COMPARATIVE ASSESSMENT OF WATER QUALITY AND TROPHIC LEVEL INDICES IN SUMBERKIMA COASTAL WATERS, BULELENG, PROVINCE OF BALI, INDONESIA

Iis TRIYULIANTI [1*], Eghbert Elvan AMPOU [2], Dessy BERLIANTY [3], Yoke Hany RESTIANGSIH [3] & Vivi Eka INDRAYANI [4]

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ABSTRACT

The assessment of water quality in this study utilized the Water Quality Index (WQI) and Trophic State Indexes (TSI and TRIX) values as crucial components of information required for managing aquatic resources. The primary aim of this study was to compare the evaluation of water quality in the coastal waters of Sumberkima, Buleleng, Province of Bali, using the performance of WQI, TSI, and TRIX values. The WQI, TSI, and TRIX values were derived from measurements of dissolved oxygen (DO), nutrient levels, and chlorophyll-a (ChA), pH, temperature, salinity, and turbidity. Water samples were collected from the surface waters at 37 physical stations and 18 chemical and biological stations. The WQI ranged from 80.00 to 96.60 with mean value was 89.44 ± 3.66 revealed the water quality was good to excellent. The TSI and TRIX values for assessing trophic level in marine coastal waters of Sumberkima ranged from 12.76 – 65.13 with mean value was 30.73 ± 13.96 (TSI) and (4.41 ± 0.69) for TRIX values across all monitoring stations. The comparative indices of trophic level revealed that the coastal waters of Sumberkima were categorized as oligotrophic, mesotrophic, and eutrophic according to TSI values, while TRIX had four (4) classes of trophic level. Furthermore, TRIX values showed a stronger correlation with WQI (R^2= 0.3418) than TSI (R^2 = 0.006). The findings of this study suggest that the TRIX value possesses a more comprehensive and strong trophic classification to characterize water quality. This study addresses a critical research gap in the identification of trophic levels by integrating physical, chemical, and biological assessments of water quality parameters.

Keywords: *Water quality index (WQI); Trophic state index (TSI); Trophic index (TRIX); Sumberkima coastal waters; Spatial analysis.*

1. INTRODUCTION

The coastal waters of Sumberkima Village are an area in the northern waters of Bali Province, which has a unique landscape and supports diverse marine life that expands from west to east and has been utilized by the community for various fishery activities, catch and farming, and ecotourism (Ampou et al., 2023; Irawan et al., 2023; Nurjayanti et al., 2023). According to Rodrigues-Filho et al. (2023), coastal waters are dynamic ecosystems that play an essential role in maintaining biodiversity, creating resources, and driving economic activity. However, these ecosystems are increasingly threatened by human activities, including pollution from land-based sources, agricultural runoff, and industrial discharge, all of which may dramatically affect water quality and ecological balance (Sahavacharin et al., 2022).

[1*] *Research Center for Deep Sea, National Research and Innovation Agency (BRIN), Jakarta, Indonesia; Corresponding author iist001@brin.go.id (IT)*

[2] *Reseach Center for Biota Systems, National Research and Innovation Agency (BRIN), Bogor-West Java, Indonesia; eghb001@brin.go.id (EEA)*

[3] *Research Center for Oceanology, National Research and Innovation Agency (BRIN), Jakarta, Indonesia; dess011@brin.go.id (DB); yoke002@brin.go.id (YHR)*

[4] *Lombok Marine Aquaculture Center, Ministry of Marine and Fisheries of the Republic of Indonesia, Lombok, Indonesia; vivi.indrayani@kkp.go.id (VEI).*

Human stressors in coastal areas lead to a decline in water quality and biodiversity, the destruction of essential ecosystems, and a general deterioration in the residents' quality of life (Herrera-Silveira & Morales-Ojeda, 2009).

The water quality information is required because the effectiveness of marine aquaculture is strongly linked to the quality of the water used at the aquaculture site (Boyd et al., 2017). The increased use of marine space and coastal areas has provided ecological pressure that will decrease the health of the aquatic environment (Chen & Chen, 2007; Drira et al., 2017; Neumann et al., 2017). The increasing environmental degradation caused by development highlights the critical need for initial ecological assessments to determine baseline conditions, facilitating sustainable development (Reyers & Selig, 2020). The changes in water quality conditions resulting from space utilization include physical, chemical, and nutritional factors, which may adversely affect the development of cultured organisms or lead to mortality, eventually resulting in diminished output (Reid et al., 2019). The preservation of water quality and the evaluation of trophic status are critical for ensuring the sustainability of these valuable resources and the livelihoods that depend upon them (Triyulianti et al., 2021).

Evaluations are used to determine suitable management strategies and evaluate their effectiveness over time. An index that provides a simple screening tool to categorize different water bodies based on their trophic condition would be valuable. Evaluations are crucial for assessing the health of aquatic ecosystems and informing suitable conservation strategies, including disaster mitigation in urban settings (Gandaseca, 2011; Yusuf et al., 2025). Nevertheless, more comprehensive studies into water quality are required in coastal areas, where the levels of contaminants (ecological pressure) are frequently higher than those of the open sea.

A simple index could be derived from frequently measured metrics or effectively identify water bodies that are likely to be problematic or non-problematic in terms of eutrophication (O'Boyle et al., 2013). Consequently, water quality indices and risk evaluation can be used to analyze water quality in Sumberkima, a coastal area in northern Bali, and detect possible human and ecological health risks. Water quality indices offer a useful method for assessing the overall water quality by integrating various parameters into a single value. Water quality evaluations are useful in identifying and evaluating the possible hazards that pollutants pose to human and ecological health (Shaaban, 2022; Zotou et al., 2018).

The water quality index (WQI) is the most useful technique for analyzing and controlling water quality information (Radfard et al., 2019; Yousefi et al., 2019). The WQI is widely used to evaluate water quality due to its effortless form compared to physical-processed or hydrological models (Benaissa et al., 2022, 2023; Yan et al., 2022). The WQI is an effective method for evaluating the overall water quality by integrating various parameters into a single score. The scores describe the results of the risk assessments to assist in the identification and evaluation of potential risks that waste products may pose to human and ecosystem health (Shaaban, 2022; Zotou et al., 2018). Therefore, analyzing and evaluating the coastal water quality in Sumberkima coastal waters is important for managing the marine environment and enhancing water quality. Trophic State Index (TSI) and Trophic Index (TRIX) were determined with a comprehensive method that integrates ChA, DO saturation, nitrogen, and phosphorus to provide a holistic assessment of marine water productivity and marine health (Peng, 2015; Triyulianti et al., 2021).

Dissolved oxygen is a basic component of aquatic organisms, and its existence regulates several biological and chemical processes. Oxygen dissolved in the water column is a product of biological processes that directly affect aquatic life, especially aerobic respiration, growth, and reproduction (Diaz & Breitburg, 2009). In addition, nutrients in the form of inorganic nitrogen and phosphorus compounds act as vital nutrients for marine flora and fauna. Nitrogen and phosphorus enrichment is the principal eutrophication catalyst in numerous coastal habitats (Howarth & Marino, 2006).

This research represents an essential to environmental monitoring, aimed at collecting primary data that could be used to develop scientific knowledge. The main objectives of this study are (1) to evaluate the characteristics of hydro-oceanographic and water quality conditions of coastal waters in Sumberkima, Buleleng, Bali Province, Indonesia and (2) to identify and evaluate the WQI and the

Trophic State level in coastal waters of Sumberkima Village, Buleleng, Bali using TSI and TRIX indices. The water quality indicates the water enrichment level, which subsequently increases the water productivity. These indices have an efficient approach to assessing the overall water quality by integrating many parameters into a single score. The findings of this research are intended to inform the selection of marine biogeochemistry and physical oceanography parameters specifically designed to determine the productivity of tropical marine ecosystems.

2. STUDY AREA

The research was conducted on the coastal waters of Sumberkima Village, which is located at 8°S latitude and 114°E longitude (**Fig. 1**). The research location is Sumberkima Coastal Waters, Gerokgak Subdistrict, Buleleng Regency, Bali Province. The coastal waters of Sumberkima form a bay that is quite sheltered by Gili Putih sand dunes, specifically at the east site. Data collection was undertaken in April 2021.

The water quality parameters were measured at 37 stations scattered from west to east (**Fig. 1**). The station grouping is based on the coastal waters used. The selected station points are representatives of the existing land use activities in coastal waters, such as intensive marine aquaculture (fish enlargement activities in floating net cages) with its surrounding landscape as well as the all along seaside hatchery farms in the west site (St. 1, 2, 3, 4, 5, 7, 8, 9, 10, 11, 13, 15, 20, 21, 22, 31, 34, 35, 36, 37), attractive destinations of coastal tourism (coral reefs, seagrass and mangroves) and Pegametan Bay in the east site (St. 6, 12,14, 16, 17, 18, 19, 23, 24, 25, 26, 27, 28, 29, 30, 32, 33) as mentioned in corresponding table. The sampling locations represent spatial differences in the ecological characteristics of study site and documented a limited number of water quality parameters. The water quality measurement at 37 stations used the Water Quality Checker (WQC) for in situ measurement at the surface layer consisting of sea surface temperature (SST), sea surface salinity (SSS), surface current (SC), turbidity, and pH.

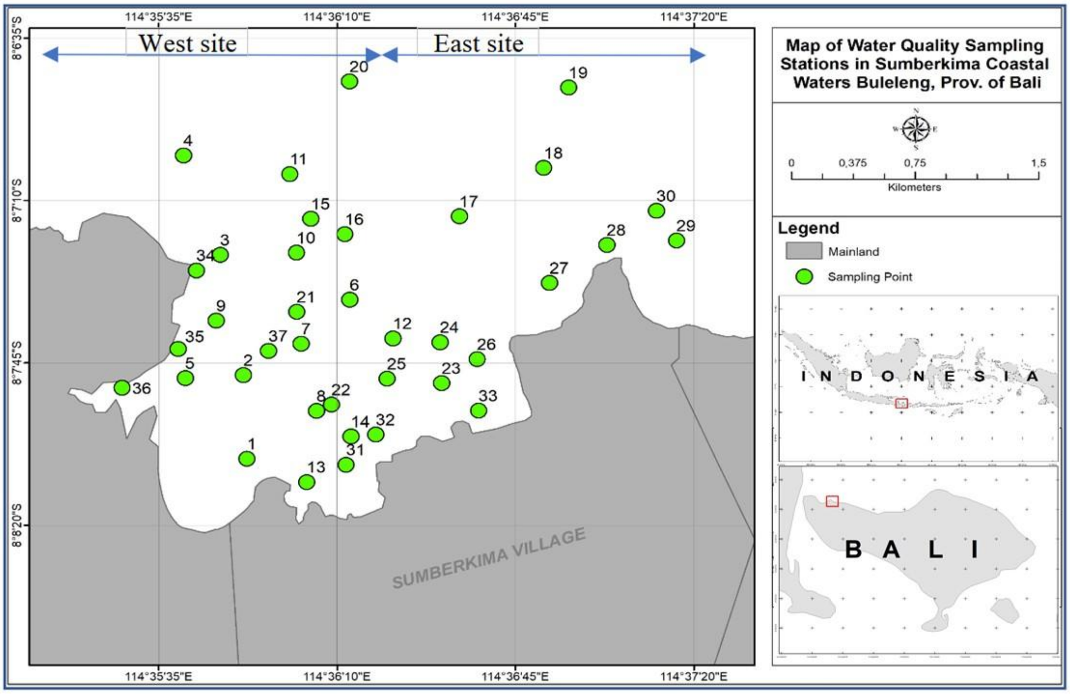

Fig. 1. Research stations (green dots with number) in the Sumberkima Coastal Waters, Indonesia.

3. DATA AND METHODS

3.1. Sampling method and water quality parameters

Water samples were taken using a Van Dorn water sampler to measure the concentration of Dissolved Oxygen (DO), Nutrients (Nitrate, Nitrite, Ammonia, Phosphate) and Chlorophyll-a (ChA) at 18 stations. The selected stations represented the west site (St. 1, 2, 3, 4, 5, 7, 8, 9, 10, 11 and 15) and the east site (St. 6, 12, 14, 16, 17, and 18). The water sample was placed in a bottle and transferred to the Laboratory of Water Quality in the Institute for Marine Research and Observation (IMRO) in Perancak, Bali Province.

Water samples were collected from the surface layer at the depth of between 0 – 25 m. The analytical detection limit (DL) of total phosphorus (TP), was around 0.001 mg/L. For statistical and trophic index estimates, concentrations below the detection limit were written as <DL and thought of as half of the detection limit.

3.2. Comparative index of water quality and trophic level

The Water Quality Index (WQI) is a widely used index for the comprehensive assessment of marine ecosystems. It has emerged as a widely utilized instrument for assessing water quality owing to its straightforward structure, which is in contrast to physical-processed or hydrological models. This index has been applied to evaluate surface water quality conditions. In this study, the WQI was measured using data derived from three water quality parameters: turbidity, TP, and DO. The WQI was calculated using the normalized values of three or more variables as follows (Pesce & Wunderlin, 2000):

$$WQI = \frac{(C_{v1} + C_{v2} + C_{v3} \dots C_{vn})}{n} \quad (1)$$

where C_v is the normalized value relative to a given water quality critical variable in the detailed system and is the number of variables involved in the calculation.

The WQI represents a mathematical integration of normalized water quality measurements through arithmetic weighting. The normalizations and weightings vary according to the specific water usages (Pesce & Wunderlin, 2000; Xu et al., 2024). **Table 1** shows the normalizing factors for the WQI index calculation for this research. The quality classification was based on the ranges of WQI values and their respective conditions could be found in **Table 2**, where WQI ≤ 25 is very bad, 26 ≤ 50 is bad, 51 ≤ WQI ≤ 70 is regular, 71 ≤ WQI ≤ 90 is good, and 91 ≤ WQI ≤ 100 is rated as excellent (Pesce & Wunderlin, 2000; Xu et al., 2024).

Table 1.

Normalizing factors for the WQI calculation (Pesce & Wunderlin, 2000).

	100	**90**	**80**	**70**	**60**	**50**	**40**	**30**	**20**	**10**	**0**
DO (µg/L)	≥ 7.5	≥7.0	≥6.5	≥6.0	≥5.0	≥4.0	≥3.5	≥2.0	≥	≥1.0	<1.0
TP (µg/L)	<0.05	<0.05	<0.05	<0.1	<0.1	<0.15	<0.15	<0.2	<0.2	<0.3	<0.3
Turb. (NTU)	<5	<10	<15	<20	<25	<30	<40	<60	<80	≤100	>100

Table 2.
Classification of Trophic State Index (TSI) (Klippel et al., 2020), Trophic Index (TRIX), and Water Quality Index (Pesce & Wunderlin, 2000; Vollenweider et al., 1998).

TSI	TRIX	WQI	Condition
Low (Oligotrophic) <30 30-40	≤ 4 Oligotrophic	Bad (≤ 50)	Scarsely productive coastal waters Good water transparency – Absence of anomalous water colors – Absence of oxygen under saturation in the bottom waters
Moderate (Mesotrophic) 40–50	4 < 5 Mesotrophyc	Regular (51 - 70)	Moderately productive waters – Occasionally water turbidity – Occasionally anomalous water colors – Occasionally bottom waters hypoxia episodes
High (Eutrophic) 50–60 60–70	5 < TRIX < 6 Mesotrophic to Eutrophic	Good (71 - 90)	Very productive waters (High productivity) – Low water transparency – Frequently anomalous waters colors – Hypoxia and occasionally anoxia episodes in the bottom layers – Suffering of the benthic communities
Very high (hypertrophic) 70–80 > 80	6 < TRIX < 10 Eutrophic	Excellent (91 - 100)	Strongly productive waters – High water turbidity – Diffuse and persistent anomaly in the water colors – Diffuse and persistent hypoxia/anoxia episodes in the bottom waters – High mortality rate of benthic organisms – Alteration of the benthic communities and strong decrease of the biodiversity

The data obtained through measurements of water quality parameters can be used to evaluate trophic status. The trophic status of bodies of water is an essential metric of aquatic ecosystem health, revealing the degree of nutrient enrichment and primary production, significantly affecting the composition and dynamics of aquatic ecosystems (Vollenweider et al., 1998). The TRIX method has been widely used to assess the eutrophic state of marine bodies (Smith et al., 1999; Stramma et al., 2008). TRIX has been developed to determine the trophic status of coastal waters through the measurement of aquatic chemistry (Pavluk & bij de Vaate, 2017).

The TRIX index is defined as a linear combination of logarithms values of 4 parameters related to eutrophication: ChA concentration in µg/L, concentration of nitrate, nitrite, ammonia (DIN), and total phosphorus (TP) in µg/L, and percent oxygen saturation deviation (aD%O) (Seisdedo et al., 2014). The results of 4 parameters measurements for applying the TRIX index (DIN, TP, aD%O, and ChA) in the study location provided an overview of the conditions of the surface water trophic level. The trophic status is determined using the TRIX index with the following formula:

$$TRIX = \frac{\log_{10}(ChA \times |\Delta DO| \times DIN \times TP) + k}{m} \tag{2}$$

$$\Delta DO = \left|\frac{DO_{observation} - DO_{saturation}}{DO_{saturation}}\right| = aD\%\text{O} \tag{3}$$

where, ChA is the concentration of chlorophyll-a (µg/L), aD %O is the concentration of oxygen as the absolute percentage deviation of oxygen saturation (100%), DIN is Dissolved Inorganic Nitrogen (µg/L) and TP is Total Phosphorus (µg/L). The coefficients k and m are 1.5 and 1.2, respectively.

TRIX index values have a scale of 0-10 that can be categorized into 4 categories or 4 levels (**Table 2**). The higher the TRIX index value (maximum 10) is, the higher the eutrophication rate of its waters (high water productivity). The TRIX index value shows the category tropic level (Pavluk & bij de Vaate, 2017), with the category assessment range in **Table 2**. Eutrophication triggers the occurrence of anoxia (Seisdedo et al., 2014). The higher the intensity or density of anthropogenic activities allows the region to experience an excessive increase in trophic status (Saygu et al., 2023).

The Trophic State Index (TSI) evaluates ecosystem health by evaluating current biological productivity levels (Klippel et al., 2020) (**Table 2**). The TSI values were determined based on the interconnected variables TP ($TSI_{(TP)}$), DIN ($TSI_{(DIN)}$), and total chlorophyll-a ($TSI_{(ChA)}$). The equation applied to compute TSI is as follows:

$$TSI_{(ChA)} = 9.81 * \ln_{(ChA)} \quad + 30.6 \left(\frac{\mu g}{l}\right) \tag{4}$$

$$TSI_{(TP)} = 14.42 * \ln_{(TP)} \quad + 4.15 \left(\frac{\mu g}{l}\right) \tag{5}$$

$$TSI_{(DIN)} = 54.4 * 14.43 * \ln_{(DIN)} \left(\frac{\mu g}{l}\right) \tag{6}$$

$$Average\,TSI = \overline{TSI_{(ChA)} + TSI_{(TP)} + TSI_{(DIN)}} \tag{7}$$

3.3. Data analysis

The water quality parameter measurements were evaluated spatially and presented in a horizontal description. Statistical analyses were performed to assess relationship between WQI, TSI, and TRIX. Pearson correlation coefficients were computed between WQI and TSI; WQI and TRIX. Data are presented as mean ± standard error of the mean (SE).

4. RESULTS

4.1. Water quality parameters

The measurable surface temperature (SST) distribution at the research site in April 2021 showed an average SST value (28.79 ± 0.26 °C) in the range of 28–29.4 °C (**Fig. 2a** and **Table 3**) with the distribution values of SST at the west site stations were 28.53 – 28.50 ºC and 28 – 29.20 ºC on the east site station. The distribution of these values characterizes the surface water temperatures of coastal waters in Indonesia in accordance with environmental quality standards. The average SST at the east site of our research area is warmer than that at the west site (**Table 3**). The research locations with the highest average SST values were close to the mainland (**Fig. 2a**).

The spatial distribution of Sea Surface Salinity (SSS) values was 31.2 – 31.9 and 31.72 ± 0.19 PSU (**Table 3**) as an average value of SSS (**Fig. 2b**), the distribution values at the west site stations were 31.50 – 31.90 PSU and 31.20 – 31.90 PSU at the east site. A marginal rise in salinity was observed in the nearshore waters in the eastern stations (St. 17, St. 18, St. 28, and St. 27), in contrast to the more oceanic waters at the northwest endpoint of each transect and the southern transects, as opposed to the eastern transects.

The SSS values of the southern transects or stations (St. 1, St. 13, St. 31, St. 14, St. 32, and St. 33) increased with distance from the coastline (**Fig. 2b**). Measurements of SST and SSS on the western and eastern sides show maximum average values that are inversely related between the two parameters. The strongest Surface Current (SC) values in April 2021 varied from 0 to 0.5 m s-1 (**Table 3**). The mean SC values at the west site were higher than those at the east site, indicating that the SC is an environmental variable that influences the productivity levels in coastal marine ecosystems. The spatial distribution of the DIN measurement results (**Fig. 3a**) in the form of nitrates (NO_3), nitrites (NO_2), and ammonia (NH_4) provides a description of the nutrient content or concentration at the research site in April 2021.

Table 3.

Statistic summary of water quality parameters collected from surface waters (0 – 25 m) in Sumberkima coastal waters, Buleleng, Bali (for N/P the values were mumtiplied by 10).

West Site Stations	SST (°C)	SSS (PSU)	SC (m/s)	*DO (µg/L)	*DIN (µg/L)	*TP (µg/L)	aD%O (%)	*ChA (µg/L)	N/P .10	pH	Turb. (NTU)
Mean	28.80	31.76	0.2	6263	35	1.2	97.72	0.15	6.7	7.95	0.82
Median	28.80	31.80	0.2	6123	32	0.5	90.71	0.11	6.6	7.96	0.01
SD	0.12	0.11	0.13	230	9	2.3	2.81	0.12	2.7	0.20	2.5
Min	28.53	31.50	0.1	5754	22	0.0005	85.32	0.05	2.8	7.55	0.01
Max	28.90	31.90	0.5	6942	55	799	95.36	0.34	11	8.24	0.30
East Site Stations	**SST (°C)**	**SSS (PSU)**	**SC (m/s)**	***DO (µg/L)**	***DIN (µg/L)**	***TP (µg/L)**	**aD%O (%)**	***ChA (µg/L)**	**N/P**	**pH**	**Turb. (NTU)**
Mean	29.01	31.15	0.12	6538	71	0.5	97.72	0.33	2.7	7.76	0.01
Median	28.97	31.77	0.1	6519	51	0.5	97.75	0.27	94	7.78	0.01
SD	0.40	0.28	0.08	480	53	0.5	6.80	0.24	13	0.21	0.00
Min	28.00	31.20	0.01	5995	38	0.5	88.98	0.07	5.9	7.51	0.01
Max	29.20	31.90	0.2	7163	176	0.5	106.31	0.78	35	7.99	0.01

** the values of DO, DIN, TP and ChA were multiplied .10*^{3}

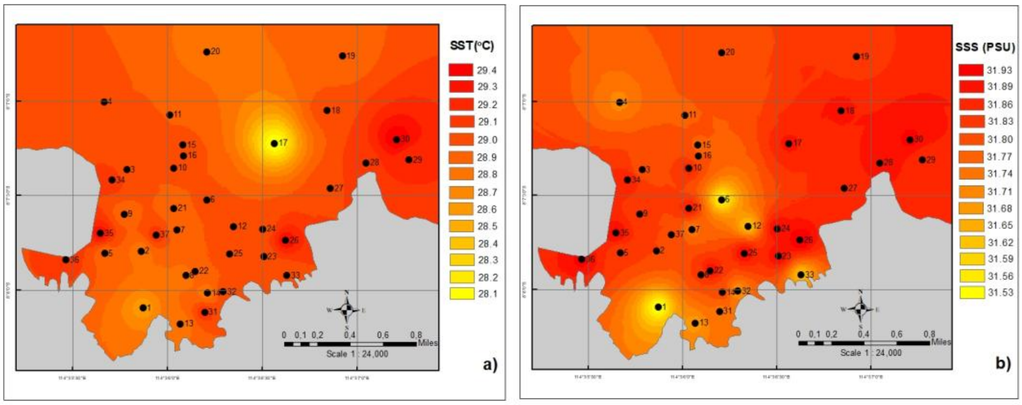

Fig. 2. Spatial distribution of (a) sea surface temperature (SST) and (b) sea surface salinity (SSS).

The spatial distribution of DIN values of the coastal waters of Sumberkima ranges from 22.2 to 176 µg/L, as depicted in **Fig. 3a**. with the average of DIN value was 38.3 ± 11.9 µg/L. The highest DIN concentration was found at St. 17, located in the middle area of the study, and the lowest concentration was found in St. 1. The measurement stations identified as having DIN concentration values below the mean value (38.3 ± 11.9 µg/L) are close to the mainland. The spatially distributed pattern of DIN concentrations revealed an increase in values from stations near the shore to those in the open sea.

The range of TP concentration values obtained in the west site stations was 0.5 – 8 µg/L, with an average value was 1.2 ± 2.3 µg/L (**Table 3**) and the distribution values illustrated in **Fig.3b**. The research location exhibited a restricted phosphate concentration (**Fig. 3b**). The TP measurement results at the study site indicated limited phosphate presence, almost under detection limit (1 µg/L).

According to the information provided in **Table 3** and **Fig. 3b**, the N/P ratio is the comparison of DIN with TP values, indicating that the availability of nutrients for algal growth was higher than 16. This finding indicates that the coastal waters of Sumberkima exhibited a phosphorus-limited state during this season (**Fig. 3b**) considering the N/P ratios. In this study, the phosphate concentrations in the coastal waters of Sumberkima are often very close to the analytical detection limit.

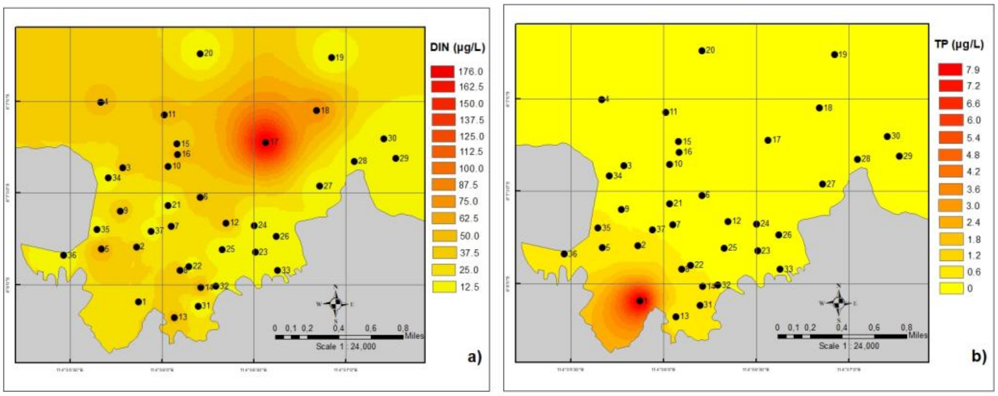

Fig. 3. Spatial distribution of (a) dissolved inorganic nitrogen (DIN) and (b) total phosphate (TP).

The measurable dissolved oxygen concentration (DO) at the study site (**Fig. 4a**) was above the standard quality threshold of ≥ 5000 µg/L (**Table 3**). The DO range at the research area was 5754 – 7163 µg/L, with the average value of DO for all station was 6243 ± 366 µg/L (**Table 3** and **Fig. 3a**), where the mean values were higher at the east site (6537 ± 480 µg/L) than at the west site (6263 ± 299 µg/L. Measurement and spatial analysis results of DO and ChA in the Sumberkima coastal waters are shown in **Figs. 4a** and **4b**, respectively. The ChA concentrations ranged from 182 to 135 µg/L, with the highest values found in the seagrass area (East site), with measurements at station St. 17 (789 µg/L) and St. 18 (450 µg/L). Station 17 had the highest concentrations of DIN, DO, and ChA, as illustrated in **Fig. 3a** (DIN), **Fig. 4a** (DO), and **Fig. 4b** (ChA).

The pH values ranged from 7.51 to 8.24, with an average of 7.95 ± 0.20 in the west site and 7.76 ± 0.21 in the east site. The stations recorded pH values above 8.0 (St. 14, 31, 13, 18, 22, 6, 7, 2, 21, 37, 5, 36, 35, 9, 34, 3, 4, 11, 20, 15, 16, and 10). The pH values were found ≥ 8 located on study area that was close to the main island (**Table 4**). The turbidity is another measurement with a range of values of 0.0-8.30 NTU with an average was 0.74 ± 2.45 NTU. The results from sampling stations at the east site were lower than those recorded at the west site (**Table 4**).

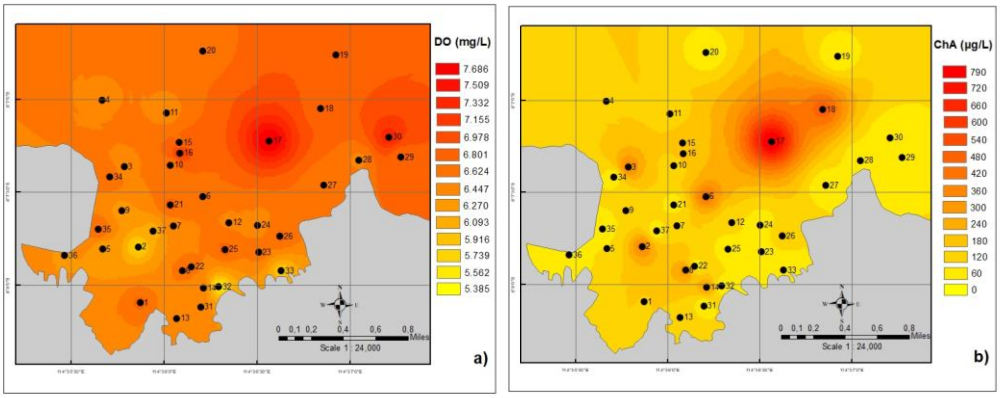

Fig. 4. Spatial Distribution of Dissolved Oxygen (DO) (a) and Chlorophyll-a (ChA).

4.2. Water quality indexes

4.2.1. Water quality index (WQI)

The WQI values in the coastal waters of Sumberkima, Buleleng, Bali Province, have a mean value of 87.88 ± 3.08 in the west station and 91 ± 3.25 (**Table 4** and **Fig. 5**), with values ranging from 80 to 97. The WQI values distribution indicated that the coastal waters quality of Sumberkima could be classified were in Good and Excellent. The water quality of Sumberkima coastal waters indicates that the condition of waters was varied in two classes (Good to Excellent) (**Table 4** and **Fig. 5**).

The comparison of the two groups of study area performed at the West site has the average value was 87.88 ± 3.08 lower than East site (91 ± 3.25). The WQI classification for assessing the water quality at stations WS 18 and WS 17 (**Fig. 5** and **Fig**. **6a**) in the East Site indicates excellent conditions, while other stations are categorized as having been in good condition. **Fig. 6a** shows the spatial distribution of WQI values, indicating that station WS18, situated in the East site, has the highest WQI value (97) characterized with the highest DO (6.94 mg/L) and the TRIX index value (6.44).

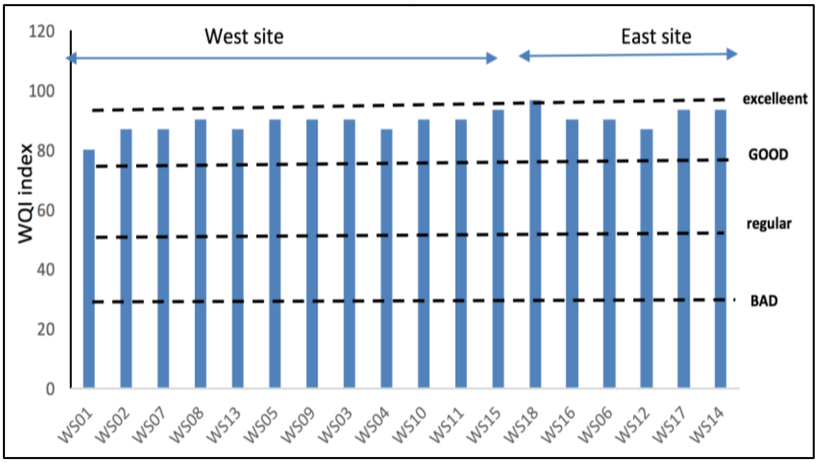

Fig. 5. Water Quality Index (WQI) in Water Sampling (WS) stations in Sumberkima coastal waters, Buleleng, Bali Province, in April 2021

4.2.2. Trophic index (TRIX) and trophic state index (TSI)

The outcomes of the calculation of the four parameters for trophic status evaluation using the TRIX index application are detectable in the distribution at the observation, as shown in **Fig. 6**. The TRIX values ranged from 3.22 to 6.50, with a mean of 4.41 ± 0.69 and the distribution values of TRIX approximates normality. The TRIX index value was found to have a range value indicates the trophic state were in the Oligotrophic, Mesotrophic, Mesotrophic to Eutrophic and Eutrophic type. The trophic condition of those TRIX values indicated that the waters were very productive (high productivity) with low water transparency into frequently anomalous waters colors and hypoxia and occasionally anoxia episodes in the bottom layers (**Table 3** and **Fig. 6b**.).

The average TRIX value in the study area was 4.41 ± 0.69 which may be characterized by the Mesotrophic to Eutrophic of the water productivity level or trophic level. The productivity level is characterized by moderately productive waters with occasionally anomalous water color. Hypoxia and occasionally anoxia episodes could also be found in the bottom layers, indicating the suffering of the benthic communities. The result of counting the TRIX algorithm also illustrates the distribution classes of marine productivity in study area.

The western site had range TRIX values were 3.22 into 6.50 means all those areas were in Oligotrophic, Mesotrophic, Mesotrophic to Eutrophic and Eutrophic condition (**Table 4**, **Fig. 6**) and the east site stations have two (2 classes) condition of trophic state were Mesotrophic and Mesotrophic to Eutrophic. The highest score of TSI found in the west site (St. 17) characterized by the highest of the DIN, ChA, and DO concentrations. Water quality assessment from the result of TSI algorithm revealed that the study areas have three classes of trophic level based on Nutrients and Chlorophyll-a concentration were Oligotrophic, Mesotrophic and Eutrophic (**Table 4** and **Fig. 6**).

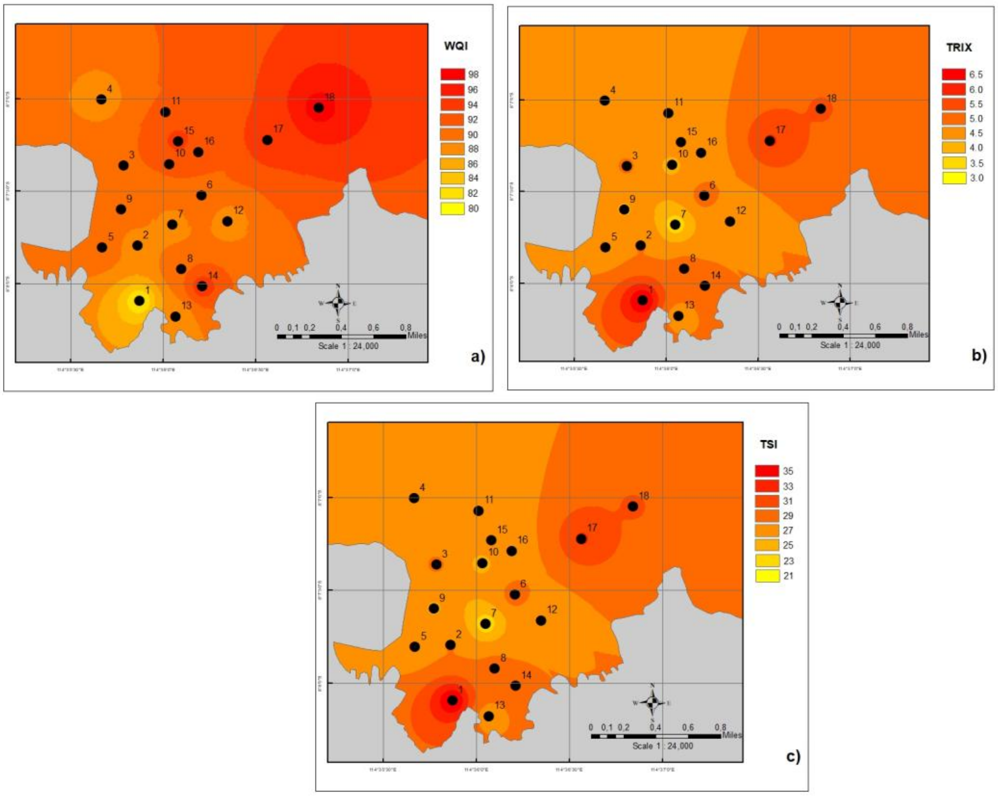

Fig. 6. Spatial distribution of WQI, TRIX, and TSI in Sumberkima coastal waters

The findings suggest that the TRIX score provides a more comprehensive and strong trophic classification to characterize water quality. The level of productivity has three classes (Oligotrophic, Mesotrophic and Eutrophic) for all stations along the West side into the East side, which illustrated the condition of the waters in **Fig. 6c**.

4.2.3. Comparison of the water quality indices

However, the evaluation of water quality is a crucial step in conserving and effectively managing coastal and marine water resources, which are constantly under threat from human-induced physical and chemical pressures (such as water over-exploitation and pollution), climate change, and uncertainty. The results of the comparative analysis using regression analysis between WQI with TRIX and TSI depicted in **Fig. 7**.

Linear regression analysis showed that WQI scores were more strongly correlated with TRIX than with TSI. Specifically, the coefficient of determination (R^2) value of TRIX with WQI shows a higher value ($R^2 = 0.3418$) than TSI ($R^2 = 0.006$). This value indicates a stronger correlation between WQI and TRIX than with TSI. The linear regression equation obtained shows a negative correlation with TRIX and a positive correlation with TSI. The negative correlation with TRIX ($y = -0.0683x + 11.934$) a potential inverse relationship with trophic status.

However, the group classification of trophic level in TSI indicated the classification of trophic levels is more widespread which has three (3) classes. The results highlight the fact that, although neither index accurately reflects the nutrient-based WQI classification, the TRIX values provide a more accurate approximation and may therefore be a more appropriate method for water quality assessment in this context.

Table 4.
Distribution of Water Quality Parameters with the Water Quality Index (WQI) and the Trophic State Index (TSI and TRIX).

Para-meter	SST (°C)	SSS (PSU)	Turb. (NTU)	pH	ChlA (μg/L)	DO (μg/L)	DIN (μg/L	TP (μg/L)	WQI	TRIX	TSI	Condi-tio/ State (Ave.)
QS*	**28-30**	**33-34**	**< 5**	**7–8.5**		**> 5000**	**308**	**15**				
West Site												
St.1	28.53	31.50	0.00	7.78	119	6338	22	8	80	6.50	57	
St.2	28.70	31.80	0.00	7.55	339	6992	176	0.5	93	4.52	65	
St.7	28.70	31.80	0.30	8.03	119	5996	28	0.5	87	3.22	30	
St.8	28.70	31.90	0.07	7.55	307	5936	27	0.5	87	4.64	19	
St.13	28.70	31.80	0.00	7.89	110	6439	40	0.5	90	4.26	34	**Oligo**
St.5	28.70	31.67	8.53	8.22	59	6036	41	0.5	87	4.15	25	**-tro-**
St.9	28.70	31.80	0.00	7.99	59	6600	55	0.5	93	3.96	38	**phic**
St.3	28.80	31.80	0.00	8.15	335	6278	55	0.5	90	4.56	23	**into**
St.4	28.80	31.80	0.00	8.24	110	6117	33	0.5	90	4.25	16	**Eu-**
St.10	28.90	31.77	0.00	8.13	51	6130	31	0.5	90	3.87	32	**Tro-**
St.11	28.90	31.70	0.00	8.14	59	5755	42	0.5	87	4.03	25	**phic**
St.15	28.90	31.83	0.03	8.04	162	6177	30	0.5	90	4.33	13	
Mean	**28.8**	**31.72**	**0.50**	**7.91**	**153**	**6263**	**35**	**1.18**	**87.8**	**4.36**	**31**	
SD	**0.26**	**0.19**	**2.0**	**0.23**	**111**	**299**	**9**	**2.3**	**3.66**	**0.82**	**16**	
Para-meter	**SST (°C)**	**SSS (PSU)**	**Turb. (NTU)**	**pH**	**ChlA (μg/L)**	**DO (μg/L)**	**DIN (μg/L**	**TP (μg/L)**	**WQI**	**TRIX**	**TSI**	**Condi-tio/ State**
QS*	**28-30**	**33-34**	**< 5**	**7–8.5**		**> 5000**	**308**	**0.015**				
East Site												
St.18	28.53	31.77	0.00	7.87	450	7163	70	0.5	90	5.02	19	**Oligo**
St.16	28.90	31.77	0.00	7.87	163	6036	47	0.5	93	4.46	24	**-tro-**
St.6	28.9	31.77	0.00	7.74	391	6439	40	0.5	97	4.72	46	**phic**
St.12	28.97	31.87	0.00	7.67	76	5596	38	0.5	90	4.09	31	**into**
St.17	29.0	31.77	0.00	7.51	789	6992	176	0.5	90	5.55	37	**Eu-**
St.14	29.1	31.2	0.00	7.90	272	6600	55	0.5	87	4.72	20	**Tro-**
Mean	**29.01**	**31.61**	**0.00**	**7.77**	**358**	**6537**	**71**	**0.5**	**91**	**4.70**	**29**	**phic**
SD	**0.12**	**0.28**	**0.00**	**0.16**	**252**	**480**	**53**	**0.00**	**3.44**	**0.58**	**11**	

**QS as Water Quality Standard for biota and marine culture based on the Environment Quality Standard No.51 2004 Republic of Indonesia*

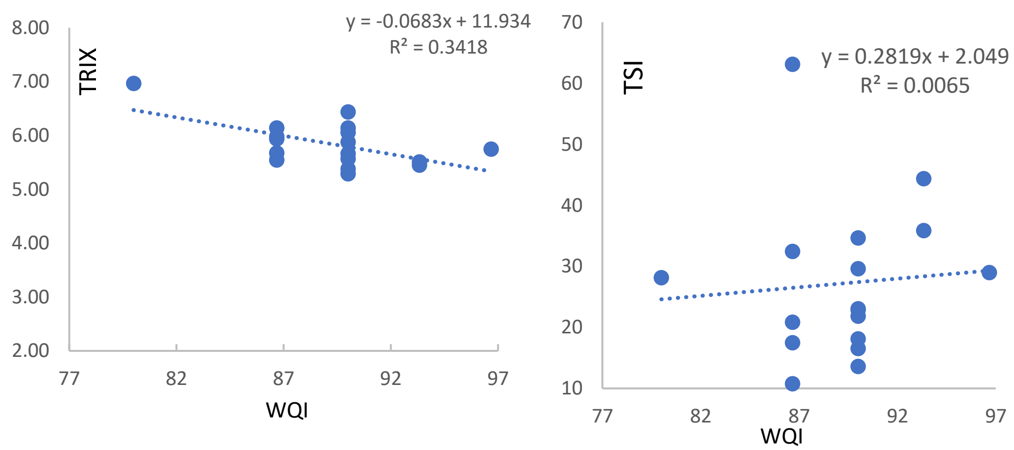

Fig. 7. Linear regression analysis of the WQI, TRIX, and TSI in the Sumberkima coastal waters. The scatterplots represent the linear regression and coefficient of determination (R^2) for each index, pointing out the direction and strength of the connections.

Fig. 8 shows a comparison of the trophic status distribution at water quality measuring stations. Approximately 50 percent of water quality monitoring stations are in good condition, predominantly classified as mesotrophic. The results indicate that water quality varies from good to excellent classes (WQI), which are related to the trophic levels of oligotrophic and mesotrophic environments (**Fig. 8**). However, there are a significant difference in TSI and others scores groups (WQI and TRIX), suggesting higher response to variations in chlorophyll-a and nutrient levels, emphasizing its fundamental function in assessing eutrophication dynamics.

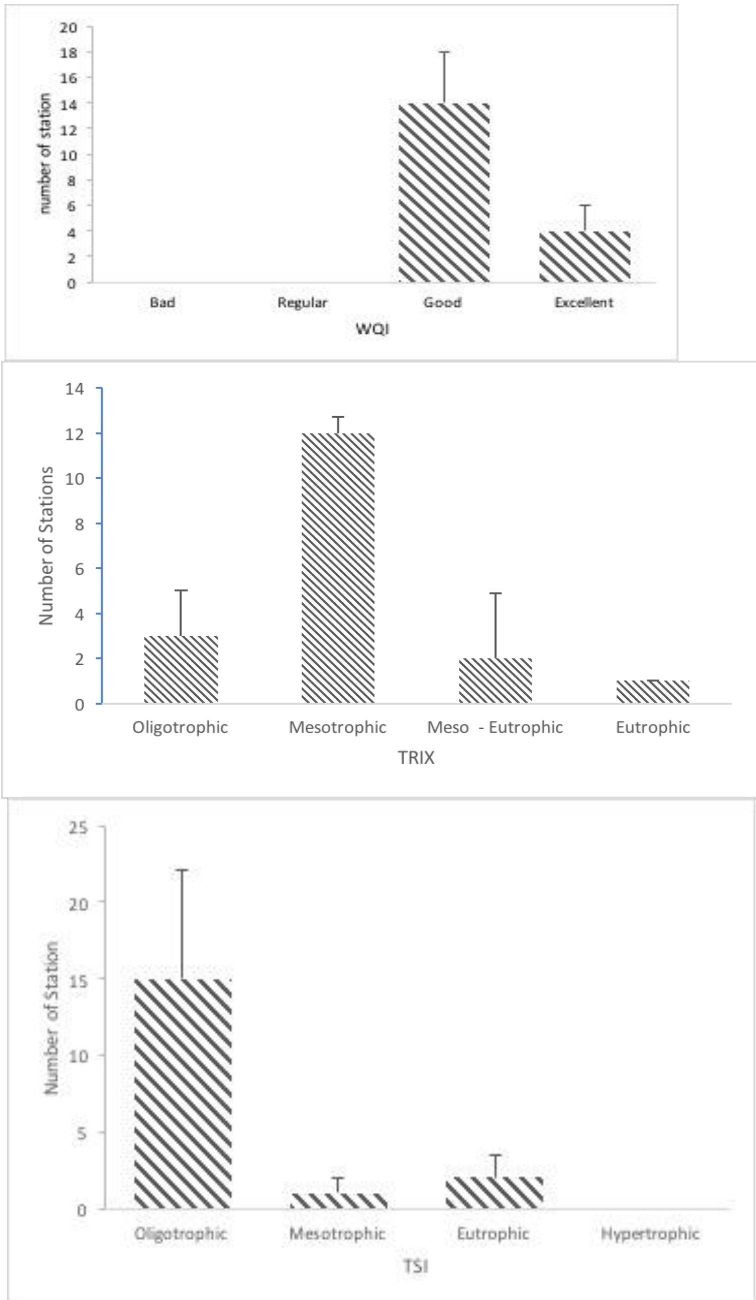

Fig. 8. Comparison of the trophic status distribution of WQI, TRIX, and TSI at water quality measuring stations.

5. DISCUSSION

5.1. Evaluation of the water quality

The sea surface water in the research area had the range values (**Table 4**) were naturally warmer due to exposure to the sun throughout the day. Nevertheless, as the wind blew, a mixing process transpired and a mixed layer was formed within the surface layer (0 m) to a depth where the temperature was uniformly still measured (Wyrtki, 1961). The SST was affected by weather conditions, whereby factors such as precipitation, evaporation rate, atmospheric humidity, air temperature, wind velocity, and solar intensity contributed to variations in SST (Tukenmez & Altiok, 2022). The mixed layer in the study areas reached temperatures of up to 28°C, Ariadji et al. (2024) also found the average of SST conducted in March 2021 was 28.6 °C. This result also aligns closely with the study by Khalishah et al., (2022) which is stated that the northern region of Bali has a surface temperature of around 27-30°C. The distribution changes of SST in marine environments are affected by solar radiation exposure (temperature of atmosphere), currents, regional season (Bradshaw & Holzapfel, 2008). Water temperature is critical to evaluating water quality and analyzing aquatic habitats. It significantly affects several chemical and biological processes and influences the dispersal of marine creatures (Ustaoğlu & Aydın, 2020).

The salinity variations are influenced by many causes, including geomorphological and topographical formations that may create disparities in salt solubility and ion ratios. The findings indicate that evaporation rates and the residence duration of coastal waters are the primary variables affecting salinity throughout the measurement period due to all the measurements were taken from 9 am to noon. Geng & Boufadel (2017) observed that evaporation significantly raised the pore water salinity, exceeding 85 g/L inside the superficial layer, which is approximately 10 cm under the sea surface. The analysis of SST and SSS values from the depth 5 – 25 m revealed that the water body was thoroughly mixed with significant vertical density gradients throughout the sample period.

Previous study by Khalishah et al., (2023) and Ilahude & Gordon (1996) found that the northern waters of Bali are predominantly influenced by water masses from the Java Sea which have the surface currents with the characteristics of the Indonesian monsoon current. The Indonesian monsoon current crosses from the China Sea into Java, extending to the Flores Sea and Banda Sea.The highest SC mean value found in the west site (0.2 ± 0.13 m/s) of the sampling stations is influenced by the movement of the monsoon winds and tidal energy. The surface currents in Bali's northern and southern waterways move from west to east (Siswanto & Suratno, 2010) and conversely, the southeast monsoon (May to October), the currents move from east to west, resulting in a dynamic marine environment.

The research area revealed a limited phosphate content, with almost the TP measurement result at the study field beings nearly below the detection limit (1 µg/L). The highest concentration was found in the west site (St.01). A previous study in Sumberkima coastal waters found that the primary source of organic matter input in marine waters, particularly in Pegametan Bay, comes from fish culture feed. The feed consists of nitrogen and phosphorus, which solubilise in water and are utilised by the cultured organisms (Ariadji et al., 2024; Mok et al., 2021). Marine organisms require nutrients to survive, and previous research has shown a positive correlation between the health of aquatic ecosystems and phosphorus and nitrogen levels (Abo-El-Khair et al., 2016). Physical and biological processes may influence the regulation of TP and DIN levels in the study areas due to the present study revealed that elevations in TP and DIN were found by decreasing in salinity, indicating the role of sewage effluents in providing N and P compounds to coastal saline ecosystems (Mahmoud et al., 2020).

According to Ahmad et al. (2017), fishing activities might contribute to the concentrations of nutrients, which is evident from Ariadji et al. (2024) found that the concentrations of NO_2 are less than the other forms of nitrogen (NO_3 and NH_3). The instability can be ascribed to its capacity to oxidated become nitrate or reduction to ammonia through chemical reactions and biological bacteria (Canfield et al., 2010; Ward, 2008). The salinity, water temperature, and dissolved oxygen are the most important factors influencing nutrient patterns in coastal regions (Pesce & Wunderlin, 2000). The ratio of Nitrogen and Phosphate is a crucial ecological parameter influencing primary production and eutrophication (Abdelmongy & El-Moselhy, 2015). The average N/P ratios in the study area was higher than 16, phytoplankton growth may be limited by phosphorus or acts as the limiting factor (Redfield et al., 1963). The fluctuation of the N/P ratios may be described to the diverse discharges entering the research region. N-limited aquatic systems exhibit N/P molar ratios above 5, whereas P-deficient aquatic systems also display N/P molar ratios above 5 (Abo-El-Khair et al., 2016b).

Oxygen compounds are those directly associated with carbon through photosynthesis and respiration processes (Oschlies et al., 2018; Stramma et al., 2008). The presence or profile of oxygen concentrations in the aquatic ecosystem area mirrors the concentration and profile of nutrient distribution as mentioned by (Diaz & Breitburg, 2009). Oceanic fronts are areas characterized by intensified surface gradients in physicochemical characteristics between adjacent water masses (Belkin & Cornillon, 2005; Belkin & O'Reilly, 2009). The observation results (**Fig. 4a**) indicate that the area surrounding station 03 has a seagrass cover percentage of 80.63%, whereas the areas around stations 17 and 18 exhibit a higher coverage of 84.22%.

The minimum and maximum DO concentrations recorded were 5755 and 7163 µg/L, respectively (**Fig. 4a**). The highest ChA concentration (7890 µg/L) was found in stations 17, which is in the East site. The similarity trend values of ChA with DO concentration exhibited correlate with those obtained at this site (**Fig. 9**). This finding suggests that DO and ChA could be used as indicators of the scale of photosynthetic aquatic organisms, as previously demonstrated by Mashoreng et al. (2019). As shown by linear regression (**Fig. 9**), the correlation between DIN, DO, and ChA suggests that these parameters are required during photosynthesis in addition to absorbed atmospheric carbon dioxide (CO_2) and oxygen (O_2) production. The weak relation between ChA and DIN (R^2 were 0.26 and 0.07) suggested that DIN availability in the primary productive process is significantly limited. However, the majority of sea surface waters are low in inorganic nitrogen, phosphorus, iron and/or silica; nutrients that limit primary generation in the ocean (Bristow et al., 2017).

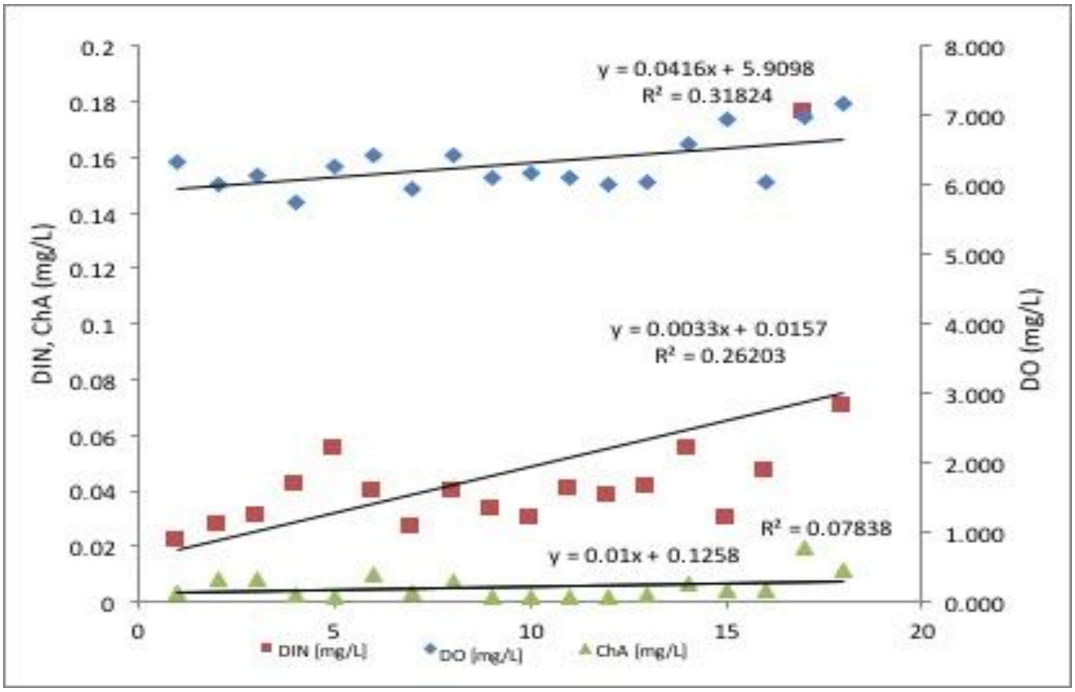

Fig. 9. Linear regression analysis of DO, TN and ChA Values at the 18 Stations of Study Areas

5.2. Comparison of water quality indices

A comparative evaluation of the efficacy of WQI, TRIX, and TSI for evaluating water quality in tropical coastal ecosystems reveals significant differences. The TRIX exhibits a significant negative relationship with WQI ($R^2 = 0.34$, $p < 0.01$), suggesting that the trophic state index significantly impact overall water quality, hence establishing TRIX as a reliable indicator of ecosystem degradation as evidenced by WQI. Increasing TRIX values, signifying enhanced nutrient enrichment and phytoplankton biomass, correlate with diminished WQI scores, indicating declining physic-chemical water quality. This pattern is found over the studied data range, suggesting that eutrophication significantly affects regional water quality.

The trophic status was calculated and assessed from four water quality parameters, namely DIN, TP, % DO, and ChA obtained an index value for all stations indicating the condition of the waters is at Mesotrophic up to Eutrophic level (Pesce & Wunderlin, 2000; Vollenweider et al., 1998). The TRIX index value also shows that the research location as a typical ecosystem of tropical coastal areas as expressed by (Welsh, 2000).

The linear regression between TSI and WQI (**Fig. 7**) indicated a negligible association between TSI and WQI ($R^2 = 0.006$) shows that fluctuations in trophic status occur independently of alterations in overall water quality, underscoring the restricted responsiveness of WQI to eutrophication-related phenomena. We analyzed the spatial distribution of the WQI, TRIX, and TSI indices (**Fig. 6a**, **Fig. 6b**, **Fig. 6c**) and discovered a value distribution pattern of those indices in which the study area with the highest WQI value coincides with lower TRIX and TSI values.

The distribution of TSI index values across all 18 sampling stations was oligotrophic to eutrophic (**Fig. 6c**). The average TSI index value at the west side research location (31±16) and stations on the east side was 29.4 ± 11, indicating mesotrophic conditions.

The highest trophic level (eutrophic) was discovered at station 17, which is located on the east side. This is attributed to the high levels of organic and inorganic waste in the region caused by increased land use, economic growth, and rapid urbanization. These findings are comparable with those of Abdel-Hamid (2017), who identified several important terrestrial and marine activities that contribute to eutrophication.

WQI integrates several physical and chemical properties to describe comprehensive water quality, whereas TRIX focuses on nutrient enrichment and phytoplankton response, making it more sensitive to eutrophication processes. A positive relationship was found between elevated productivity and persistently higher nutrient consumption levels in the studied area, suggesting that these levels transcend those of the realistic scenario (Giovanardi & Vollenweider, 2004).

According to Primpas & Karydis (2011), TRIX is useful for quantifying environmental quality due to it's has several advantages: (a) it produces a single number, (b) it is a multimetric index that includes four variables related to eutrophication, and (c) the environmental variables involved can be measured directly on a regular basis. Evaluating trophic status is crucial for determining the health of coastal aquatic ecosystems. By analysing nutrient concentrations and trophic interactions, researchers and policymakers can comprehend the ecological condition of coastal marine ecosystems (Bricker et al., 1999).

In April 2021, the water quality of coastal waters in Sumberkima, Buleleng, Bali Province, typically revealed that the results of measurements are still within the range of Standard Quality (SQ) criteria for marine biota and marine culture (Kementerian Lingkungan Hidup, 2004), excepts for nutrients as mentioned in **Table 4**. The results of the previous study found the condition of environmental degradation of marine culture in the north Bali coastal waters district has not occurred yet, but continuously efforts to control and anticipate it should be done as to achieve integrated marinculture Soto (2009). Soto (2009) proposed that integrated mariculture provides a mitigation strategy for the surplus nutrients and organic matter produced by intense aquaculture practices, especially in marine environments.

6. CONCLUSION

This study highlights that WQI, TRIX, and TSI provide complementary but distinct insights into water quality situations. The significant negative correlation between TRIX and WQI indicates that eutrophication is a principal factor in a decline of water quality in the studied area. The lack of a significant correlation between TSI and WQI suggests that fluctuations in trophic status may occur independently of alterations in overall water quality.

Comparing these indicators with nutrient concentration measurements in Sumberkima coastal waters, Bali Province offers a more comprehensive understanding of the determinants influencing water quality and presents a more complete overview of the condition of coastal aquatic ecosystems. Among the assessed indices, the WQI and TRIX indices exhibit a more robust significant correlation than the TSI. TRIX and TSI offer a more precise representation of trophic conditions affected by nutrients. The TRIX index demonstrates increased sensitivity in categorizing ecosystems as oligotrophic, mesotrophic, mesotrophic to Eutrophic and Eutrophic. These findings strengthen its potential as a dependable biomarker for identifying modest trophic changes in nutrient-dense environments.

The findings of this study represent conditions from an a single sampling time (April 2021) and should be regarded as a temporal snapshot. Additional multi-seasonal measurements are necessary to fully comprehend the seasonal variability in the research area. One of the future challenge in this research is to ensure data quality and consistency collecting, particularly under changing environmental circumstances. Adaptive sampling techniques may be necessary due to the potential for findings to be impacted by external influences, such as seasonal variations or unpredictable disruptions. Moreover, restricted access to advanced tools and processing resources can affect comprehensive research. Addressing these problems requires careful analysis, ongoing oversight, and cooperation with field specialists. This study may get more accurate and significant results by using advanced technology and enhancing procedures.

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