to twice per month during HAB events. Shellfish sampling conducted	Threshold not specified	Sabah: Localized bloom alerts issued to village heads and fish breeders Sarawak: Awareness programs conducted Kelantan: Warning signboards displayed. Fishermen groups spread HAB event information to the public	(Mohyedin et al. 2019)

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Penang, Malaysia	Routine water quality parameters monitoring (temperature, dissolved oxygen, salinity, pH, ammonia, phosphates, nitrates) and weather data (wind speed, atmospheric pressure, humidity, rainfall)	Threshold not specified	Centre for Marine and Coastal Studies (CEMACS) provides early warnings to communities about potential HABs. Fish farm to take preventive actions such as early harvesting or relocating farms	(Gristwood 2022)
Sabah, Malaysia	Microscopy-based quantitative and qualitative analysis, visual water color inspections, and bioassay monitoring of shellfish poisoning, conducted monthly	*P. bahamense* exceeding 7 cells mL^{-1} and *M. polykrikoides* exceeding 5 cells mL^{-1} trigger weekly monitoring	Fish farm operators advised to harvest early or relocate stock. Press statements issued by the Department of Fisheries warning against seafood consumption from affected areas	(Jipanin et al. 2019)
Malaysia	Regular HAB monitoring since 1976	PSP toxin levels exceeding 400 MU in seafood considered hazardous	Localized warnings issued via press releases, TV broadcasts, and radio. Public distribution of precautionary leaflets and guidelines. HAB awareness campaigns integrated into state festivities. Public forums conducted for local communities and students	(Eong & Sulit 2017)
Cambodia	No routine screening reported. Upon reported deaths from seafood poisoning; samples sent to Vietnam for HPLC-based toxin analysis	No specific threshold reported	No control measures documented	(Eong & Sulit 2017)
Singapore	Water samples analyzed for species identification using microscopy and molecular methods; toxins tested via HPLC	No specific threshold reported	Fish farms shift pens to unaffected areas. Public announcements made via phone, newspapers, TV, and online platforms	(Chew 2016; Lim & Leong 2019)
Singapore	No routine screening reported	No specific threshold reported	Canvas and closed containment systems are used to reduce HAB impact. Emergency harvesting of fish deemed safe for consumption. Government support includes alert messages, assistance with dead fish disposal, stock relocation, and collaboration with cold storage facilities	(Eong & Sulit 2017)
Philippines	Shellfish tested for PSP using mouse bioassay; monitoring established in previously affected areas	Shellfish containing PSP toxins exceeding 600 $\mu g\ kg^{-1}$ trigger an alert	Public bulletins issued twice a week to notify affected communities	(Yñiguez et al. 2021)
Philippines	HAB monitoring and species identification conducted regularly. Shellfish tested for the presence of HAB toxins	No specific threshold reported	A guidebook on HAB monitoring and management created for authorities. Shellfish bulletins released biweekly	(Eong & Sulit 2017)

This highlights a gap that existing responses only limit immediate damage without addressing underlying HAB causes, leading to recurring outbreaks and continued stress on marine ecosystems and public health. Malaysia's overreliance on inconsistent reactive measures hinders effective HAB management, particularly as climate change and nutrient pollution increase bloom frequency.

In contrast to localized approaches, nations such as France, the United States, the Philippines, and Singapore employ proactive and coordinated strategies to manage HAB risks. International responses include seafood closures and public advisories, often with public education (Agúndez, Chenouf & Raux 2022; Fisheries 2022; Yñiguez et al. 2021). More advanced approaches involve relocating fish cages, seafood detoxification (France), and actively suppressing blooms with clay flocculation, algicides, or pathogens (United States) (Elizabeth et al. 2008). Singapore utilizes physical barriers and closed containment systems for aquaculture protection (Eong & Sulit 2017). Malaysia remains vulnerable without transitioning to a preventive management model, necessitating a centralized alert system, investment in predictive monitoring, and addressing root causes like nutrient runoff. Reactive responses alone will be insufficient against escalating HAB risks.

CHALLENGES AND RECOMMENDATIONS

CENTRALIZED COORDINATION OF HAB MANAGEMENT

A major challenge in Malaysia's current HAB management is the lack of a centralized national task force. State-level monitoring leads to inconsistent guidelines and fragmented inter-agency coordination (Jipanin et al. 2019; Mohyedin et al. 2019), causing response delays and limited data sharing. Establishing a national task force would streamline decision-making and ensure policy consistency while optimizing resource allocation for public health (Cao, Huang & Liew 2025; Luo et al. 2019; Yang et al. 2021). The effectiveness of centralized approach is demonstrated by China's vertical reforms between 2016 and 2019 (Chen et al. 2022). Previously, a decentralized system allowed local governments to prioritize economic growth over pollution control, which led to weak inspections and inconsistent enforcement. Centralizing authority allowed for uniform enforcement and prioritized environmental safety over local industrial interests, providing a clear template for Malaysia to improve its own regulatory framework.

ENHANCING HAB MANAGEMENT STRATEGIES

Malaysia primarily employs reactive HAB management strategies. A shift towards proactive, sustainable mitigation is needed, incorporating biological controls (bacteria, zooplankton, natural inhibitors like red seaweed/rice straw) (Anabtawi et al. 2024; Benitt et al. 2022; Hua et al. 2018). While current responses involve harvesting restrictions, fish stock relocation, and public health advisories (Eong & Sulit 2017; Lim, Gires & Leaw 2012), adopting a selective banning approach for contaminated seafood, similar to France (Agúndez, Chenouf & Raux 2022), alongside regular toxin testing and public awareness, would enhance consumer confidence and reduce economic losses.

HAB RESEARCH AND MONITORING TECHNOLOGY

The current landscape of HAB research in Malaysia is characterized by a critical need to transition from traditional laboratory-based methods to advance *in situ* technologies. Conventional monitoring largely relies on manual water sampling and microscopic cell counting which are labor intensive and often fail to provide the real-time data necessary for rapid response (Jipanin et al. 2019).

The development of biosensors offers a promising solution by enabling the high sensitivity detection of specific toxins and species directly in the marine environment (Chin et al. 2022). These devices utilize selective biorecognition elements to convert biological responses into measurable electrical signals, which reduces the reliance on expensive and bulky laboratory equipment.

The modular nature of biosensor components presents a significant opportunity to build low-cost and portable sensing platforms (de Lima et al. 2021; Moschopoulou et al. 2024; Perdomo et al. 2021) that can be deployed across wide geographical areas. Integrating these cost-effective tools into a digitized network would allow for the continuous monitoring of coastal waters to ensure that potential blooms are detected at their earliest stages. This technological shift is essential for providing the aquaculture sector with an affordable early warning system that can help prevent seafood contamination and protect public health.

ADVANCED HAB MONITORING TECHNOLOGIES

Microscopy remains the standard for HAB detection in Malaysia, but PCR-based methods offer improved sensitivity despite higher costs and expertise requirements (Smith, Stuart & Rhodes 2024; Woodworth & Pyle 2013). Integrating portable biosensors and DNA-based molecular detection into routine monitoring could enable real-time, field-based detection and reduce reliance on costly lab analyses (Fernández et al. 2023; Mir et al. 2023; Salam et al. 2017). Predictive gene expression (Brunson et al. 2024) and multi-target DNA biosensors (for *sxtA4*) also hold promises.

On the other hand, satellite-based monitoring is explored globally (Hill et al. 2020; Seegers et al. 2015), its efficacy is hindered by weather dependency, particularly regarding persistent cloud cover in Malaysia (Cheng, Chan & Lee 2020; Ministry of Natural Resources and Environmental Sustainability 2024). These sensors cannot penetrate clouds and primarily detect surface-layer conditions; consequently, blooms located below the surface or under persistent overcast may be missed (Stroming et al. 2020). Furthermore, rapid bloom dynamics, interference from aquatic vegetation, and uncertainties in atmospheric or water-column corrections introduce significant errors into satellite-derived HAB indicators (Liu et al. 2022). Such limitations suggest a need for complementary local technologies to ensure more reliable monitoring.

HAB REPORTING GAP

A common challenge in evaluating the historical and current status of HABs in Malaysia is the significant discrepancy between actual occurrences and documented records. Existing data in peer-reviewed literature, news media, and global databases such as HAEDAT likely represent a conservative estimate, as reporting is frequently filtered by event significance. Blooms that do not result in immediate economic losses (such as large-scale fish kills in aquaculture) or public health crises (human poisoning events) often go unrecorded. Similar observations have been reported in the United States, where a review by Anderson et al. (2021) noted that data on ciguatera (ciguatoxin-related events) are insufficient for time-series analysis due to a lack of monitoring programs, and that the true scale of the problem is obscured by misdiagnosis and underreporting to health authorities.

Furthermore, a monitoring bias exists in which regions with established infrastructure, particularly in Sabah, appear to have higher HAB frequencies (Adam et al. 2011), while remote or less-monitored areas remain data-poor. This creates spatial and temporal underrepresentation that complicates the development of a comprehensive national risk map.

To address these gaps, a transition from event-based reporting to a more integrated national framework is recommended, using the Sabah Department of Fisheries (DOFS) model as a benchmark. Since 1976, Sabah has maintained a robust year-round monitoring program across multiple coastal stations, providing a high-density data stream that captures routine biological fluctuations rather than only catastrophic events (Jipanin et al. 2019). Expanding similar high-frequency routine monitoring to other high-risk zones in Peninsular Malaysia and Sarawak, together with the integration of low-cost *in situ* sensing and community-based citizen science reporting, would reduce reliance on reports that only highlight major outbreaks. This approach would ensure that even low-impact blooms are recorded, providing a more scientifically accurate baseline for predictive modelling and climate change impact assessments.

ENVIRONMENTAL AND HUMAN FACTORS DRIVING HABS AND MITIGATION STRATEGIES

Malaysia's tropical climate and abundant sunlight create ideal conditions for year-round HAB growth, which are further enhanced by excessive nutrient pollution from agricultural runoff, industrial discharges, and untreated sewage (Lan et al. 2024; Wurtsbaugh, Paerl & Dodds 2019). This situation is compounded by rapid land-use transformation, including deforestation for agriculture such as oil palm cultivation (Rajah et al. 2017), as well as increasing urbanization and aquaculture discharges (Kawasaki et al. 2016; Obi et al. 2025), leading to widespread eutrophication.

Several coastal regions in Malaysia illustrate how nutrient pollution contributes to HAB development. The Johor River area collects pollution from cities, farms, and factories, which eventually flows into the East Johor Strait. This pollution mainly originates from sewage treatment plants and agricultural fertilizers, which act as major sources of ammonia. During dry weather, sewage becomes the dominant source of pollution. The water in the strait contains high levels of nutrients such as ammonium and phosphate, which are naturally recycled within the water and continue to support algal blooms. Research has shown that nutrient levels in waters near urban and industrial areas are between 1.5 and 148 times higher than those in less polluted areas (Cheong et al. 2024).

Similarly, in Penang, industrial waste and densely populated residential areas, particularly near the Sungai Pinang basin, are major sources of organic pollution (Siti Noor Syafika 2018). These inputs elevate dissolved inorganic nutrients such as ammonia, which contributes significantly to the overall organic pollution index.

In West Sabah, the risk of algal blooms along the coast is mainly driven by farming and other human activities that wash nutrients such as nitrate and phosphate into the sea, especially during the rainy monsoon season. Higher nutrient levels are strongly linked to more frequent and dense algal blooms. Areas such as Sepanggar Bay show much higher nutrient pollution than less developed locations like Kota Belud (Al Azad, Shaleh & Soon 2016). Rivers carry farm waste and sediments into coastal waters, providing the nutrients that allow harmful algae such as *P. bahamense* to grow rapidly.

Climate change further increases HAB risk. Rising sea surface temperatures create more favorable conditions for bloom-forming species such as *P. bahamense* and *Margalefidinium polykrikoides* (Banguera-Hinestroza et al. 2016; Fatemi et al. 2012; Mahmood & Guinto 2022; Yu & Wee 2023). Together, nutrient enrichment and warming waters escalate HAB risks, leading to mass fish mortalities, seafood contamination, and significant economic and public health concerns (Oh et al. 2023).

Implementing precision fertilization (Shobri, Sakip & Omar 2016; Wang et al. 2024) and upgrading wastewater treatment with advanced nutrient removal technologies such as the Bardenpho or Johannesburg systems (Ejike et al. 2024; Morelli et al. 2018; Preisner, Neverova-Dziopak & Kowalewski 2021) are great strategies for reducing nutrient inputs and mitigating future HAB events.

Table 4 summarizes the challenges and key recommendations for improving HAB management in Malaysia, highlighting proposed solutions, implementation strategies, and expected outcomes.

TABLE 4. Summary of challenges, recommendations, and mitigation strategies for HAB management in Malaysia

Challenge	Recommended solution	Implementation strategy	Expected outcome
Lack of coordination in HAB management	Establish a National HAB Task Force	Centralized oversight under the DOFM to unify monitoring efforts across states	Improved inter-agency coordination, faster response times, and standardized HAB protocols
Incomplete data & reporting gaps	Transition from event-based to routine, year-round monitoring	Adopt the Sabah DOFS Model (1976) nationwide; establish permanent sampling stations in high-risk zones regardless of active blooms	A scientifically accurate baseline that captures ‘low-impact’ blooms; improved predictive modeling for climate change
Lack of effective mitigation measures	Implement biological control strategies for HAB suppression. Improve seafood safety monitoring and public awareness	Explore the use of microbes such as *Streptococcus thermophilus* and natural inhibitors like red seaweed and rice straw as sustainable mitigation techniques	Reduction in HAB severity, lower environmental impact compared to chemical treatments, minimized economic losses in aquaculture and fisheries
		Conduct regular seafood toxin testing, public advisory campaigns, and adopt France’s selective banning approach to reduce economic losses	Reduced health risks, increased consumer confidence, and stable seafood trade
Delayed detection & reactive response	Deploy portable biosensors with predictive models	Integrate electrochemical biosensors, DNA-based molecular tools, and forecasting models into routine monitoring	Faster and more accurate early detection, enabling proactive mitigation efforts
Nutrient pollution driving HAB growth	Strengthening agricultural runoff and wastewater regulations	Introduce buffer zones, controlled fertilizer application, and stricter wastewater treatment standards (Bardenpho & Johannesburg systems)	Lower nutrient inflow into coastal waters, reducing eutrophication and HAB frequency

CONCLUSION

HABs pose an increasing challenge for Malaysia, impacting marine ecosystems, fisheries, public health, and local economies. The evolution of HAB occurrences in Malaysia is marked by a significant geographical expansion and increased species diversity. While toxic events were historically localized primarily to the coastal waters of Sabah, this concentration is largely a reflection of the state's long-standing and robust monitoring infrastructure. As surveillance efforts improve nationwide, toxic events are being recorded with greater frequency along the coasts of Peninsular Malaysia. Furthermore, the diversification of HAB species, including the transition from dominant *P. bahamense* blooms to a variety of other toxic dinoflagellates and diatoms, emphasizes the growing complexity of the threat.

Despite ongoing monitoring efforts, current strategies remain largely reactive and focus on post-bloom interventions rather than proactive mitigation. This review has identified several key challenges in Malaysia's management framework, including institutional fragmentation, HAB reporting gaps, and the growing influence of climate change and nutrient pollution. The absence of a centralized national task force hinders timely responses and effective data sharing across state borders. Additionally, the continued reliance on legacy laboratory methods and localized monitoring infrastructure restricts the nationwide adoption of more advanced and cost-effective *in situ* detection solutions. Addressing these gaps requires a fundamental shift from reactive crisis management toward proactive risk reduction. This transition will require integrating real-time detection capabilities and embracing sustainable practices that mitigate the root causes of proliferation. The evolving nature of HABs in Malaysian waters requires a collaborative and science-driven approach to ensure the long-term protection of marine resources and the communities that depend upon them.

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