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Fish Kills Related to Harmful Algal Bloom Events in Southeast Asia

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Abstract: Fish kills in Southeast Asia are frequently associated with harmful algal blooms (HABs) and cause significant ecological and economic impacts. This paper serves as a review of fish kill events with focus on those related to HABs within the region. It examines the causative algal species, known mechanisms of fish mortality, and socio-economic consequences. Fish kills have been reported across multiple countries within Southeast Asia, with notable hotspots in the Philippines, Malaysia, Singapore, Indonesia, and Thailand. The common harmful microalgal species span a diverse group including dinoflagellates (*Karenia* spp., *Karlodinium* spp., *Margalefidinium polykrikoides, Noctiluca scintillans*), raphidophytes (*Chattonella* spp.), diatoms (*Skeletonema* spp. and *Chaetoceros* spp.), and cyanobacteria (*Trichodesmium* spp.). These microalgae lead to fish kills through mechanisms such as hypoxia, physical gill damage, and ichthyotoxin production. Freshwater fish kills linked to HABs have also been documented for the Philippines, but there is no or limited information for the region. Our review highlights the widespread and recurring nature of fish kills, their impact on fisheries and aquaculture, and challenges in managing and mitigating their effects. There are efforts at enhancing management and mitigation using clay and early-warning systems. However, it is essential to further improve monitoring efforts, the development and deployment of early-warning systems, and viable and holistic mitigation strategies to protect the region's aquatic resources and dependent communities, especially as aquaculture and coastal development are increasing concurrent with a changing climate that can exacerbate the risks of fish kills and HABs in Southeast Asia.

Keywords: aquaculture; dinoflagellates; ichthyotoxic; harmful microalgae; hypoxia; raphidophytes

1. Introduction

Massive fish kills refer to the sudden and large-scale deaths of fish that can occur in brackish, marine, and freshwaters. Fish kills can be caused by several biotic and abiotic factors. Pollution from industrial waste, agricultural runoff, and improper waste disposal can introduce harmful substances into water bodies, leading to the death of fish and other aquatic organisms. Changes in the environment such as sudden increase or decrease in temperature, drastic changes in salinity due to discharge from freshwater reservoirs, often due to weather changes or human activities, can disrupt

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the delicate balance of aquatic ecosystems and stress cultured fish, often in high densities, causing them to die. When oxygen levels in the water drop below a tolerable threshold, a condition called hypoxia, fish and other aquatic organisms suffocate and die. Hypoxia can occur due to an increase in temperature, as well as the excessive growth of algal species and the release of organic matter into the water which consumes oxygen during the decomposition process. The most common cause of fish kill has been algal blooms and the resulting water quality issues such as low oxygen or production of toxins e.g., [1–4]. Oxygen depletion can also allow sulfide from the sediments to appear in the water column and poison fish [5]. Several diatom species with needle-like structures (e.g., setae) cause injury or damage to fish gills [6,7] or induce excessive mucus production that results in fish suffocation [8]. Raphidophytes could cause hemolytic changes to fish gills that lead to impaired osmoregulation and death [9,10]. Several dinoflagellate species are known to produce toxins or related compounds with hemolytic effects and are responsible for fish mortality [11,12].

1.1. Fish Killing Mechanisms

The fish killing mechanism by microalgal species can be divided into four main types, 1) algal blooms-induced hypoxia that cause fish suffocation, 2) physical irritation injury and suffocation due to mucus production, 3) direct effect due to ichthyotoxins or bioactive compounds from algae cells or 4) micropredation by microalgae towards fish or farmed organisms.

Algal cell-induced hypoxia occurs due to poor water exchange in the mariculture areas (mostly within the embayment) or close to the shoreline with shallow depth. During the day, when sunlight is available, dissolved oxygen (DO) in the water remains on the higher side due to photosynthesis, occasionally with DO super-saturation (>9 mg/L). However, DO declines from sunset and reaches the lowest level from midnight to early dawn due to the high respiration of algal biomass [13]. High organic discharge from riverine sources sometimes can also cause fish kills due to low DO from the decomposition of organic matter.

Some diatom species (e.g., *Chaetoceros*) possess needle-like structures (setae) that can cause physical irritation leading to heavy mucus production covering the gills, resulting in fish suffocation [6,7]. Some dinoflagellates from the genus *Ceratium* are also known to cause similar effects on cultured fish [14]. Some species of the naked dinoflagellates *Karenia*, *Karlodinium*, *Margalefidinium* and *Takayama*, and thecate dinoflagellates *Gonyaulax* and *Heterocapsa* were reported to cause fish kills [15]. *Margalefidinium polykrikoides* is known to possess mucocysts in the cell [16]. Dinoflagellates in the Kareniaceae may produce bioactive compounds, such as brevetoxins in *Karenia brevis*, gymnocins in *Karenia mikimotoi*, gymnodimines in *Karenia selliformis*, karlotoxins in *Karlodinium veneficum*, and karmitoxins in *Karlodinium armiger* [17–20]. However, the particular toxins responsible for fish kills are not fully understood in other fish-killing kareniaceans, e.g., *K. selliformis* (group I), *Karlodinium australe* and *Takayama acrotrocha* [21–25]. Fish and *Artemia* bioassay evaluated and confirmed the presence of highly potent ichthyotoxic compounds in *K. veneficum* (e.g., [19]). Several studies also demonstrated the stronger micropredation capability of *Karlodinium* species, e.g., *K. armiger*, *K. australe*, *K. azanzae* and *K. veneficum* [26–29]. The presence of polysaccharide compounds or reactive oxygen species (ROS) has been confirmed in some harmful algae. The mechanisms still need to be fully clarified in some of these toxic dinoflagellates.

1.2. Fish Killing Microalgal Species in the Southeast Asia

Microalgal species forming harmful algal blooms and producing shellfish or fish toxins in coastal marine environments have been compiled and updated in the IOC list of harmful algae [15]. In Southeast Asia, some of the harmful microalgal species have formed blooms associated with fish kills [4,30]. Fish killing algal blooms have been frequently documented in East Asia, e.g., the raphidophyte *Chattonella* and dinoflagellates of the Kareniaceae and *Margalefidinium* [31], and these species were also found in Southeast Asia [4,30,32].

The raphidophyte *Chattonella marina* and *C. subsalsa* have occurred in Southeast Asia [33,34], and *C. marina* has been recorded from Indonesia and Malaysia [35,36] and *C. subsalsa* from the Philippines, Singapore, and Thailand [34,37]. Two other species *Chattonella malayana* and *C. tenuiplastida* were

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recently described from Malaysia and Thailand, of which the former has formed a huge red tide associated with wild fish kills [36]. The raphidophyte *Fibrocapsa japonica* and *Heterosigma akashiwo* has also been reported from Singapore and Thailand [38–41].

The unarmored dinoflagellates in the Kareniaceae, or Brachidiniaceae, have been reported from Southeast Asia [22,27,42]. *Karenia mikimotoi*, one of the most harmful bloom species in the world, has been recorded from Malaysia, Philippines and Singapore [4,42–44]. In the genus *Karlodinium*, *K. australe* (Malaysia, Philippines, Singapore), *K. azanzae* (Philippines), *K. ballantinum* (Philippines), *K. veneficum* (Malaysia, Singapore), and *K. zhouanum* (Philippines) have so far been recorded in Southeast Asia [22,27,43,44]. In the genus *Takayama*, the species observed and identified was *T. acrotrocha* or *T. xiamenensis* from the Philippines and Singapore [4,21].

The chain-forming unarmored dinoflagellate *Margalefidinium polykrikoides* (= *Cochlodinium polykrikoides*) has occurred in Brunei, Indonesia, Malaysia, and Philippines [32,45–49]. The other *Margalefidinium* species, *M. fulvescens* (= *Cochlodinium fulvescens*) has also been reported from Indonesia, Malaysia, and Vietnam [48,50,51].

Microalgal species commonly found in the coastal waters of Southeast Asia, such as the cyanobacteria *Trichodesmium*, and dinoflagellates *Ceratium*, *Noctiluca*, *Prorocentrum* and *Pyrodinium*, have also formed blooms that are sometimes associated with fish kills [30,52]. Blooms of the cyanobacteria *Trichodesmium* spp., reported as *T. erythraeum* and *T. thiebautii*, have been documented with fish mass mortalities in Indonesia [53,54]. Blooms of the dinoflagellate *Ceratium furca* in Malaysia and Thailand [51,55,56], *Noctiluca scintillans* in Cambodia, Indonesia, and Thailand [53,57], and *Prorocentrum cordatum* (= *P. minimum*) in Malaysia and Philippines [58,59], were documented with fish kill records. The paralytic shellfish toxin-producing dinoflagellate *Pyrodinium bahamense*, widely distributed in the Southeast Asia (e.g., [4,60,61], has also caused fish kills in Brunei and Indonesia [62–64].

In the South China Sea, fish and shellfish killing dinoflagellates such as *Karenia longicanalis*, *Karlodinium digitatum*, *Heterocapsa circularisquama* and *Pseudocochlodinium profundisulcus* have been recorded from Hong Kong and adjacent waters [65–68], but not in the Southeast Asian coast. The mucilaginous colony-forming haptophyte *Phaeocystis globosa* has been recorded in the Chinese coasts of the South China Sea and has occurred infrequently in the coast of Vietnam [69].

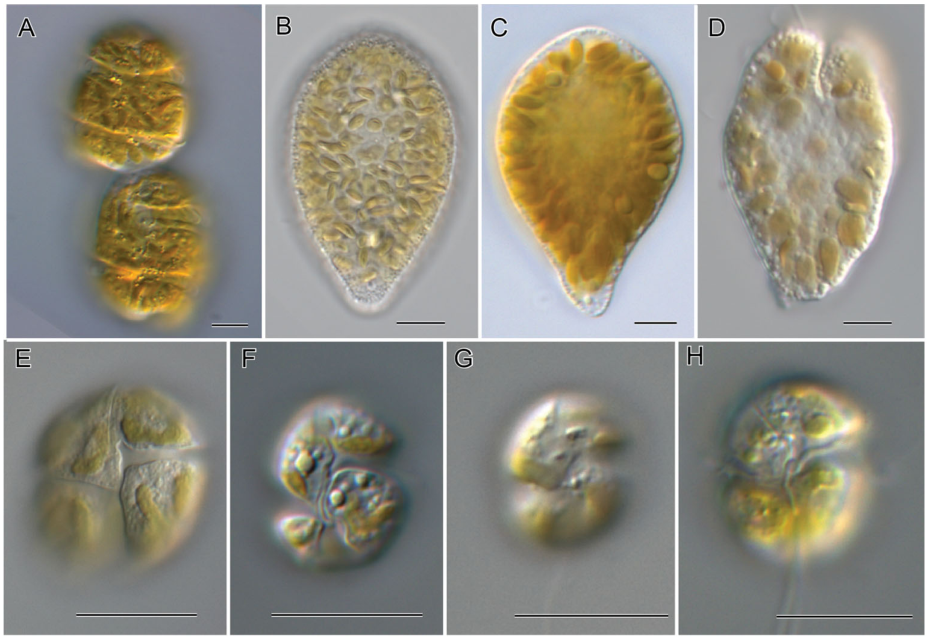

Figure 1. Common harmful fish killing microalgal species in Southeast Asia. A. Margalefidinium polykrikoides; B, Chattonella marina; C, Chattonella subsalsa; D, Chattonella malayana; E, Karenia mikimotoi; F, Karlodinium australe; G, Karlodinium veneficum; H, Takayama acrotrocha. Scales, 10 μm.

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1.3. Consequences

Fish kills can disrupt the natural balance of ecosystems, affecting other species and their habitats. This disruption can have cascading effects on the overall health of the ecosystem, leading to long-term economic losses for industries dependent on ecosystem services, such as fisheries, aquaculture, and tourism.

Fish kills resulting from harmful algal blooms (HABs) have substantial socio-economic impacts, as fisheries and aquaculture industries are important sectors in many coastal countries of Southeast Asia [70]. This issue has been a recurring problem since the 1970s, leading to significant economic losses in many countries. For example, the estimated financial impact on fish farmers in Malaysia has reached approximately 9 million USD [22,51,71–73] (Figure 2). Not all fish kill reports quantify losses in monetary terms; some only describe the extent of biomass loss. A notable incident in 2016 at the Udang River in Penang reported 20-50% of caged fish died due to an unidentified microalgal bloom [74]. Additionally, smaller-scale wild fish kill events from 2016 to 2019 in the Johor Strait were difficult to quantify in terms of tonnes and monetary value [75]. These cases pose a challenge to accurately assessing the economic impact of microalgal-related fish-kill incidents. The economic impact should ideally be determined through a counterfactual analysis, comparing outcomes to those if HAB events had not occurred, including mitigation and clean-up costs [76,77].

In the Philippines, a massive fish kill in the coastal waters of Bolinao in 2002 incurred an estimated loss of 85 million USD [1]. In addition to milkfish, other marine organisms such as reef fishes, eels, sea urchins, and octopus died and were washed ashore [59]. There was another fish kill in Bolinao in 2007 that caused 1.7 million USD. In June 2010, approximately 0.85 million USD worth of milkfish were lost in the Caquiputan Channel of Anda, which also affected Bolinao [78]. The fish kill that occurred in June 2018 resulted in 1.4 million USD in losses to Anda [79]. In Lake Buhi, the occurrence and recurrence of fish kills from 1998–2018 caused economic losses estimated at 5.5 million USD and becoming a threat to food security [80–83]. In 2023, the fish kills in Lake Sebu and Taal Lake resulted in 0.1-0.17 million USD and 0.77 million USD loss, respectively.

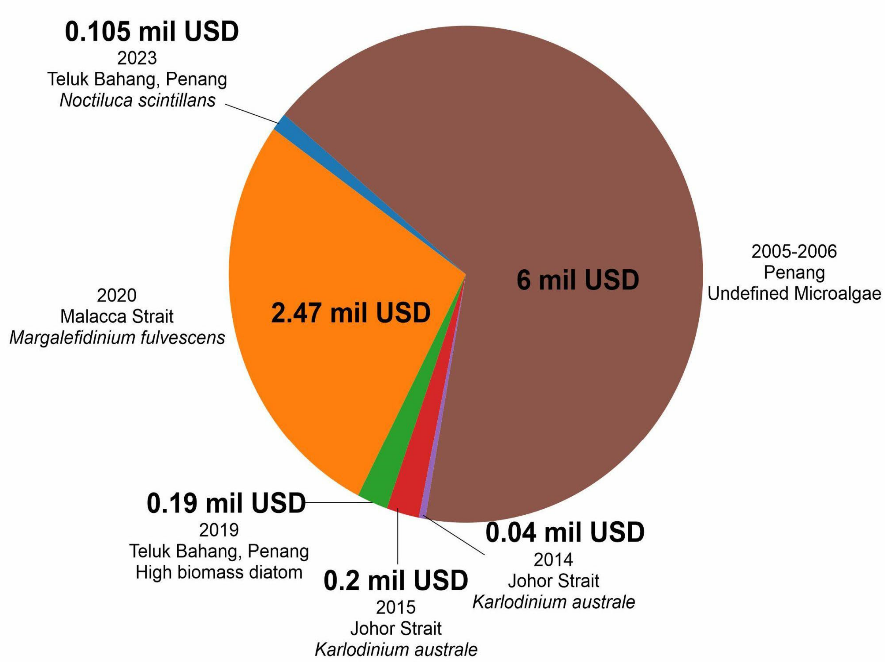

Figure 2. Fish kill losses due to microalgae with monetary values reported from Malaysia since 1978.

Beyond direct financial losses, there are innumerable hidden costs associated with large-scale fish kills, which can lead to temporary or permanent job losses, exacerbating poverty and reducing

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the quality of life. For instance, the fisheries and aquaculture sectors in Malaysia employed about 132,305 people in 2017, with 15% fully engaged in aquaculture [84]. Recurrent fish-kill events caused aquaculturists and investors to lose confidence in fisheries and aquaculture industries, impacting the country's economic income. This was particularly evident during two consecutive blooms of *Karlodinium australe* in the years 2014 and 2015 that caused the losses of tonnes of fish in the Johor Strait. These incidents caused many small-scale aquaculturists to cease their operation. Fish kill events also indirectly affect the tourism industry, particularly when wild fish kills occurred, leading to environmental and aesthetic issues. The sight and smell of decaying fish along the shores create an unpleasant environment, deterring visitors from spending time in affected tourist areas. For example, massive fish kills caused by *Noctiluca scintillans* blooms in Teluk Bahang led to fish floating and washing up on several beaches in Penang [85]. Additionally, multi-species blooms, such as those involving *Margalefidinium polykrikoides* and *Pyrodinium bahamense* in Sabah in 2023, prompted Malaysian authorities not only to ban shellfish but also to advise against swimming in the affected areas around Kota Kinabalu and Tuaran [86]. These incidents led to the suspension of popular water-based tourism activities such as swimming and snorkelling. In addition to the direct impacts, countries affected also incurs significant expenses related to fish kill events affecting aquaculture. For instance, during the Teluk Bahang fish kill in 2023, the Penang State Agrotechnology, Food Security, and Cooperative Development has provided financial aid to the farmers affected by the fish kill losses to help ease their financial burden [87]. Furthermore, the state government also covers the costs of cleaning after these fish kill events. The socio-economic consequences of fish kill events underscore their profound and wide-ranging effects on various sectors, from fisheries and aquaculture to tourism and the broader economy. These incidents not only inflict immediate economic distress but also erode confidence in the industries, disrupt the livelihoods of communities, and degrade the aesthetic and environmental quality of affected areas. The recurring fish kill events present an ongoing challenge, emphasizing the significant impact these events continue to have across the region.

2. Fish kill events in the Philippines

2.1. Fish Kills in Coastal Waters

Fish kills have occurred in brackish, marine, and freshwater fish farms (ponds, pens, cages), with *Chanos chanos* (milkfish) and *Oreochromis* sp. (tilapia) as the commonly cultured fish in these farms [88]. Table 1 presents the fish kill events in coastal waters from 1976 to 2023 [4]. The first documented fish kill was in 1976 in Tawi-Tawi located south of the Philippines, with cause not reported [89]. In 1978, the fish kill in Manila Bay was due to a bloom of the green *Noctiluca scintillans.* The next reported fish kill event was in 2002. This was a massive fish kill of milkfish that occurred in Bolinao, Pangasinan northwest of the Philippines which coincided with bloom of the dinoflagellate *Prorocentrum cordatum* (as *P. minimum*), coupled with low oxygen levels (<2 mg/L) in the fish cages and pens. This fish kill event is linked to uncontrolled proliferation of mariculture structures to double the prescribed carrying capacity thereby resulting in eutrophication and deterioration of water quality conditions [1,59]. Most of the documented fish kills in the country (11 out or 21) have occurred in Bolinao and its neighboring town of Anda, Pangasinan (Table 1, from [4]. Fish kill incidents at these sites can happen yearly or skip one or a few years, with different species of algae found in the waters during fish kills, i.e., *Prorocentrum cordatum* in 2002, *Alexandrium minutum* in 2003, *Chattonella subsalsa* in 2004, *Skeletonema* sp. in 2005, *Rhizosolenia* sp. in 2011, *Takayama* sp. in 2016 and 2018 [4,90]. Recently, naked dinoflagellates such as *Takayama* sp. have been common causative species for fish kills in Bolinao.

Table 1. Fisk kill events in coastal waters of the Philippines from 1976 to 2023.

Year	*Month*	*Site*	*Estimated loss*	*Reported cause*	*Source*
1976		Tawi-Tawi		unknown	[89]
1987	July	Manila Bay		algal bloom - *Noctiluca scintillans*	[91]

2002	Jan, Feb	Bolinao-Anda, Pangasinan	8.5M USD	algal bloom - *Prorocentrum minimum (P. cordatum)*	[1,59]
2002	May	Eastern side of Luzon		Unknown	[92]
2002	June	Balayan Bay, Batangas		algal bloom - *Margalefidinium polykrikoides*, *Karenia mikimotoi*	[92]
2002	June	San Antonio, Zambales		*Alexandrium* sp.	[92]
2002	July	Dumanquillas Bay, Zamboanga		Unknown	[92]
2003	May	Bolinao-Anda, Pangasinan		algal bloom - *Alexandrium minutum*	[93]; PhilHABs unpublished monitoring data
2004	May	Bolinao-Anda, Pangasinan		algal bloom - *Chattonella subsalsa*	PhilHABs unpublished monitoring data
2005	Feb	West coast of Palawan		algal bloom - *Margalefidinium polykrikoides*	[46]
2005	June	Bolinao-Anda, Pangasinan		algal bloom -*Skeletonema* sp.	PhilHABs unpublished data
2007	June	Bolinao-Anda, Pangasinan	1.7M USD	Increase in temp	PhilHABs unpublished data; [94]
2010	June	Bolinao-Anda, Pangasinan	0.85M USD	algal bloom - *Skeletonema* sp.	[95]
2011	Aug	Bolinao-Anda, Pangasinan	0.77M USD	algal bloom - *Rhizosolenia* sp.	[93]
2015	Apr	Bolinao-Anda, Pangasinan	3.7M USD	Unknown	[96]
2016	May	Bolinao-Anda, Pangasinan	0.68M USD	algal bloom - *Takayama* sp.	[90,97]
2018	May	Bolinao-Anda, Pangasinan	1.8M USD	algal bloom – *Takayama* sp.	PhilHABS unpublished monitoring data; [79,90]
2018	May	Bulacan, Manila Bay	0.49M USD	High temp, low tide	[98]
2018	June	Anda, Pangasinan	1.4M USD	High temp, low oxygen, pollution	[79]
2019	Oct	Las Piñas, Parañaque		Low dissolved oxygen, high NH_3 and PO_4	[99]
2023	Nov	Cañacao Bay, Cavite City		Low dissolved oxygen	[100]

2.2. Fish Kills in Freshwater Lakes

Table 2 gives a list of fish kills in lakes in the Philippines from 1972 to 2023, many of which have occurred in Lake Taal, a crater lake in the main island of Luzon, Philippines [101]. The first year of monitoring (2000) saw the highest fish kill frequency in Lake Taal with 21 incidents [80]. According to the BFAR-IFRS fish kill report, these were caused by isopod (*Corallana grandiventra*) infestation (11 occurrences), oxygen depletion (9), and sulfur upwelling (1). In the early part of the decade, fish kills were mainly due to isopod infestation, and in later years, fish kills were attributed to anomalies in oxygen (i.e., 2002, 2003, 2005, 2011), sulfide (2003), and nitrogen (NO_2 and NH_3) compounds (2008). The decrease in oxygen is linked to high organic load from excess feeds and fish waste from fish cages in the lake. Monsoon-driven fish kills were reported in 2005 and 2010. Some fish kills were preceded by high wind speed, or high and at times prolonged high air temperature (2005, 2010) [80]. Wind speed was seen as a driver of change in Lake Taal. Strong winds affect water currents, transport of dissolved substances, and water column mixing [102], thereby influencing biogeochemical processes in a lake. The sudden change in temperature from heavy rainfall resulted in a decrease of surface temperature that may have overturned the water column of Lake Taal [80]. Consequently, low oxygen bottom waters, toxic nutrients, sulfide from the sediments can move to surface layers and cause fish kills.

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Fish kills in Laguna de Bay, the largest lake in the country, were reported in the 1930s [103]. At the onset of aquaculture with data mainly from unpublished sources and reports from fisherfolks, 60% of fish kill incidents from 1972 to 1998 were due to low dissolved oxygen with over half of these cases associated with blooms of blue-green phytoplankton. Other reasons cited for Laguna de Bay were pollution from agriculture and industries, fish pathogens and other causes. During this period, 80% of fish kills occurred during the months of May to September mostly in the central arm of the lake followed by its west arm [103]. HABs due to *Microcystis* sp. has been occurring frequently in Laguna de Bay and has been related to decreased dissolved oxygen [104].

In Lake Buhi, Camarines Sur the occurrence and recurrence of fish kills have been reported annually [105,106]. Fish kills are attributed to dissolved oxygen depletion, high ammonia and sulfide [107,108] triggered by typhoons and monsoons, presence of too many cages, unsustainable fishing practices, and improper waste disposal. The interaction between water temperature, dissolved oxygen, wind mixing, and products of organic matter decomposition are key elements of fish kills in Lake Buhi.

Table 2. Fish kill events in lakes of the Philippines from 1972 to 2023.

Year	*Month*	*Site*	*Fish*	*Estimated loss*	*Reported Cause*	*Source*
1972-1998	May to Sept	Laguna de Bay			Low dissolved oxygen, blooms of blue green phytoplankton (*Microcystis aeruginosa*)	[103,109]
1998-2018		Lake Buhi		5.5M USD	DO depletion (35%), Strong wind and heavy rain by SW monsoon (10%), typhoon caused overturn-upwelling (25%), changes in temperature (5%), feed contamination (5%), NH_3 levels (10%), traces of H_2S (5%), overstocking (5%)	[105]
2000		Taal Lake			Isopod infestation, oxygen depletion, sulfur upwelling	[80]
2002		Taal Lake			Anomalies in oxygen	[80]
2003		Taal Lake			Anomalies in oxygen, sulfur upwelling	[80]
2005		Taal Lake			Anomalies in oxygen, monsoon driven	[80]
2008		Taal Lake			Levels of nitrogen (NO_2 and NH_3) compounds	[80]
2010		Taal Lake			Monsoon driven	[80]
2013		Ilog River, Negros Oriental			Low DO levels	[110]
2017-2018		Lake Buhi, Camarines Sur			Low DO, overturn and/or upwelling bringing up toxic by-products of decomposition	[105]
2017		Lake Sebu, South Cotabato	Tilapia	0.34M USD	"Kemohong" or rise of sulfuric acid that eventually lowers the dissolved oxygen	[111]
2019	Feb	Hinoba-an River			Unknown cause	[112]
2019	April	Fishponds in Isabela	Tilapia	3.4M USD	High temperature	[113]
2021	Jan	Laguna de Bay	Tilapia		Low DO levels	[114]
2022	April	Lake Sebu, South Cotabato	Tilapia	0.1M USD	Low DO levels, overcrowding of fish cages, waste and debris from excess feeds	[115]
2023	Jan	Lake Sebu, South Cotabato	Tilapia	0.17M USD	Low DO levels, overcrowding of fish cages, waste and debris from excess feeds	[116,117]

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2023	Jul	Taal Lake, Batangas	Tilapia and Bangus	0.77M USD	Low DO levels	[118]
2023	Nov	Lake Buhi, Camarines Sur	Tilapia		Low DO levels	[106]

3. Fish Kill Events in Malaysia

Fish kill events in Malaysia, predominantly resulting from harmful algal blooms (HABs), have emerged as a major environmental and economic concern over the past decades. The earliest reported fish kill incident was dated in 1978, which happened in Teluk Kumbar, Penang, where blooms of *Noctiluca scintillans* were identified as the cause [119]. Over the decades, the frequency and severity of such fish kill events have escalated, with various harmful species of microalgae being identified from the hotspots (Figure 3).

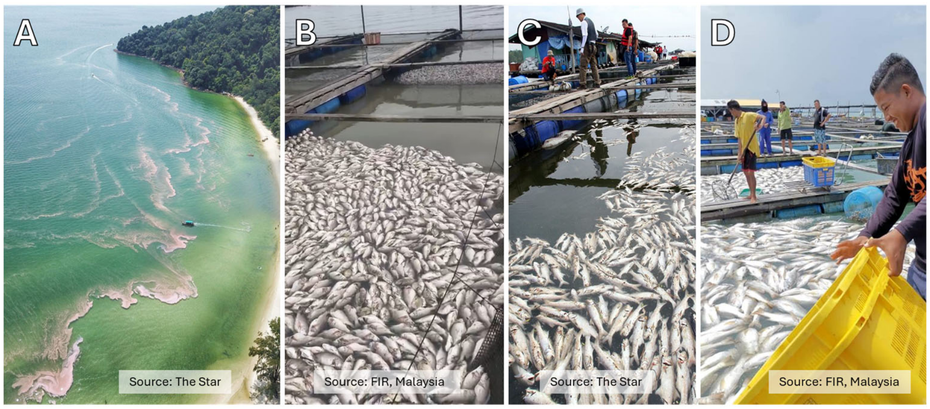

Figure 3. Discoloration and massive fish mortality events along the coasts of Malaysia.

Discoloration and massive fish mortality events have occurred along the coasts of Malaysia. A wide area of water discoloration in pink was observed in the northwestern part of Penang Island due to a massive bloom of *Noctiluca scintillans* (Figure 3A), leading to significant losses for local farmers at Teluk Bahang, Penang in 2023 (Figure 3B). *Karlodinium australe* blooms in 2014 and 2015 in the Johor Strait had caused massive caged-fish kills (Figure 3C). A bloom of *Margalefidinium fulvescens* in 2020 from the coastline of Penang to Perak led to severe losses for local farmers, with more than 400 tons of caged fish affected (Figure 3D).

Figure 4 illustrates the chronological incidents, their impact, and economic losses in Malaysian waters. In 2002, an unprecedented bloom of *Prorocentrum cordatum* (as *P. minimum*) was reported in the Johor Strait [58]. While the bloom has resulted in water discoloration, there have been no reported instances of fish mortality during the bloom. The impact due to harmful algal blooms, however, worsened in subsequent years. In 2005, blooms of *Margalefidinium polykrikoides* were detected along the waters of Kota Kinabalu, Sabah [45]. In the same year, massive fish mortality at Penang aquaculture sites resulted in significant losses to the aquaculture operators, estimated at 4 million USD [71]. The fish kill episode was believed to be caused by microalgae with high cell density, which depleted dissolved oxygen in the water, and created hypoxic or anoxic conditions that killed the fish. Unfortunately, the bloom species responsible for this incident remained unknown because there was no monitoring in place at the time. This highlights the importance of regular monitoring and HAB early detection in aquaculture areas to prevent such devastating losses. Another noteworthy bloom event occurred in 2006 involving *Margalefidinium polykrikoides*, an ichthyotoxic unarmoured dinoflagellate. This bloom dispersed and extended from the west coast of Sabah to the southern part of Malaysia Borneo, Muara Tebas, Kuching, Sarawak [45,71]. In 2007 and 2008, blooms of *Tripos furca* caused massive fish mortality along the coastal waters of Sungai Dinding, Lumut, Perak [51,55].

Blooms of *M. polykrikoides* reoccurred in Perak in 2013, resulting in substantial losses for local fishermen [120].

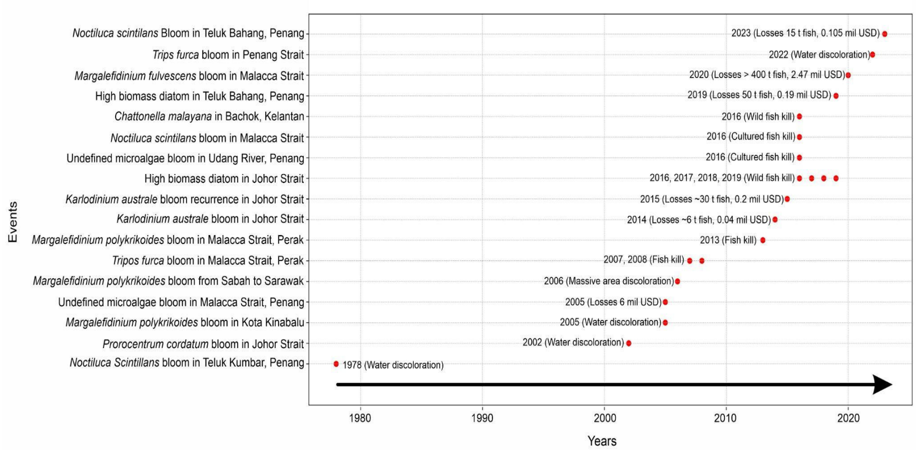

Figure 4. Chronology of fish kill events in Malaysian waters (2000–2023) related to harmful algal blooms, with associated economic losses. Each red circle signifies a specific incident, marked with the year.

The frequency of fish kill events increased significantly starting from 2014. In the year 2014, massive fish kills, impacting both captive and wild populations, were reported in the east Johor Strait (Figure 3C). This event was attributed to the blooms of *Karlodinium australe*, an ichthyotoxic dinoflagellate [22]. Malaysia experienced a significant impact, with a loss of six tonnes of fish. Similarly, Singapore, sharing the same water of Johor Strait, suffered a substantial loss of 160 tonnes of diverse fish species, including groupers, threadfin golden trevally, and rabbitfish [22]. In the subsequent year, 2015, there was a recurrence bloom of *K. australe* in the Johor Strait, leading to more severe losses (approximately 30 tonnes) for aquaculture in Malaysia [72]. The recurrence resulted in the cessation of numerous fish farms in the Johor Strait, hence adversely impacting the socio-economy of the local community. From 2016 onwards, there have been frequent occurrences of smaller-scale wild fish kill events in the Johor Strait. In contrast to earlier episodes, the fish kill incidents were not attributed to toxic microalgae but rather were plausibly caused by the presence of high biomass diatom blooms. The formation of hypoxic-anoxic zones along the inner parts of the Johor Strait was caused by proliferation of various coastal diatom species, including *Skeletonema*, *Chaetoceros*, *Rhizosolenia*, and *Thalassiosira*. This hypoxic-anoxic zone, as revealed in [75], exhibited alarmingly low dissolved oxygen (DO) levels, ranging from 0.19 to 1.7 mg/L. This zone was found to cover an approximate area of 10.3 km^2 in the strait. These microalgal blooms may have been exacerbated by nutrient runoff from human activities, highlighting the need for better management practices in the strait. The findings of fish killing HAB species in the strait underscore the importance of monitoring and addressing water quality issues to prevent further fish kill events in the Johor Strait.

In early 2016, Udang River Penang encountered a mortality of cultured fish in aquaculture farms, although the causative organisms responsible for this event have yet to be determined [74]. Subsequently, Kuala Gula, Perak was hit by the bloom of *Noctiluca scintillans*, which led to massive fish mortality, likely due to the depletion of dissolved oxygen levels [121,122].

Records of shrimp kills by the raphidophyte *Chattonella* were first documented in Johor Strait in 1983 and 1985 [123,124], and the potential causative species was later suggested to be *C. subsalsa* found in the area [34,125]. Since then, fisheries damage by *Chattonella* in Johor Strait has not been observed, but cells of *Chattonella* were observed together with the HABs of other dinoflagellates, such as *Gymnodinium catenatum* and *Prorocentrum cordatum* [58,124]. In 2016, a novel fish-killing raphidophyte species in the genus *Chattonella* was identified subsequent to a significant episode of wild fish mortality incident in the northeastern coast of Peninsular Malaysia in Bachok, Kelantan. This incident, which caused seawater discoloration along the shore, was later ascribed to *Chattonella*

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malayana [36], marking a concerning inclusion in the inventory of ichthyotoxic microalgae in the region.

A subsequent severe incident occurred in 2019 in Teluk Bahang, Penang, wherein a hypoxia-inducing microalgal bloom resulted in the death of over 50 tonnes of caged fish, valued at approximately 190,000 USD. The survey conducted in [73] revealed that the predominant algal group in the microalgal assemblage was the harmless diatom species, including *Coscinodiscus* sp. (2.5×10^4 cells/L), along with *Chaetoceros* spp., *Proboscia* sp., *Rhizosolenia* sp., *Guinardia* sp., and *Leptocylindrus* sp. This highlighted the diverse and significant impact of these blooms in Malaysia's coastal ecosystems and fisheries [73].

In 2020, a significant fish kill event impacted a vast area of the Malacca Strait, throughout the coastline of Penang and Perak (Figure 3D). *Margalefidinium fulvescens* was identified as the causative organism, exhibiting a maximum cell density of 6.22×10^5 cells/L during the bloom period. The local community suffered significant losses as a result of this occurrence, with over 400 tonnes of caged fish lost, amounting to an estimated 2.47 million USD [51]. In 2022, a red-tide-forming dinophyte, *Tripos furca*, was noticed blooming in the Penang Strait, causing red discoloration across the Penang Strait. Fortunately, the early warning to the farmers enabled them to proactively implement preventive measures, such as early harvesting in order to minimize losses. In 2023, a recurrence of *Noctiluca scintillans* bloom was observed in Teluk Bahang, Penang (Figure 3A). The bloom led to a loss of 15 tonnes of caged fish [126].

4. Fish Kills Events in Singapore

Singapore's coastal waters have increasingly been affected by harmful algal blooms (HABs), which have been responsible for several significant fish kill events over the years. These events not only disrupt the marine ecosystem but also pose serious economic threats to local mariculture.

The study by [44] specifically addresses multiple fish kill events and their association with dinoflagellate blooms in the Johor Strait, a narrow body of water separating Singapore and Peninsula Malaysia. Historically, Singapore waters have experienced blooms that are both toxic and nontoxic, caused by species like *Karlodinium* and *Karenia* which produce potent biotoxins known for their ichthyotoxic properties.

One of the earliest documented events was in December 2009 when a toxic algal bloom caused by both dinoflagellates *Karlodinium australe* and *Karenia mikimotoi* in the East Johor Strait led to substantial fish kills, severely impacting local fish farms. After which, there was an escalation in the number and severity of such events. For instance, during February 2014 and 2015, significant dinoflagellate bloom events occurred, affecting both the East and West Johor Strait, causing massive fish kills, which translated into millions of dollars in losses. This event underscored the increasing vulnerability of the region to HAB occurrences.

Dinoflagellates such as *Karenia mikimotoi* and two species of *Karlodinium* (i.e., *K. australe* and *K. veneficum*) were linked to these incidents. Some of these species were detected for the first time in Singapore waters and were associated with the observed fish kills.

The environmental conditions conducive to these blooms were closely studied. Factors such as eutrophication, high nitrogen concentrations and certain physical conditions like neap tides were found to encourage the proliferation of these dinoflagellates. Furthermore, the studies suggested that the dynamics of nitrogen and phosphorus availability, as well as the physical structure of the water column during different tidal conditions, played critical roles in the development and maintenance of these blooms.

From these observations, it becomes evident that the management and monitoring of HABs need to be a priority to ensure the health of Singapore's coastal waters. The implementation of science-based management programs to monitor and mitigate the impacts of these blooms is essential. This includes regular monitoring of water quality and marine biodiversity, as well as the development of strategies to prevent nutrient enrichment from terrestrial runoff.

The ongoing challenge is to understand the complex interactions between multiple environmental factors that contribute to the severity and frequency of HABs. As Singapore continues to develop its coastal areas, maintaining a balance between development and environmental sustainability becomes crucial. Future efforts should focus on enhancing the resilience of marine ecosystems and the local economy to the impacts of harmful algal blooms.

5. Reported Occurrences of Fish Kills in Other Southeast Asian Countries

Fish kills associated with HABs have been also frequently occurring in other Southeast Asian countries, especially in Indonesia, Thailand, and Vietnam, and few reports in Brunei and Cambodia (Table 3). These countries are also particularly vulnerable to impacts of HABs due to their extensive coastlines, diverse marine ecosystem and reliance on fisheries for food security and livelihood. Based on earlier reports, fish kill incidences in these countries have been caused not only by HABs but also due to pollution (disposal of harmful chemicals, oil spill, and environmental stressors such as low dissolved oxygen and high temperature [127–131]. In this section, however, focus is given to HAB-related fish kill either due to release of ichthyotoxins, mechanical damage or formation of mucus in gills, and depletion of oxygen due to the collapse of high biomass blooms.

In Indonesia, fish kills implicated with HABs were common in Jakarta Bay, Ambon Bay and Lampung Bay [132]. Fish kills in these three major embayments were caused by a number of harmful microalgal species. For example, in Jakarta Bay, fish kills were caused by bloom of the diatoms, *Skeletonema* sp. and *Chaetoceros* sp., cyanobacteria *Trichodesmium* and a large-sized dinoflagellate *Noctiluca scintillas* [53,132–135]. Similarly, fish mortalities that happened in Lampung Bay was caused by the red tide of *Noctiluca scintillans* in 2005 and 2008, *Trichodesmium* sp. from 2002 to 2012, *Ceratium furca* in 2011 and more recently the red tide of *Margalefidinium polykrikoides* in 2012 [32,132,136]. In Ambon Bay, one of the earliest fish kills related to HAB was attributed to the bloom of *Pyrodinium bahamense* in 1994. Since then, red tides have been a common occurrence with reports of fish kill due to *Alexandrium affine* in 1997, diatoms *Chaetoceros* sp. and *Skeletonema* sp. in 2006 [132]. Other coastal areas of Indonesia such Kep Seribu, Papua and North Sulawese have also experienced HAB-related fish kills mainly attributed to the bloom of *Trichodesmium erythraeum* and *T. thiebautii* [52,54].

In Thailand, harmful algal blooms that caused fish kills were usually caused by the cyanobacterium *Trichodesmium erythraeum*, dinoflagellates *Noctiluca scintillans* and *Ceratium furca* [137–141]. A few fish kill incidences caused by the bloom of ciliate *Mesodinium rubrum* and raphidophyte *Chattonella* have also been recorded [34,38,142]. Recently, the occurrences of the harmful *Karenia mikimotoi*, *Karenia selliformis*, *Karlodinium australe* and *Karlodinium digitatum* have also been detected by metabarcoding, although their blooms nor fish kill incidents have never been reported [143].

In Vietnam, the bloom of the haptophyte *Phaeocystis globosa* in 2002 caused an enormous economic loss of 0.65 million USD due to mortality of marine plants and animals [144]. Fish and shrimp kills inflicted by the raphidophyte *Chattonella* have also been recorded [34,145], particularly in 2012 in Ha Long Bay, where 0.035 million USD was lost due to mass mortality of mariculture fishes [146]. Other harmful dinoflagellates that have caused fish, clam and lobster kills include *Ceratium furca* and *Noctiluca scintillans* [146,147]. The lobster mortality by *N. scintillans* in 1995 recorded a 0.24 million USD economic loss [147].

In Cambodia and Brunei, records of fish killing HABs are scarce and only a few incidents caused by the dinoflagellates *Pyrodinium bahamense*, *Margalefidinium polykrikoides* and *Noctiluca scintillans* have been documented [52]. Unfortunately, no documented records of HABs in Laos, Myanmar and Timor Leste are found, although fish kills due to low DO have been reported from Myanmar [147].

Table 3. Reported fish kill events in other Southeast Asian countries.

Country	Location	Year	Month	Cause	Mortality	Reference
Brunei		1976	Mar-May	HABs (*Pyrodinium bahamense*)	Fish	[148]
		2012		HABs (*Pyrodinium bahamense* and *Margalefidinium polykrikoides*)	Wild fish	[52,63]

Cambodia	Kep	2016	Apr	HABs (*Noctiluca scintillans*)	Crabs, fish	[52,57]
Indonesia	Jakarta Bay	1986	Jul	HABs (*Noctiluca scintillans*)	Demersal fish and benthic organisms	[52,133]
	Lampung Bay	1991	Jul-Aug	HABs (*Trichodesmium erythraeum*)	Fish, Shrimp	[52,54,133]
	Kep Seribu	1999		HABs (*Trichodesmium erythraeum*)	Fish	[52,54]
	Papua	1999		HABs (*Trichodesmium thiebautii*)	Fish	[52,54]
	North Sulawesi	2000		HABs (*Trichodesmium thiebautii*)	Fish	[52,54]
	Jakarta Bay	2004	May	HABs (*Noctiluca scintillans* and *Trichodesmium erythraeum*)	Fish	[53]
	Lampung Bay	2004		HABs (*Pyrodinium bahamense*)	Fish	[52,54]
	Jakarta Bay	2005		Weak water mass circulation and oxygen depletion after algal blooms	Fish	[149]
	Jakarta Bay	2007		Weak water mass circulation and oxygen depletion after algal blooms	Fish	[149]
	Ambon Bay	2012	Jul	HABs (*Pyrodinium bahamense* and *Chaetoceros* sp.)	Cultured fish	[62,64]
	Lampung Bay	2012	Oct-Nov	HABs (*Pyrodinium bahamense* and *Margalefidinium polykrikoides*)	Cultured fish	[32,49,136]
	Lampung Bay	2013		HABs (*Pyrodinium bahamense*)	Cultured fish	[52,54]
	Lake Maninjau			Low levels of dissolved oxygen	Fish	[131]
Myanmar	Southern Indawgyi Lake	2021	Dec	Low levels of dissolved oxygen	Fish	[150]
Thailand	Tha Chin River mouth, Samut Sakhon	1981		HABs (*Noctiluca* sp.)	Fish	[52,56]
	Gulf of Thailand	1982	May-Jun	HABs (brownish bloom)	Fish	[52,56]
	East coast of the Gulf of Thailand	1983		HABs (*Trichodesmium erythraeum*)	Fish	[151]
	Gulf of Thailand	1983	May-Jun	HABs (brownish bloom)	Fish	[52,56]
	Sriracha, Chonburi	1985		HABs (*Noctiluca* sp.)	Fish	[52,56]
	Gulf of Thailand	1989		HABs (*Trichodesmium* sp.)	Fish, Shrimp	[152]
		1989		HABs (*Mesodinium* sp.)	Fish	[52,56]
	Gulf of Thailand	1991	Jan-Sep	HABs (*Noctiluca scintillans*)	Fish	[52,56]

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	Si Racha Bay	1991	Aug	HABs (*Noctiluca* sp.)	Fish	[140]
	Gulf of Thailand	1992	Jan-May	HABs (*Noctiluca scintillans*)	Fish	[52,56]
	Chanthaburi	1995		HABs (*Chattonella* sp.)	Shrimp	[34,38]
	Gulf of Thailand	2000	Oct	HABs (*Noctiluca scintillans* and *Ceratium furca*)	Fish	[52,56]
	Krabi, Andaman Sea	2007	Mar	HABs (red bloom)	Fish	[52,56]
	Rayong, Gulf of Thailand	2016	Mar	HABs (*Skeletonema* sp.)	Fish	[52]
	Hua Hin Beach	2017	Oct	Low levels of dissolved oxygen	Fish	[153]
	Chumphon Province	2023	Jun	Plankton bloom due to climate change	Fish	[154]
	Thung Wua Laen Beach	2023	Jun	Red tide (toxic algal bloom)	Fish	[155]
	Chonburi	2023	Aug	Green plankton bloom	Fish	[156]
	Bang Saen and Wonnapha Beach	2023	Sep	Low levels of dissolved oxygen	Fish	[157]
	Bang Saen Beach	2023	Sep	Plankton bloom / Oil spill at a nearby town (Si Racha)	Fish	[158]
	Sri Racha, Bang Phra Beach	2023	Sep	Lack of oxygen due to plankton bloom	Fish	[159]
Vietnam		1987		HABs (*Chattonella antiqua*)	Shrimp	[34,160]
	Van Phong Bay, Khanh Hoa	1995	May	HABs (*Noctiluca scintillans*)	Fish, Lobster	[147]
	Khanh Hoa	1996		HABs (*Chattonella* cf. *antiqua*)	Shrimp	[34,145]
	Binh Thuan	2002	Jun	HABs	Fish	[161]
	Tonkin Gulf	2002	Jul-Aug	HABs (*Ceratium furca*)	Fish	[146]
	Phan Ri Bay	2002	Jun-Jul	HABs (*Phaeocystis globosa*)	Fish	[69,162]
	Ha Long Bay	2011	Jul	HABs (*Ceratium furca*)	Fish	[146]
	Cat Ba Island	2011	Nov	HABs (*Phaeocystis globosa*)	Clam	[146]
	Cat Ba Island	2012	Apr	HABs (*Noctiluca scintillans*)	Clam	[146]
	Ha Long Bay	2012	Aug	HABs (*Chattonella* sp.)	Fish	[146]
	Mekong Basin	2016	Jan-Jun	HABs (cyanobacteria)	Fish	[163]
	La Nga River	2019	May	Low levels of dissolved oxygen	Fish	[164]

6. Management and Mitigation

Efforts to mitigate fish kills include strategies to prevent or reduce their occurrence and impact. Implementing effective HAB monitoring programs can help mitigate the impacts on aquaculture operations and protect the livelihoods of those dependent on these resources. Monitoring programs should be developed to include monitoring the changes in water quality, dissolved oxygen levels, and other factors that can lead to fish kills.

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Early warning systems should be put in place to alert authorities and stakeholders to take preventive measures before a fish kill occurs. Emergency response plans should be developed and implemented to quickly respond to and mitigate fish kills when they happen. This means coordinating efforts among government agencies, local communities, and stakeholders. In the Philippines, a prototype early-warning system was developed that included HAB and environmental rapid monitoring and machine learning models for toxic and fish kill blooms [165]. This was able to forecast fish kill events in May 2018 and May 2022, where during the latter incident, the local government unit and stakeholders in Bolinao were informed leading to the option for early harvest and reduction in caged fish losses. This system needs to be further enhanced and expanded across different sites, but it also highlights the need for long-term monitoring data in order to properly train the models.

Addressing ultimate causes should be a priority, wherein there should be regulations to control pollution sources such as discharges from aquaculture, domestic sewage, agriculture, and industry. Measures can involve stricter pollution control standards, regular inspection, and penalties for those who do not comply. Nutrient inputs from aquaculture and agriculture should be managed since this can lead to algal blooms and subsequent oxygen depletion.

In general, control and mitigation of algal blooms can be divided into four main categories, including environmental, physical, chemical and biological approaches. One of the successful examples of environmental controls was wastewater discharge management in the Seto Inland Sea in Japan [166]. Through pollution control policies imposed strictly in the mid-20th century, nutrient levels in the coastal environments of Seto Inland Sea were controlled and reduced followed by a lower number of algal bloom events annually recorded in the region [16,167].

Physical control by application of natural clays was adopted in several East Asian countries (e.g. South Korea, Japan and China) and the US to control the spreading of algal blooms into the aquaculture areas. Clay particles (or mixed clay materials) are sprayed on the surface water during algal bloom event, the dense clay particles will "bind" the algal cells and form aggregation of cells and clays materials through flocculation process, and subsequently be removed from the water column. In South Korea, natural clays have been adopted from the mid-1990s to exterminate HABs, especially *Margalefidinium polykrikoides* [169]. Clay was also used to control the blooms of dinoflagellate *Karenia brevis* during bloom events in Florida [170]. The flocculation and sinking process remove algal cells from the water column without harming the animals (e.g., [171]. However, the application of clay was not widely adopted in this region for several reasons, this included the usage of large amounts of clays, the low efficacy of natural clays in the flocculation process of algal cells, and mostly the concern about the impact of clays on the benthic ecosystems. In Malaysia, natural clay was also used to test the removal of toxic dinoflagellate *Alexandrium minutum*. Although the efficacy was confirmed at a laboratory scale using a clonal culture of dinoflagellate, *Alexandrium minutum*, the method was never tested at mesocosm or in the field [172], and the effect on benthic organisms was not fully clarified. The modified clay method was recently introduced to Malaysia. This method required a much smaller amount of clay compared to natural clays and was more effective in removal of several HAB species in China and Chile [173,174]. The method should be evaluated and considered for further testing against the selected harmful algae species in Malaysia.

In the Philippines, ball clay had the highest removal efficiency for *Pyrodinium bahamense* as compared to other HAB species under laboratory conditions [175,176]. The efficiency, however, decreased when culture volume increased and water motion was introduced [175]. A study on the effect of ball clay on non-target organisms suggests that 1 g/L of ball concentration has no negative effects on non-harmful macroalgae and diatom, mussel, and milkfish under laboratory conditions [177].

The use of biological control (e.g. parasites, bacteria) have been reported in numerous studies, for instance, the use of potential Syndiniales parasites that infect several bloom-forming dinoflagellate species, including *Alexandrium* species. Biological control of HABs remains at the laboratory scale due to the limited supporting scientific evidence on the effectiveness of the method and the unintended environmental impacts of releasing these biological agents into the natural

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environments. The use of species-specific viruses in bloom control was also tested with positive findings in several studies in Japan, but the method was never put into practical use in bloom control [178].

In Malaysia, several counter-measures were used by mariculture operators in dealing with algal bloom events. Farmers will act after observing signs of water discoloration or cultured fishes with signs of illness or drastic increase in mortality of fishes in the farms. Aeration will be applied to the farms continuously to improve water exchange and DO levels when fish show signs of suffocation. Most farm operators will also respond by harvesting marketable-size fish as an immediate countermeasure to minimize losses due to mass mortality. These counter-measures seem to be effective in the bloom events of non-toxic diatom (e.g. *Skeletonema* spp., *Thalassiosira* spp.) or dinoflagellate species (*Tripos* spp., *Noctiluca scintillans*) when fish mortality occurs gradually in the farms. Unfortunately, aeration was reported to be ineffective for some toxic dinoflagellates with high ichthyotoxic activities (e.g. *Karlodinium australe*). Some farmers in Johor Strait observed that aeration did not show positive effect in minimizing the fish mortality during the event in 2015.

Copper sulfate had been tested to control *Karenia* blooms; for *K. mikimotoi* in Japan in 1930s, and for *K. brevis* in US in the mid-1950s [179,180]. Other chemical methods including the use of dispersant, algicide have been proposed and tested. Unfortunately, these methods were not economically feasible due to the high cost of some algicides and other chemicals. The use of chemical control was also not used due to the potential toxicity effect of these chemicals on the environments (including flora and fauna) and the lack of substantial scientific data to support its field application.

7. Challenges and Knowledge Gaps

There are various challenges in fish kill monitoring. Identifying the cause of fish kills is one since they can occur due to a variety of reasons. Fish kill can happen suddenly and spread quickly hence rapid response and timely monitoring is needed. There should be effective communication and coordination among stakeholders, especially when dealing with fish kills that span across several local governments (e.g., [181]) or involve multiple sources of pollution. Implementing a monitoring program requires financial resources for the equipment, personnel, training, and data management systems. Raising public awareness about the importance of fish kill monitoring and engaging local communities in reporting and monitoring efforts can be challenging. This requires strategies for effective communication, education programs, and community outreach initiatives to guarantee active participation and sustained support. Fish kill data collected needs to be managed and examined using analytical tools to identify patterns, trends, and causes. All the data and information should be properly compiled by a designated government office where fish kill reports are sourced and disseminated. Majority of the information for fish kills associated with HABs in the region are for those occurring in coastal and marine areas, information on freshwater HABs and fish kills is a large gap that needs to be addressed.

Climate change is a challenge that can have a significant impact on harmful algal blooms, which can lead to fish kills. However, it is difficult to pinpoint the impacts of climate change on fish kills and HABs in the region due to the limited and intermittent records. Previous work has shown that global warming results in warmer water temperatures that can create more favorable conditions for the growth, geographical expansion and proliferation of harmful algal species [182]. Moreover, increase in storms, precipitation and nutrient runoff can also contribute to the development of algal blooms [183]. As experienced in Bolinao, Philippines, the nitrogen supplied by rivers at onset of the wet season becomes critical for the formation of algal blooms with consequent hypoxia and fish kills [2]. Should harmful algal blooms increase in frequency and intensity due to climate change, the risk of fish kills also rises. These blooms can produce toxins that are harmful to fish and other aquatic organisms, leading to mass die-offs. In addition, the progressing deoxygenation in the ocean [184] might further worsen the depletion of oxygen in the water caused by the decomposition of algal biomass, that can further stress fish populations and contribute to fish kills. Overall, climate change can exacerbate the factors that contribute to harmful algal blooms, leading to more frequent and severe fish kills in affected areas. This emphasizes the importance of long-term monitoring and research programs in order to properly evaluate the relationship of climate change relative to increasing mariculture activities with fish kills and HABs [185]. Given that the aquaculture and coastal development in Southeast Asian countries are also increasing, efforts to mitigate climate change and reduce nutrient pollution in the region should be prioritized to help lessen the impact of harmful algal blooms on fish populations.

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