Monsoonal Effects and Hydro–Biogeochemical Characteristics in Maritime Cargo Areas of Siracha Bay, Eastern Upper Gulf of Thailand

Saranya Rakseree, Prasarn Intacharoen, Vichaya Gunboa and Anukul Buranapratheprat*

ABSTRACT

Nutrient dynamics play a crucial role in regulating seawater quality and maintaining ecological balance in coastal environments. While moderate nutrient inputs support productivity, excessive loading, often linked to human activities, can lead to eutrophication and oxygen depletion. This study investigated seasonal variations in marine water quality in the cargo area off Sriracha and Sichang Island, Chonburi Province, Thailand, using water samples collected from 16 locations during the dry season (March 2020) and rainy season (August 2020). Results showed elevated concentrations of ammonia (50.77±8.28 μg $N \cdot L^{-1}$), nitrite (21.40±13.19 μg $N \cdot L^{-1}$), nitrate (10.82±3.32 μg $N \cdot L^{-1}$), and particulate organic matter (0.08±0.05%) in near-bottom waters at the loading site during the rainy season. In contrast, total nitrogen (82.98±15.29 μg $N \cdot L^{-1}$) and total phosphorus (24.16±2.49 μg $P \cdot L^{-1}$) were elevated during the dry season. These patterns indicate that loading activities contribute to organic matter accumulation in sediments, which subsequently release inorganic nutrients into the water column. High nutrient concentrations and low dissolved oxygen during the rainy season were associated with water column stratification. Most parameters met seawater standards, except for orthophosphate in near-bottom water during the rainy season. Further research is needed to determine the degradation rate of tapioca starch, identify associated byproducts, and evaluate its contribution to hypoxia. A systematic investigation will help clarify its long-term environmental impact and support improved water quality management in maritime cargo areas.

Keywords: Hydro–biogeochemical features, Maritime cargo loading, Monsoonal effects, Nutrient input, Water quality impacts

INTRODUCTION

The quality of seawater depends on nutrient movement, which plays a crucial role in maintaining ecosystem balance. Excessive nutrient input, however, can disrupt marine ecosystems (Yang *et al*., 2008). The inner Gulf of Thailand is a semi-enclosed bay, making it highly susceptible to nutrient and pollutant inflows from land-based sources (Cheevaporn and Menasveta, 2003). In addition to river discharges, maritime cargo activities, including loading and unloading of goods, may also contribute to pollution. With over 80% of Thailand's international trade volume transported by sea (UNCTAD, 2021), ports like Sriracha have become major economic hubs, driving growth in Chonburi Province (Figure 1). While Sriracha is a key center for trade and logistics, the surrounding area is also important for tourism and fisheries. It is known for its rich marine biodiversity and supports various coastal livelihoods (Department of Marine and Coastal Resources, 2018). However, concerns have been raised about the environmental impact of ongoing cargo operations, particularly regarding potential water quality degradation and ecosystem disturbances. Balancing economic growth with marine conservation is essential to maintaining the long-term sustainability of the region.

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Sriracha Bay's physical characteristics make it well-suited for maritime operations. The area is characterized by minimal wind waves, weak currents, and a sandy seabed that is easy to dredge (Suktanon, 2011). It has an average water depth of 15 m and a tidal range of 1–3 m (Buranapratheprat *et al*., 2008), providing stable conditions for port activities. The bay experiences three distinct monsoonal seasons: the southeast monsoon (February-April), the southwest monsoon (May-September), and the northeast monsoon (October-February). Coastal currents primarily flow parallel to the shoreline, with flood tides moving northward at 0.2–0.5 $m{\cdot}s^{-1}$ and ebb tides flowing southward at 0.1–0.3 $m{\cdot}s^{-1}$ (Wattayakorn and Rungsupa, 2012). Additionally, the region receives an average annual precipitation of 1,220 mm (Thai Meteorological Department, 2022), influencing hydrodynamic processes in the bay.

Cargo transport activities are particularly intense in the deep-water channel between Sichang Island and the mainland, where products are transferred from ship to ship. The unloading of dry bulk cargo using grab buckets can result in the scattering of small dust particles into the sea. Particles from agricultural products such as tapioca starch and soybeans, falling into the sea, can lead to nutrient enrichment, causing algal blooms and hypoxic conditions detrimental to marine life. Additionally, escaped dust from chemical product handling can react with seawater elements, negatively impacting water quality. Contamination of the marine environment can also result from routine washing of cargo residues from vessel holds and the discharge of bilgewater and sewage. Numerous reports, such as Bonamano *et al*. (2017) and Popek *et al*. (2022), highlight the negative impacts of these activities on water quality and marine organisms.

It is concerning that contamination from agricultural product loading activities can increase organic material and nutrient levels, which, after decomposition, contribute to eutrophication in the water column. When a water body becomes overly enriched with nutrients, it triggers excessive growth of phytoplankton, leading to eutrophication (Lirdwitayaprasit *et al*., 2006). Frequent phytoplankton blooms have been recorded in the Sriracha Bay area. For instance, eight blooms were documented between 2007 and 2008 (Department of Marine and Coastal Resources, 2018), while 16 blooms occurred in 2022 (Department of Marine and Coastal Resources, 2023). These events have caused significant damage to natural aquatic resources, large-scale coastal aquaculture, and tourism potential (Pollution Control Department, 2014). Although it is well established that plankton blooms during the southwest monsoon are influenced by nutrient input from river discharges in the northern part of the inner Gulf of Thailand (Buranapratheprat *et al*., 2008), the potential contribution of organic materials from agricultural product loading remains uncertain. However, recent findings by Rakseree *et al*. (2024) indicate consistently high levels of total organic matter in sediment within the tapioca transfer zone, suggesting that these deposits may contribute to nutrient release into the water column through microbial decomposition and organic matter breakdown, which can further influence water quality and biogeochemical processes in the area.

This study investigates changes in marine water quality influenced by agricultural product transport activities, including the connection between seasonal variations and environmental conditions. The study also examines the spatial and seasonal variability of water quality around maritime cargo areas. These findings help facilitate early detection of potential pollution sources and provide essential water quality data to support effective management practices for shipping activities in and around Sriracha Bay.

MATERIALS AND METHODS

Water quality variability in the cargo loading area of Sriracha Bay and Sichang Island, located in the northeastern part of the inner Gulf of Thailand (13°20' to 13°04'N and 100°77' to 100°85'E; Figure 1), was investigated in 2020. Water samples were collected from 16 stations (SC–1 to SC–16) at three depths: 1 m below the surface, mid–depth, and 1 m above the seabed. Mid–depth sampling was omitted at some shallow stations. For chemical analysis, samples were collected in pre–cleaned 1 liter polyethylene bottles, acidified for nitrate and total phosphate analysis, stored in ice–packed Styrofoam boxes (below 4 °C), and transported to Burapha University for analysis within two days.

Two surveys were conducted: the first from 20–22 March 2020, and the second from 1–3 August 2020, representing the dry and rainy seasons, respectively. The March sampling occurred during the spring tide, corresponding to the 1st to 3rd lunar days after the New Moon. The August sampling also coincided with a spring tide, corresponding to the 12th to 14th lunar days before the Full Moon. These periods were selected because sea conditions are typically calm during spring tides, providing safe conditions for fieldwork.

Water temperature, transparency, salinity, and dissolved oxygen (DO) along vertical profiles were measured using a YSI Pro 2030 multiparameter water quality meter. pH was measured with a Horiba WQ–330 pH meter. Laboratory analyses of total suspended solids (TSS), ammonia, nitrite, nitrate, total nitrogen (TN), orthophosphate, total phosphorus (TP), chlorophyll–*a*, and particulate organic matter (POM) were conducted using methods summarized in Table 1.

Water quality data were analyzed to identify spatial and temporal differences. Prior to conducting a two–way analysis of variance (ANOVA), the Kolmogorov–Smirnov one–sample test was executed to assess the normal distribution

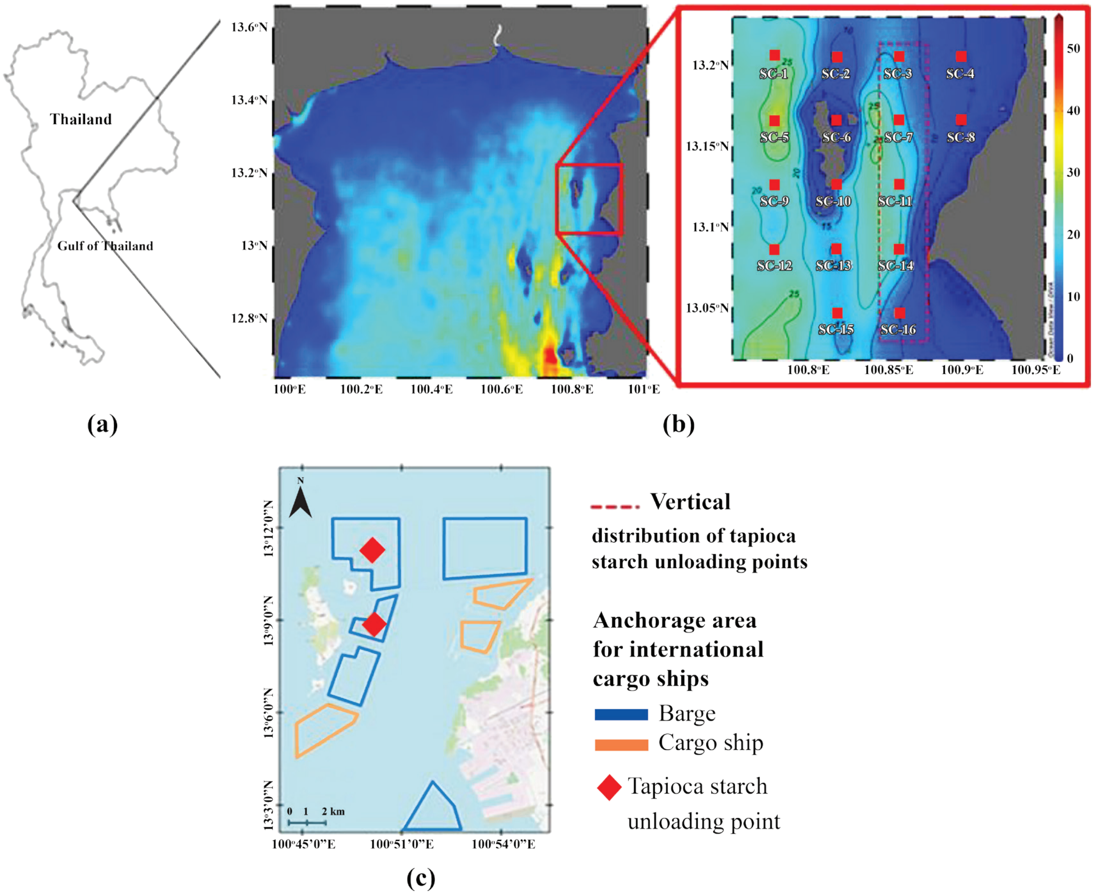

Figure 1. Study area offshore of Sriracha District: (a, b) sampling sites and water depth in the study area (stations within the red frame were used for cross–sectional water quality plot); (c) anchorage area for tapioca starch transport.

Table 1. Analysis methods for water chemical properties.

Water quality parameter	Analysis method
Total suspended solids (mg.L-1)	Gravimetric (APHA, 1992)
Ammonia (µg N·L^{-1})	Phenol–hypochlorite (Boyd and Tucker, 1992)
Nitrite (µg N·L^{-1})	Colorimetric Method (Boyd and Tucker, 1992)
Nitrate (µg N·L^{-1})	Colorimetric, Cadmium Reduction Method (Grasshoff *et al*., 1983)
Total nitrogen (µg N·L^{-1})	Digestion, Cadmium reduction, and Diazotization (Strickland and Parsons, 1972)
Orthophosphate (µg N·L^{-1})	Ascorbic acid (Strickland and Parsons,1972)
Total phosphorus (µg N·L^{-1})	Digestion, Ascorbic acid (Strickland and Parsons, 1972)
Chlorophyll–*a* (µg N·L^{-1})	Spectrophotometric (Strickland and Parsons, 1972)
Particulate organic matter, POM (%)	Ignition loss (Verardo *et al*., 1990; Thimdee *et al*., 2003)

of the water quality parameter. When a variable did not follow a normal distribution, a logarithmic transformation was applied. Duncan's multiple range test was employed to identify significant differences between stations and seasons. The relationship between season and water quality values was examined using Pearson's correlation coefficient. All statistical tests were considered significant at $p<0.05$. Contour plots were generated using the Ocean Data View program to visually represent selected datasets (Schlitzer, 2007).

RESULTS AND DISCUSSION

Temperature and salinity of the seawater showed clear seasonal differences across all stations ($p<0.05$). The rainy season brought warmer waters, with average temperatures of 30.48±0.31 °C, about 1 °C higher than the dry season's 29.75±0.47 °C. Meanwhile, salinity flipped the other way: during the dry season, salinity averaged 31.65±0.48 ppt, roughly 2 ppt higher than in the rainy season, where it dropped to 28.98±1.82 ppt. pH, DO, and TSS showed no significant differences ($p\geq0.05$). During the dry season, the average values were 8.27±0.05 for pH, 18.55±10.17 mg·L^{-1} for TSS, and 5.21±0.50 mg·L^{-1} for DO. During the rainy season, they slightly changed to 8.26±0.16 for pH, 16.80±5.86 mg·L^{-1} for TSS, and 5.59±1.33 mg·L^{-1} for DO.

During the dry season (March 2020), the temperature remained relatively uniform across all water layers (Figure 2a). In contrast, during the rainy season (August 2020), temperature variations became more pronounced, particularly at the surface, where temperatures ranged from approximately 30 °C to over 31 °C across different locations. Warmer waters were observed in the western and central parts of the study area, while slightly cooler temperatures appeared in the eastern region. This variability was likely influenced by increased freshwater input, localized atmospheric conditions, and daily fluctuations in solar radiation. The time of day may play a role in surface temperature changes, while the middle and bottom layers remain largely unaffected due to the high specific heat capacity of water. Temperature in the deeper layers remained more stable, with temperatures hovering around 30.5 °C, showing less spatial variation compared to the surface (Figure 2a).

Salinity showed a significant seasonal influence ($p<0.05$) but followed a consistent vertical trend. In the dry season, salinity was relatively uniform across stations, except for two northeastern locations where slightly lower values were observed (Figure 2b). However, during the rainy season, salinity levels decreased overall, and the water column exhibited moderate stratification, with lower salinity at the surface and higher salinity at the bottom. Stratification was observed across almost the entire area, where surface salinity dropped below 28 ppt, while bottom salinity remained above 31 ppt (Figure 2b). This pattern suggests a strong influence of freshwater input from precipitation and runoff, creating vertical salinity gradients that were absent in the dry season.

During the dry season, vertical profiles of pH and DO remain relatively stable across water layers at most stations (Figure 3e, 3i). In contrast, the rainy season showed surface enrichment with higher pH and DO levels compared to deeper layers (Figure 3f, 3j). This vertical pattern was not attributed to photosynthetic activity, as Chlorophyll–*a* concentration did not differ significantly between areas of high and low pH or DO levels (Figure 6d). This suggests a limited role of phytoplankton in driving these changes. Instead, processes such as air–sea gas exchange and organic matter decomposition likely played a more prominent role. DO levels in bottom waters declined to approximately 3 mg·L^{-1} at station SC–3 during the rainy season, indicating localized oxygen depletion likely linked to microbial respiration and reduced vertical mixing. This coincided with a drop in pH, further supporting the role of organic matter breakdown in acidifying bottom waters. Across both seasons, TSS concentrations were consistently higher in the middle and bottom layers, with much lower values at the surface (Figure 3g, 3h). Elevated TSS in deeper layers may have limited light penetration, reinforcing the minimal influence of photosynthesis on pH and DO near the bottom.

Average concentrations of ammonia and nitrite were substantially higher during the rainy season, reaching 28.62±16.14 µg N·L^{-1} and 6.53±9.86 µg N·L^{-1}, respectively, compared to 19.98±10.66 µg N·L^{-1} for ammonia and 1.24±0.71 µg N·L^{-1} for nitrite in the dry season (Figure 4). Nitrate concentrations showed no significant seasonal variation between the dry season (4.60±4.24 µg N·L^{-1}) and the rainy season (4.00±2.66 µg N·L^{-1}). Orthophosphate concentrations varied spatially among stations but did not differ between seasons, with averages of 1.18±0.18 µg P·L^{-1} in the dry season and 1.19±0.15 µg P·L^{-1} in the rainy season.

Vertical profiles of nutrient concentrations revealed clear seasonal variations (Figure 5). During the dry season, concentrations of ammonia, nitrite, nitrate, and orthophosphate remained relatively low, generally below 25 µg N·L^{-1} for ammonia, 2 µg N·L^{-1} for nitrite, 8 µg N·L^{-1} for nitrate, and 20 µg P·L^{-1} for orthophosphate. In contrast, during the rainy season, all nutrient concentrations increased, particularly in bottom waters near Station SC–3, where barges were present. Elevated nutrient levels in deeper waters suggest nutrient accumulation driven by sediment resuspension and reduced vertical mixing, with values exceeding 55 µg N·L^{-1} for ammonia, 30 µg N·L^{-1} for nitrite, 20 µg N·L^{-1} for nitrate, and 25 µg P·L^{-1} for orthophosphate.

Concentrations of TN were higher in the dry season, increasing with depth and peaking in the north and northeast areas (Figure 6a). TP also showed greater concentration in the bottom layer in the northern part of the study area. In the rainy season, TP concentrations were moderately high and more evenly distributed at the water surface during the POM displayed a uniform vertical distribution during the dry season, while in the rainy season, POM levels increased with depth and were concentrated in the north and northeast, coinciding with the barges location (Figure 6b, 6c). Chlorophyll–*a* concentrations showed greater spatial variation during the dry season, with elevated concentrations at the surface and mid–depths compared to the bottom (Figure 6d).

The average values of DO, pH, and TSS showed no significant differences ($p \geq 0.05$) across sampling stations or between seasons. In contrast, average concentrations of POM, ammonia, nitrite, and nitrate varied significantly by both station and season. POM concentrations were significantly higher in the dry season compared to the rainy season ($p<0.05$). Stations SC–2, SC–3, SC–5, SC–6, SC–7, and SC–10, located near the tapioca starch unloading point, exhibited significantly higher POM levels than Stations SC–9, SC–11, SC–12, SC–13, SC–14, SC–15, and SC–16, which are situated further south of the unloading area. Among the nitrogen compounds, ammonia and

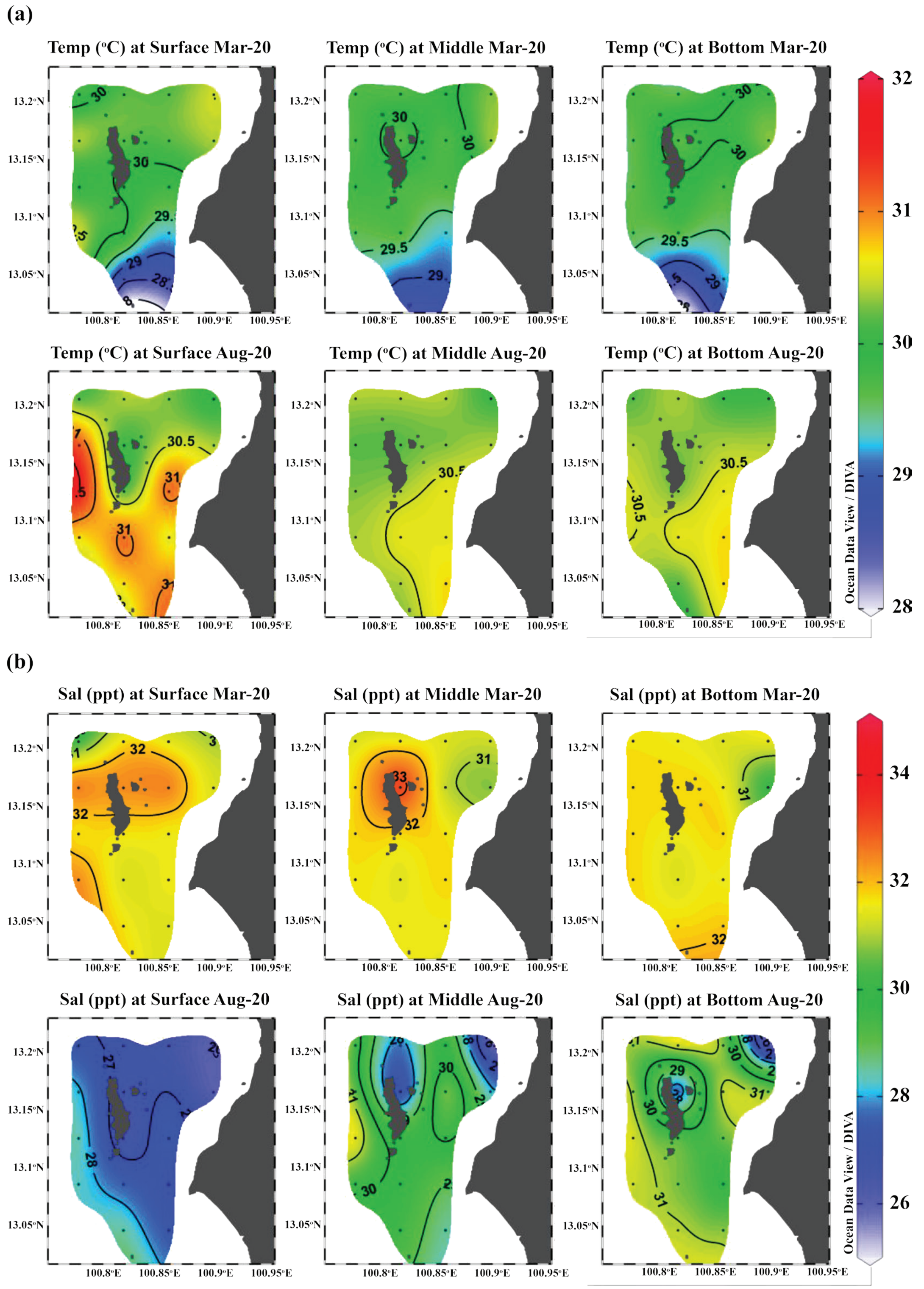

Figure 2. Spatial distribution of (a) water temperature and (b) salinity at different depths offshore in the Sriracha cargo transfer area. Color contours indicate concentration gradients, with warmer colors (e.g., red and orange) representing higher values and cooler colors (e.g., blue and green) indicating lower values.

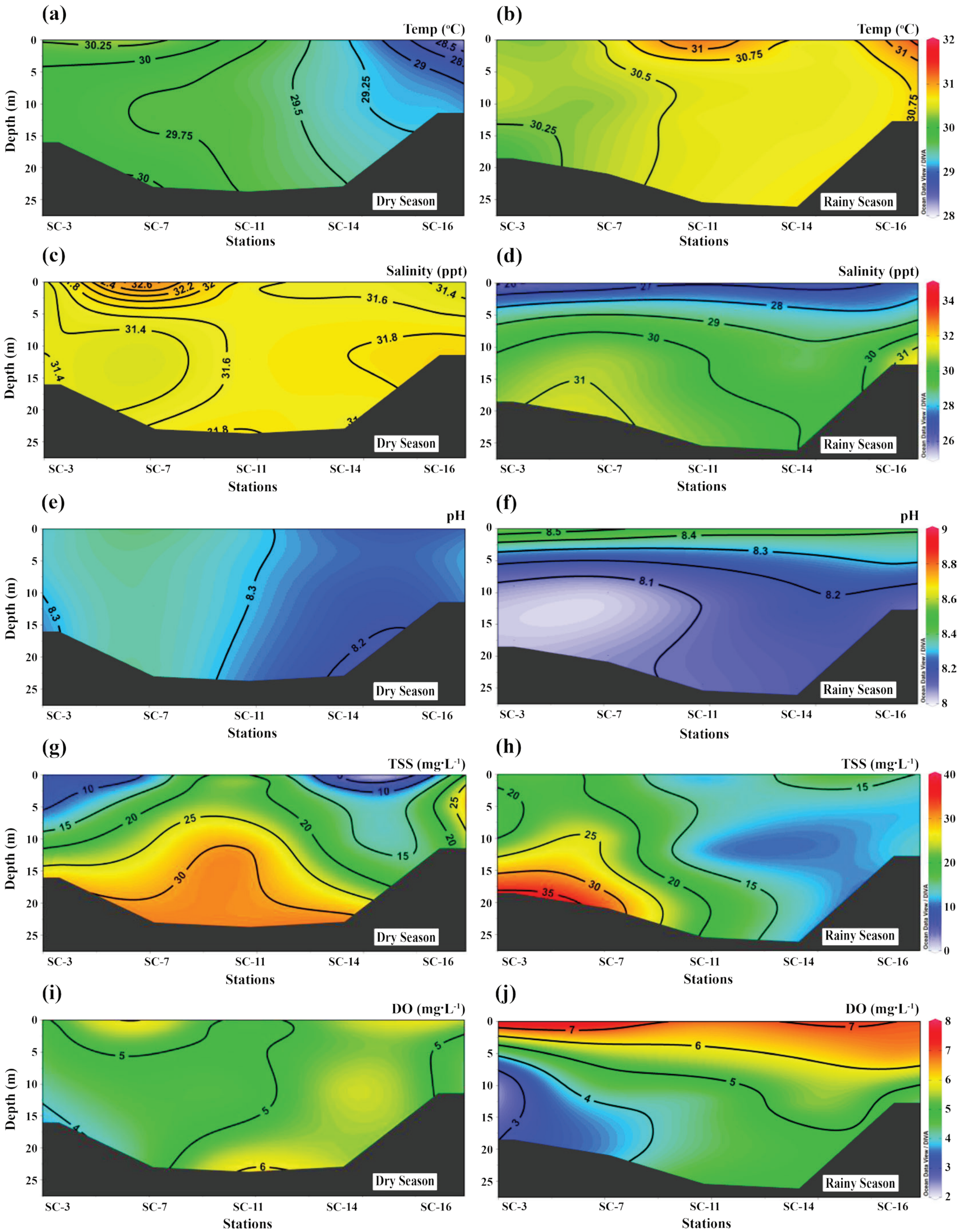

Figure 3. Vertical distribution of temperature (a, b), salinity (c, d), pH (e, f), total suspended solids (TSS) (g, h), and DO (i, j) in offshore waters around the Sriracha cargo transfer area during the dry season (left panels) and rainy season (right panels), along the transect line shown in Figure 1. Color contours indicate concentration gradients, with warmer colors (e.g., red and orange) representing higher values and cooler colors (e.g., blue and green) indicating lower values.

nitrite concentrations were significantly higher in the rainy season ($p<0.05$), whereas nitrate concentrations were significantly higher during the dry season ($p<0.05$). At the station level, the highest ammonia concentrations were recorded at Stations SC–1, SC–7, and SC–10, with SC–7 and SC–10 situated close to the unloading site. The lowest ammonia concentration was observed at Station SC–16, a reference station ($p<0.05$). The highest nitrite concentration was found at SC–10, though it was not significantly different from Station SC–1, SC–3, and SC–7 ($p\geq0.05$), all of which are near the unloading area.

Significant differences in phosphate and TP concentrations were observed among stations but not between seasons ($p\geq0.05$). The highest phosphate concentrations were found at Stations SC–2 and SC–3, significantly exceeding those at Station SC–1, SC–5, SC–11, SC–12, and SC–13 ($p<0.05$). Similarly, TP concentrations were highest at Station SC–3, with significantly higher values compared to Station SC–1, SC–5, SC–8, SC–9, SC–11, SC–12, SC–13, SC–14, SC–15, and SC–16 ($p<0.05$). Chlorophyll–*a* concentrations were significantly higher in the dry season than in the rainy season ($p<0.05$), although no significant differences were detected among stations ($p\geq0.05$). However, during the dry season, Station SC–6 exhibited the highest chlorophyll-a concentration.

During the rainy season, pH values in surface water were slightly alkaline and evenly distributed across all sampling stations, consistent with the high DO concentrations observed in the same area. At all sampling sites, concentrations of

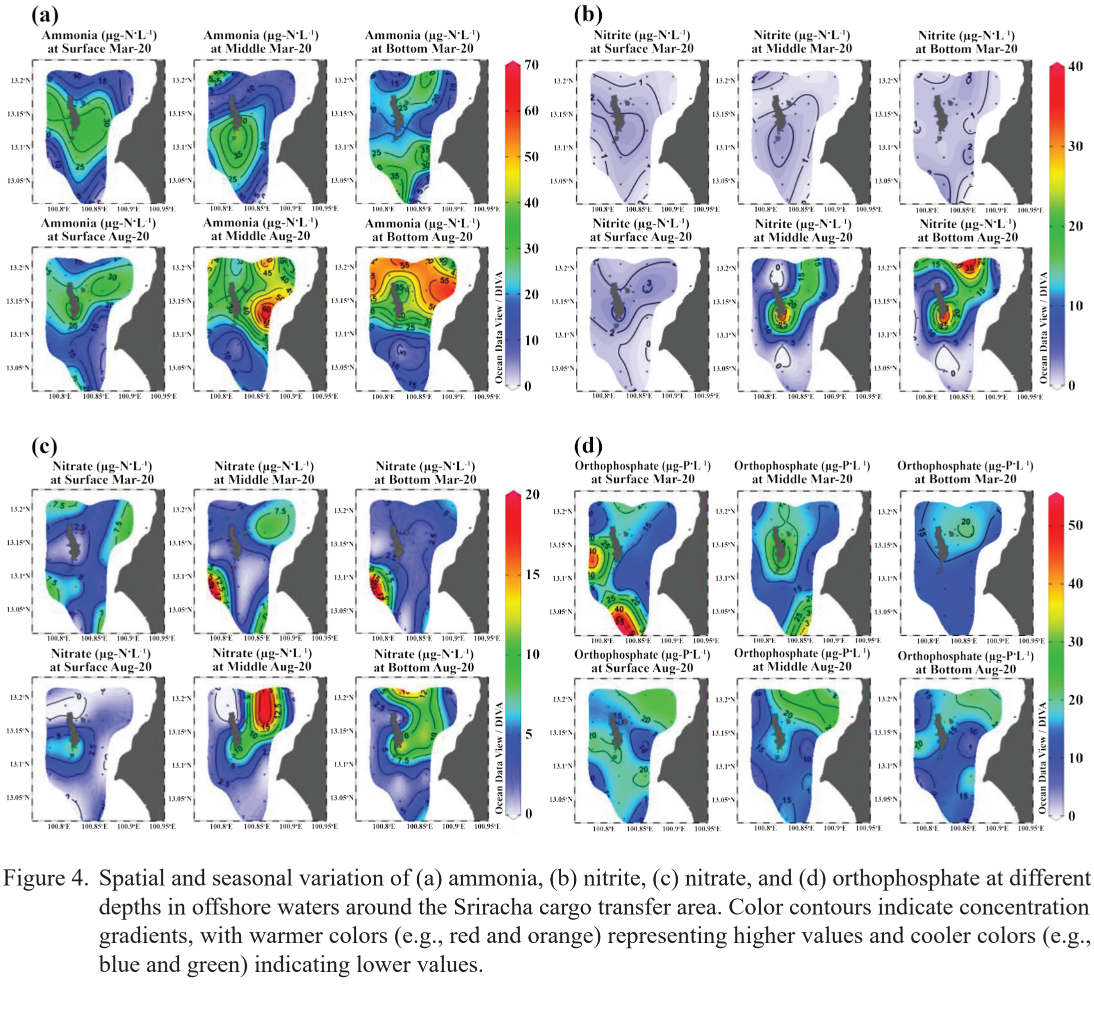

Figure 4. Spatial and seasonal variation of (a) ammonia, (b) nitrite, (c) nitrate, and (d) orthophosphate at different depths in offshore waters around the Sriracha cargo transfer area. Color contours indicate concentration gradients, with warmer colors (e.g., red and orange) representing higher values and cooler colors (e.g., blue and green) indicating lower values.

ammonia, nitrite, and nitrate in near-bottom waters were high during the rainy season. These elevated levels were associated with higher particulate organic matter (POM), particularly at Station SC–3, located in the northeastern part of Sichang Island, an area affected by heavy tapioca loading activities (Figures 1 and 6c). Although the quantity of tapioca starch loaded did not differ significantly March (approximately 300,000 t) and August (approximately 350,000 t) (data source: Laem Chabang Port Customs Office), the absence of POM accumulation in bottom water during March is likely attributed to vertically well–mixed water column conditions (Figure 3c). In contrast, in August, stratification induced by freshwater inflow during the rainy season (Figure 3d) limited vertical mixing, allowing POM to accumulate in the bottom layer.

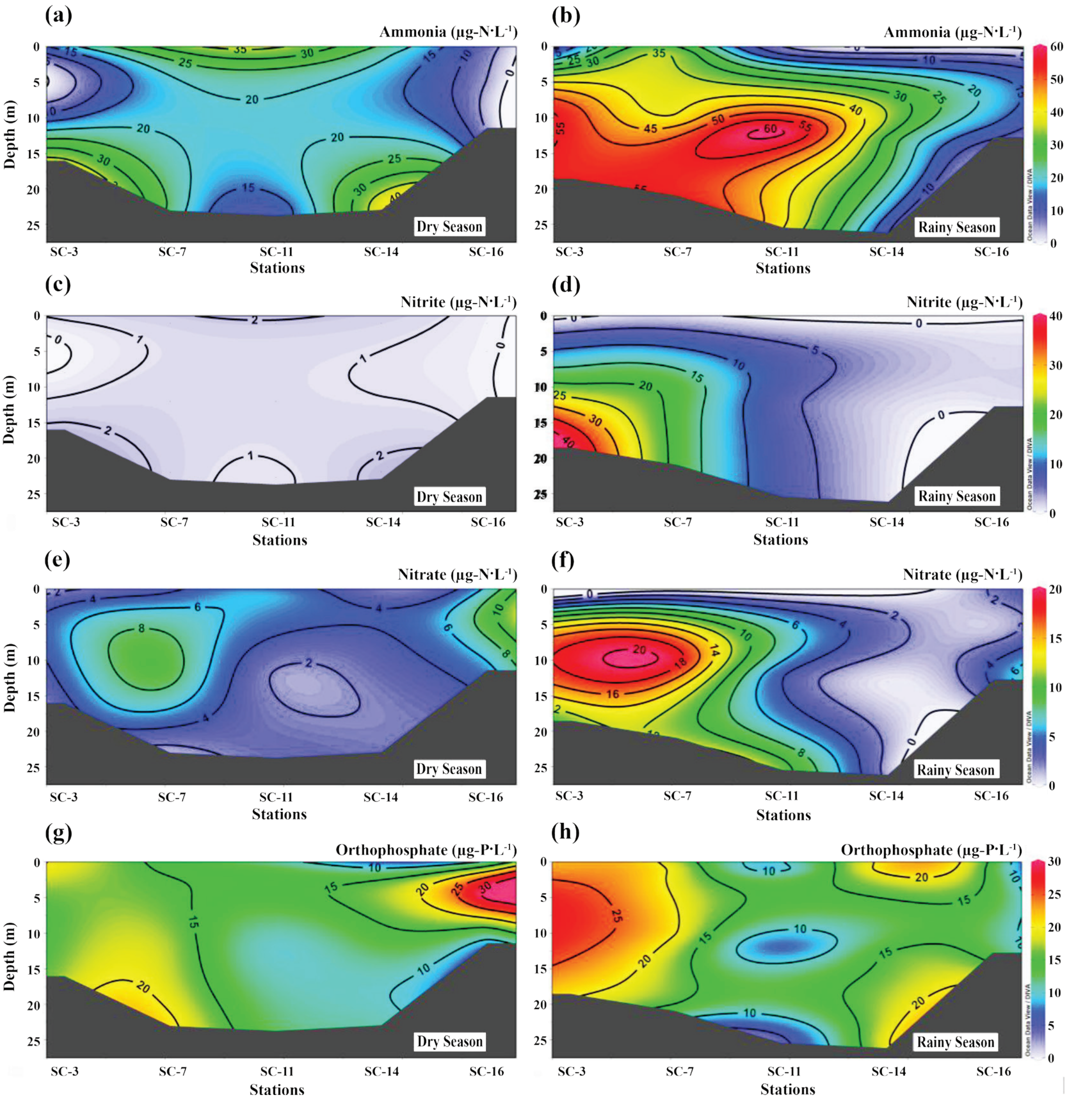

Figure 5. Vertical distribution and seasonal variation of inorganic substances; ammonia (a, b), nitrite (c, d), nitrate (e, f), and orthophosphate (g, h) in offshore waters around the Sriracha cargo transfer area during the dry season (left panels) and rainy season (right panels), along the transect line shown in Figure 1. Color contours indicate concentration gradients, with warmer colors (e.g., red and orange) representing higher values and cooler colors (e.g., blue and green) indicating lower values.

High POM accumulation inhibited oxygen diffusion, promoted the formation of sulfide gas, and created inhospitable conditions for benthic organisms. Conversely, sites located in the southern part of the study, farther from cargo handling activities and used as reference sites (e.g., Station SC–5), exhibited lower concentrations of nitrogen nutrients. The pattern of elevated nutrient levels near the bottom and lower concentrations near the surface suggests that these nutrients may have been released from sediments that accumulated waste from cargo operations, particularly near Station SC–3. This interpretation aligns with the findings of Rakseree *et al*. (2024), who reported that total organic material (TOM) in sediments near the tapioca starch loading area exceeded 10% of sediment dry weight, whereas other areas showed significantly lower TOM levels, around 4-5%.

Specific studies on the decomposition of tapioca in seawater are limited. However, research on cassava starch–based bioplastics indicates that decomposition begins after approximately seven days and continues for up to two weeks (Yusnizam *et al*., 2023). When present as tapioca powder, decomposition is likely to occur more rapidly due to the increased surface area and better dispersion in water, which facilitates microbial colonization and enzymatic activity. Although tapioca is not the only bulk organic material transported in the study area, the only other major cargo is refined sugar, which generates considerably less organic dust compared to tapioca. As a result, tapioca isconsidered the primary source of organic contamination in both seawater and sediments in the area. This emphasizes the environmental significance of its transport activities.

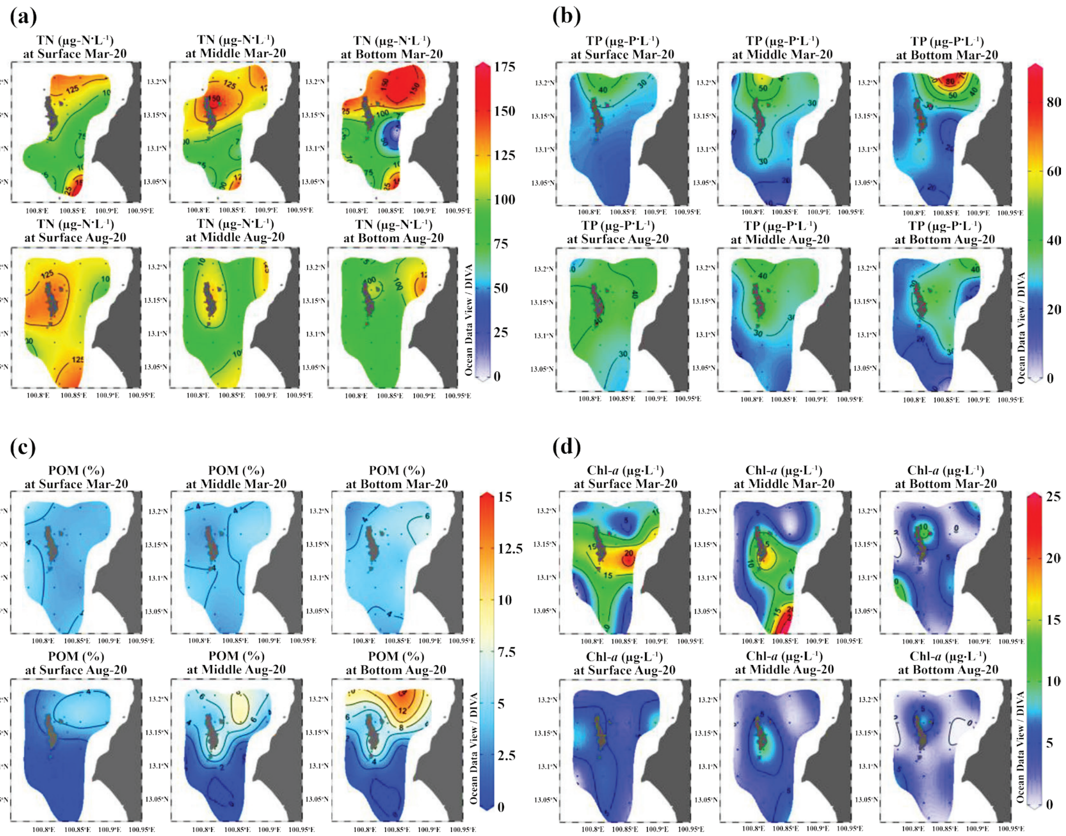

Figure 6. Spatial and seasonal variation of (a) total nitrogen, (b) total phosphorus, (c) particulate organic matter, and (d) chlorophyll–*a* at different depths in offshore waters around the Sriracha cargo transfer area. Color contours indicate concentration gradients, with warmer colors (e.g., red and orange) representing higher values and cooler colors (e.g., blue and green) indicating lower values.

The accumulation of nutrients and low DO levels in bottom waters during the rainy season can be attributed to water column stratification, as indicated by lower surface salinity compared to bottom layers (Figure 3d). DO concentrations as low as 3 mg·L^{-1} near the loading site suggest that hypoxia conditions may be developing. Limited vertical mixing under stratified conditions likely contributes to the accumulation of organic matter and associated nutrients in deeper water masses.

In contrast, the elevated concentrations of TN and TP observed during the dry season (Figure 6a, 6b) may result from intensified tapioca loading activities, which could cause the release of organic substances into the water. These substances may not have fully decomposed at the time of sampling, leading to high TN and TP levels but relatively low concentrations of other inorganic nutrients such as DIN and DIP. Nevertheless, higher concentrations near the seabed compared to the sea surface were still observed. However, due to effective vertical mixing during the dry season, such accumulation in deep waters is unlikely to persist.

The overall water quality across all sampling sites throughout the year complied with the seawater quality standards for natural resource conservation and met the criteria for industrial and port activities (Notification of the Environmental Committee, 2021). These findings are consistent with previous reports (Swingle, 1969; Graham and Wilcox, 2000; Na-u-dom *et al*., 2013; Kongpradit and Buranapratheprat, 2023). Although ammonia and nitrate concentrations generally meet seawater quality standards set by the Pollution Control Department (2014), orthophosphate concentrations at some stations exceeded the threshold limit of 15 µg P·L^{-1}, even in areas not directly impacted by cargo handling activities. This suggests that the primary source of orthophosphate contamination may not be cargo handling activities but rather domestic wastewater discharges from land-based settlements and islands in the area, as well as direct discharge from vessels. Consequently, orthophosphate levels tend to be higher in surface waters and lower near the sea bottom.

The orthophosphate concentrations recorded in this study were higher than those reported in earlier surveys conducted in 2001 (Yoosamran *et al*., 2004), and 2013 (Marboon *et al*., 2017), and they may promote plankton blooms, particularly during the rainy season. Chlorophyll–*a* concentrations ranged from 0.27 to 23.34 µg·L^{-1}, suggesting mesotrophic to hypertrophic conditions (Niles *et al*., 1996). These values were generally higher during the dry season (Figure 4g), possibly due to elevated orthophosphate levels stimulating phytoplankton growth. As with orthophosphate, chlorophyll–*a* levels did not appear to be directly influenced by cargo activities. In fact, the chlorophyll–*a* concentrations in this study were higher than previously reported values, which ranged from 0.035 to 0.574 mg·L^{-1} (Pollution Control Department, 2014).

Although direct studies on the relationship between tapioca and other agricultural product handling and water quality are limited, it is reasonable to infer that organic matter from such activities eventually decomposed via microbial action, releasing nutrients into the water. This logical connection forms the basis of our investigation. The environmental impact of tapioca transfer, the most significant bulk loading activity in the study area, has received little attention, and this study seeks to address that gap. While our findings may not provide conclusive answers, they represent a critical starting point in understanding the environmental implications of this large–scale activity. Given that hundreds of thousands of tons of tapioca products are transferred each month, it is vital to consider their potential impact on marine ecosystems. Our results suggest that tapioca transport may contribute to elevated nutrient levels, raising concerns about eutrophication and oxygen depletion. Further research is needed to determine the precise degradation rate of tapioca starch in seawater, identify decomposition byproducts, and assess the potential for hypoxia. A more systematic investigation is essential to fully understand the long–term ecological consequences and to guide appropriate environmental management strategies in maritime cargo areas.

CONCLUSIONS

Water quality offshore of Sriracha and Sichang Island was assessed in March and August 2020 to evaluate the impact of maritime cargo loading activities. Particulate organic matter (POM), ammonia, nitrite, and nitrate were significantly higher during the rainy season, with high concentrations observed in the near-bottom waters of the northern and northeastern areas adjacent to the loading zone. In contrast, total nitrogen (TN) and total phosphorus (TP) were also higher during the dry season, particularly in near–bottom waters of the same area.

Orthophosphate and TP showed significant spatial variation but no clear seasonal trend, while chlorophyll–*a* exhibited seasonal variation without distinct spatial patterns. All parameters complied with seawater quality standards, except for orthophosphate, which exceeded the permissible limit at several stations. Surface water quality remained good overall, but the accumulation of particulate organic matter (POM) and certain inorganic substances near the sea floor close to cargo handling areas suggests localized deterioration.

These findings indicate that the transport of agricultural products, especially tapioca, can influence the marine environment by contributing organic matter to sediments. As this organic matter decomposes, it releases inorganic nutrients into the water column, potentially affecting ecosystem health and contributing to eutrophication near the cargo transfer zones.

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