Effects of Transporting Tapioca Products on Sediment Quality Offshore of Sriracha Bay, Chonburi Province, Thailand

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ABSTRACT

Transporting tapioca starch in coastal areas leads to dust dispersion, contributing to pollution in Sriracha Bay, Chonburi Province, Thailand. This pollution poses a threat to marine life, highlighting the need for monitoring to prevent environmental harm. To address this issue, sediment samples were collected from 16 locations in Sriracha during both the dry season (March 2020) and the rainy season (August 2020). The study aimed to examine variations in organic matter, a byproduct of tapioca dust transportation, over time. Analysis revealed that silty-clay sediments predominated in the area. During the dry season, sedimentary parameters such as total organic matter (TOM) (8.72±3.21%) and hydrogen sulfide (0.03±0.02 mg $S \cdot g^{-1}$), were notably high. In contrast, the rainy season revealed elevated water content, carbon, sulphur (53.59±14.48%, 2.31±0.22 $mg \cdot g^{-1}$ and 0.16±0.12 $mg \cdot g^{-1}$, respectively) and higher nutrient levels in pore water, including ammonia, nitrite and total nitrogen (18.12±4.11, 0.14± 0.09 and 121.27±31.77 mg $N \cdot L^{-1}$, respectively). Organic matter in the sediment was particularly concentrated in the northeast region, where tapioca starch was loaded onto ships, coinciding with relatively acidic conditions. These areas showed higher levels of TOM (11.30–15.91%), especially during the dry season. The study advocates for dust management during tapioca starch transshipment as a crucial measure to mitigate the rise in TOM and hydrogen sulfide, which could jeopardize the marine ecosystem.

Keywords: Offshore of Sriracha, Sediment quality, Tapioca products transporting

INTRODUCTION

Seaborne transport plays a vital role in boosting exports and imports, facilitating international trade through accessible seaports. However, while these activities foster economic growth, they also pose environmental challenges such as air, water, and marine pollution due to dust dispersion or material leakage during loading operations.

Sriracha District in Chonburi Province, Thailand, serves as a significant industrial hub, housing major manufacturing and shipping industries. The Port of Laem Chabang, ranked as the 20th largest port globally (World Shipping Council, 2024), is a critical component of this district. The Sriracha transshipment area, located between Sichang Island and the mainland (Figure 1), features a deep-sea channel with depths of 12–18 m and mild wind waves (Port Authority of Thailand, 1991). These conditions make it ideal for large cargo ship transport. Currently, it is Thailand's foremost transshipment area, handling the highest volume of sea freight (Kobkaew, 2019). Cargo in this region falls into two categories: bulk products, such as cement, tapioca starch, chips, pellets, and imports like coal, fertilizers, soybeans, and soda ash. The second category includes packaged products requiring manual unloading, such as sugar, rice, corn, and tapioca starch (Siamratanakij *et al*., 2021).

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The continuous loading and transport of agricultural products in large volumes and accidents involving ships carrying items like fertilizers or pesticides can severely impact the environment. Spills may contaminate water bodies, harm marine life, and disrupt ecosystems. For example, nutrient-rich fertilizer spills can trigger eutrophication, causing algal blooms and oxygen depletion, ultimately affecting marine biodiversity and fisheries (FAO, 2019). Similarly, dry bulk loading using grab buckets generates dust particles that enter seawater, and vessel cleaning contributes to further contamination, degrading water quality and sediment around loading sites. Numerous studies have documented ecological damage and its effects on marine resources in the region (Yoosamran *et al*., 2006; Khuntong *et al*., 2010; Vichkovitten *et al*., 2017; 2018; Siamratanakij *et al*., 2022).

Sedimentary organic matter plays a critical role in the coastal biogeochemical cycle (Vaalgamaa *et al*., 2013). However, excessive sedimentation can smother benthic habitats, reduce light penetration, and disrupt filter-feeding organisms. Sediment can also transport pollutants and nutrients, degrading water quality and marine ecosystems. In marine sediments, tapioca dust decomposes, enriching nutrients in pore water. Microorganisms decompose this organic matter, facilitating nutrient cycling but also consuming oxygen (Meksumpun *et al*., 2013). High decomposition rates can deplete oxygen levels, harm benthic organisms, and create conditions for harmful substances such as hydrogen sulfide (Izah *et al*., 2018), posing a significant threat to marine life. Seaport activities affect marine environments in multiple ways, including impacts on water quality, coastal hydrology, bottom contamination, air quality, noise and vibration, marine ecology, waste management, socio-cultural aspects, and visual aesthetics. The transportation of tapioca starch in the Sriracha transshipment area has persisted for at least 17 years (Intarachart *et al*., 2009). Since 2017, local communities have raised concerns over dust dispersion (MGR Online, 2017), which not only contaminates the air but also settles into marine sediments. Understanding the spatial distribution of organic matter and sediment quality in the surface sediments of Sriracha Bay is essential for effective environmental management and conversation.

MATERIALS AND METHODS

Study area and sampling point

The study area is located offshore of Sriracha District in Chonburi Province, spanning the coordinates 13°20'–13°04'N and 100°77'–100°85'E (Figure 1). This region lies within the continental monsoon climate zone, experiencing an annual average precipitation of 1,220 mm (Thai Meteorological Department, 2022). The primary site for tapioca loading and transportation is situated in the Gulf of Thailand, approximately six kilometers from the shoreline.

To evaluate the environmental impact of shipping activities, 15 sampling stations were strategically placed around Sichang Island and Sriracha Bay. An additional sampling station (SC-5), located outside the influence of shipping operations, was designated as a reference point. Sampling was conducted twice, during the dry season (March 2020) and the rainy season (August 2020), to capture seasonal variations.

Sample collection and preparation

Surface sediment samples (0–1 cm depth) were collected from 16 locations (Figure 1), with three subsamples obtained at each site using an Ekman-Birge bottom sampler. Approximately 500 g of sediment from each location was placed in zip-lock bags and transported in a dark container filled with ice, maintaining a temperature below 4 ºC. Samples were stored at -20 °C upon arrival at the laboratory to preserve their integrity for subsequent analyses.

Sample analysis

The sediment samples were air-dried at room temperature until a constant weight was achieved, with stones and plant residues removed. Analytical methods employed are summarized in Table 1.

Physical properties of the sediments were assessed as follows: Grain size was determined using a sieving method. Sediments were pulverized

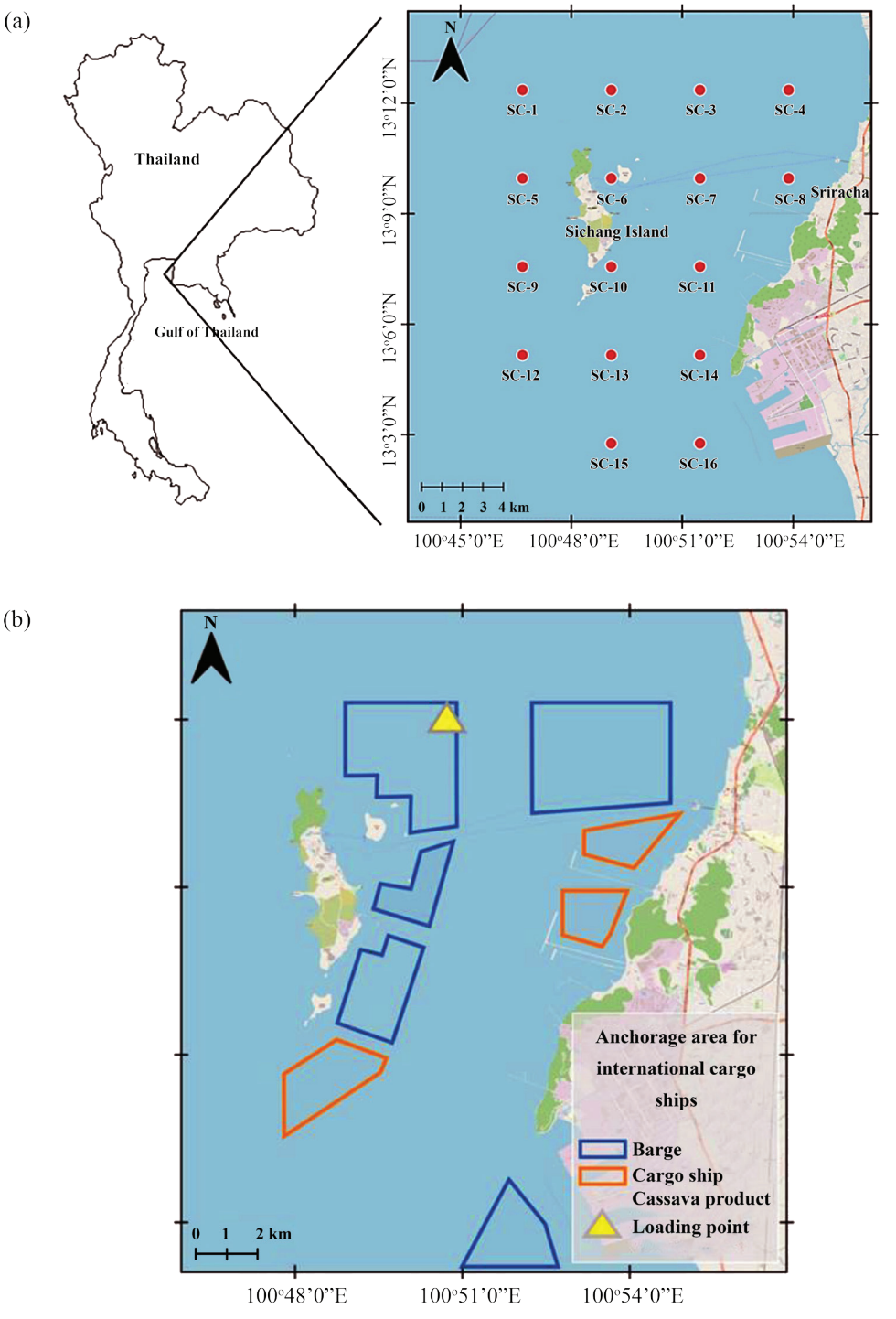

Figure 1. Study area offshore of Sriracha District: (a) sampling sites around Sichang Island and Sriracha Bay; (b) anchorage area designated for international cargo ships.

Table 1. Analysis methods of different sediment parameter.

Sediment parameter	Analysis method
Grain size	Sieve analysis (Carter, 1993)
Water content (%)	Oven drying (Chuan and Sugahara,1984)
Total organic matter (TOM) content (%)	Losson Ignition (Verardo *et al*., 1990)
Acid volatile sulfide (AVS) content (mg $S \cdot g^{-1}$)	Acid volatile sulfide test column (Chuan and Sugahara, 1984)
Sediment pH	1:1 mixture (Dewis and Freitas, 1970)
Net nutrients in pore water (mg $N \cdot L^{-1}$)	
- Ammonia (NH_3+NH_4^+)	Phenate Method (Boyd and Tucker, 1992)
- Nitrite (NO_2^-)	Colorimetric Method (Boyd and Tucker, 1992)
- Nitrate (NO_3^-)	Colorimetric, Cadmium Reduction Method Grasshoff *et al*. (1983)
- Total nitrogen (TN)	Digestion, Cadmium reduction, and Diazotization (Strickland and Parsons, 1972)
Elements content (mg·g^{-1} dry weight)	Instrument Method (Thermo ScientificTM
- Carbon, hydrogen, nitrogen and sulphur	FLASH, 2000)

and sequentially sieved through mesh sizes of 1.00, 0.425, 0.250, 0.125, and 0.063 mm. The sediment retained on each sieve was oven-dried at 80 ºC for three days, after which the weight of the dried sediment was measured, and the proportion of sediment particles was calculated. Water content (%) was determined gravimetrically by calculating the mass of water lost, following the methodology outlined by Chuan and Sugahara (1984). The difference between wet and dry weight was calculated after drying for 8 h at 110 ºC.

To assess variations in sediment chemical properties across sites, the analysis focused on TOM, hydrogen sulfide, and pH levels. The determination of TOM employed the lost-on-ignition method (Verardo *et al*., 1990). Initially, sediment samples were dried 9 overnight at 100 °C to measure water loss, followed by furnace treatment at 550 °C for 4 h. TOM was calculated as the weight loss (%) relative to the dry weight after ignition. For acid volatile sulfides (AVS) content, the procedure outlined by Chuan and Sugahara (1984) was followed. Wet sediment samples (0.5–1.0 g) were analyzed to convert sulfide (HS^-, S^{2-}, and FeS_2) into hydrogen sulfide (H_2S) using 18 N sulfuric acid (H_2SO_4). The Hedrotek column (AVS test column) was used to measure the amount of hydrogen sulfide, enabling the calculation of total sulfide per unit dry weight of the sediment. The analysis of pH levels followed the methodology of Dewis and Freitas (1970). Ten g of wet sediment were combined with 1 N potassium chloride (20–25 mL), thoroughly mixed, and left for 30 min. The clear supernatant was then measured using a pH meter to determine the sediment's pH.

The nutritional composition of sediments was assessed by analyzing ammonia (NH_3+NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), and total nitrogen (TN). The process began with the extraction of pore water from sediment samples via centrifugation. The resulting centrifugate was filtered through a GF/C filter to eliminate finer particulate matter. Aliquots of the filtered extract were then treated for the analysis of ammonia, nitrite, nitrate, and total nitrogen. Ammonium concentration was determined using the indophenol blue colorimetric method, while nitrite levels were ascertained using the NED red colorimetric technique (Boyd and Tucker, 1992). Nitrate concentrations were measured spectrophotometrically following reduction with

cadmium, as outlined by Grasshoff *et al*. (1983). Total nitrogen was analyzed as nitrate after alkaline persulfate mineralization, following the procedure of Strickland and Parsons (1972). The elemental compositions of organic substances, including carbon, hydrogen, nitrogen, and sulphur, were analyzed in homogenized samples after acidification with 2 N HCl (Hedges and Stern, 1984). This analysis was conducted using an elemental 119 analyzer (FLASH 2000; Thermo Scientific, Wilmington, DE, USA) at the Scientific and Technological Research Equipment Centre, Chulalongkorn University.

Data analysis

The sediment quality analysis data underwent a comparison to discern spatial and temporal differences. Before conducting two-way statistical analysis, the original dataset underwent pretreatment, and subsequently, Duncan's test was employed to identify dissimilarities between stations and seasons. Before delving into statistical analysis, a Kolmogorov-Smirnov single-sample test was executed to assess the goodness-of-fit for the normal distribution of sediment quality parameters. The correlation between season and water quality values was scrutinized using Pearson's Correlation Coefficient. To visually represent some of the data, contour lines were generated using the Ocean program Data View (Schlitzer, 2007).

RESULTS

Physical properties

The physical characteristics of the sediment offshore of Sriracha were assessed based on two parameters: particle size distribution and *in-situ* water content. The sediments predominantly consisted of a silt-clay mixture, averaging 68.39% during the dry season and 55.37% in the rainy season (Figure 2). Particle size distribution varied among sampling sites. Stations SC–3, SC–3, SC–4, SC–8, and SC–14 displayed a higher percentage of silt-clay in the dry season, while SC–3, SC–4, and SC–10 exhibited a similar trend in the rainy season. The highest proportion of coarse sand was consistently observed at station SC–13 in both seasons.

The water content in the surface sediment was significantly influenced ($p<0.05$) by spatial variation ($F_{0.05}(14,43) = 46.13$), seasonal variation ($F_{0.05}(1,43) = 83.89$), and their interaction ($F_{0.05}(13,43) = 7.01$), as illustrated in Figure 3. The water content ranged from 19.12% to 79.19%, with higher values observed during the rainy season (average 53.59±14.27%) compared to the dry season (average 44.39±12.24%). Spatial variations in water content were also evident. During the rainy season, the highest mean water content was recorded at

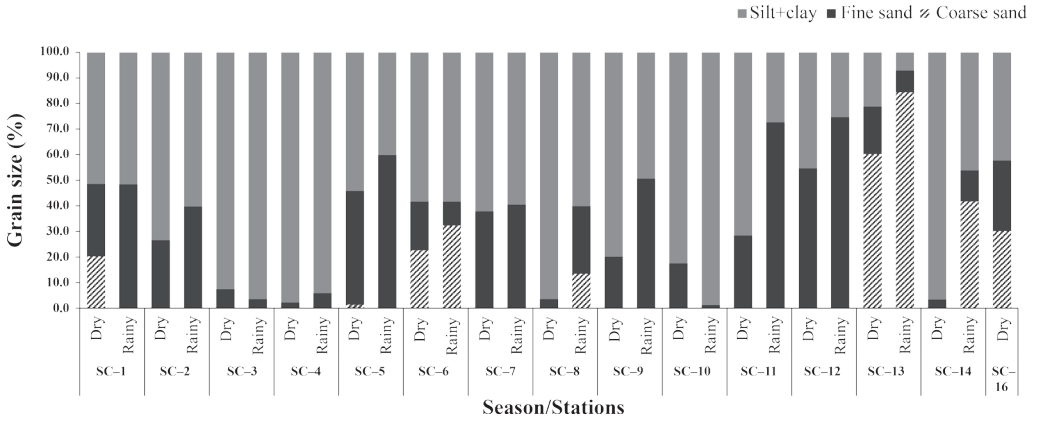

Figure 2. Sediment grain size offshore around the Sriracha transshipment area.
Note: Samples could not be collected in station 15 in the dry season and in stations 15 and 16 in the rainy season, due to the hard sea floor.

station SC–8, followed closely by SC–3. In the dry season, elevated water content was observed at stations SC–3 and SC–7. The interaction analysis revealed that the highest water content occurred at stations SC–3 and SC–8 during the rainy season (Figure 3).

During the rainy season, an increase in small sediment particles was observed, particularly in the northeastern region. In contrast, during the dry season, small particle sizes predominated across most stations, except for station SC–13, where larger particles were more prevalent. Sediment water content was also higher in the northeastern region where regular loading of tapioca starch onto ships occurs. The spatial distribution of surface sediment particle sizes and their corresponding water content is illustrated in Figure 4.

Sedimentary chemical properties

Throughout the study, the two main factors and their interactions affected the changes in the mean values of TOM, pH, and hydrogen sulfide (H_2S). The ranges of TOM, pH, and H_2S were 4.7%–6.2%, 5.3–8.2, and 0.0015–0.0930 mg S·g^{-1}, respectively. Higher levels ($p<0.05$) of TOM, pH, and H_2S were identified in the dry season, with averaging 8.72±3.21%, 6.42±0.87, and 0.030± 0.023 mg S·g^{-1}, respectively, compared to the rainy season, with averaging 6.17±0.69%, 6.17±0.69, and 0.041±0.026 mg S·g^{-1}, respectively ($F_{0.05}(1,58)$ = 3,793.22, 522.01 and 48.36, respectively). Spatial variations in these parameters were also observed. During the dry season, the highest TOM content was recorded at station SC–3, the maximum pH at station SC–13, and the peak H_2S concentration at station SC–4. In the rainy season, the highest TOM was recorded at station SC–13, the maximum pH at station SC–13, and the highest H_2S concentration at station SC–2. Interaction analysis revealed that the highest TOM, pH, and H_2S values were found during the dry season at stations SC–3, SC–16, and SC–16, respectively (Figure 5).

Figure 6 illustrates the spatial distribution of TOM, pH, and H_2S in surface sediment. The TOM levels tended to be higher in the northeastern region, coinciding with the regular loading of tapioca starch as indicated in Figure 1. Across most locations, the pH was slightly acidic, except for the southern part where the value was towards a natural level.

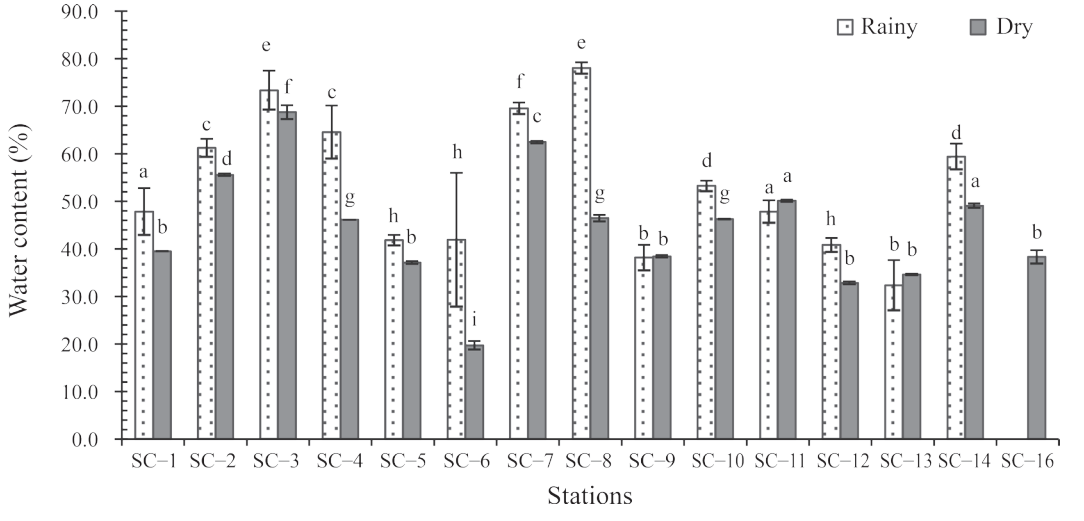

Figure 3. Water content in sediments collected from various sites offshore around Sriracha transshipment area during the rainy and dry seasons.

Note: Sampling could not be collected in station 15 in the dry season and in stations 15 and 16 in the rainy season, due to the hard sea floor. Bars represent mean values and error bars represent standard deviation (SD); Different lowercase superscripts above bars indicate significant differences ($p<0.05$) between means.

The highest concentration of H_2S was detected in the northeast site, while the lowest concentration served as a reference point in areas unaffected by shipping activities in the west of Sichang Island.

Nutrients in pore water

The nutrient levels in the pore water were significantly affected by the two main factors and their interactions. During the rainy season, higher concentrations ($p<0.05$) of ammonia, nitrite, and total nitrogen were observed, with averages of 18.12±4.11, 0.14±0.09, and 121.27±31.77 mg $N{\cdot}L^{-1}$, respectively, compared to the dry season, where the averages were 16.43±5.22, 0.02±0.04, and 45.62±13.56 mg $N{\cdot}L^{-1}$, respectively ($F_{0.05}(1,58) = 10.39$, 141.94, and 14,285.57, respectively). These nutrient levels also showed considerable spatial variation. In the dry season, the highest ammonia concentration was recorded at station SC–6, the nitrite peak at station SC–9, the maximum nitrate at station SC–1, and the highest total nitrogen at station SC–3. Conversely, during the rainy season, the highest ammonia was observed at station SC–3, the peak nitrite at station SC–1, the maximum nitrate at station SC–13, and the highest total ammonia at station SC–6. The interaction analysis revealed that the highest concentrations of ammonia, nitrite, and total nitrogen in pore water were observed during the rainy season at stations SC–3, SC–9, and SC–3, respectively. In contrast, the highest nitrate concentration was recorded during the dry season at station SC–1 (Figure 7).

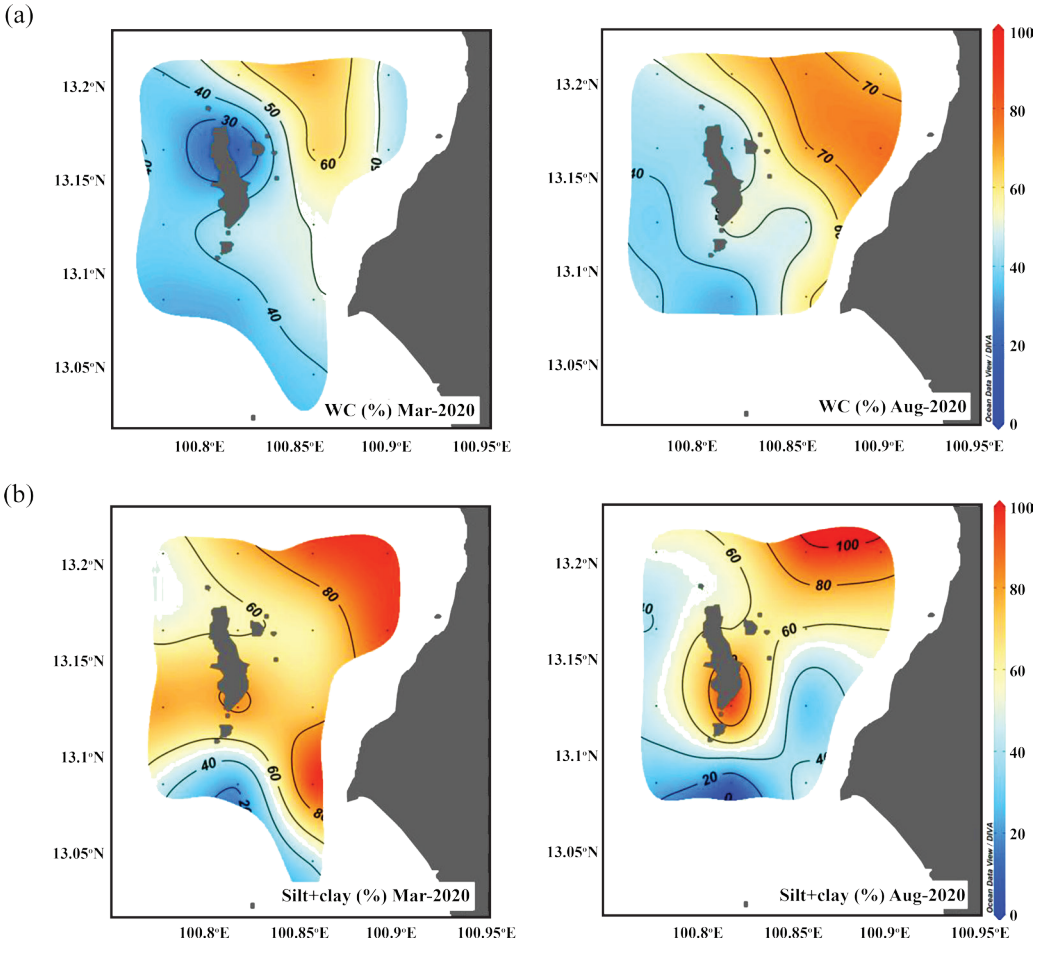

Figure 4. Spatial distribution of water content (a) and particle size (b) in surface sediment of the study area.

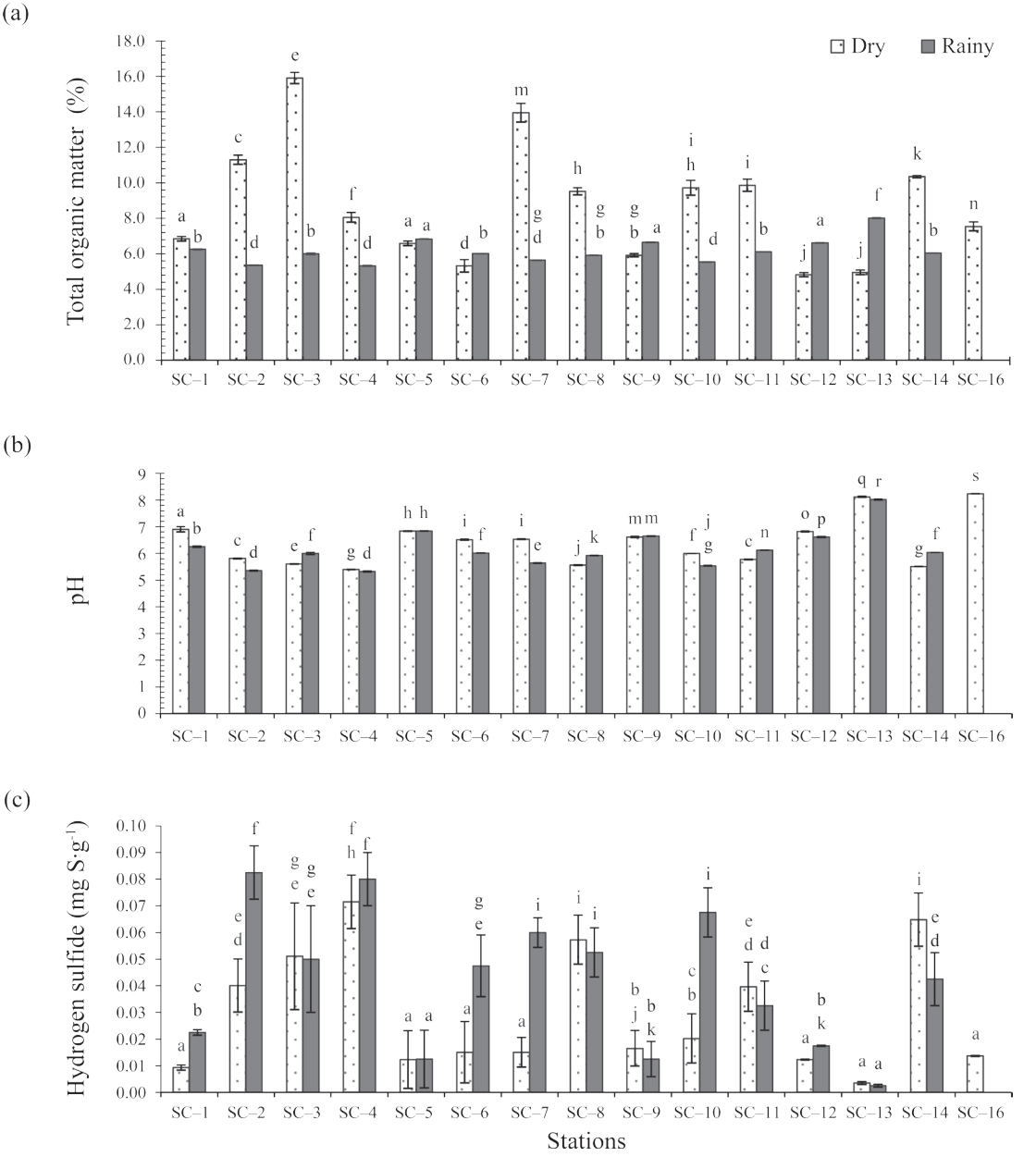

Figure 5. Sedimentary chemical properties at each sampling site during the rainy and dry seasons: (a) total organic matter (TOM), (b) pH, and (c) hydrogen sulfide (H_2S) in sediments from the offshore area around Sriracha transshipment zone.

Note: Samples could not be collected at station 15 in the dry season and at stations 15 and 16 in the rainy season, due to the hard sea floor. Bars represent mean values and error bars represent standard deviation (SD); Different lowercase superscripts above bars indicate significant differences ($p<0.05$) between means.

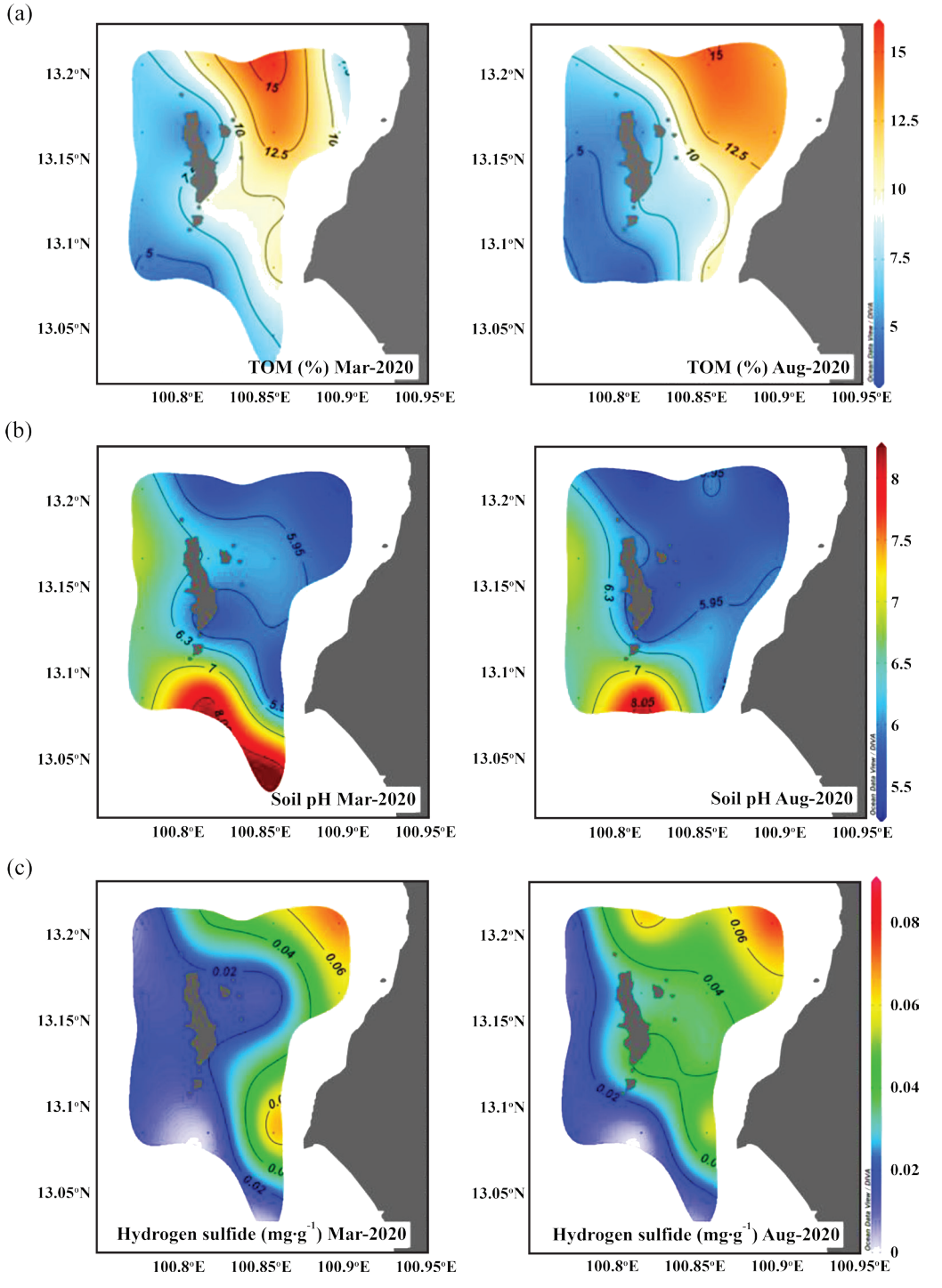

Figure 6. Spatial distribution of sedimentary chemical properties in surface sediments of the study area: (a) TOM, (b) pH, and (c) H_2S.

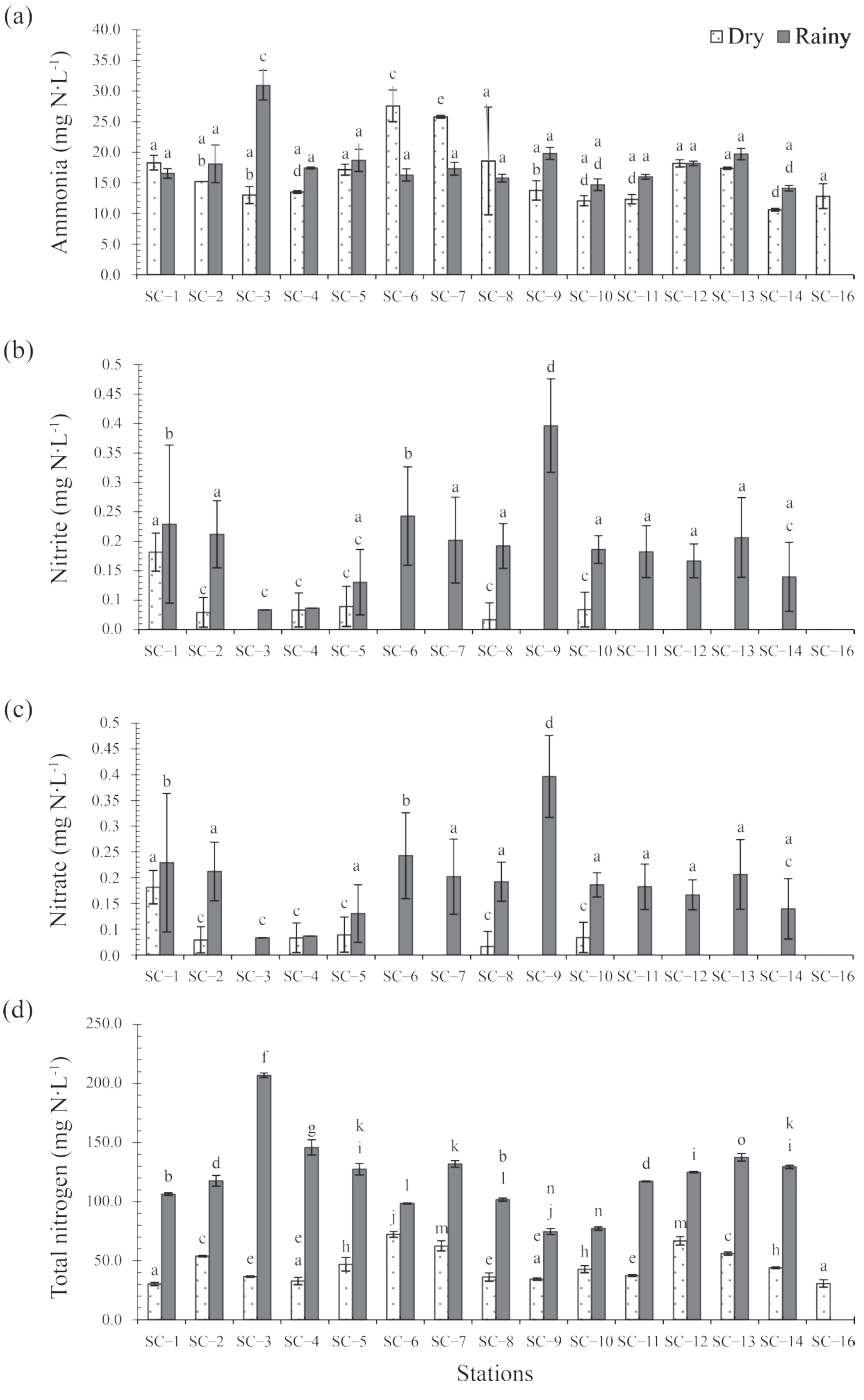

Figure 7. Nutrients in pore water in sediments collected from various sampling sites around the Sriracha transshipment area during the rainy and dry seasons: (a) ammonia; (b) nitrite; (c) nitrate; (d) total nitrogen.

Note: Samples could not be collected at station 15 in the dry season and at stations 15 and 16 in the rainy season, due to the hard sea floor. Bars represent mean values and error bars represent standard deviation (SD); Different lowercase superscripts above bars indicate significant differences ($p<0.05$) between means.

The spatial distribution of pore water nutrients within surface sediment is depicted in Figure 8. High nitrite concentrations were identified in the northeastern region, as well as in the barge and cargo ship areas during the dry and rainy seasons, respectively. Total nitrogen levels displayed slight fluctuations in the dry season but exhibited a sharp increase in most locations during the rainy season, except in areas further west of the barge and cargo zone. In the dry season, high nitrate was detected in the northwest, while in the rainy season, it was low with slight fluctuations across the area.

Elements in sediment

The elements in organic matter in sediment, hydrogen, and nitrogen, exhibit no significant seasonal variations ($p>0.05$), maintaining averages of 6.47±3.54 mg·g^{-1} dry weight and 1.06±0.99 mg·g^{-1} dry weight during the dry season and 6.43± 3.58 mg·g^{-1} dry weight and 1.1±0.94 mg·g^{-1} dry weight during the rainy season ($F_{0.05}(1,29) = 0.98$ and 0.007). The interaction results showed that the highest hydrogen and nitrogen were found at stations SC–3 in both seasons. In contrast, carbon and sulphur show notable differences ($F_{0.05}(1,29) =$ 57.22 and 12.69), with significantly higher levels recorded during the rainy season (averaging 23.11± 9.28 mg·g^{-1} dry weight and 1.59±1.21 mg·g^{-1} dry weight, respectively) compared to the dry season (averaging 22.67±11.20 mg·g^{-1} dry weight and 1.33±0.78 mg·g^{-1} dry weight, respectively). The interaction results showed that the highest carbon was found in the dry season at stations SC–16; while the highest sulphur was found in the rainy season at stations SC–3 (Figure 9).

Carbon content, ranging from 10.80 to 43.95 mg·g^{-1} dry weight, was more prevalent in the central area of the study, particularly near the radius of transfer activity, compared to other sites. Sulphur content in sediment, ranging from 0.00 to 3.70 mg·g^{-1} dry weight, displayed a relatively uniform distribution throughout the area in the dry season but showed higher concentrations in the northeastern region in the rainy season. The hydrogen content in sediment ranged from 1.80 to 13.55 mg·g^{-1} dry weight. During the dry season, higher hydrogen concentrations were distributed in a north-to-south direction, whereas, during the rainy season, elevated hydrogen levels were predominantly concentrated in the northern area. Nitrogen content in sediment varied from 0.00 to 3.35 mg·g^{-1} dry weight, with higher concentrations mainly found in the northeast area of the study region (Figure 10).

DISCUSSION

The research revealed that sediment grain sizes near the tapioca starch shipping point were generally smaller than those further away. These areas also exhibited higher water content and TOM. Smaller grain sizes provide a larger surface area for organic matter attachment and accumulation (Carling, 1996). This phenomenon is linked to tapioca product loading, where dust and debris from these activities enter the seawater. These particles settle on the seafloor in the surrounding area. The sediment grain size varied by season, with finer grains being more widespread during the dry season due to increased tapioca starch transport activities (Pollution Control Department, 2014). The decomposition of organic matter in marine sediment influences redox reactions. In anaerobic conditions, microbial processes such as sulfate reduction produce hydrogen sulfide, a substance that lowers the pH of sediment pore water (Rheinheimer, 1992). Consequently, areas with tapioca dust deposits exhibit higher TOM, hydrogen sulfide levels, and lower pH.

The water content of sediment serves as a crucial indicator of whether the seafloor consists of liquid mud or clay. According to Van Rijn (2023), sediment with water content exceeding 50% typically denotes liquid mud. Clay-rich sediment facilitates organic matter accumulation. Sampling stations near the tapioca starch loading point (SC–2, SC–3, SC–4, SC–7, and SC–8) showed high TOM accumulation and water content exceeding 50%, suggesting a seafloor of liquid mud or clay. These conditions inhibit oxygen diffusion, promoting sulfide gas formation and creating inhospitable environments for benthic organisms. The highest TOM levels occurred during the dry season, while the highest hydrogen sulfide concentrations were recorded in the rainy season, reflecting the time required for microbial decomposition under low oxygen conditions.

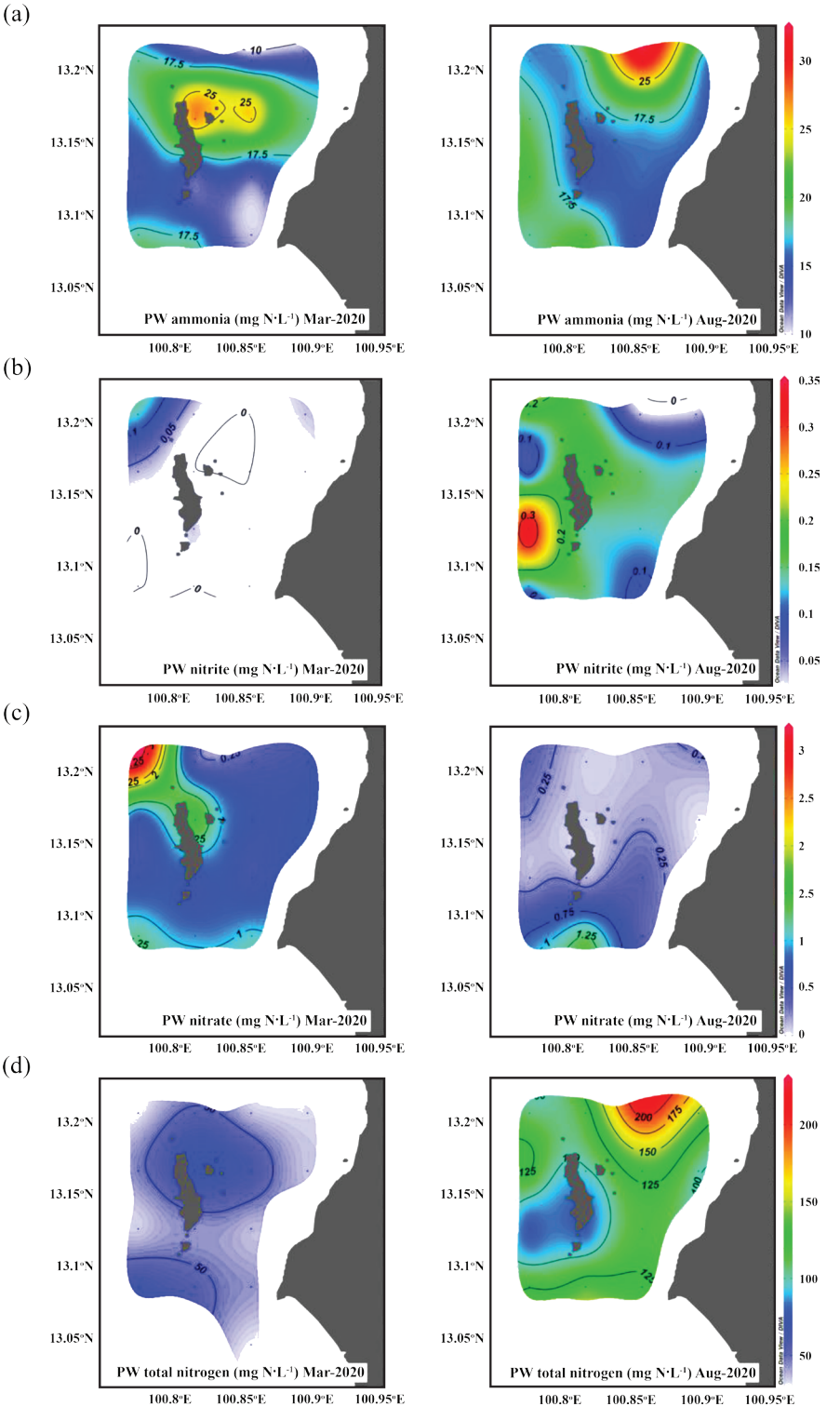

Figure 8. Spatial distribution of nutrients in pore water in surface sediment of the study area: (a) ammonia; (b) nitrite; (c) nitrate; (d) total nitrogen.

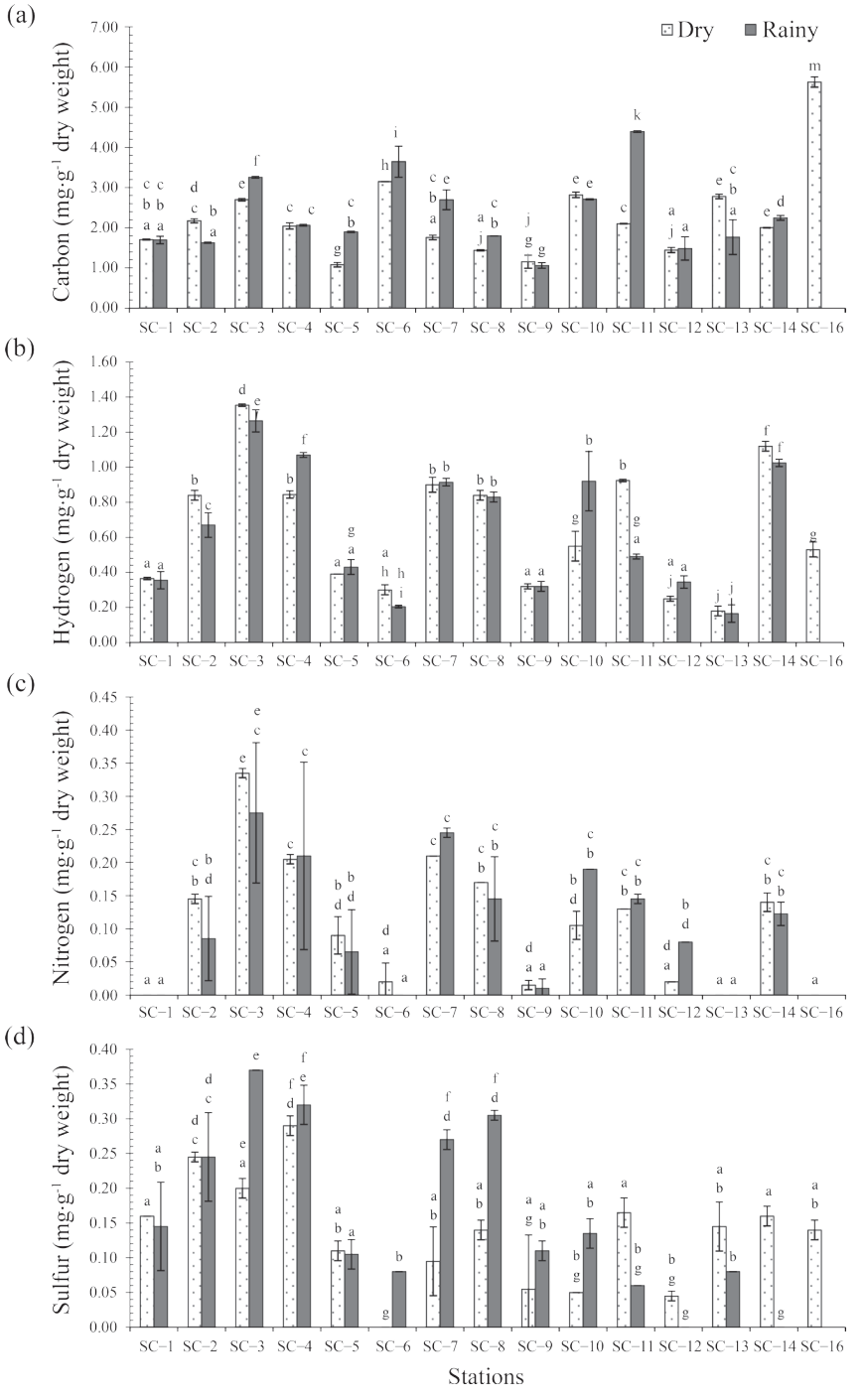

Figure 9. Composition of elements in organic matter from sediments collected at various sampling sites around the Sriracha transshipment area during the rainy and dry seasons: (a) carbon; (b) hydrogen; (c) nitrogen; (d) sulphur.

Note: Samples could not be collected at station 15 in the dry season and at stations 15 and 16 in the rainy season, due to the hard sea floor. Bars represent mean values and error bars represent standard deviation (SD); Different lowercase superscripts above bars indicate significant differences ($p<0.05$) between means.

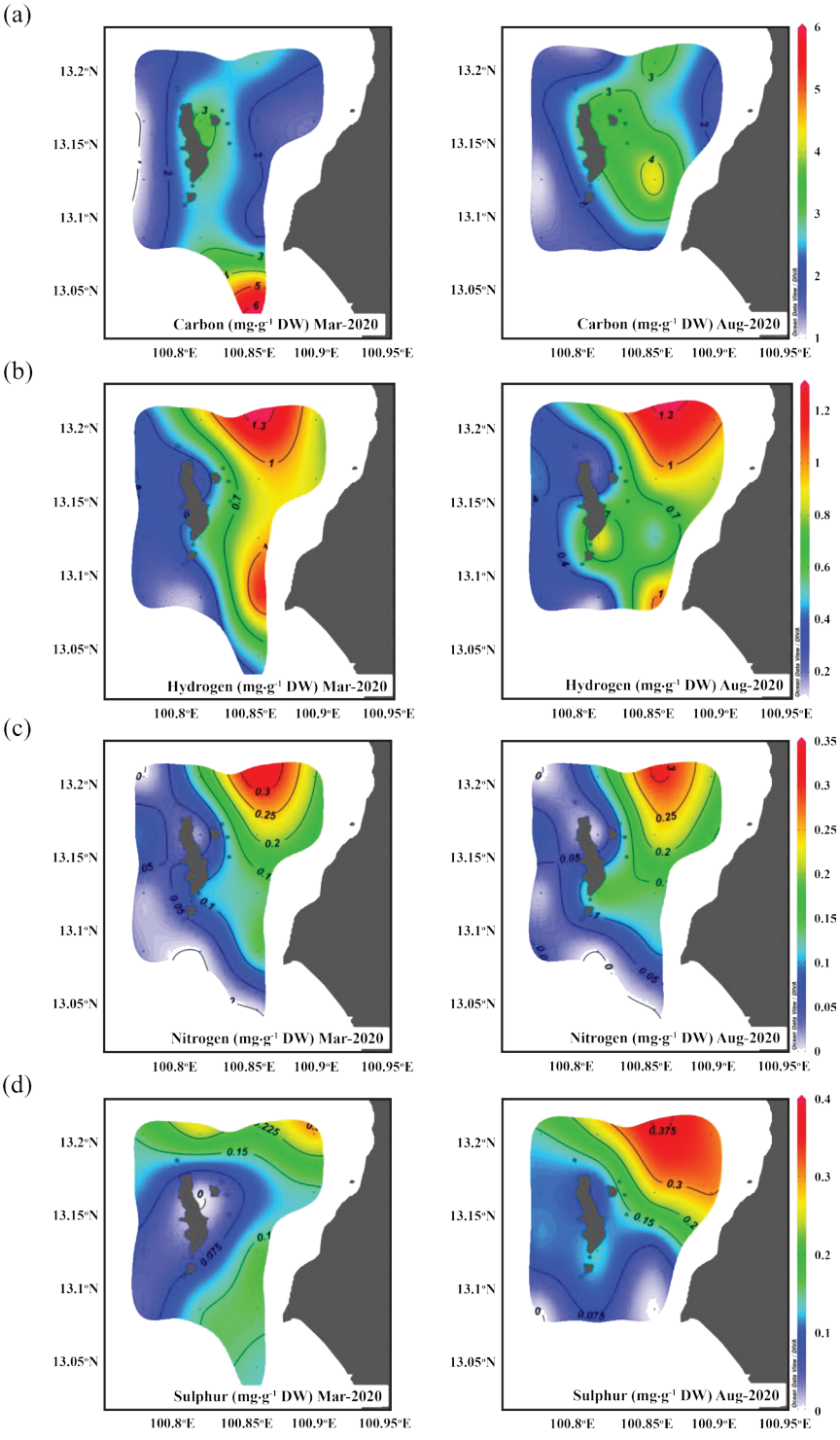

Figure 10. Spatial distribution of elements in surface sediment of the study area: (a) carbon; (b) hydrogen; (c) nitrogen; (d) sulphur.

Tapioca products, containing up to 40% carbohydrates (Agbemafle, 2019), pose a significant risk of carbohydrate contamination in sediment. Carbohydrates entering water and sediment undergo microbial decomposition, gradually transforming into smaller organic substances that contribute to the nutrient cycle. This study revealed that the tapioca starch transfer points (SC–2, SC–3, SC–4, SC–7, and SC–8) showed significantly high water content, TOM, and AVS. Sites near tapioca loading points consistently exhibited TOM levels exceeding 10%, with values above 13% potentially reducing marine life biomass (Thaipichitburapa *et al*., 2022). AVS levels at the tapioca transfer points were also higher than those previously reported in Sriracha Bay and other areas on the Gulf of Thailand's eastern coast (Khaodon *et al*., 2011).

Nutrients in sediment play an important role in marine plant growth, with concentrations typically 100 times higher than in the water column (Meksamphan, 2023). These nutrients can be released into the water column, contributing to eutrophication. Inorganic nitrogen, ammonia, and total nitrogen were abundant throughout the study area. Their quantities exceeded those reported by Kongpradit and Buranapratheprat (2023) and Senpradit *et al*. (2022), indicating fine-grained sediment with substantial accumulations of organic matter. Rapid organic matter decomposition depletes oxygen, promoting anaerobic conditions that facilitate ammonia accumulation in sediment.

Higher levels of inorganic nitrogen, ammonia, nitrite, and total nitrogen during the rainy season were attributed to increased water content, which enhances microbial activity, promotes nitrogen transformations, and elevates inorganic nitrogen accumulation (Hulth *et al*., 1999). In certain areas, such as the upper Gulf of Thailand, these inorganic nitrogen substances have been linked to phytoplankton blooms, which reduce oxygen levels at night, and adversely affect the survival of aquatic species.

Tapioca products are rich in carbohydrates, which consist primarily of carbon, hydrogen. Monitoring these elements was essential to confirm that the organic substances accumulating in the sediments originated from tapioca transport activities. High levels of carbon in the tapioca loading area would indicate substantial carbohydrates input from tapioca products. The study revealed that carbon concentrations at sampling points near the tapioca transfer area were significantly higher ($p<0.05$) than those at more distant locations.

CONCLUSIONS

The transfer of tapioca commodities was a key factor altering sediment quality. This study identified the tapioca starch transfer area as a zone of liquid mud or clay, with water content ranging from 46.48±0.68% to 78.03±1.17%, TOM from 5.32±0.35% to 15.91±0.31%, and AVS from 0.02± 0.00 to 0.08±0.00 mg $S \cdot g^{-1}$. Ammonia and total nitrogen were high throughout the study area, ranging from 10.61±0.23 to 30.94±2.41 mg $N \cdot L^{-1}$ and 30.34±1.31 to 207.02±1.88 mg $N \cdot L^{-1}$. These parameters were significantly higher ($p<0.05$) in the tapioca transfer zone compared to other areas. The consistently high TOM (exceeding 10%) and high AVS levels in the tapioca transferring zone raise concerns about the potential adverse impacts on the surrounding benthic and aquatic ecosystems.

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