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REVIEW

Deepening Knowledge of Nutrient Dynamics in Coastal Waters

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ABSTRACT Nutrients are important compounds in waterbodies that regulate primary productivity and phytoplankton growth, the basis of food webs. Increased nutrient concentration has become a serious concern because it causes eutrophication and threatens the sustainability of ecosystems. Eutrophication is the process of nutrient enrichment in water bodies that affects their productivity and decreases water quality. Although information about nutrient distribution, limiting nutrients, and nutrient budgets is important for coastal water management, studies of wide-scale nutrient dynamics in Indonesian waters remain limited. To provide comprehensive data on nutrients, this review summarized the concentrations and compositions of nutrients in coastal waters, compared the limiting nutrients in various coastal waters based on the Redfield ratio, and described the factors affecting nutrient budgets using the database in ScienceDirect and Google Scholar. Curation was performed to summarize the nutrient dynamics in coastal waters. Results showed that nutrient concentration differed in each region due to many factors. Anthropogenic inputs greatly affected nutrients in tropical areas, such as Jakarta Bay (Indonesia). Understanding the quality and characteristics of water can help in managing waterbodies. This study provided knowledge related to nutrient dynamics in Indonesian waters and global biogeochemistry.

1. INTRODUCTION

Nutrients play a major role in supporting and preserving marine environments. Primary productivity, biogeochemical processes, and food chains are regulated by dissolved inorganic nutrients, such as dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), and dissolved silicate (DSi). Nutrients can also be used as the main index in assessing environmental quality (Wang et al. 2014; Dan et al. 2019; Yang et al. 2020).

Nutrient availability is important in biomass accumulation in the marine environment, particularly in terms of regulating phytoplankton growth. Thus, the temporal and spatial distribution of nutrients can influence the ecological structure (Paytan and McLaughlin 2007; Niu et al. 2020).

The role of nutrients in biogeochemical processes can be studied, for instance, during the reaction of each compound. Being less active than DIP, DIN can be easily eliminated via denitrification caused by a suboxic air interface or sediment in oxygenated waters (Yang et al. 2020). Meanwhile, DIP easily reacts with metal oxyhydroxides and is absorbed by sediment and suspended matter; this process is affected by pH and proceeds efficiently under high-oxygen conditions. The majority of DIP in waters is influenced by absorption or desorption from suspended particulate matter, precipitation or dissolution, biological utilization, and organic matter remineralization. The presence of DIP ultimately limits the growth of phytoplankton in many marine waters (Dan et al. 2019; Zhang et al. 2019; Yang et al. 2020). Different from N and P that are systematically considered and measured as the main factors controlling eutrophication, silica has not been systematically calculated (Glibert et al. 2008). DSi sources are diatom sedimentation and weathering processes such as the interactions of rock types, tectonic activities, and climate factors (Soetaert et al. 2006; Liu et al. 2009).

Nutrient dynamics in the ocean is seriously affected by human activities; increasing anthropogenic stressors over recent decades have changed the nutrient input and consequently altered the nutrient compositions and concentrations (Wei et al. 2015). Nutrient input to coastal oceans comes from rivers, atmospheric deposition, organic matter regeneration, and groundwater exchange with offshore waters (Liu et al. 2012; Jickells et al. 2014). In addition, human activities in the form of agriculture, fisheries, waste treatment, and fossil fuel usage can lead to changes in nutrient distribution (Liu et al. 2012; Niu et al. 2020). Nutrient input creates changes in the biomolecule composition of phytoplankton, which reflects their different C, N, and P requirements for biosynthesis (Wei et al. 2015). The effects of high nutrient concentrations include alteration of species diversity and food web structures, explosion of harmful algal blooms, acidification of seawater, hypoxia, degradation of water quality, and decrease in biodiversity (Howarth 2008; Flynn 2008; Jickells et al. 2014; Dan et al. 2019; Yang et al. 2020).

Furthermore, eutrophication resulting from nutrient over-enrichment can threaten the abundance and biodiversity of ecosystems (Bricker et al. 2008; Howarth 2008). Mineralization of organic matter releases nutrients that regenerate and use oxidized compounds, inducing dead zones

(Cabral and Fonseca 2019). Given these various impacts, the development of appropriate nutrient management strategies is extremely important (Conley et al. 2009).

Nutrient dynamics can be studied by assessing nutrient stoichiometry (i.e., molar ratio). For instance, nutrient molar ratios can be used to describe alterations in phytoplankton community assemblage, phytoplankton dynamics, potential nutrient limitations (Jin et al. 2013; Chen et al. 2019), nutrient regeneration, and transportation mechanisms in seawater (Jin et al. 2013). The stoichiometric ratio of N and P also shows the variability of phytoplankton species (Yuan et al. 2018; Zhang et al. 2019). The increasing ratio of C to N or P in phytoplankton indicates that N and P are the limiting nutrients. The C:N:P ratio varies within compounds depending on the requirements for biomolecule formation (Grosse et al. 2017). Phytoplankton composition varies in response to nutrient concentration and structure. Structure differences in nutrients lead to their varying functions in phytoplankton growth. For instance, phytoplankton N is an important element in light-sensitive pigments, such as chlorophyll (Niu et al. 2020).

Understanding biogeochemical processes including the source, distribution, and composition of nutrients is important to environmental protection and evolution studies (Flynn 2008; Yang et al. 2020). However, the biogeochemical cycle of nutrients in Indonesian waters, which serves as the main element affecting primary productivity, has not been systematically studied. Information on the distribution of dissolved nutrients, limiting nutrients, and nutrient budgets in the country's coastal waters remains lacking. This review aims to summarize the concentration and composition of nutrients in some coastal waters, compare the limiting nutrients based on Redfield ratios in coastal waters, and describe the factors affecting nutrient budgets. Literature study was conducted by searching with keywords "nutrient concentration," "distribution of nutrients," "nutrient budget," "coastal waters," "eutrophication status," "eutrophication assessment," and "TRIX index" in ScienceDirect and Google Scholar databases. A total of 207 results were filtered, and 76 papers were reviewed. The reviewed documents were selected mainly based on relevance (i.e., the locus on Indonesian waters and surrounding area that may be correlated to the waters and coastal nutrient dynamics). This study could provide significant knowledge relating to nutrient dynamics in Indonesian waters and may also be widely applicable to global biogeochemistry.

2. NUTRIENT CONCENTRATION AND COMPOSITION

Nutrient concentrations vary depending on season and time and are influenced mainly by hydrological and biochemical reactions (Costa et al. 2009). However, the spatial distribution of nutrients can be affected by several factors, such as inputs from land, variations in river flows, atmospheric deposition, precipitation, phytoplankton reproduction, and organic matter decomposition (Wei et al. 2015; Yang et al. 2020). In recent decades, nitrogen and phosphate concentrations have increased, whereas silica concentration has decreased. The shifting composition of these nutrients can impact ecological changes (Su et al. 2005).

The effect of human activity (sediment–water regulation events) on the increase in nutrient concentration was observed in Huanghe Estuary in 2008–2009. Study results showed that DIN concentrations increased by 2–4 times during sediment–water regulation events and phosphates and silicates increased by 2–2.6 times. The water in the estuary was rich in nitrates and silicates but scarce in phosphates (Liu et al. 2012). A similar pattern was found in Changjiang Estuary, which had high DIN and silicate concentrations and low phosphate concentration. Agricultural activities and domestic waste were the causes of the high nutrient concentrations, and phosphate adsorption by particulate matter was the cause of low phosphate concentration (Liu et al. 2016; Ding et al. 2019).

Nutrient concentrations in the Yellow Sea have risen in recent decades. NO_3^-, PO_4^{3-}, and SiO_3^{2-} concentrations in 2009 were 5.91 ± 2.39, 0.45 ± 0.15, and 10.6 ± 3.73 μmol/L, respectively. Around 57%–76% of DIN and 46%–68% of PO_4^{3-} were used by growing phytoplankton (Jin et al. 2013). According to long-term data, the nitrate and DIN concentrations in the southern Yellow Sea continued to increase in 1985–2006. Between 1997–1999 and 2006–2007, the DIN concentration at the estuary surface increased by 1.53 μmol/L. By contrast, in 1992–1998, the phosphate concentrations decreased and then increased in 2000–2004; meanwhile, silicate showed a downward trend in 1976–1992 but an upward trend in 1994–2004 (Wei et al. 2015). In the north Yellow Sea, the DIN, DIP, and DSi concentrations in water surface during 2016–2017 were 3.08–11.52, 0.24–0.67, and 0.71–6.82 μmol/L, respectively. The composition of DIN was 58% NO_3^-, 38% NO_2^-, and 4% NH_4^+ (Yang et al. 2020).

In Jiaozhou Bay, the mean concentration of DIN in surface waters during 2015–2016 was 15.98 μM, which comprised 50% NO_3-N and 45% NH_4-N. These values differ from those before 2001, in which NH_4^+ was the main element of DIN. The increase in NO_3^- concentration in Jiaozhou Bay is related to the controlling effect on ammonia concentration in the water. The high value of nitrate flux and total nitrate input causes the alteration of NH_4^+ to NO_3^- (Li et al. 2018; Yuan et al. 2018). DIN has a negative correlation with salinity but a positive correlation with PO_4^{3-} and SiO_3^{2-}, indicating that this nutrient involves similar cyclic processes such as assimilation and remineralization. The PO_4^{3-} concentration in this period was similar to that in 2012–2013 but 50% lower than that in 2002–2003. However, SiO_3^{2-} concentration was lower than in 2012–2013 but higher than that in 2002–2003. This finding indicated a stable trend in the preceding decade (Lu et al. 2016; Yuan et al. 2018).

The DIN and DIP concentrations in surface Hainan Island waters during 2017 were 7.60 ± 10.71 and 0.24 ± 0.31 μmol/L, respectively. DIN consisted of 46.0% NO_3-N, 40.1% NH_4-N, and 13.9% NO_2-N (Zhang et al. 2020). In the Pearl River Estuary, the DIN and DIP concentrations increased significantly during 1986–2017. The average DIN and DIP concentrations in 2015–2016 were 1.33 and 0.032 mg/L, respectively (Niu et al. 2020). In the northern area of the East China Sea, the NO_3^- and PO_4^{3-} concentrations in 2003–2005 were between 2.6–12.4 and 0.17–0.61 μmol/kg, respectively. This location had high nutrient levels because of nutrient supply from vertical mixing (Kim et al. 2006).

In November 2014, Rao et al. (2017) measured the levels of dissolved nutrients in the southeastern Arabian Sea by dividing the research location into south and north regions. The mean DIN, NH_4^+, and NO_3^- concentrations were 2.74, 1.19, and 1.64 μM in the south region, respectively, and 3.36, 1.59, and 1.27 μM in the northern region, respectively. NO_3^- had higher concentrations than NH_4^+ and NO_2^-. The

DIP concentrations in the southeastern Arabian Sea ranged 0.05–0.68 μM with a mean of 0.28 μM, and the DSI concentrations ranged 1.65–9.95 μM with a mean of 4.41 μM.

In another study, the average concentrations of phosphate, DIN, and silicate measured in Tambelan and Serasan waters (Natuna District, Indonesia) were 0.06, 2.07, and 3.66 μM, respectively (Prayitno and Suherman 2012). These concentrations are within the appropriate range for phytoplankton growth. The results also showed that silicate concentration is related to N/P ratio, that is, the former is low when the latter reaches 16 (the Redfield ratio). At this level, the researchers estimated that diatoms effectively consume silicates, thereby leading to a decrease in silicate concentration (Prayitno and Suherman 2012).

Nitrate concentrations in Jakarta Bay (Jakarta, Indonesia) in December 2015 ranged between <0.214 and 27.77 μmol/L (Putri et al. 2017). After the mass mortality of fish, the ammonia concentrations in the same study locations ranged between 13.64 and 138.8 μmol/L. The phosphate concentrations ranged from 26.18 μmol/L to 53.37 μmol/L, and high phosphate levels were observed in marine waters from all the research locations. Excessive nutrient intake is also one of the causes of fish mortality in Jakarta Bay. Frequent heavy rains carry large amounts of organic waste to the sea and contribute to 75% of water pollution in Jakarta Bay. The high ammonia levels in the waters of Jakarta Bay indicated that this location is highly polluted and unsuitable for aquatic organisms (Putri et al. 2017). The input from the river is the main contributor for eutrophication in Jakarta Bay (Damar et al. 2019).

In Weda Bay (North Maluku, Indonesia), low nutrient concentrations were reported as follows: 0.03–4.87 μmol/L for nitrate, 0.011–0.852 μmol/L for phosphate, and 0.04–1.21 μmol/L for silicate. According to the data on vertical nutrient distribution, nutrient concentration was low in the surface seawater layer and increased with the water depth. From the thermocline layer to the deep layer, nitrate concentration tended to increase due to scavenging at a depth of 500 m to 1500 m (Hamzah et al. 2015).

In Hurun Bay (Lampung, Indonesia), Santoso (2006) reported the following nutrient concentrations: a range of 0.313–1.708 μM with mean of 0.807 μM for ammonia, a range of 0.017–0.453 μM with mean of 0.107 μM for nitrite, a range of 0.079–0.558 μM with mean of 0.350 μM for nitrate, and a range of 0.070–0.185 μM with mean of 0.117 μM for phosphate. Meanwhile, Ikhsani et al. (2016) investigated the nutrients in the inner Ambon Bay (Maluku, Indonesia) during northwest and southeast monsoons. During the northwest monsoon, the phosphate and nitrate concentrations ranged 0.0471–0.0549 mg/L and undetected to 0.0976 mg/L, respectively. During the southeast monsoon, the phosphate concentration ranged between 0.0495 and 0.0676 mg/L, and the nitrate concentration ranged between 0.0247 and 0.4019 mg/L (Ikhsani et al. 2016).

Meirinawati and Muchtar (2017) reported nutrient concentration in the waters of Bintan Island (Riau Islands Province, Indonesia) and Selayar Island (South Sulawesi, Indonesia). In Bintan Island waters, the concentrations of nitrate in April and August were 0.051 and 0.026 mg/L, respectively, those of phosphate were 0.005 and 0.016 mg/L, respectively, and those of silicate were 0.266 and 0.057 mg/L, respectively. In Selayar Island, the nitrate, phosphate, and silicate concentrations were 0.080, 0.014, and 0.441 mg/L in May, respectively, and 0.033, 0.005, and 0.188 mg/L in August, respectively (Meirinawati and Afdal 2019). Table 1 is a summary of studies on nutritional dynamics in coastal areas from tropics to subtropics.

2.1 Eutrophication status based on nutrient concentration

Many seawater quality standards have been proposed. For instance, Bricker et al. (1999) categorized seawater quality based on DIN and DIP concentrations as follows: high (DIN ≥ 1 mg/L and DIP ≥ 0.1 mg/L), medium (DIN < 1 mg/L; ≥0.1 mg/L and DIP < 0.1 mg/L; ≥0.01 mg/L), and low (DIN < 0.1 mg/L and DIP < 0.01 mg/L). The ASEAN established the following seawater quality standards for aquatic life: 70 μg/L for ammonia, 60 μg/L for nitrate, 55 μg/L for nitrite, and 15 μg/L and 45 μg/L for phosphate in coastal and estuarine areas, respectively (ASEAN Working Group on Coastal Marine Environment 2008). In another report about coastal waters in southern Caribbean, the water quality was monitored with the thresholds for DIN = 1 μmol/L and PO_4^{3-} = 0.1 μmol/L (Slijkerman et al. 2014).

DIN and DIP could be used to evaluate potential eutrophication in the coastal area (Table 2) (Weidong et al. 1998). The values in Table 2 were obtained from the assessment model developed by Weidong et al. (1998) to determine the eutrophication status of the Xiamen Sea and coastal waters in China. No global standard exists for eutrophication assessment. In the USA, the Assessment of Estuarine Trophic Status was developed and has been applied in European estuaries. The data were collected from a series survey conducted by NOAA (Bricker et al. 2003). USEPA proposed the method National Coastal Assessment Water Quality Index (United States Environmental Protection Agency 2004). However, no standard has been proposed for tropical areas. For instance, in Indonesia, the Indonesian Government regulation (PP No. 2 tahun 2021) is the only stated seawater quality standard. For marine biota, the standard values of total ammonia, phosphate, and nitrate are 0.3, 0.015, and 0.06 mg/L, respectively (Pemerintah Republik Indonesia 2021). Hence, the nutrient level in Table 2 can be used as criteria for eutrophication status in tropical areas (e.g., Indonesia) (Baohong et al. 2016).

Using Table 2, we can classify the nutrient levels in various coastal waters. Waters around the Yangma Island, Cross River Estuary, southern Yellow Sea, Yellow Sea, coastal waters of Madura Strait, Pagametan Bay, and Tambelan and Serasan waters were classified as grade I oligotrophic level. Tagus estuary was grade III eutrophication level. The coastal zone area (North Sea) was grade V, with moderate phosphate limiting potential eutrophication. Jiaozhou Bay, Huanghe (Yellow River) Estuary, Changjiang Estuary, and Jakarta Bay were grade VI with phosphate limiting potential eutrophication.

In addition to DIN and DIP used for eutrophication assessment, DON, DOP, Si, and Chl a are employed for seawater status classification. Lu et al. (2021) used principal component analysis to evaluate the eutrophication status in Maowei Sea and reported that nitrate and dissolved organic nitrogen were the most influential factors for eutrophication.

3. TROPHIC INDEX

Vollenweider et al. (1998) developed a trophic index (TRIX) to characterize the trophic status of coastal ecosystems and suggested its use as an indicator of eutrophication.

TABLE 1. Variation of nutrient concentration (μmol/L) and DIN/DIP ratios in some coastal areas.

Zone	Location	Sampling time	DIN		DIP		DSi		DIP/DIN		Reference
			Range	Mean	Range	Mean	Range	Mean	Range	Mean	
Tropical	Bacanga River Estuary			32.23		26.53				1.21	Sá et al. (2021)
	Coastal waters in Hainan Island	2017	1.07–56.64	7.60±10.71	0.00–2.71	0.24±0.31			7–702	65±81	Zhang et al. (2020)
	Cross River Estuary			1.84±0.72		0.29±0.07		14.26±1.73		6.34	Dan et al. (2019)
	Jakarta Bay (annuals)	2001		20.8		5.1		46.8			Damar et al. (2019)
	Jakarta Bay (annuals)	2007		18.1		4.2		48.3			Damar et al. (2019)
	Jakarta Bay (annuals)	2013		10.9		5.4		45.2			Damar et al. (2019)
	Pagametan Bay	Aug 2014	1.42–17.14	7.85	0–0.97	0.65				12.08	Tammi et al. (2015)
	Lampung Bay			14.3		2.3		39.3		6.22	Damar et al. (2012)
	Semangka Bay			3.5		0.4		28.4		8.75	Damar et al. (2012)
	Tambelan and Serasan waters	Nov 2010	0.78–11.6	2.07	0.02–0.13	0.06	2.03–4.8	3.66	11.2–133.7	40.04	Prayitno and Suherman (2012)
	Jakarta Bay	Feb 2007		41.46		0.21		7.82		197	Nugrahadi et al. (2010)
	Coastal waters of Madura Strait			0.3		0.1		55.4		30	Jennerjahn et al. (2004)
Subtropical	Tagus Estuary	2018	7.3–63.2	31.1	0.5–2.9	1.66	4.5–89.2	38.1		18.7	Rodrigues et al. (2020)
	Coastal waters of the northern Shandong Peninsula	Mar 2016–Nov 2017	0.61–20.77	7.07 ± 3.94	0.01–2.67	0.43±0.27	0.15–23.22	3.88±2.96	0.89–81.6	16.4±12.9	Yang et al. (2020)
	Jiaozhou Bay	2015–2016		16±13.8		0.27±0.2		5.48±3.81		76	Yuan et al. (2018)
	Coastal zone area (North Sea)	Mar 2013		38.47		0.71		16.6		54	Grosse et al. (2017)
	Southern Yellow Sea	2006–2007		5.76		0.25		6		23.7	Wei et al. (2015)
	Yellow Sea	Jun 2009	0.48–18.4	2.4	nd–0.13	0.03	0.87–16.6	4.37	4.5–19.2	14.5±1.4	Jin et al. (2013)
	Huanghe (Yellow River) estuary	2008–2009		307		0.45		114		682	Liu et al. (2012)
	Ebro estuary	1999–2000		15.2		0.11		1.4		138	Falco et al. (2010)
	Changjiang estuary			66.18		0.68		93		97	Liu et al. (2009)
	Mullica River–Great Bay estuarine system	1991–2003		32		0.15				213	Flynn (2008)
	Jiaozhou Bay	Aug 2001		46.1		0.1 ± 0.1		1.4 ± 1		461	Su et al. (2005)

TABLE 2. Nutrient level criteria for eutrophication.

Grade	Nutrient level	DIN (μmol/L)	DIP (μmol/L)	DIN/DIP
I	Oligotrophic level	<14.28	<0.97	8–30
II	Medium-level nutrient	14.28–21.41	0.97–1.45	8–30
III	Eutrophication	>21.41	>1.45	8–30
IV_P	Medium-level nutrient, Phosphate limiting	14.28–21.41		>30
V_P	Phosphate medium limiting potential eutrophication	>21.41		30–60
VI_P	Phosphate limiting potential eutrophication	>21.41		>60
IV_N	Medium-level nutrient, Nitrogen limiting		0.97–1.45	<8
V_N	Nitrogen medium limiting potential eutrophication		>1.45	4–8
VI_N	Nitrogen limiting potential eutrophication		>1.45	<4

TABLE 3. Classification of trophic status based on TRIX value according to Vollenweider et al. (1998)

Grade	TRIX value	Trophic status	Condition
I	0-4	Oligotrophic	Low primary productivity
II	4–5	Mesotrophic	Intermediate primary productivity
III	5–6	Mesotrophic to eutrophic	Intermediate to high primary productivity
IV	6–10	Eutrophic	High primary productivity

Trophic status is dependent on the amount of organic material that is present in the water (Bricker et al. 2008).

TRIX has been tested under oligotrophic to eutrophic conditions (Yang et al. 2020). This index uses four variables that affect eutrophication and is calculated using the following formula (Vollenweider et al. 1998; Primpas and Karydis 2011):

$$TRIX = \frac{\log_{10}(DIN \times DIP \times Chla \times D\%O_2)}{1.2} \quad (1)$$

where DIN, DIP, and *Chla* are in μg/L units, and $D\%O_2$ indicates the percent deviation of oxygen concentration from saturation. The numbers 1.5 and 1.2 are scale coefficients used to settle the lower limit of the index and set the scale range from 0 to 10 (Giovanardi and Vollenweider 2004). The index ranges from 0 to 10 across the following four trophic categories (Table 3): oligotrophic, mesotrophic, mesotrophic to eutrophic, and eutrophic. This range is based on monitoring research in Italian coast and the trophic condition of the NW Adriatic Sea and Northern Tyrrhenian Sea. Values higher than 6 are considered as high primary productivity (Vollenweider et al. 1998).

Some nutrient assessment studies in Indonesia used TRIX as a characterization tool (Table 4; Figure 1). In

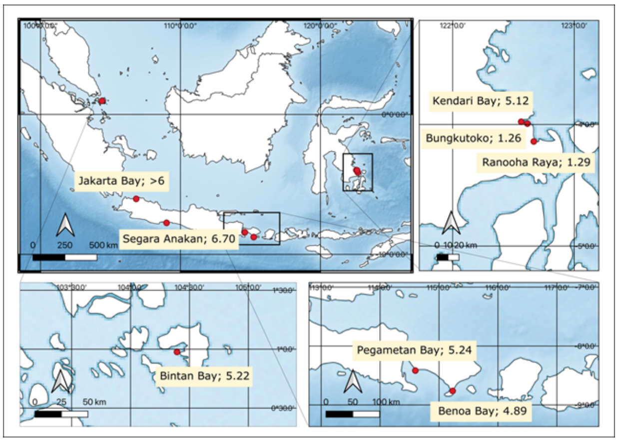


FIGURE 1. Nutrient assessment in several locations in Indonesia using TRIX as indicator.

Kendari Bay (southeast Sulawesi), the TRIX index was 5.12, indicating that the status of the bay was mesotrophic to eutrophic (Irawati 2014). Therefore, the bay required attention because its condition was close to the eutrophic range; with further input of nutrients, its status would reach the high nutrient level (Irawati 2014). In 2016, Kendari Bay was classified as oligotrophic with TRIX below 4. This finding indicated that the condition of the waters in the bay decreased from mesotrophic to oligotrophic (Asriyana and Irawati 2019). Similarly, Bungkutoko Island waters had TRIX value <4 and thus were categorized as oligotrophic (Linus et al. 2017). In Segara Anakan Lagoon, the recent trophic status was eutrophic with TRIX in the range of $6.1 < TRIX \leq 10$. Therefore, these waters can be classified as extremely productive with occasional anoxic conditions (Dewi et al. 2020). Pegametan Bay, Bali was divided into K1 for the region of the bay coast and K2 for the middle and the end of the bay. TRIX significantly differed between these locations with 4.97±0.92 for K1 and 5.51±0.90 for K2. In terms of trophic status, K1 was mesotrophic, and K2 was mesotrophic to eutrophic. K2 had higher TRIX than K1 because the former is a cluster consisting of the middle area and end of the bay and the latter is the inlet to the bay and is the only area containing seaweed cultivation activities (Tammi et al. 2015). In the Bay of Penaga Village, Bintan Island, TRIX was 4.75 at low tide and 5.69 at high tide, indicating that these waters are moderate (mesotrophic) at low tide and mesotrophic to eutrophic at high tide (Sitorus et al. 2020). The waters of Ranooha Raya Village, located in southeast Sulawesi, had TRIX ranging from 1.286 to 1.311 and therefore can be classified as oligotrophic (Sulasri 2021). In Jakarta Bay, Damar et al. (2020) reported an increase in eutrophic area and a decrease in mesotrophic area from 2001 to 2019. The eutrophic area is found in the coastal zone and the center of the bay (Prismayanti et al. 2019).

Suteja et al. (2021) recently updated the trophic status of Benoa Bay and reported a TRIX of 4.9, thus classifying the location as mesotrophic.

4. NUTRIENT RATIOS

The nutrient ratio, also known as the Redfield ratio (N:P:Si = 16:1:1), indicates the stoichiometric nutrient requirements for phytoplankton growth in seawater (Redfield et al. 1963; Egge and Aksnes 1992). This value is calculated from nutrient availability in waters and is used to decide nutrient limitations. The availability of nutrients controls the growth

TABLE 4. TRIX values in coastal areas

Location	Sampling time	TRIX Range	TRIX Mean	Reference
Coastal waters of the northern Shandong Peninsula	Mar. 2016–Nov. 2017	2.64–6.28	4.57	Yang et al. (2020)
Ribeirão Lagoon	2010–2012		6.3±1.0	Cabral and Fonseca (2019)
Tagus Estuary	2018	5–6		Rodrigues et al. (2020)
Kendari Bay	2012	5.6–7.1	5.12	Irawati (2014)
Segara Anakan Lagoon	2019	0.7–9.3	6.7	Dewi et al. (2020)
Pagametan Bay	2014	4.97–5.51	5.24	Tammi et al. (2015)
Bintan Bay	2019	4.75–5.69	5.22	Sitorus et al. (2020)
Bungkutoko Island Waters	2016	1.25–1.28	1.26	Linus et al. (2017)
Waters of Ranooha Raya Village	2020	1.287–1.307	1.29	Sulasri (2021)
Benoa Bay	2017	2.7–9.2	4.89	Suteja et al. (2021)
Jakarta Bay	2017	4–8	>6	Prismayanti et al. (2019)

and composition of the phytoplankton community(Yunev et al. 2007; Wang et al. 2014; Yuan et al. 2018). The nutrient limiting the phytoplankton growth in marine waters is usually DIP but can also be DIN or DSi in some locations (Yuan et al. 2018). Justić et al. (1995) proposed that the limiting nutrient is N at N:P <10 and N:Si <1, silicate at N:Si >1 and P:Si >3, and phosphate at N:P >20–30 and Si:P >20–30.

Yang et al. (2020) determined that the minimum values of DIN, DIP, and DSi at 1, 0.1, and 2 µmol/L, respectively, are required for phytoplankton growth. In places with high N and P concentrations and low Si concentration, such as in Tamsui estuary (Taiwan), a nitrogen range of 19–83.8 µM, and Si:N < 1 (Wu and Chou 2003), the composition of phytoplankton communities will change and result in limited diatoms. Diatoms prefer to grow in the presence of abundant DSi; when DSi is low, diatoms are replaced by dinoflagellates. This situation can also result from P deficiency (Conley et al. 2008). Thus, DSi regulates the composition of phytoplankton (Egge and Aksnes 1992).

High DIN/DIP was reported in Hainan Island water where N concentration was high and P concentration was low, indicating P limitation. The range of DIN/DIP ratio was 7–702 with an average of 65 (Zhang et al. 2019). This environment might influence primary production and phytoplankton distribution in the waters of Hainan Island. Human activities and exchange capacity are important causes of excessive nutrient levels (Zhang et al. 2020).

The molar N/P ratio (DIN/PO_4) increased in most Pearl River Estuary locations because of the increasing DIN and PO_4 concentrations, indicating that PO_4 was the limiting nutrient; as a result, the phytoplankton composition was altered (Niu et al. 2020). In Jiaozhou Bay, the DIP concentration decreased, and the mean DIN/PO_4^{3-} ratio increased with PO_4^{3-} as the limiting nutrient (Yuan et al. 2018). Before 2015, PO_4^{3-} concentration was low, and the limiting nutrient was silicon (Liu et al. 2009; Yuan et al. 2018).

In the central Yellow Sea, the average ratio of DIN/DIP was 14.5±1.4 (Jin et al. 2013). This number is close to the Redfield ratio, indicating that the DIN/DIP ratio was suitable for phytoplankton growth. However, when the season changed and blooms occurred, the DIN/DIP ratios in the euphotic zone (upper 30 m) were lower than the Redfield ratio, indicating nitrogen limitation. The rapid rate of phosphate regeneration increased the phosphate concentration compared with the nitrogen concentration (Jin et al. 2013).

In Changjiang, high ratio values of DIN/DIP and DSi/DIP were reported in the ranges of 66 to 167 and 45 to 122, respectively, and low Si/DIN was observed in the range of 0.5 to 0.9 (Liu et al. 2016). In 1980–2000, DIN ratios to other nutrients were significantly enhanced due to human activities (Liu et al. 2016; Ding et al. 2019). DIN/DIP ratios in the Changjiang River Estuary increased significantly but showed variations in the 2000s (Yuan et al. 2018). In the Pearl River Estuary, the limiting nutrient was nitrogen, and the DIN/Si ratio was low and decreased when salinity increased (Lui and Chen 2011). Meanwhile, in the Huanghe Estuary, the limiting nutrient was phosphorus (Liu et al. 2012).

The DIN/PO_4^{3-} ratio in China waters showed an increasing trend. For example, in 1995–2013, the average DIN/PO_4^{3-} ratios in the Bohai Bay varied from 28 to 111 (Qiao et al. 2017). From 1997–1999 to 2006–2007, this ratio in the southern Yellow Sea increased from 20.7 to 23.7 and reached 97.7 as a maximum value in 2012. The N/P ratio increased gradually from the 1980s and reached 416 in 2015 (Wei et al. 2015). Huanghe waters exhibited seasonal variations with high DIN/PO_4^{3-} ratios varying from 439 to 818 and high Si/PO_4^{3-} ratios varying from 167 to 343. This nutrient enrichment was caused by events that changed water movements and nutrient flux (Liu et al. 2012).

Nitrate was reported as a limiting nutrient in the East China Sea. N:P ratios showed a high correlation with nitrate concentration but a low correlation with phosphate concentration (Kim et al. 2006). The N:P ratio in the area was lower than 16 (the Redfield ratio), indicating that the environment was subject to N deficiency (Kim et al. 2006).

The Si/DIN ratios in the Yellow Sea in all seasons were >1, indicating that Si was more abundant than DIN. The high silicate concentration is related to the acidification in the Changjiang river that enhanced weathering processes (Wei et al. 2015). As a result, diatoms became the prominent species in the phytoplankton community. When the concentration of DSi decreased, the ratio of diatoms in phytoplankton cells increased (Jin et al. 2013). In the Changjiang River Estuary, the mean SiO_3^{2-}/DIN ratio was also reduced by 52% from 2.7 in 2002 to 1.3 in 2006. The limiting nutrient in this area changed from SiO_3^{2-} to DIP. In Changjiang, the Si/DIN ratio ranged from 0.5 to 0.9 (Liu et al. 2016) as reflected by the increased DIN/DIP ratio and the fixed SiO_3^{2-}/DIN ratio (Yuan et al. 2018). A different situation occurred in the south Yellow Sea, in which the SiO_3^{2-}/DIN ratio was preserved at close to 1. The decreased Si/N and Si/P ratios implied that Si was the limiting nutrient (Wei et al. 2015).

In the southeastern Arabian Sea, the N/P ratio ranged from 3.1 to 58 with an average of 18.94 (Rao et al. 2017). The N/P ratios in the south and north regions were 12.2 and 18.7, respectively. The N/P ratio in the south region was lower than in the north, indicating that phosphate was the limiting factor (Rao et al. 2017).

The N/P ratio in Tambelan and Serasan Islands waters ranged from 11.2 to 133.7 (Prayitno and Suherman 2012). Hamzah et al. (2015) found that the N/P and N/Si ratios in Weda Bay range were 3.83–37.99 and 0.12–10.98 with an average N/P ratio of 14.3, and nitrate predominated in these waters.

5. NUTRIENT BUDGET CALCULATION

Nutrient budgets are used to describe nutrient movement in estuary and coastal ecosystems by measuring nutrient input and output (Flynn 2008; Lui and Chen 2011; Dan et al. 2019). Gordon Jr. et al. (1996) proposed a biogeochemical mass–balance box model named land–Ocean Interactions in the coastal zone (LOICZ) to calculate nutrient budgets. LOICZ develops water and dissolved nutrient budgets for coastal waters and defines the biogeochemical processes and nutrient pathways (Gordon Jr. et al. 1996; Flynn 2008; Liu et al. 2009). For the implementation of this model, the framework must be in a steady state and considered a single well-mixed box. Analyzing nutrient budgets to understand how the nutrient cycle impacts the ecosystem is important for coastal area management (Flynn 2008; Swaney et al. 2011).

Many studies were carried out on nutrient budgets in China's coastal waters. For example, Ding et al. (2021) reported a nutrient budget in the Bohai Sea and stated that the nutrient budget depends on the season. The highest nutrient budgets were found in the winter season with DIN, DIP, and DSi allocations of 15.7, 0.6, and 17.1 mmol m^{-2} d^{-1}, respectively. The lowest nutrient budgets were found in the summer season with DIN, DIP, and DSi allocations of 8.7, 0.2, and 12.5 mmol m^{-2} d^{-1}, respectively. In another study on the nutrient budgets in Shandong Peninsula waters, the input was determined to originate from five sources: terrestrial sources, atmospheric deposition, inputs from the Bohai Sea and south Yellow Sea to study area, excretion, and input of sediment. Outputs were obtained from evaporation, sedimentation, and output from the study area to the Bohai and south Yellow Seas (Yang et al. 2020). The net budget of water and dissolved nutrients in Shandong Peninsula waters was quantified as follows:

$$QT + QA - QE + Qin - Qout + \Delta Q = 0 \quad (2)$$

$$QT \times CT(i) + QA \times CA(i) + Qin \times Cin(i) - Qout \times Cout(i) + \Delta M(i) = 0 \quad (3)$$

where Q denotes the mass of water from inputs (+) (T = terrestrial, A = atmospheric, in = input from the Bohai Sea and the South Yellow Sea) and outflows (–) (E = evaporation, out = output to the Bohai Sea and south Yellow Sea; Q is water budget; ΔM is nutrient budget; C is nutrient concentration; (i) is a specific nutrient (DIN, DIP or DSi). The net budgets for DIN, DIP, and DSi were $136.7 \times 10^3, 7.3 \times 10^3$ and $485.5 \times 10^3 mol/km^2yr$, respectively (Yang et al. 2020). Shandong Peninsula is one of the fastest developing areas in Southeast Asia (i.e., Jakarta and Manila). Therefore, the factors influencing the nutrient budgets in this area must be identified.

In Jiaozhou Bay, the annual nutrient budgets of NO_3^-, NH_4^+, PO_4^{3-}, and SiO_3^{2-} were $81.6 \times 10^6, 13.2 \times 10^6, 2.45 \times 10^6$, and 29.9×10^6 mol/year, respectively (Yuan et al. 2018). The inputs were from flux wet and dry deposition, rivers, wastewater, and submarine fresh groundwater discharge. Outputs were from residual flow and mixing flow. According to nutrient budgets, riverine inputs were the main sources of NH_4^+ and DIP, wastewater was the main source of NO_3^-, and Si was notably derived from submarine fresh groundwater discharge (Yuan et al. 2018).

In Cross River Estuary, dissolved nutrient budgets were calculated as the total of the residual flow (V_RC_R) of three river estuaries. DIP was 137 × 10^3 mol/day, DIN was 7,189 × 10^3 mol/day, and DSi was 108,068 × 10^3 mol/day (Dan et al. 2019). In Ebro estuary, the nutrient budgets for DIN, DIP, and DSi were 422.3, 22.4, and 102 tons/year, respectively (Falco et al. 2010).

Nutrient fluxes (ΔY) can be calculated based on water budgets and nutrient concentrations:

$$\Delta Y = \Sigma outflux - \Sigma influx = V_R C_R + V_X C_X - V_Q C_Q - V_P C_P \quad (4)$$

where C_R = residual flow boundary

$$C_R = \frac{C_{system} + C_{ocean}}{2} \quad (5)$$

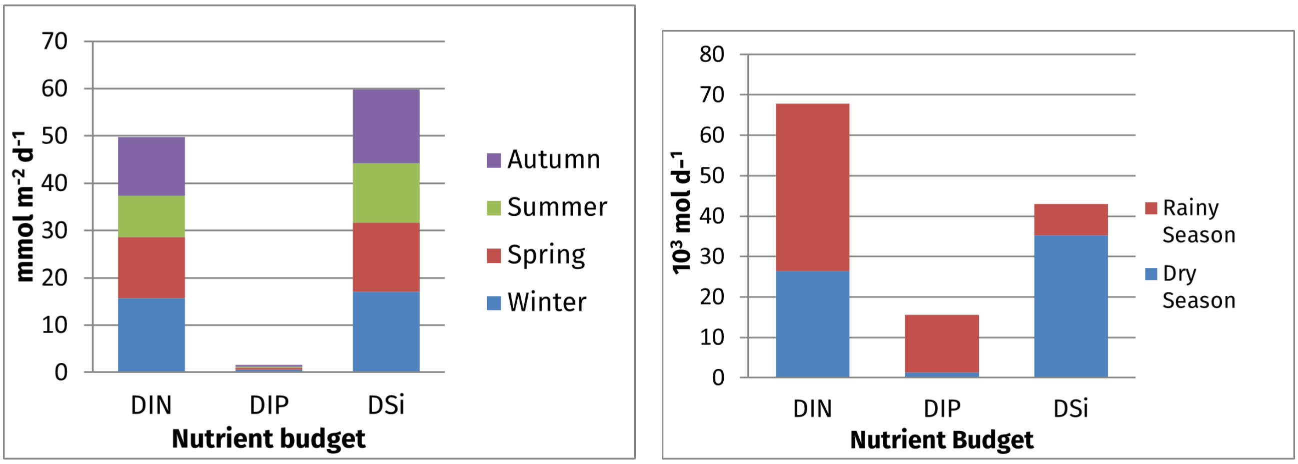
C_X = mixing flow

$$C_X = C_{system} - C_{ocean} \quad (6)$$

C_Q and C_P indicate concentration in river runoff and precipitation. ΔY (–) indicates that the system is a sink, and ΔY (+) shows that the system is a source. Liu et al. (2009) reported that most of the estuaries in China are NO_3^- sources.

In Jakarta Bay, the DIP loads measured by river runoff acted as sinks at -12.09×10^3 mol/day in the dry season and -150×10^3 mol/day in the rainy season (Nugrahadi et al. 2010). DIN budget involves residual outflow and mixing. Residual outflow removed about 34.41×10^3 mol/day in the dry season and 416.37×10^3 mol/day DIN in the rainy season. Mixing added 1044×10^3 mol/day and removed 4006×10^3 mol/day of DIN in the dry and rainy seasons, respectively (Nugrahadi et al. 2010). Jakarta Bay acted as a sink for 176×10^3 and 7237×10^3 mol/day of DIN in the dry and rainy seasons, respectively. DSi budget involves river input, residual outflow, and mixing. Riverine supplies of silicate were about 1464×10^3 and 1667×10^3 mol/day in the dry and rainy seasons, respectively. Residual outflow removed 27.04 mol/day of DSi in the dry season and 94.64×10^3 mol/day in the rainy season, respectively. Meanwhile, mixing removed 47×10^3 mol/day in the dry season and 438×10^3 mol/day in the rainy season (Nugrahadi et al. 2010). The DSi budgets were 1537×10^3 and 2199×10^3 mol/day in the dry and rainy seasons, respectively (Nugrahadi et al. 2010). Overall, the budgeting approach showed that nutrients are subjected to seasonal variability in Jakarta Bay. The temporal variability of nutrient budgets is acquired from the inputs and exchanges of nutrients (Nugrahadi et al. 2010).

As shown in Figure 2, the nutrient budgets in the subtropical zone (Bohai Sea) were lower than those in the tropical zone (Jakarta Bay). Biological processes mainly determine the nutrient budgets in the Bohai Sea. In summer, the nutrient budgets were the lowest because of the highest nutrient uptake by phytoplankton. In addition, the nutri-



(a) (b)

FIGURE 2. Nutrient budgets in (a) Subtropical Zone, Bohai Sea (b) Tropical Zone, Jakarta Bay.

ent input from the river was lower than the nutrient loss used by phytoplankton (Ding et al. 2021). The nutrient budgets in Jakarta Bay were high because of riverine input. Anthropogenic activities mainly influence Jakarta Bay; hence, during the rainy season, the nutrient from the land will be transported to the bay through the river (Nugrahadi et al. 2010). The difference between the two regions was that the nutrient budgets in Bohai Sea involved biological and benthic processes. Meanwhile, in Jakarta Bay, the dominant factor influencing the nutrient budget was riverine input.

6. CONCLUSIONS

Nutrient concentration and composition differ for each of the studied coastal waters and depend on seasonal and temporal factors. Nutrient dynamics are influenced mainly by hydrological and biochemical reactions. Nutrient distribution in waters is dependent on natural and anthropogenic factors that affect nutrient concentration. Nutrient concentration can also determine the eutrophication status of waters and is one of the parameters required for calculating TRIX. Nutrient ratios can decide limiting factors for phytoplankton growth and control phytoplankton composition. The movement of nutrients from land to coastal waters can be measured by nutrient budgets using the LOICZ model, which can explain biogeochemical processes and nutrient fluxes to the oceans. A decrease in water quality has recently occurred because of the increasing anthropogenic activities. Therefore, serious efforts are needed to overcome this problem. For instance, long-term monitoring data are important in evaluating nutrient enrichment and should be updated regularly. By using the nutrient concentrations in a coastal area as the basis, we can determine the waters' quality and status and help manage and maintain the waters. We hope that in the future, Indonesia can collect primary data for water quality in the whole area to identify the condition of the waters and establish standards for eutrophication.

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AUTHORS' CONTRIBUTIONS

Both authors are main contributors. HM provided conceptualization, collected the articles, and prepared the initial draft of the manuscript. AJW was responsible for conceptualization, review and validation, and manuscript editing and proofreading.

COMPETING INTERESTS

The authors declare no competing interests.

REFERENCES

ASEAN Working Group on Coastal Marine Environment. 2008. ASEAN Marine Water Quality: Management Guidelines and Monitoring Manual.

Asriyana, Irawati N. 2019. Assessment of the trophic status in kendari bay, indonesia: A case study. AACL Bioflux. 12:650–663.

Baohong C, Muchtar M, Tingting F, Hongzhe C, Jigang W, Kaiwen Z, Jianguo D, Hui L, Bin C. 2016. A baseline study of coastal water quality in the lembeh strait of north sulawesi , indonesia , in 2013. Marine Pollution Bulletin. 104:364–370. doi:10.1016/j.marpolbul.2016.01.020. http://dx.doi.org/10.1016/j.marpolbul.2016.01.020.

Bricker S, Ferreira J, Simas T. 2003. An integrated methodology for assessment of estuarine trophic status. Ecological Modelling. 169:39–60. doi:10.1016/S0304-3800(03)00199-6. https://linkinghub.elsevier.com/retrieve/pii/S0304380003001996.

Bricker SB, Clement CG, Pirhalla DE, Orlando SP, Farrow DRG. 1999. National estuarine eutrophication assessment: Effects of nutrient enrichment in the nation's estuaries.

Bricker SB, Longstaff B, Dennison W, Jones A, Boicourt K, Wicks C, Woerner J. 2008. Effects of nutrient enrichment in the nation's estuaries: A decade of change. Harmful Algae. 8:21–32. doi:10.1016/j.hal.2008.08.028.

Cabral A, Fonseca A. 2019. Coupled effects of anthropogenic nutrient sources and meteo-oceanographic events in the trophic state of a subtropical estuarine system. Estuarine, Coastal and Shelf Science. 225. doi:10.1016/j.ecss.2019.05.010.

Chen Y, Cheng W, Zhang H, Qiao J, Liu J, Shi Z, Gong W. 2019. Evaluation of the total maximum allocated load of dissolved inorganic nitrogen using a watershed–coastal ocean coupled model. Science of the Total Environment. 673:734–749. doi:10.1016/j.scitotenv.2019.04.036.

Conley DJ, Humborg C, Smedberg E, Rahm L, Papush L, Åsa Danielsson, Clarke A, Pastuszak M, Aigars J, Ciuffa D, Mörth CM. 2008. Past, present and future state of the biogeochemical si cycle in the baltic sea. Journal of Marine Systems. 73:338–346. doi:10.1016/j.jmarsys.2007.10.016.

Conley DJ, Paerl HW, Howarth RW, Boesch DF, Seitzinger SP, Havens KE, Lancelot C, Likens GE. 2009. Controlling eutrophication: Nitrogen and phosphorus. Science. 323:1014–1015. doi:10.1126/science.1167755. https://www.science.org/doi/10.1126/science.1167755.

Costa LS, Huszar VLM, Ovalle AR. 2009. Phytoplankton functional groups in a tropical estuary: Hydrological control and nutrient limitation. Estuaries and Coasts. 32:508–521. doi:10.1007/s12237-009-9142-3.

Damar A, Colijn F, Hesse KJ, Adrianto L, Yonvitner, Fahrudin A, Kurniawan F, Prismayanti AD, Rahayu SM, Rudianto BY, Ramli A. 2020. Phytoplankton biomass dynamics in tropical coastal waters of jakarta bay, indonesia in the period between 2001 and 2019. Journal of Marine Science and Engineering. 8:1–17. doi:10.3390/jmse8090674.

Damar A, Colijn F, Hesse KJ, Wardiatno Y. 2012. The eutrophication states of jakarta, lampung and semangka bays: Nutrient and phytoplankton dynamics in indonesian tropical waters.pdf. Journal of Tropical Biology and Conservation. 9:61–81.

Damar A, j Hesse K, Colijn F, Vitner Y. 2019. The eutrophication states of the indonesian sea large marine ecosystem : Jakarta bay, 2001-2013. Deep-Sea Research Part II. doi:10.1016/j.dsr2.2019.05.012. https://doi.org/10.1016/j.dsr2.2019.05.012.

Dan SF, Liu SM, Udoh EC, Ding S. 2019. Nutrient biogeochemistry in the cross river estuary system and adjacent gulf of guinea, south east nigeria (west africa). Continental Shelf Research. 179:1–17. doi:10.1016/j.csr.2019.04.001.

Dewi R, Harisam T, Hidayat RR, Endrawati H, Rahayu NL, Seprianto A. 2020. Penilaian Status Trofik Laguna Segara Anakan pada Musim Timur dengan Aplikasi Indeks TRIX. Jurnal Harpodon Borneo. 13(1):1–9. doi:10.35334/harpodon.v13i1.1400. http://jurnal.borneo.ac.id/index.php/harpodon/article/view/1400.

Ding S, Chen P, Liu S, Zhang G, Zhang J, Dan SF. 2019. Nutrient dynamics in the changjiang and retention effect in the three gorges reservoir. Journal of Hydrology. 574:96–109. doi:10.1016/j.jhydrol.2019.04.034.

Ding X, Guo X, Gao H, Gao J, Shi J, Yu X, Wu Z. 2021. Seasonal variations of nutrient concentrations and their ratios in the central bohai sea. Science of the Total Environment. 799. doi:10.1016/j.scitotenv.2021.149416.

Egge JK, Aksnes DL. 1992. Silicate as regulating nutrient in phytoplankton competition. Marine Ecology Progress Series. 83:281–289. doi:10.3354/meps083281.

Falco S, Niencheski LF, Rodilla M, Romero I, del Río JG, Sierra JP, Mösso C. 2010. Nutrient flux and budget in the ebro estuary. Estuarine, Coastal and Shelf Science. 87:92–102. doi:10.1016/j.ecss.2009.12.020.

Flynn AM. 2008. Organic matter and nutrient cycling in a coastal plain estuary: Carbon, nitrogen, and phosphorus distributions, budgets, and fluxes. Journal of Coastal Research. 10055:76–94. doi:10.2112/si55-010.1.

Giovanardi F, Vollenweider RA. 2004. Trophic conditions of marine coastal waters: Experience in applying the trophic index trix to two areas of the adriatic and tyrrhenian seas. Journal of Limnology. 63:199–218. doi:10.4081/jlimnol.2004.199.

Glibert PM, Mayorga E, Seitzinger S. 2008. Prorocentrum minimum tracks anthropogenic nitrogen and phosphorus inputs on a global basis: Application of spatially explicit nutrient export models. Harmful Algae. 8:33–38. doi:10.1016/j.hal.2008.08.023.

Gordon Jr DC, Boudreau PR, Mann KH, Ong JE, Silvert WL, Smith SV, Wattayakorn G, Wulff F, Yanagi T, Gordon JDC. 1996. Loicz biogeochemical modelling guidelines - loicz reports and studies no.5. LOICZ Core Project:36.

Grosse J, van Breugel P, Brussaard CPD, Boschker HTS. 2017. A biosynthesis view on nutrient stress in coastal phytoplankton. Limnology and Oceanography. 62:490–506. doi:10.1002/lno.10439.

Hamzah F, Basit A, Triyulianti I. 2015. Pola sebaran vertikal nutrien pada musim peralihan di teluk weda, maluku utara. Jurnal Ilmu dan Teknologi Kelautan Tropis. 7:415–431. doi:10.13841/j.cnki.jxsj.2013.01.021. http://library.gpntb.ru/cgi-bin/irbis64r/62/cgiirbis_64.exe?C21COM=S&I21DBN=RSK&P21DBN=RSK&S21FMT=fullwebr&Z21ID=&S21STN=1&S21REF=10&Z21MFN=856891.

Howarth RW. 2008. Coastal nitrogen pollution: A review of sources and trends globally and regionally. Harmful Algae. 8:14–20. doi:10.1016/j.hal.2008.08.015. https://linkinghub.elsevier.com/retrieve/pii/S1568988308001078.

Ikhsani IY, Abdul MS, Lekalette JD. 2016. Phosphate and nitrate distribution in inner ambon bay during northwest and southeast monsoon. Widyariset. 2:86. doi:10.14203/widyariset.2.2.2016.86-95. http://widyariset.pusbindiklat.lipi.go.id/index.php/widyariset/article/view/559.

Irawati N. 2014. Pendugaan kesuburan perairan berdasarkan sebaran nutrien dan klorofil-a di teluk kendari sulawesi tenggara. Jurnal Ilmu Perikanan dan Sumberdaya Perairan:193–200.

Jennerjahn T, Ittekkot V, Klöpper S, Adi S, Nugroho SP, Sudiana N, Yusmal A, Prihartanto, Gaye-Haake B. 2004. Biogeochemistry of a tropical river affected by human activities in its catchment: Brantas river estuary and coastal waters of madura strait, java, indonesia. Estuarine, Coastal and Shelf Science. 60:503–514. doi:10.1016/j.ecss.2004.02.008.

Jickells TD, Andrews JE, Parkes DJ, Suratman S, Aziz AA, Hee YY. 2014. Nutrient transport through estuaries: The importance of the estuarine geography. Estuarine, Coastal and Shelf Science. 150:215–229. doi:10.1016/j.ecss.2014.03.014.

Jin J, Liu SM, Ren JL, Liu CG, Zhang J, Zhang GL, Huang DJ. 2013. Nutrient dynamics and coupling with phytoplankton species composition during the spring blooms in the yellow sea. Deep-Sea Research Part II: Topical Studies in Oceanography. 97:16–32. doi:10.1016/j.dsr2.2013.05.002. http://dx.doi.org/10.1016/j.dsr2.2013.05.002.

Justić D, Rabalais NN, Turner RE, Dortch Q. 1995. Changes in nutrient structure of river-dominated coastal waters: Stoichiometric nutrient balance and its consequences. Estuarine, Coastal and Shelf Science. 40:339–356. doi:10.1016/S0272-7714(05)80014-9.

Kim D, Shim J, Yoo S. 2006. Seasonal variations in nutrients

and chlorophyll-a concentrations in the northern east china sea. Ocean Science Journal. 41:125–137.
Li K, He J, Li J, Guo Q, Liang S, Li Y, Wang X. 2018. Linking water quality with the total pollutant load control management for nitrogen in jiaozhou bay, china. Ecological Indicators. 85:57–66. doi:10.1016/j.ecolind.2017.10.019.
Linus Y, Salwiyah, Irawati N. 2017. Status kesuburan perairan berdasarkan kandungan klorofil- a di perairan bungkutoko kota kendari. Manajemen Sumber Daya Perairan. 2:101–111.
Liu SM, Hong GH, Zhang J, Ye XW, Jiang XL. 2009. Nutrient budgets for large chinese estuaries. Biogeosciences. 6:2245–2263. doi:10.5194/bg-6-2245-2009.
Liu SM, Li LW, Zhang GL, Liu Z, Yu Z, Ren JL. 2012. Impacts of human activities on nutrient transports in the huanghe (yellow river) estuary. Journal of Hydrology. 430-431:103–110. doi:10.1016/j.jhydrol.2012.02.005.
Liu SM, Qi XH, Li X, Ye HR, Wu Y, Ren JL, Zhang J, Xu WY. 2016. Nutrient dynamics from the changjiang (yangtze river) estuary to the east china sea. Journal of Marine Systems. 154:15–27. doi:10.1016/j.jmarsys.2015.05.010.
Lu D, Huang X, Yang B, Dan SF, Kang Z, Zhou J, Lao Y, Zhong Q, Wu H. 2021. Composition and distributions of nitrogen and phosphorus and assessment of eutrophication status in the maowei sea. Journal of Ocean University of China. 20:361–371. doi:10.1007/s11802-021-4557-y. http://link.springer.com/10.1007/s11802-021-4557-y.
Lu D, Yang N, Liang S, Li K, Wang X. 2016. Comparison of land-based sources with ambient estuarine concentrations of total dissolved nitrogen in jiaozhou bay (china). Estuarine, Coastal and Shelf Science. 180:82–90. doi:10.1016/j.ecss.2016.06.032.
Lui HK, Chen CTA. 2011. Shifts in limiting nutrients in an estuary caused by mixing and biological activity. Limnology and Oceanography. 56:989–998. doi:10.4319/lo.2011.56.3.0989.
Meirinawati H, Afdal. 2019. Distribusi spasiotemporal klorofil-a dan nutrien di kepulauan selayar. Ikatan Sarjana Oseanologi Indonesia.
Meirinawati H, Muchtar M. 2017. Fluktuasi nitrat, fosfat dan silikat di perairan pulau bintan. Jurnal Segara. 13:141–148. doi:10.15578/segara.v13i3.6493. http://ejournal-balitbang.kkp.go.id/index.php/segara/article/view/6493.
Niu L, Luo X, Hu S, Liu F, Cai H, Ren L, Ou S, Zeng D, Yang Q. 2020. Impact of anthropogenic forcing on the environmental controls of phytoplankton dynamics between 1974 and 2017 in the pearl river estuary, china. Ecological Indicators. 116. doi:10.1016/j.ecolind.2020.106484.
Nugrahadi MS, Yanagi T, Tejakusuma IG, Adi S, Darmawan RA. 2010. Seasonal variations of nutrient budgets in jakarta bay, indonesia. Marine Research in Indonesia. 35:9–20. doi:10.14203/mri.v35i1.7.
Paytan A, McLaughlin K. 2007. The oceanic phosphorus cycle. Chemical Reviews. 107:563–576. doi:10.1021/cr0503613. https://pubs.acs.org/doi/10.1021/cr0503613.
Pemerintah Republik Indonesia. 2021. Peraturan pemerintah (pp) tentang penyelenggaraan perlindungan dan pengelolaan lingkungan hidup. https://peraturan.bpk.go.id/Home/Details/161852/pp-no-22-tahun-2021.
Prayitno HB, Suherman. 2012. Hubungan antara rasio n/p dan konsentrasi silikat di perairan kepulauan tambelan dan kepulauan serasan. Jurnal Segara. 8:19–26.
Primpas I, Karydis M. 2011. Scaling the trophic index (trix) in oligotrophic marine environments. Environmental Monitoring and Assessment. 178:257–269. doi:10.1007/s10661-010-1687-x.
Prismayanti AD, Damar A, Pratiwi NTM. 2019. Distributions of dissolved inorganic nitrogen to estimate trophic state in jakarta bay. IOP Conference Series: Earth and Environmental Science. 241. doi:10.1088/1755-1315/241/1/012023.
Putri MRA, Hartati ST, Satria F. 2017. Kematian massal ikan dan sebaran parameter kualitas air di teluk jakarta. BAWAL Widya Riset Perikanan Tangkap. 8:77. doi:10.15578/bawal.8.2.2016.77-90. http://ejournal-balitbang.kkp.go.id/index.php/bawal/article/view/1381.
Qiao Y, Feng J, Cui S, Zhu L. 2017. Long-term changes in nutrients, chlorophyll a and their relationships in a semi-enclosed eutrophic ecosystem, bohai bay, china. Marine Pollution Bulletin. 117:222–228. doi:10.1016/j.marpolbul.2017.02.002.
Rao GD, Kanuri VV, Kumaraswami M, Ezhilarasan P, Rao V, Patra S, Dash S, Peter M, Rao VR, Ramu K. 2017. Dissolved nutrient dynamics along the southwest coastal waters of india during northeast monsoon: a case study. Chemistry and Ecology. 33:229–246. doi:10.1080/02757540.2017.1287903. https://www.tandfonline.com/doi/full/10.1080/02757540.2017.1287903.
Redfield AC, Ketchum BH, Richards FA. 1963. The Influence of Organism on The Composition of Sea Water. Wiley Interscience.
Rodrigues M, Cravo A, Freire P, Rosa A, Santos D. 2020. Temporal assessment of the water quality along an urban estuary (tagus estuary, portugal). Marine Chemistry. 223. doi:10.1016/j.marchem.2020.103824.
Santoso AD. 2006. Kualitas nutrien perairan teluk hurun, lampung. Jurnal Teknologi Lingkingan. 7:140–144. doi:10.29122/jtl.v7i2.375. https://ejurnal.bppt.go.id/index.php/JTL/article/view/375.
Sitorus T, Apriadi T, Melani WR. 2020. Tingkat kesuburan perairan di teluk desa penaga kecamatan teluk bintan kabupaten bintan. Jurnal Manajemen Riset dan Teknologi Universitas Karimun. 8:28–33. doi:10.51742/ojsm.v2i1.85.
Slijkerman DME, León RD, Vries PD. 2014. A baseline water quality assessment of the coastal reefs of bonaire , southern caribbean. Marine Pollution Bulletin. 86:523–529. doi:10.1016/j.marpolbul.2014.06.054. http://dx.doi.org/10.1016/j.marpolbul.2014.06.054.
Soetaert K, Middelburg JJ, Heip C, Meire P, Damme SV, Maris T. 2006. Long-term change in dissolved inorganic nutrients in the heterotrophic scheldt estuary (belgium, the netherlands). Limnology and Oceanography. 51:409–423. doi:10.4319/lo.2006.51.1_part_2.0409.
Su ML, Zhang J, Hong TC, Guo SZ. 2005. Factors influencing nutrient dynamics in the eutrophic jiaozhou bay, north china. Progress in Oceanography. 66:66–85. doi:10.1016/j.pocean.2005.03.009.
Sulasri S. 2021. Kesuburan perairan berdasarkan tropik indeks di perairan desa ranooha raya kecamatan moramo kabupaten konawe selatan [water fertility based on the trophic index in the waters of ranooha raya village , moramo district , south konawe regency] perairan des. 6:71–82.
Suteja Y, Dirgayusa IGNP, Afdal, Cordova MR, Rachman A, Rintaka WE, Takarina ND, Putri WAE, Isnaini, Purwiyanto AIS. 2021. Identification of potentially harmful

microalgal species and eutrophication status update in benoa bay, bali, indonesia. Ocean and Coastal Management. 210. doi:10.1016/j.ocecoaman.2021.105698.

Swaney D, Smith S, Wulff F. 2011. The loicz biogeochemical modeling protocol and its application to estuarine ecosystems. doi:10.1016/B978-0-12-374711-2.00907-4. https://linkinghub.elsevier.com/retrieve/pii/B9780123747112009074.

Sá A, Cutrim MVJ, Costa DS, Cavalcanti LF, Ferreira FS, Oliveira ALL, Serejo JHF. 2021. Algal blooms and trophic state in a tropical estuary blocked by a dam (northeastern brazil). Ocean and Coastal Research. 69. doi:10.1590/2675-2824069.20-006akddss. http://www.scielo.br/scielo.php?script=sci_arttext&pid=S2675-28242021000100306&tlng=en.

Tammi T, Pratiwi NTM, Radiarta IN. 2015. Aplikasi analisis klaster dan indeks trix untuk mengkaji variabilitas status trofik di teluk pegametan, singaraja, bali. Jurnal Riset Akuakultur. 10:271. doi:10.15578/jra.10.2.2015.271-281.

United States Environmental Protection Agency. 2004. National Coastal Condition Report II.

Vollenweider RA, Giovanardi F, Montanari G, Rinaldi A. 1998. Characterization of the trophic conditions of marine coastal waters with special reference to the nw adriatic sea: Proposal for a trophic scale, turbidity and generalized water quality index. Environmetrics. 9:329–357. doi:10.1002/(SICI)1099-095X(199805/06)9:3<329::AID-ENV308>3.0.CO;2-9.

Wang F, Wang B, Liu CQ, Liu X, Gao Y, Zhang J, Li S. 2014. Changes in nutrient ratios and phytoplankton community structure caused by hydropower development in the maotiao river, china. Environmental Geochemistry and Health. 36:595–603. doi:10.1007/s10653-013-9583-2.

Wei Q, Yao Q, Wang B, Wang H, Yu Z. 2015. Long-term variation of nutrients in the southern yellow sea. Continental Shelf Research. 111:184–196. doi:10.1016/j.csr.2015.08.003.

Weidong G, Xiaoming Z, Yiping Y, Minghui H. 1998. Potential eutrophication assessment for chinese coastal waters. Journal of Oceanography in Taiwan Starit. 17:64–70.

Wu JT, Chou TL. 2003. Silicate as the limiting nutrient for phytoplankton in a subtropical eutrophic estuary of taiwan. Estuarine, Coastal and Shelf Science. 58:155–162. doi:10.1016/S0272-7714(03)00070-2. https://linkinghub.elsevier.com/retrieve/pii/S0272771403000702.

Yang B, Gao X, Zhao J, Lu Y, Gao T. 2020. Biogeochemistry of dissolved inorganic nutrients in an oligotrophic coastal mariculture region of the northern shandong peninsula, north yellow sea. Marine Pollution Bulletin. 150:110693. doi:10.1016/j.marpolbul.2019.110693. https://linkinghub.elsevier.com/retrieve/pii/S0025326X19308495.

Yuan H, Song J, Xing J, Li X, Li N, Duan L, Qu B, Wang Q. 2018. Spatial and seasonal variations, partitioning and fluxes of dissolved and particulate nutrients in jiaozhou bay. Continental Shelf Research. 171:140–149. doi:10.1016/j.csr.2018.11.004.

Yunev OA, Carstensen J, Moncheva S, Khaliulin A, Ærtebjerg G, Nixon S. 2007. Nutrient and phytoplankton trends on the western black sea shelf in response to cultural eutrophication and climate changes. Estuarine, Coastal and Shelf Science. 74:63–76. doi:10.1016/j.ecss.2007.03.030.

Zhang JB, Zhang P, Dai PD, Lai JY, Chen Y. 2019. Spatiotemporal distributions of dip and the eutrophication in hainan island adjacent coastal water. Zhongguo Huanjing Kexue/China Environmental Science. 39:2541–2548.

Zhang P, Ruan H, Dai P, Zhao L, Zhang J. 2020. Spatiotemporal river flux and composition of nutrients affecting adjacent coastal water quality in hainan island, china. Journal of Hydrology. 591:125293. doi:10.1016/j.jhydrol.2020.125293. https://linkinghub.elsevier.com/retrieve/pii/S0022169420307538.