



Review

Nutrients and harmful algal blooms in Kenya's coastal and marine waters: A review

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ABSTRACT

Nutrients and Phytoplankton composition are important indicators of coastal water quality used for fisheries, tourism, and recreational purposes, which are the cornerstone of the blue economy. This is a comprehensive review and synthesis of the outcome of previous empirical studies conducted on anthropogenic nutrients (nitrogen and phosphorus) and phytoplankton productivity and community composition with a particular focus on harmful algal blooms (HABs) in Kenya's coastal and marine waters. Our results indicate that localized nutrient pollution occurs in estuaries and creeks adjacent to urban areas. Nitrogen speciation was characterized by high ammonium relative to nitrate concentrations with evidence of nitrogen limitation (N:P < 16). Based on all studies' average chlorophyll *a* concentration, seawater in coral and seagrass ecosystems was classified as mesotrophic, mangroves and nearshore as higher mesotrophic, and estuarine and creeks as eutrophic. Additionally, 44 species of potential toxin-producing HAB-forming species belonging to 22 genera were established in low abundances (3 ± 2 - 210 ± 11 cells/l) below the standards of HAB's warning thresholds. Their drivers, spatial and temporal trends are, however, unclear. This review revealed the existence of localized nutrient pollution and a low abundance of toxin-producing HABs species in Kenya's coastal waters. The existing data is, however, very fragmented and inadequate to guide coastal managers in addressing the problem of anthropogenic nutrient pollution and HABs in the area. We, therefore, recommend the inclusion of anthropogenic nutrients and toxic HABs in routine water quality monitoring in the area, especially in potential fisheries, aquaculture, tourism, and recreational sites.

1. Introduction

Coastal fisheries and tourism support the livelihoods of about 4.3 million people in Kenya (Treasury, 2019) with the former supplying 95% of the country's total marine catch, generating approximately US\$ 3.2 million per year (ASCLME, 2012). Fisheries and tourism depend on healthy coastal ecosystems to thrive. However, the health of coastal and marine ecosystems are globally threatened by the enrichment of nutrients (nitrogen-N and phosphorus-P) originating from anthropogenic sources like agricultural run-offs, untreated sewage, and industrial discharges through the surface and groundwater (Long et al., 2014; Malone

and Newton, 2020). Additionally, benthic fluxes from pore water are also a major source of nitrate, ammonium, phosphate, and silicate nutrients in bottom waters and shallow coastal environments (Mathis et al., 2014).

Nitrogen (N) and phosphorus (P) are essential for primary production with P limitation occurring in most freshwaters, N limitation usually in marine and estuarine waters, and a co-limitation of both N and P reported in tropical coastal and marine waters (Anderson et al., 2002; Glibert et al., 2011). Diatoms require silicon (Si) as a major nutrient in addition to N and P to form their silicified cell walls. The availability, forms, and stoichiometry of these nutrients, therefore govern the growth

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and composition of phytoplankton species that determine fisheries productivity in coastal waters (Heil et al., 2007).

Increased use of inorganic fertilizers, fossil fuels, and generation of sewage effluents has caused the elevation of P and N relative to Si to occur in coastal waters (Howarth et al., 2002; Malone and Newton, 2020). The resulting imbalance in P, N, and Si can transform the phytoplankton community composition favoring the development of harmful algal blooms (HABs), which include dinoflagellates, cyanobacteria, toxin-producing pelagic diatoms, and flagellates (Davidson et al., 2012, 2014; Mead et al., 2013). The resulting transformation in phytoplankton composition can affect the entire food web with serious consequences to marine life, human health, and local livelihoods (Berdalet et al., 2016).

There is currently a global increase in frequency, amplitude, and toxicity of HABs in coastal waters, which has been associated with the increasing temperatures and anthropogenic supply of N and P (Glibert et al., 2005; Anderson et al., 2008; Berdalet et al., 2016; Glibert, 2020). Tropical developing countries are particularly vulnerable to the occurrences and impacts of HABs due to high reliance on artisanal fisheries, increasing use of artificial fertilizers in river catchment areas (Malone and Newton, 2020), and poor management of sewage discharges in coastal areas (e.g. Kithiia and Majambo, 2020). Moreover, in these areas, the anthropogenic nutrient pollution and HABs dynamics in

coastal waters are understudied and therefore, poorly understood.

Like many other developing coastal countries, Kenya is currently diversifying its economy by exploiting its blue economy potential to achieve Sustainable Development Goals (SDGs). It also has set economic development goals namely ‘The BIG 4 Agenda and Vision 2030’ (cn.invest.go.ke, 2017). The country plans to expand agriculture, aquaculture, and maritime transport to deliver food security and employment opportunities, with the latter two being the cornerstone of the blue economy. Thus, understanding the coastal and marine ecosystem’s dynamics, including nutrient fluxes and consequent occurrence of HABs is important to realize the full potential of the blue economy. Furthermore, the planned expansions may increase the supply of nutrients N and P from agricultural fertilizers, sewage, and ballast water if no early management plans are put in place.

Efficient management of anthropogenic nutrient pollution and its associated effects like HABs requires sufficient scientific information for policy formulation. This review, therefore, examines the status and trends of anthropogenic nutrient enrichment and HABs as presented in the previous empirical studies. It was conducted to: *identify the major drivers, sources, pathways, and forms of anthropogenic nutrient (N and P) pollution, highlight links between nutrients conditions and phytoplankton community composition and primary production, and lastly establish the status of harmful algal blooming species in Kenya’s coastal and marine*

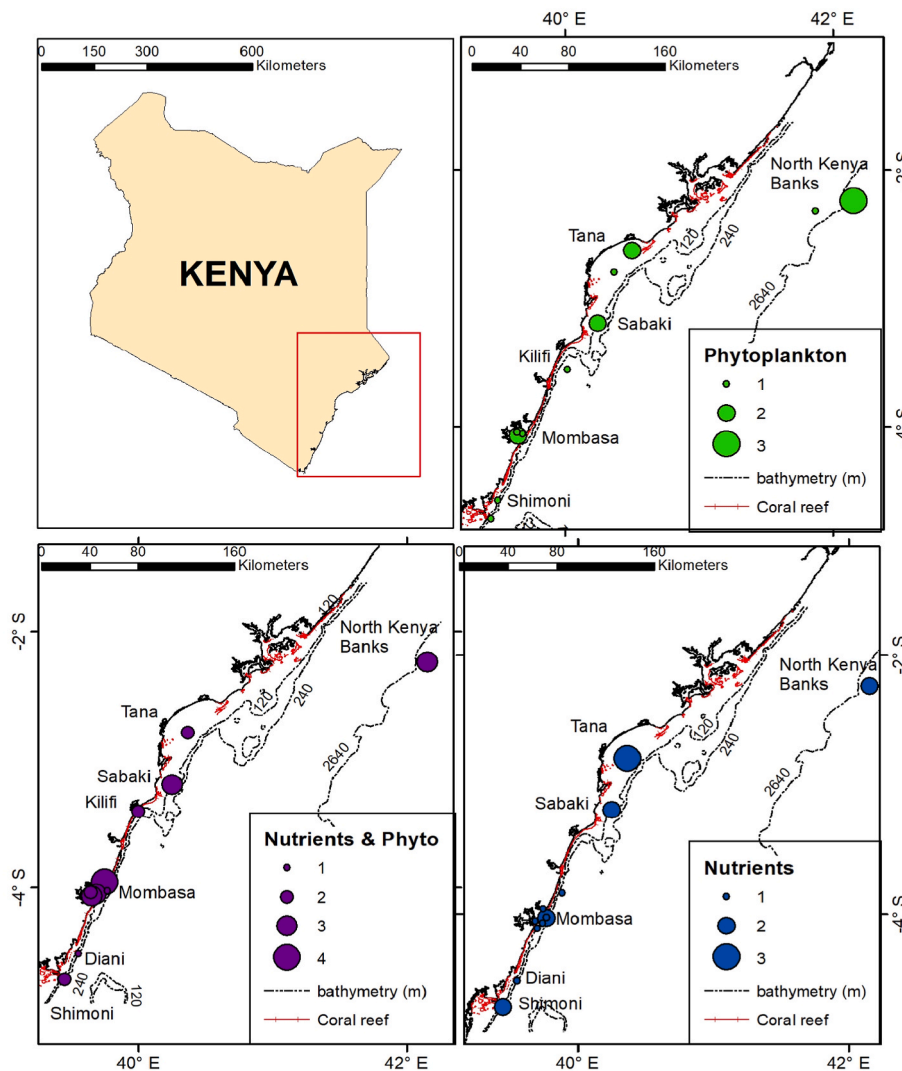


Fig. 1. A map of the study area showing the location of studies on phytoplankton (top right), nutrients (bottom left), and a combination of the two (bottom left) in Kenya’s coastal and marine environment.

waters. It thus provides insights into the available information and existing gaps that need special consideration in future research to understand the drivers of nutrient pollution and HABs development as well as coastal ecosystem's responses for management purposes to ensure full utilization of the blue economy potential.

2. Methodology

2.1. Study area

Kenya is located on the east coast of Africa with a coastline length of about 640 km extending from 1°30'S to 4°30'S. Kenya's coast is characterized by many creeks, estuaries, fringing coral reefs, seagrass beds, and mangrove swamps (Fig. 1). It experiences semi-diurnal tides with amplitudes between 1 and 3 m (Kitheka et al., 1996), and a mean sea surface temperature (SST) of 28.2 °C (ASCLME, 2012). The annual rainfall ranges between 1000 and 1200 mm and experiences a modified equatorial climate with two rainy seasons (October to December and March to May) (Obura, 2001; ASCLME, 2012). The region has two major river systems, Tana and Athi-Sabaki rivers, which drain into the Indian ocean in the north coast with great implications to sediments and nutrient inputs in the area compared to south coast of Kenya with smaller semi-permanent rivers (Ramisi, Umba, Mwache, Mkurumuji, Rare and Kombeni).

2.2. Literature search and publications screening

Systematic literature searches were conducted between June 2021 and March 2022 with search terms targeting studies on anthropogenic nutrients (nitrogen and phosphorus) sources, pathways, conditions (concentrations and ratios), and phytoplankton composition including the occurrence of HABs in Kenyan waters (Fig. 2). We searched Web of Science, Science Direct and Google scholar for topics with keywords including nutrients, phytoplankton, primary production, HABs, coasts or marine and Kenya. Inclusion criteria were journal articles, book chapters, and technical reports with empirical data, published in 2021 or earlier, and a study focus on Kenya's coastal and marine waters. Exclusion criteria were editorial and meeting proceeding articles, conference abstracts and lack of information on nutrients pollution, phytoplankton, and HABs (Fig. 2). The articles were then manually screened for inclusion based on the language of publication (only those in English were considered), and the availability of information on nutrients, phytoplankton, and HABs. The initial list of literature established then yielded further sources through snowball and citation searches. We decided to include seven articles from grey literature sources, such as technical reports from government bodies or non-governmental organizations (NGOs) and these because of limited available data in the peer-reviewed literature (Appendix 1). Data were extracted from original empirical research articles only to avoid duplication. MendeleyDesktop Version 1.19.4.0 was used for article organization and the removal of duplicates.

2.3. Data collection

To establish anthropogenic nutrient sources, pathways, and drivers of pollution and HABs development, data were extracted for: the type of

water (e.g. seawater, pore-water, and groundwater) and the type of ecosystem from the selected articles. The ecosystems were classified based on hydrological features or ecological conditions. These categories were: estuarine (areas lying within river mouths), creek (tidal channels with mostly saline water and low river influence), mangroves (mangrove-covered areas), seagrass (areas covered by seagrass), and coral reefs (open areas covered by coral reefs), nearshore (areas close to land with no mangrove, seagrass or coral coverage), offshore (open waters). Data were extracted for nutrient concentrations and ratios (dissolved inorganic nitrogen –nitrates and ammonium, phosphates and silicates), primary production (phytoplankton biomass-chlorophyll *a* (*Chl-a*) and daily primary production), phytoplankton composition, abundance, and diversity where they existed. The sampling year, month, and season were also recorded. Studies from similar environments in other areas were used to aid the interpretation of the established results.

2.4. Data analysis

To examine anthropogenic nutrient conditions (nitrate –NO₃ and ammonium-NH₄⁺ and phosphate-PO₄, and N: P ratio) and phytoplankton biomass (*Chl-a*) and composition (HABs) in Kenyan coastal waters, descriptive statistics and an F-test Two Sample Variance was conducted followed by *t*-test at $\alpha = 0.05$ significance level. All nutrient concentration data were converted into $\mu\text{mol/L}$ and *Chl-a* to $\mu\text{g/L}$. Threshold levels for nutrients and *Chl-a* were defined based on standard water quality variables criteria (Simbaura et al., 2005). All analyses and data presentations were conducted using MS Excel 2016, SigmaPlot 14.0. and PRIMER-E (v7.).

3. Results

The results from a total of 40 articles with empirical studies indicated that the mean nitrate and phosphate concentrations across all studies ranged between 2.07 and 1254 $\mu\text{mol/L}$, and 1.22 and 19.26 $\mu\text{mol/L}$ in Kenya's coastal and marine waters. The mean *Chl-a* and daily carbon primary production were $2.17 \pm 0.31 \mu\text{g/L}$ and $185.66 \pm 28.10 \text{ mgC/L}^{-\text{d}}$, respectively, and 56 species of potentially harmful algal blooms were recorded during the study.

3.1. Articles composition and distribution

A total of 40 articles published between 1983 and 2021 were found relevant, containing empirical data used in this review. About 78% were on nutrients, 18% on HABs, and 28% on phytoplankton composition while only 45% covered both nutrients and phytoplankton community composition including HABs. Most studies were conducted on the creeks ($n = 24$) and estuaries ($n = 16$) with the creeks around Mombasa (Tudor, Kilindini, and Mtwapa) and Sabaki as the most studied creeks ($n = 5$) and estuary ($n = 7$), respectively. Most of the studies were published after 1990, with an average of twelve studies per decade.

3.2. Sources and pathways of anthropogenic nutrients in Kenya's coastal and marine waters

Average nitrate and silicate concentrations were substantially higher in groundwater compared to pore and seawater. The highest mean

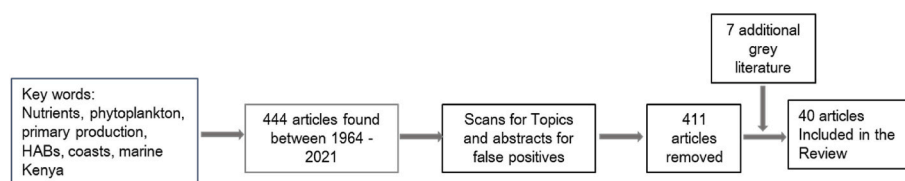


Fig. 2. Systematic search and review process undertaken.

phosphate concentration in the study was registered in the pore water while the highest N: P ratio was in groundwater (Table 1). Elevated nitrate levels were observed in both ground and pore water in urbanized nearshore waters (Nyali in Mombasa). The mean and ranges for dissolved inorganic nitrogen (NO_3^- and NH_4^+), PO_4^- and dissolved silicate- SiO_3^{2-} , as well as N: P and N: Si in ground, sea, and pore water established from this review varied across groundwater, pore water and seawater (Table 1).

In the groundwater, the highest concentration of NO_3^- , NH_4^+ and PO_4^- was established in the creek waters while the nearshore urban waters in Nyali were very rich in nitrate but deficient in phosphate. The groundwater nutrient concentrations were also characterized by elevated nitrogen nutrients, especially the nitrate form, relative to phosphate. The review established a strong insignificant positive correlation ($r = 0.733$, $p = 0.1501$) between nitrate and phosphate concentrations in groundwater in all the sites (Fig. 3).

In the pore water, the highest mean nitrate and ammonium concentrations were established in the nearshore reef waters, the site where lowest phosphate concentrations were established while the highest phosphate was recorded in the mangrove creek waters. The ammonium levels were $<0.1 \mu\text{mol/L}$ for the nearshore urban waters in Mombasa while the silicates ranged between 0.1 and $1.25 \mu\text{mol/L}$ in the pore water (Fig. 4).

Nutrient concentrations in seawater varied significantly between the different locations ($p < 0.05$). A significant variation was established among nutrient concentrations in the different locations ($p < 0.05$). The review's highest mean nitrate and phosphates sea water concentrations were established in estuarine waters. Ammonia concentrations exceeded nitrate in all locations apart from estuarine waters. The highest value was recorded in the creeks (Fig. 5 and Table 2).

A spatial analysis of nutrient conditions in estuarine waters established the highest mean nitrate concentrations in one of the longest rivers (River Sabaki) located on the north coast of Kenya. The lowest phosphate concentration was established in River Tana, which is also another major river draining through a large catchment area. Almost similar mean nutrient concentrations were established in rivers located on the south coast (Mwena, Ramisi, and Uмба) (Fig. 6).

In the creeks, relatively higher ammonium levels were recorded compared to nitrate in all the creeks apart from Mida and Malindi (Fig. 6). The maximum ammonium concentration ($23.07 \mu\text{mol/L}$) encountered in the whole study was reported in the urban site of Mtwapa while the creeks adjacent to informal settlements in Mombasa (Makupa and Tudor) recorded the highest mean NH_4^+ concentrations ($3.85 \mu\text{mol/L}$) recorded in this study. Both ammonium and phosphates were higher than nitrates in creeks exposed to maritime activities (Kilindini) and informal settlements (Makupa) (Fig. 6).

A significant seasonal variation was established between dry and wet seasons' nutrient concentrations in all the locations ($p < 0.001$). Higher NO_3^- and NH_4^+ were established during the wet season compared to the dry season in all the sites (Fig. 7).

The average seawater N: P ratios were below the Redfield ratio (N: P

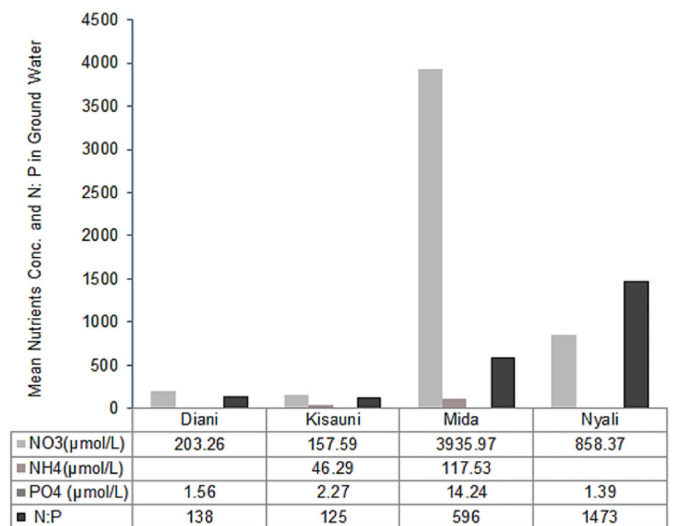


Fig. 3. Mean Nitrate- NO_3 , Ammonium- NH_4^+ , and Phosphate- PO_4 concentrations and N: P ratios in groundwater across all studies along the coast of Kenya.

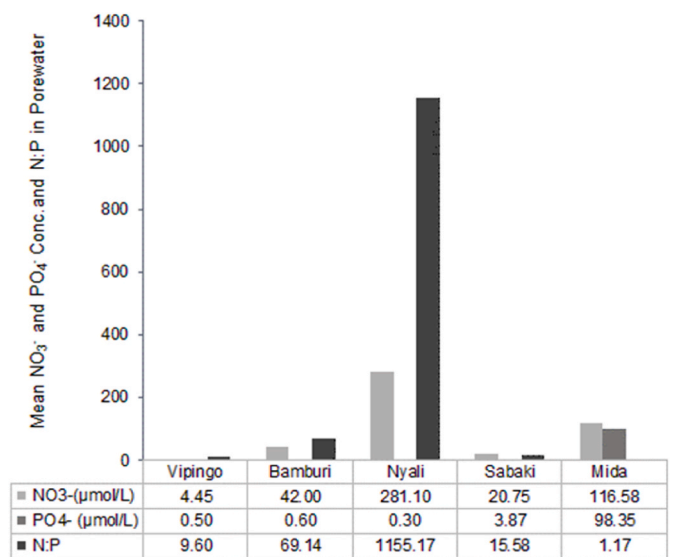


Fig. 4. Mean Nitrate- NO_3 , Ammonium- NH_4^+ , and Phosphate- PO_4 concentrations and N: P ratios in Pore water across all studies along the coast of Kenya.

= 16) in almost all the sites apart from nearshore waters with the lowest values (<2) recorded in mangrove and seagrass waters (Fig. 8).

Based on specific locations (water types), the highest N: P ratio, which was above the Redfield ratios (N: P > 16) was observed in creek

Table 1

The Mean, Standard Deviation (SD), and ranges of nutrient concentrations (NO_3^- , NH_4^+ , PO_4^- , SiO_3^{2-}) and ratios (N: P and N: Si) in the ground, pore, and seawater in Kenya's coastal and marine environment.

Nutrients Conditions	Groundwater (n = 6) ^a		Pore water (n = 3)		Sea water (n = 38)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
NO_3^- (µmol/L)	1255 ± 502.7	59.4–4900	71.8 ± 23.0	1.50–495.5	2.07 ± 0.42	<DL – 82.8
NH_4^+ (µmol/L)	78.7 ± 40.0	0.40–907	0.59 ± 0.10	0.20–1.00	2.25 ± 0.21	0.01–23.1
PO_4^- (µmol/L)	4.73 ± 2.00	0.38–71.3	19.3 ± 8.7	0.10–164.7	1.22 ± 0.24	<DL – 49.2
SiO_3^{2-} (µmol/L)	250 ± 48.0	86.0–597	56.35 ± 9.5	1.20–134	33.5 ± 6.9	4.00–163.5
N: P	592.5 ± 176.8	18.7–6997	165.9 ± 88.8	0.39–1782	11.8 ± 4.2	0.02–849.5
N: Si	26.39 ± 14.8	0.16–26.3	0.50 ± 0.09	0.10–1.25	0.17 ± 0.03	0.01–0.56

^a Data presented for groundwater were extracted from studies conducted in Mombasa, Diani, and Mida Creek and surface pore water in reefs (Mwaura et al., 2017), estuarine (Ohowa, 1996), and mangroves (Mwashote et al., 2005). The ground and pore water silicates data were only available for Mida Creek and Sabaki estuary while the ammonium data for pore water was only for nearshore sites around Mombasa (Vipingo, Bamburi, and Nyali).

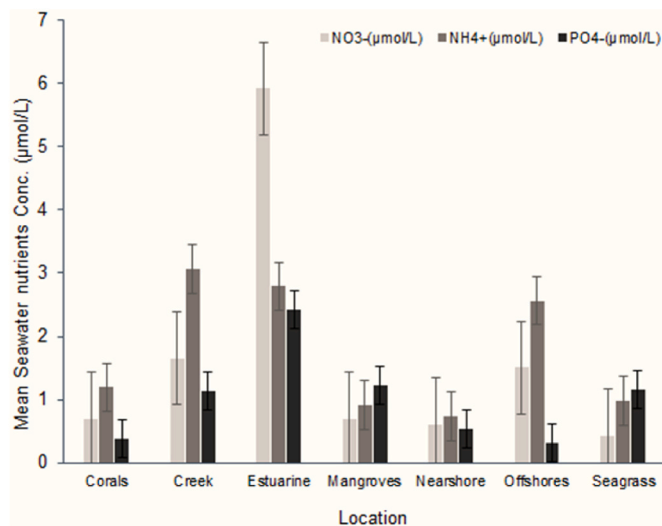


Fig. 5. Mean Nitrate-NO₃⁻, Ammonium-NH₄⁺, and Phosphate-PO₄⁻ concentrations in seawater in various locations (study site type) across all studies along the coast of Kenya.

waters in Mida while the lowest values were in populated urban areas in Tudor and Mtwapa creeks. In the estuarine waters, only Tana had N: P values above the Redfield ratio while the rest had low values < 10 with

Table 2

Minimum and Maximum values of nutrient concentrations (NO₃⁻, NH₄⁺, PO₄⁻ and SiO₃²⁻) and ratios (N: P and N: Si), *Chl-a*, and daily primary production (PP) registered in different ecosystems during the study. Abbreviations “Min” means minimum, “Max” means maximum.

Parameter	Min/Max	Offshore	Corals	Seagrass	Mangroves	Nearshore	Estuarine	Creeks
NO ₃ (µmol/L)	Min	0.10	0.10	0.04	0.69	<DL	0.01	0.002
	Max	5.30	2.50	1.20	0.93	3.09	82.8	18.0
NH ₄ (µmol/L)	Min	0.98	0.07	0.25	0.92	0.01	0.16	0.27
	Max	3.80	3.42	1.80	1.37	2.31	11.1	23.1
PO ₄ (µmol/L)	Min	0.12	0.08	0.38	1.23	<DL	<DL	0.05
	Max	0.56	0.80	2.32	2.47	9.63	49.2	13.8
SiO ₃ ²⁻ (µmol/L)	Min	-	-	-	-	-	5.00	4.00
	Max	-	-	-	-	-	100	164
N: P	Min	0.54	1.61	1.18	0.81	0.02	0.23	0.08
	Max	51.7	47.5	2.18	1.88	111	76.3	30.0
N: Si	Min	-	-	-	-	-	0.03	0.01
	Max	-	-	-	-	-	0.56	0.32
<i>Chl-a</i> (µg/l)	Min	0.20	0.02	0.04	0.75	0.03	0.17	0.06
	Max	1.20	0.90	1.80	3.00	4.71	40.9	21.5
PP(mgC/L-d)	Min	-	100	190	100	-	-	100
	Max	-	356	1050	435	-	-	1600

values < 2.0 recorded in Mamburi and Umba. Greater N: P values were also established during the wet season compared to the dry season in nearshore and offshore waters while a contrasting pattern was observed in coral and estuarine areas for the same (Fig. 9).

3.3. Nutrient conditions, primary production, and phytoplankton community composition

Primary production was analyzed in seawater using *Chl-a* concentrations and daily carbon primary production (Table 2). Very few studies existed on daily primary production (n = 3), with the highest value of 1600 and 1050 mgC/L-d) established in the creeks and seagrass during the dry (October) and towards the end of the wet season in July respectively. None of these studies assessed the PP in estuarine environments. On the other hand, *Chl-a* was the most used proxy for examining primary production in the area. The highest *Chl* concentration of 40.9 µg/L, encountered throughout the study was established in estuarine waters during the dry month of September. The highest and lowest mean *Chl-a* concentrations averaged across all studies were established in estuarine and coral waters respectively (Fig. 8). In the corals, the highest *Chl-a* was also in October, during the dry season while the lowest value was during the wet season. In the creeks and nearshore waters, a mixed observation was made in different sites with both high and low *Chl-a* concentrations during both seasons, making it difficult to establish the seasonal influence of primary production in the areas. Productivity in mangroves indicated a higher mean *Chl-a* concentrations

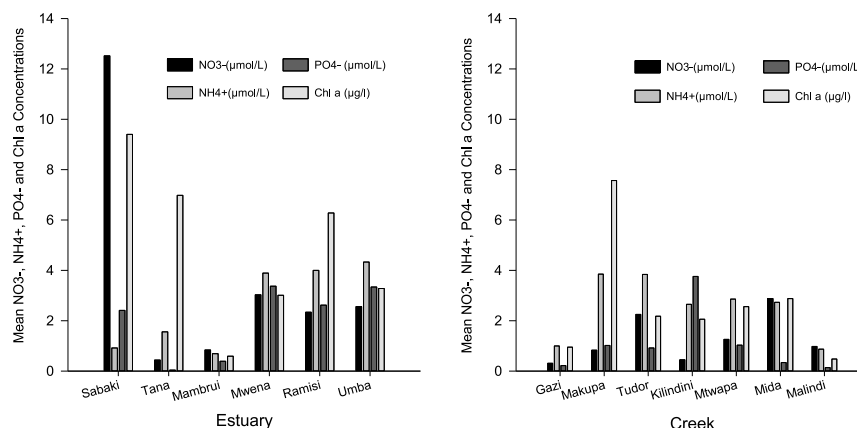


Fig. 6. Mean NO₃⁻, NH₄⁺ and PO₄⁻ Concentrations averaged across all studies in estuarine (left) and creek (right) waters along the coast of Kenya.

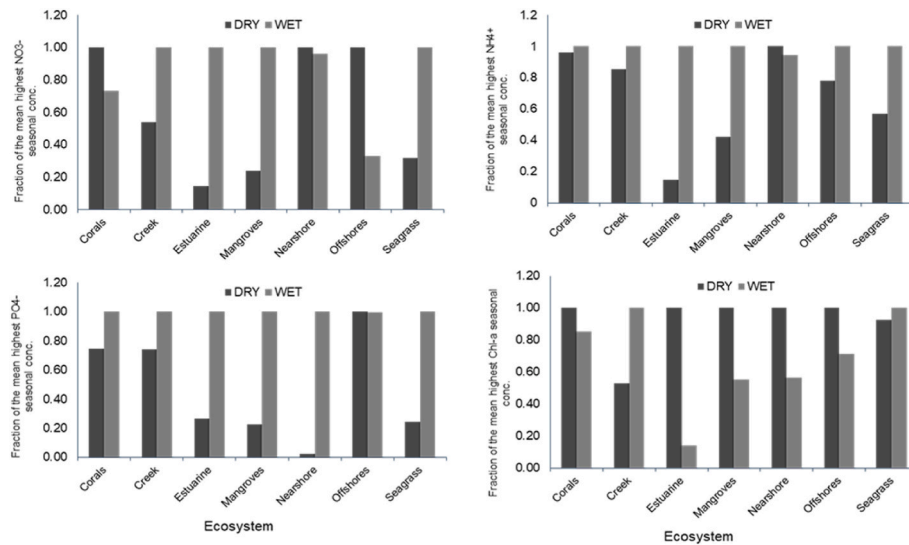


Fig. 7. Mean seasonal variation of NO_3^- (top left), NH_4^+ (top right), PO_4 (bottom left), and Chl-a (bottom right) concentrations across all studies in different ecosystems along the coast of Kenya. Values are shown as a fraction of the average concentration during the season with the highest concentration.

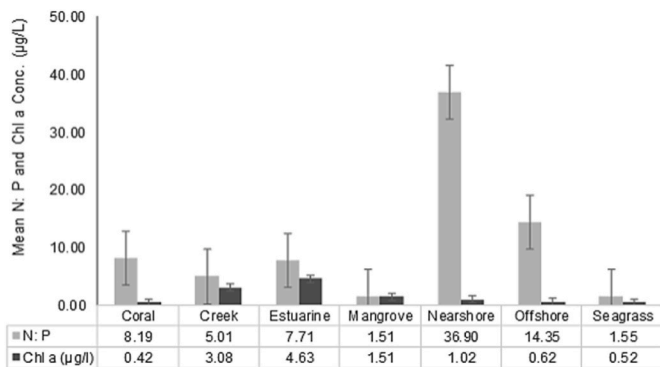


Fig. 8. Mean N:P ratios and Chl-a in different ecosystems in Kenya's coastal and marine waters.

during the dry season compared to the wet season (0.8 and 1.45 $\mu\text{g/L}$). The study of primary production was however limited with those in mangroves only presented in one study, while seagrass and corals were available in 3 studies. Based on specific sites, the lowest and highest estuarine Chl-a concentrations were in Mambui and Sabaki respectively. In the creeks, the highest Chl-a concentration was in Makupa which also corresponded to the high NH_4^+ recorded at the site.

A strong positive correlation was established between Chl-a and nutrient concentration in seawater among all five locations that

provided both data ($r(5) = 0.99, p < 0.05$). The correlation was significant with phosphate ($p < 0.001$) and insignificant for nitrate and ammonium concentrations ($p > 0.05$).

A significant seasonal variation was established between dry and wet seasons ($p < 0.05$) with higher mean Chl-a concentration recorded in estuarine and creek waters during dry and wet seasons respectively (Fig. 7). During the dry season, the Chl-a concentration was significantly correlated with both ammonium and phosphates in all the stations. This study classified coral and seagrass waters as mesotrophic, mangroves and nearshore stations are higher mesotrophic while estuarine and creek waters are eutrophic based on mean Chl-a concentrations following the classification criteria by Simbaura et al. (2005). The trophic classification of different studies in Kenya's waters is also presented in this study (Table 3).

The studies on phytoplankton established and presented in this review were for micro-phytoplankton size classes $< 20 \mu\text{m}$ sampled in the surface waters ($\leq 5 \text{ m}$). The phytoplankton species richness ranged between 40 and 295 species belonging to 78 genera (Mwashote et al., 2005; Adala et al., 2007; Kiteresi et al., 2012). The cell density in the area ranged between $1614 \text{ cells l}^{-1}$ and $68,515 \text{ cells l}^{-1}$ in the creek, estuarine, and nearshore waters (Kitheka et al., 1996; Mwangi et al., 2001; Kiteresi et al., 2012).

Diatoms dominated the micro-phytoplankton community group in all reviewed studies. Dominance and localized blooms of the nitrogen-fixing cyanobacteria (*Oscillatoria* sp., *Chroococcus limneticus*, and *Trichodesmium* sp.) were reported offshore (Kromkamp et al., 1997) and in

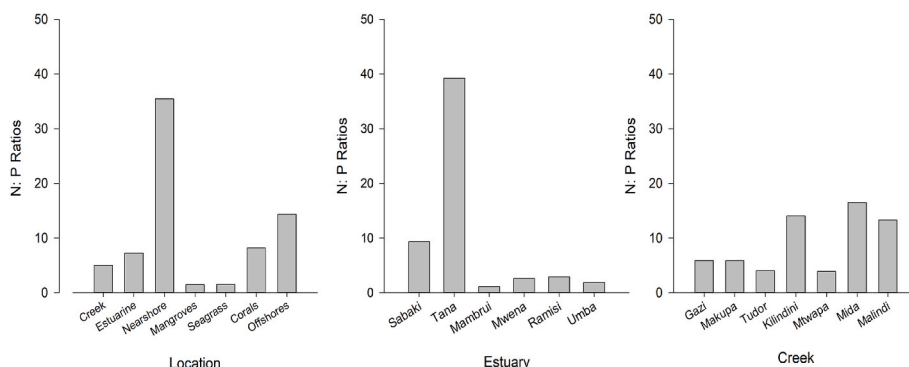


Fig. 9. Mean molar N:P Ratios in different locations (left), specific estuaries (center), and creeks (right) in the study area.

Table 3
Trophic status classification based on individual studies.

Site	Classification	Criteria	Source
Kenya's coastal waters	Oligotrophic	<i>Chl-a</i> levels (predominance of regenerated production)	Mengesha et al. (1999)
Tudor Creek	Oligotrophic	Nitrate concentrations	Kazungu et al. (1989)
	Higher mesotrophic	<i>Chl-a</i> levels	Okuku et al., 2011
Makupa Creek	Eutrophic	<i>Chl-a</i> levels	Okuku et al., 2011
Mtwapa Creeks	Higher mesotrophic	<i>Chl-a</i> levels	Okuku et al., 2011
	Eutrophic	Bacterial contamination	Mwangi et al., 2001
	Oligotrophic	Nitrate level	Pole et al. (2016)
Gazi Creek	Oligotrophic	<i>Chl-a</i> levels	Okuku et al., 2011
Mida Creek	Mesotrophic	Phytoplankton diversity	Mwashote et al., 2005

coastal waters (Mwangi et al., 2001; Mwashote et al., 2005; Kiteresi et al., 2012). Other dominant species are *Chaetoceros* sp., *Rhizosolenia* sp., *Bacteriastrium* sp., *Nitzschia delicatissima*, *Tabellaria fenestrata* (Lyngbye), *Pseudo-nitzschia* sp., *Coscinodiscus* sp., *Prorocentrum* sp., *Protoperidinium* sp., *Eutreptiella* sp., *Thalassiosira* sp., *Peridinium* sp., *Actinoptychus* sp., *Ceratium* sp., and *Gymnodinium* sp. (Kiteresi et al., 2012) (Table 4).

3.4. HABs in Kenya's coastal and marine waters

This review established a total of 56 species of potentially harmful algal blooms existing in Kenya's coastal and marine waters. The species were grouped using two major criteria, i.e. taxonomic groups (dinoflagellates, diatoms, flagellates, and others) and the impact factors (toxin producers, oxygen depleters, and stranglers) (Hansen and Turquet, 2001). About 56% of the total number of established HABs species was made up of dinoflagellates while flagellates were the least in the group. Based on impact categorization, 67% composition was made up of toxin-producing species (Fig. 10). At least 24 species have been reported in Shirazi, Kilindini, Kilifi, and Ngomeni reported (Hansen and Turquet, 2001); 9 species reported off the southern coast of Kenya (ASCLME, 2012); and 24 species identified in Kilindini Creek (Ogongo et al., 2015a,b). Additionally, 26 and 16 potential harmful algal blooming species have been registered in the Ramisi-Vanga system (Kiteresi et al., 2012) and Shirazi creek, respectively. About 67% of the total identified HABs species were registered in Kilindini Creek. The highest abundance for the blooming species was 215,000 cells/l reported in Kilindini (Hansen et al., 2001a, 2001b) while the toxin-producing species ranged between 3 ± 2 – 407 ± 87 cells/l (Ogongo et al., 2015a,b). Contrasting, much higher values have been reported for the toxic *Pseudo-nitzschia pungens* with as high as 60,000 cells/l in Shirazi creek and 7000 cells/l in Kilindini and Kilifi Creeks. A full list of all identified potential harmful algal blooming species in Kenya's coastal and marine waters including the nature of effect and site of identification established from this study is provided in this review (Appendix 3).

Table 4
Phytoplankton composition in east African waters based on past studies.

Taxonomic Group				Location/Ecosystem	Source
Diatoms (%)	Dinoflagellates (%)	Flagellates (%)	'Others'/Cyanobacteria (%)		
57.6	41.1	1.3	–	Mombasa (Urban/tourism)	Adala et al. (2007)
51.1	22.7	6.8	19.3	Ramisi-Vanga system (Estuarine and Oceanic)	Kiteresi et al. (2012)
65.8	32.9	–	1.3	Pemba Channel (Oceanic/Fishing)	Sekadende et al. (2021)
70.0	24.0	–	6.0	Zanzibar coast (Urban/tourism)	Moto et al. (2018)

4. Discussion

Groundwater is widely used for drinking while seawater is utilized for fisheries and recreational purposes in the area. However, higher dissolved inorganic nutrients (NO_3^- , NH_4^+ , and PO_4^-), which exceeded the international standards recommended thresholds ($\text{NH}_4^+ = 0.2$ mg/L; $\text{NO}_3^- = 10$ mg/L) (WHO, 1996) and U.S. EPA ($\text{NH}_4^+ = 1$ mg/L; $\text{NO}_3^- = 10$ mg/L) (U.S. EPA, 2000) were established in ground water used for drinking and recreational seawaters (Mwaguni, 2002; Mwashote et al., 2005; Barongo et al., 2006; Abdulaziz Hamid, 2017).

Anthropogenic nutrient inputs from agriculture and urbanization account for the major nutrient sources supplied into coastal waters worldwide (Howarth, 2008). About 80% of municipal wastewater is released into the environment untreated globally and human sewage was reported to be the most prevalent urban source of nutrients in coastal waters (Malone and Newton, 2020). High organic matter inputs supplied by untreated wastewater as established in the study, have been reported earlier and linked to high nutrients in pore water due to remineralization processes (Kaiser et al., 2015). Elevated nutrient concentrations in the creeks around urban areas and estuaries can thus be associated with the supply of untreated sewage, industrial discharges, stormwater, and agricultural runoff. Nitrogen supply from nitrogen fixation (Kromkamp et al., 1997), localized upwelling in nearshore waters (Obura, 2001), and groundwater (Mwaura et al., 2017) around Mombasa and Kilifi areas were also reported and can be linked to the elevated nitrate concentration in nearshore waters.

A seasonal comparison indicated higher nutrient levels during the rainy season compared to the dry season. This suggests a greater abundance of nutrients being washed from diffuse land-based sources by surface run-offs during the rainy season. A recent review reported that about 20% of anthropogenic nitrogen used in coastal watersheds is exported into the coastal waters (Malone and Newton, 2020). Elsewhere, an earlier study by Glibert and Burkholder (2006) established a direct relationship between population development, fertilizer application, and riverine nitrogen and phosphorus fluxes. The elevated nutrient levels reported during the wet seasons in the estuarine waters can thus be a result of agricultural runoffs from the river catchment areas, characterized by the use of synthetic fertilizers. Existing spatial variations established among estuaries and creeks can be a result of differences in the intensity of anthropogenic activities in the watersheds as has been reported in other studies (Jickells et al., 2017). This is evident in the highest nitrate concentrations established in one of the major rivers (River Sabaki) draining over wide geographical areas in Kenya's highlands with intensive agriculture and the use of artificial fertilizers (ASCLME, 2012). These variations suggest that the expansion of agriculture and the use of artificial fertilizers in the river catchment as planned under the country's development plans could increase nutrient supply in the estuaries and coastal ocean.

The creeks located around urban populated areas also experience a high generation of municipal and domestic sewage from densely populated residential areas and tourism hotels. These get into the seawater through direct discharges, stormwater, and seepage from pit latrines and septic tanks. Open defecation, poor sanitation, and infrastructure facilities in informal settlements were linked to raw sewage discharges into the ocean (Kithiia and Majambo, 2020). Elevated nutrients in the ground and sea waters around densely populated areas established in this

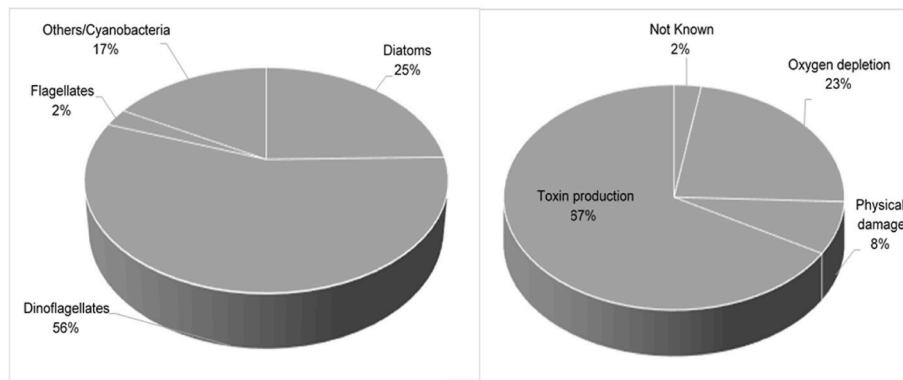


Fig. 10. Taxonomic (left) and impact category composition of major groups forming Potential HABs in Kenya's Coastal and Marine waters (n = 56).

review point toward a sewage management problem. The planned expansion of affordable housing along the coastal region under the country's development plans (cn.invest.go.ke, 2017) should thus be accompanied by a development in sanitation facilities to avoid sewage contamination of water resources. The problem of anthropogenic nutrient pollution was also reported in other urban areas in the region e.g. Chapwani in Zanzibar (Kyewalyanga and Lugomela, 2001) and Dar es salam (Hamisi and Mamboya, 2014) and internationally e.g. Indonesia (Adyasari et al., 2018), Long Island, Brazil (Niencheski et al., 2007) and Kaneohe Bay in Hawaii (Hoagland et al., 2002). This indicates that sewage-linked nutrient pollution is a global problem, particularly in developing countries.

The analysis of N-forms revealed elevated levels of NH_4^+ over NO_3^- in almost all the locations in the study. The supply of ammonium in the coastal waters is caused by bacterial remineralization of organic matter under anoxic conditions (Mengesha et al., 1999; Hensen et al., 2006), ballast water, urea fertilizers, aquaculture activities, and increased atmospheric deposition (Glibert, 2017; Jickells et al., 2017). Since aquaculture and atmospheric deposition studies have not been verified in the area, elevated levels of dissolved ammonium can be caused by high bacterial remineralization of high organic matter supplied by sewage and terrestrial runoff in the area. High NH_4^+ relative to NO_3^- may also be due to the high consumption of NO_3^- by phytoplankton for primary production. The elevated ammonium levels over nitrates are a threat to the ecosystem's health as they can enhance the development of harmful algal blooms as discussed in the next section.

The N:P ratios in the dissolved nutrient pool were consistently below the Redfield value (N:P = 16) in all the sites (Fig. 9). Low N:P ratios were reported in other coastal areas and linked to increases in the anthropogenic supply of P and high assimilation of N during spring blooms (Malone and Newton, 2020). Low N:P established in the creek, seagrass, and reef waters thus suggests either higher assimilation or lower supply of dissolved inorganic nitrogen (DIN) relative to phosphorus in the area. Sewage discharges released in the coastal waters may have contributed to this due to the high use of detergents containing P nutrients. The nitrogen limitation established in this study agrees with earlier reports about tropical coastal waters (Glibert, 2017). Elevated N:P values established in nearshore and estuarine waters can be due to localized effects of dissolved nitrogen-enriched sewage effluents from hotels and residential areas seeping into the ocean through groundwater (Mwaguni et al., 2017; Mwaura et al., 2017) and agricultural runoff.

Coastal habitats like coral reefs and seagrasses play a critical role in supporting coastal biodiversity and livelihoods. However, elevated nutrient levels in coral reefs can threaten their health by stimulating phytoplankton growth hindering light penetration for the benthic macrophytes and corals. (Raj et al., 2020). High levels of DIN from sewage can affect the coral reefs' physiology, making them vulnerable to diseases (Bruno et al., 2003). High nutrient inputs from sewage reported in nearshore coral reef waters adjacent to dense tourism hotels should be

treated with care and monitoring established to ensure that nutrient limits recommended for healthy corals are maintained.

Acute N limitation (N:P < 2) established in seagrass, reef waters, and some estuarine waters is a signal of the vulnerability of these habitats to nitrogen pollution as was reported in the Gulf of California (Beman et al., 2005). This indicates that many processes in these ecosystems are nitrogen-limited and any slight supply of nitrogen can lead to an outburst in the ecological processes like primary production in the system. Very low N:P ratios were reported to promote the growth of N-fixing organisms like *Trichodesmium* spp. in reef waters. *Trichodesmium* spp. Blooms are known to be a potential source of ciguatoxins in the ciguatera food chain (Malone and Newton, 2020). Data were missing for Si apart from estuaries and creeks that registered values below normal (N:Si < 1) an indication of Si limitation relative to N for phytoplankton (diatoms) growth. Limitation of Si relative to N, and N relative to P can promote the growth of non-diatom nitrogen-fixing phytoplankton species mainly harmful algal blooms (Glibert et al., 2005, 2011).

A positive correlation was established between phytoplankton biomass (*Chl-a* concentration), phosphates, and ammonium nitrogen. This may be an indication that phosphates and ammonium are major drivers of primary production in the area. Phosphate and N limitation for primary production has been reported in earlier studies (Turner and Rabalais, 2013). High primary production coincided with high NO_3^- registered in the Sabaki estuary indicating that nitrate could be the source of nitrogen nutrition at the site. All these agree with the claims that human activities are affecting nutrient chemistry and enhancing algal growth in the receiving coastal waters (Anderson et al., 2002; Malone and Newton, 2020).

The review also established lower *Chl-a* during the wet season when nutrient levels were high compared to the dry season in the estuarine and creek waters. This may have been caused by either dilution of the *Chl-a* concentrations by the incoming rainwater or reduced primary production water turbidity caused by sedimentation from runoffs (Kitheka et al., 2005). Land-use changes characterized by intensive agriculture in the river catchment areas have facilitated high erosion and deposition of loose particulate matter and sediment in the estuaries during the early rains causing water turbidity (Tamooh et al., 2014; Geeraert et al., 2015).

Although most *Chl-a* concentration in the ecological sites is still below the eutrophication threshold values e.g. $\text{DIN} \sim 1 \mu\text{M}$; $\text{P-PO}_4 \sim 0.1\text{--}0.2 \mu\text{M}$ for corals (Bell, 1992). The higher mean *Chl-a* concentrations (>0.2 $\mu\text{mol/L}$) established in nearshore corals adjacent to urbanized areas is an early warning to reduce the release of untreated sewage effluents into the ocean and poor use of agricultural fertilizers in river catchment areas. Low *Chl-a* concentrations are very ideal for seagrass and corals since high phytoplankton biomass can affect the health of these habitats as earlier stated in this review (Furnas et al., 2005). These findings compare with the recent report from the neighboring waters,

which indicated ammonium and nitrate as the drivers of high *Chl-a* in the coastal waters of Unguja (Peter et al., 2018). The presence of ammonium has been reported to enhance phytoplankton primary production due to the discriminate preference of ammonium compared to other N-forms due to its low energy requirement during assimilation (Lundgren et al., 2016; Glibert, 2017).

Diatoms play a very critical role in oceans' primary production and biological processes. Their dominance in Kenya's coastal waters is significant to fisheries production since several juvenile fish larvae are herbivores depending on diatoms as the basic source of food (Arshad et al., 2013).

Cyanobacteria, chlorophytes, and dinoflagellates have a high affinity for NH_4^+ while diatoms, which are important in fisheries food web, depend on NO_3^- uptake as a growth N substrate and to sustain cell energy balance (Lundgren et al., 2016). Elevated NH_4^+ levels ($>1 \mu\text{mol/L}$) can therefore repress NO_3^- uptake and favor the blooming species over the non-blooming diatom resulting in a reduction in fisheries (Glibert, 2017). The reported cyanobacteria dominance in the area during the dry season due to their small sizes (Falkowski and Knoll, 2007), nitrogen-fixing ability during N-limiting situations (Sumich and Morrissey, 2004), allelopathic strategies against other phytoplankton species and ability to use organic forms of phosphorus (Labry et al., 2002). Low flagellate abundance established in Mombasa can be due to their motile nature, enabling them to move to areas with favorable environmental conditions.

Nutrient ratios shape the phytoplankton community structure. Relatively low N: P ratios were reported to change the phytoplankton abundance from a diatom-dominated to a more toxic mixotrophic dinoflagellate (Glibert, 2017; Chia et al., 2018). Nutrients supplied from sewage and agriculture as demonstrated in the creeks and estuaries, and those likely to occur with the expansion of aquaculture and maritime transport can potentially cause shifts in the ratio N:P or N: Si resulting in an outbreak of HABs. This was reported in some U.S., European, and Asian coastal waters (Glibert, 2017) and aquaculture lagoons (Hassina et al., 2008). Urbanized coastal areas and estuaries exposed to intensive use of synthetic urea fertilizers in the catchment area are also vulnerable to HABs development (Anderson et al., 2002).

The results from Kilindini concur with those reported high toxic dinoflagellate composition in areas of ballast water discharges (Smayda, 2007). The reported dominance of dinoflagellates can be a threat to fisheries since they compete with juvenile fish larvae for diatoms. *Peridinium* sp. and *Protoperidinium* sp. are heterotrophic, they feed on diatoms to supplement their nutritional requirement during periods of low nutrient supply (Siano and Montesor, 2005). A decline in fish diversity with an increase in dinoflagellates has also been confirmed in other coastal waters (Glibert et al., 2011).

Although the abundance of the HABs species is still below the HABs warning threshold, the presence of saxitoxin-producing species and other potentially toxic forms of dinoflagellates (*Alexandrium* sp., and *Dinophysis* sp.) (Ogongo et al., 2015a,b) should be treated with caution. Additionally, seven out of twenty species of *Pseudo-nitzschia* species in the Western Indian Ocean (WIO) region, have been noted as domoic acid producers (Hansen and Turquet, 2001). These HABs can cause oxygen depletion, fish kills, and human intoxication when they bloom resulting in indiscriminate marine wildlife and physical harm through damaging and clogging of gills of fish and invertebrates.

Harmful algal blooms can cause habitat destruction by smothering and killing corals, seagrass, and mangroves with adverse impacts on fisheries and tourism, public health, and local livelihoods. *Heterosigma akashiwo*, *Trichodesmium*, and *Lyngbya majuscula* also threaten recreational activities due to their dermatological effects (skin irritation) with the impacts already reported in neighboring waters of Tanzania (Msuya, 2015; Aziza et al., 2018; Kimambo et al., 2021). The blooming of *Microcystis* species seriously affected salt production in Kenya in 1992 and 1993 (Munga et al., 1992; ASCLME, 2012). Additionally, the bloom reported in Kiunga in 2002 caused dead zones resulting in extensive

mortalities of marine life including fish and turtles; a ban on consumption and trade in shellfish, a halt in tourism, and human health problems like eye irritations and headaches, and greatly affected the local livelihoods (IUCN Eastern Africa Programme, 2004; ASCLME, 2012).

The abundance of HABs species recorded in Kenya is much higher than those of Lugomela (2013) who reported low *Pseudo-nitzschia* sp. abundances of <16 cells/l around sheltered inshore waters in Dar es Salaam throughout the 1-year and <18 cells/l reported in the offshore water of the Pemba Channel (Sekadende et al., 2021). Earlier incidences and impacts of HABs were reported in the region on the coast of Somalia (Obura, 2001), and periodic recurrent of *Microcystis* spp. Blooms in salt ponds in Kenya, the occurrence of red tides in November during the onset of the northeast monsoon (ASCLME, 2012), and blooms of *Gymnodinium* sp. caused by strong upwelling in the Kiunga Marine National Reserve (IUCN Eastern Africa Programme, 2004). The blooming of *Noctiluca scintillans* (Dinoflagellate), *Peridinium quinquecorne*, and *Trichodesmium erythraeum* are also common in the Indian Ocean (Hansen and Turquet, 2001).

5. Implications to management

The combination of nutrient conditions and phytoplankton plays a very critical role in determining the integrity and health of the coastal and marine ecosystem. Improved knowledge of nutrient concentration, stoichiometry, and phytoplankton community composition is thus important to the wider interest in the monitoring of these areas. Elevated nutrients reported in the creeks and estuaries (Okuku et al., 2011; Ongore et al., 2013) caused by sewage and terrestrial run-off from agriculture, especially during the rainy season is a clear indication of poor management of sewage and use of agricultural fertilizers in the river catchment areas. The eutrophic conditions established can have major consequences for the existing biodiversity and the benefits provide to society like fish production. Although the area seems to be experiencing N limitation that may be linked to high inputs of P from anthropogenic sources. The inputs of both N and P should be managed to ensure a stoichiometric balance of both nutrients since P limitation was also reported in some areas.

Toxic phytoplankton blooms have harmed fisheries, coastal and marine ecosystems, public health, and coastal economies (Hoagland et al., 2002). This review has summarized several harmful and potentially harmful algal species occurring in different locations in the area. The reported species like *Trichodesmium* spp., *Pseudo-nitzschia* sp., and *Dinophysis* sp have the potential to be harmful, however, none of them were highly abundant and calls for alarm with reference HAB's warning systems (Albright et al., 1993). Their presence in low abundances does not mean toxicity in the coastal waters and therefore their threat to seafood and human health should be deemed minimal pending confirmation. However, a high abundance of *Pseudo-nitzschia* sp. was established in the Ramisi-Vanga system (Kiteresi et al., 2012) and Kilindini creek (Hansen et al., 2001a, 2001b; Ogongo et al., 2015a,b) needs further investigations as some species are toxic with the capability of producing domoic acid responsible for amnesic shellfish poisoning (ASP). The established nitrogen limitation can enhance the occurrences of N-fixing cyanobacteria some of which are toxic. Reef fisheries are a major practice supporting many livelihoods in the area. However, blooms of *Trichodesmium* spp., caused by low N: P ratios can produce ciguatoxins causing contamination of seafood in the reef waters. Regular monitoring is thus important not only for the species but also to understand the HABs dynamics, detect existence of new species or toxicity of endemic species and manage the effects of naturally occurring blooms especially if mariculture and offshore fisheries expansion is expected.

A rapidly expanding human population like the one occurring along the coast of Kenya was positively correlated with nutrient enrichment in adjacent coastal waters (Anderson et al., 2002; Glibert et al., 2005) an outbreak of HABs (Trainer et al., 2003) in other areas. Planned activities (expansion of industries, agriculture, and housing) under the country's

economic development agenda (Nyonje, 2018), will also be characterized by increased generation of nutrients (N and P) to the adjacent coastal waters if no subsequent sewage, industrial effluent, and agricultural management actions are established. Additionally, the outbreak of harmful dinoflagellate blooms may occur with an increase in ballast water. Improvement of existing sewage management infrastructures, the establishment of new ones where they are lacking and regulation of agricultural activities in the catchment areas is thus necessary to manage the nutrients and reduce their effects on the environment.

6. Conclusion

This review provides insight into the status of nutrient pollution and HABs that can guide coastal managers. This is a systematic review of previous studies including forty original empirical research articles. The results indicate nitrogen limitation and occurrences of localized nutrient pollution in the creeks around major towns and estuarine environments. The review also established elevated *Chl-a* concentration in the estuaries and nearshore coral reefs. The toxic harmful algal species were identified in all existing studies indicating that they are widespread in Kenya's coastal and marine waters below HABs warning standards.

The results from this review call for regular monitoring programs on HABs and precautions on consuming related seafood to ensure public health safety. Elevated *Chl-a* concentrations in the estuaries and nearshore coral reefs also calls for mechanisms to reduce sewage discharges and sustainable agricultural practices in the catchment areas to safeguard the reefs and other critical habitats in the area. There was also a spatial and temporal inconsistency in the existing studies making them difficult to compare and inhibiting the establishment of trends in nutrient and HABs dynamics in Kenya's coastal waters. To facilitate effective management decisions, comparative field studies of different sites are necessary especially in potential fisheries, aquaculture, and tourism sites.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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