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Distribution, sources and influencing factors of organic carbon in the surface sediments of the coastal tidal flats in Jiangsu Province

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Coastal tidal flats are situated in the interaction zone between the ocean and land and are vulnerable to natural changes, human activities, and global changes; these areas serve as an important mixing zone and burial area for carbon and nitrogen storage. Coastal tidal flats contribute significantly to the global carbon cycle due to their high biological productivity, high sedimentation rate, and low decomposition rate. However, there is a lack of research on the sources and influencing factors of organic carbon in surface sediments in the coastal tidal flat area of Jiangsu Province. In this study, fourteen surface sediment samples were collected from the Jiangsu coastal tidal flats, and the distribution of organic carbon was analyzed. The sources and influencing factors of sediment organic carbon were also investigated by analyzing the contents, ratios and stable isotopes of carbon and nitrogen in the sediments. The results indicated that the total organic carbon (TOC) and total nitrogen (TN) contents in the surface sediments of Jiangsu coastal tidal flats ranged from 0.09% to 0.82% and from 0.01% to 0.1%, with mean values of 0.36% and 0.04%, respectively, and that there was a significant positive correlation between TOC and TN. Moreover, the high-value areas were located mostly along the borders or in sections covered in vegetation, whereas the mudflat areas without vegetation had lower values. Considering the status of the Jiangsu coastal zone, the abandoned Yellow River estuary, Yangtze River inlet, marine benthic microalgae, C3 plants and C4 plants were selected as end members of organic carbon concentrations. The contributions of different sources were quantified using a Bayesian mixture model (MixSIAR). Among them, the abandoned Yellow River estuary and Yangtze River inlet contributed 28.1% and 19.3%, respectively, followed by marine benthic microalgae with a contribution of 26%, whereas C3 and C4 plants made limited contributions of 9% and 8.8%, respectively. Additionally, the sediment particle size, hydrodynamics, and tidal flat vegetation such as *Spartina alterniflora* were the key factors influencing the organic carbon distribution. In general, this study contributes to a better understanding of the biogeochemical processes and sources of organic carbon in coastal tidal flats. It also provides a solid foundation for the creation of carbon sink measures in nearshore tidal flats.

KEYWORDS

sediments, organic carbon, source, C/N, coastal tidal flats, Jiangsu Province

1 Introduction

It is an indisputable fact that global warming is caused by continuous increases in greenhouse gases such as carbon dioxide (CO_2) (IPCC, 2022), and the effective control of CO_2 concentration for mitigating regional and global climate change has become a key issue faced by all humanity. At present, there are two major methods to reduce the atmospheric CO_2 concentration: one is to develop and utilize new energy sources, and the other is to sequester carbon. Many studies have noted that carbon sequestration in ecosystems can reduce atmospheric CO_2 emissions, so improving the carbon sequestration capacity of ecosystems is particularly important (Lenka and Lal, 2013; Sommer and Bossio, 2014). Intertidal shoals are widely distributed in coastal plains where large rivers enter the sea. Intertidal shoals experience strong interactions between the ocean and land as transition areas. Because rivers carry large amounts of organisms and suspended sediments into the sea, these areas become key mixing and burial areas for marine and terrestrial carbon and nitrogen storage, with high biological productivity, high deposition rates, and low decomposition rates (Connor et al., 2001; Hussein et al., 2004). More than 90% of marine blue carbon is preserved and buried in coastal tidal flat areas (Ramaswamy et al., 2008; Gao et al., 2012), which are sensitive to natural changes, human activities and global changes and are affected by the combined effects of physical, chemical, biological and other processes, as well as the dual effects of human activities and tidal hydrodynamics (Wu and Wang, 2005; Zhang C et al., 2012). Therefore, the coastal tidal flat area is an important part of the global carbon cycle and plays a highly important role in global climate change, making it an ideal place to study carbon processes.

The Sheyang Estuary to Beiling Estuary in the middle of the Jiangsu coastal zone is a typical silt-length tidal flat with a wide distribution and a fast silt-growing and mature tidal flat system; this estuary plays an important role in carbon sequestration. The important sediment sources of organic carbon in this region are large *ex situ* terrigenous sediments brought by rivers, *ex situ* marine materials, and *in situ* biomass of intertidal vegetation (Thornton and McManus, 1994). These material sources significantly impact the ecosystems of the coastal tidal flats in Jiangsu. Many studies have shown that environmental factors such as sediment grain size and vegetation condition may influence the distribution of organic carbon and change the content, distribution and source composition of organic matter in sediments (Wang et al., 2010). The stable carbon and nitrogen isotopes ($\delta^{13}C$ and $\delta^{15}N$), as well as the elemental ratio of total organic carbon (TOC) to total nitrogen (TN) (C/N), depend on the natural abundance differences in their values in terrestrial and marine environments. They have been widely used as a proxy variable to determine the sources and biogeochemical processes of organic carbon in the coastal tidal flat environment in Jiangsu Province (Hu et al., 2006; Ramaswamy et al., 2008; Wang et al., 2013; Li et al., 2016; Liu et al., 2020). In recent decades, numerous studies have evaluated environmental pollution (Chen et al., 2020), the distribution pattern of organic carbon (Yang et al., 2021) and the factors influencing carbon distribution (Gao et al., 2022) in the tidal flats of Jiangsu Province. However, there is a lack of systematic studies on the burial, sources and influencing factors of organic carbon in the Jiangsu nearshore tidal flat sediments. In addition, the carbon source method of distinction is relatively crude and simple. Consequently, in this study, we investigated the distribution characteristics, source composition and influencing factors of organic carbon in surface sediments of Jiangsu coastal tidal flats by analyzing organic carbon, nitrogen content, stable isotopes and sediment grain size in surface sediments. The results will help us to better understand the role of tidal flat areas in mitigating global climate change and provide a scientific basis for the formulation of coastal tidal flat carbon sequestration measures.

2 Materials and methods

2.1 Study area

The study area is located in the coastal tidal flats of Jiangsu between the Sheyang estuary and Rudong; the surface sediments here are mainly silts and sandy silts influenced by the sediment transport of the abandoned Yellow River and the modern Yangtze River. The coast of Jiangsu is located in the East Asian monsoon region, with a remarkable monsoon climate influenced by both continental and oceanic climates. The average annual temperature is 13.5~15.5°C, the average precipitation is 900~1200 mm, and the precipitation gradually increases from north to south. Easterly and southeasterly winds prevail in this region, with an average wind speed of 4~5 cm/s throughout the year (Zou et al., 1999; Xue and Zhang, 2010). The coastal area of Jiangsu is dominated by regular semidiurnal tide, with an average tidal range of 4.13~5.5 m, and the wave effect is weak. The Jiangsu coastal area is mainly influenced by two tidal wave systems, the East China Sea progressive tide and the South Yellow River rotating tide formed after its reflection on the southern coast of the Shandong Peninsula, which converge at the nearshore waters of the Jianggang area (Zhang and Zhang, 1996). The biological species along the coastal tidal flats of Jiangsu are extremely diverse, with about 450 aquatic species including phytoplankton and zooplankton (Zhang et al., 2009). In comparison, the terrestrial salt marsh vegetation consists of simple species, and its dominant species are mainly *Spartina alterniflora*, whose extremely high extension rate dramatically increases the siltation rate of the tidal flats (Wu and Wang, 2005). In addition, the rapid development of tidal flats and predatory reclamation in this region threaten the growth of primary halophytic vegetation along the coast of Jiangsu (Wang et al., 2016).

2.2 Sample collection

In July 2018, 14 surface (0~5 cm) sediment samples were collected using a stainless steel grab bucket sampler in the coastal tidal flats area (within 1 km from the coast) of Jiangsu Province. The collected sediments were placed in polyethylene bags, air-drained and sealed, and labeled with numbers (N1 to N14 in Figure 1). Among them, the N1, N3, N4 and N6~N11 samples were located in

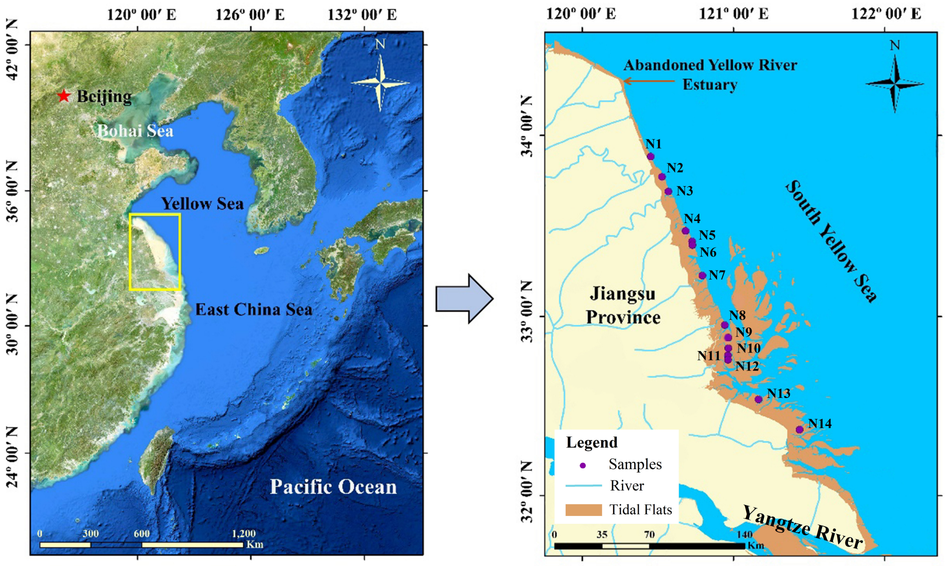

FIGURE 1
Location of the study area and distribution of sediment sampling sites.

the growth area or edge of *Spartina alterniflora*. The vegetation had a more significant influence on its sedimentation effect and sediment composition changes, etc. The others samples were from the mudflats. Sediment samples were transported to the laboratory at 4°C and later placed in a freezer at -20°C for freezing and storage until subsequent pretreatment. Before extraction, all samples were freeze-dried, ground and sieved.

2.3 Analysis method

2.3.1 Grain size analysis

The grain size measurements of sediment samples in this study were carried out at the School of Marine Science and Engineering, Nanjing Normal University, Nanjing, China. The test instrument was Mastersizer 2000 laser particle sizer (Malvern Instruments, UK) with a particle size measurement range of 0.02-2000μm and a relative error of less than 3% for multiple replicate measurements. Before the particle size analysis, the bulk samples were pretreated. Firstly, the 30% H_2O_2 solution of 15~20 ml was added to remove organic matter. After 48 hours, HCI (1mol/L) was added to remove carbonate. Then, $Na(PO_3)_6$ dispersant with a concentration of 10‰ was added and placed in an ultrasonic oscillator until the samples were fully dispersed and then tested on the machine. The test results were calculated using the Walker-Ford graphical formula (Folk and Ward, 1957) to obtain four sample size characteristic parameters: grain size (M_z), sorting coefficient (σ_1), skewness coefficient (SK) and kurtosis coefficient (K_G).

2.3.2 Carbon, nitrogen and stable isotope analysis

About 2g of the sample was weighed into a 100 mL beaker, and the appropriate amount of 10% HCl solution was slowly added to react with the sediment to remove carbonates. Then the sample was diluted with ultrapure water until the pH value was close to neutral. Total organic carbon (TOC) and total nitrogen (TN) contents were determined by an elemental analyzer (Vario MACRO), and carbon isotope ($\delta^{13}C$) content was determined by Delta Advantage isotope ratio mass spectrometer. The formula for obtaining $\delta^{13}C$ content was as follows:

$$\delta(‰) = [(R_{sample})/(R_{standard}) - 1] \times 1000 \qquad (2-1)$$

Where δ (‰) is $\delta^{13}C$ (‰) or $\delta^{15}N$ (‰), and R_{sample} and $R_{standard}$ are the isotopic ratios of the measured samples to the standards, respectively. The $R_{standard}C$ adopts the international "PDB" standard (Peedee Belemnite, from the Cretaceous Epididyl Formation, South Carolina, USA), with an analytical error of< ± 0.2‰). The $R_{standard}N$ adopts N_2 from the atmosphere. Organic geochemical analyses were conducted at Xiamen University.

2.3.3 Bayesian mixture model

In this study, a Bayesian mixture model (MixSIAR) was used to quantitatively assess the contribution of each potential source of the sediment organic carbon. Based on the R Studio, the MixSIAR model combines the advantages of MixSIR and SIAR, and uses information from stable isotope data to more accurately estimate the contribution ratio of different sources to sinks. The model is commonly used to calculate carbon sources in ecosystems (Du et al., 2018). In this study, the input data of MixSIAR model include source data (mean and variance of each potential source tracer) and mixture data (original tracer data at each sampling point), and it was assumed that no isotopic fractionation occurs. The runtime of Markov chain Monte Carlo (MCMC) was set to "Very long" and the model error was set to "Process only". Gelman and Geweke diagnostics were used to determine whether the model converged, and the model output was expressed as the median value. The equations of the MixSIAR model are as follows:

$$\delta_M = f_A\delta_A + f_B\delta_B + \ldots + f_N\delta_N \quad (2-2)$$

$$1 = f_A + f_B + \ldots + f_N \quad (2-3)$$

Where δ_A, δ_B,…, δ_N represent the isotopic composition of each source, δ_M means the isotopic composition of the surface sediments in this study area, and f_A, f_B,…, f_N are the contribution ratios of each source.

Statistical analyzes were performed using Microsoft Excel 2019 and R (R version 4.1.3), significance tests and correlation analysis were performed using SPSS 24.0, and graphs were made using ArcMap 10.2 and Origin 2016.

3 Results

3.1 Distribution characteristics of TOC and TN in sediments

The average TOC and TN contents in the surface sediment of the Jiangsu coastal tidal flat area were 0.36% and 0.04%, respectively, and their spatial distributions were clearly consistent (Figure 2). The TOC concentrations ranged from 0.09% to 0.82%, with a coefficient of variation at 70.78%. Thus our results were consistent with the conclusion that the average sediment TOC content in the coastal areas of Jiangsu is below 1% (Zheng et al., 2017). However, this content was lower than that measured in the coastal wetlands of Jiaozhou Bay (Zi et al., 2016). The TN concentrations ranged from 0.01% to 0.1%, and the coefficient of variation was 72.06%. TOC and TN showed a significant positive correlation (R^2 = 0.925, P<0.01) (Figure 3), which indicated that most of the nitrogen in this sediment was organic nitrogen. The fluctuation of TOC and TN contents in the surface sediment of the Jiangsu coastal tidal flats showed a disorder with no noticeable change pattern. However, combined with the regional vegetation cover, it can be concluded that TOC and TN contents were higher in the vegetation cover or edge areas, especially in N8 and N9. In contrast, the mudflats without vegetation growth were relatively lower (Figure 4).

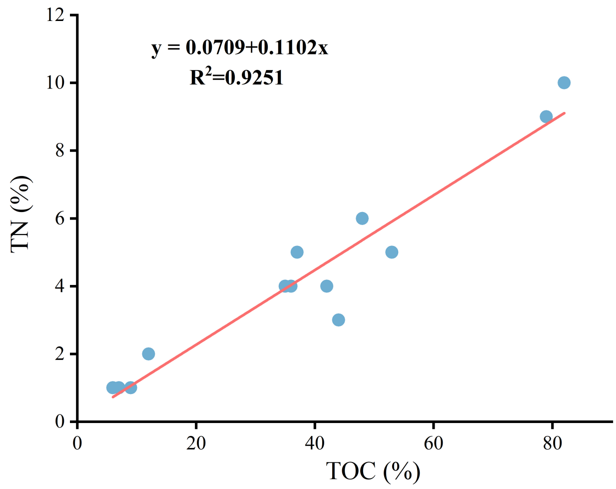

FIGURE 3
The relationship between TOC and TN in surface sediments of Jiangsu coastal tidal flats.

3.2 Variations in C/N, δ^{13}C, and δ^{15}N in sediments

The C/N values of the surface sediments of the coastal tidal flats in Jiangsu ranged from 6.31 to 12.91, with a mean value of 8.65 (Figure 5A). This was similar to the C/N values of surface sediments in the South Yellow Sea (5.8~11.8) but higher than those in the Pearl River Estuary and the South China Sea shelf (1.8~9.1) (Hu et al., 2006; Zhang W.G. et al., 2012; Liu et al., 2020). Overall, the C/N values in the surface sediments of the coastal tidal flats in Jiangsu

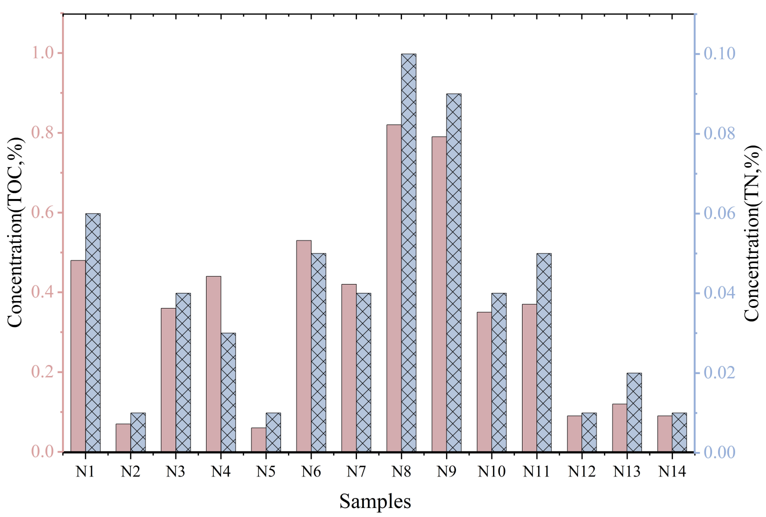

FIGURE 2
Distributions of TOC and TN in surface sediments of Jiangsu coastal tidal flats.

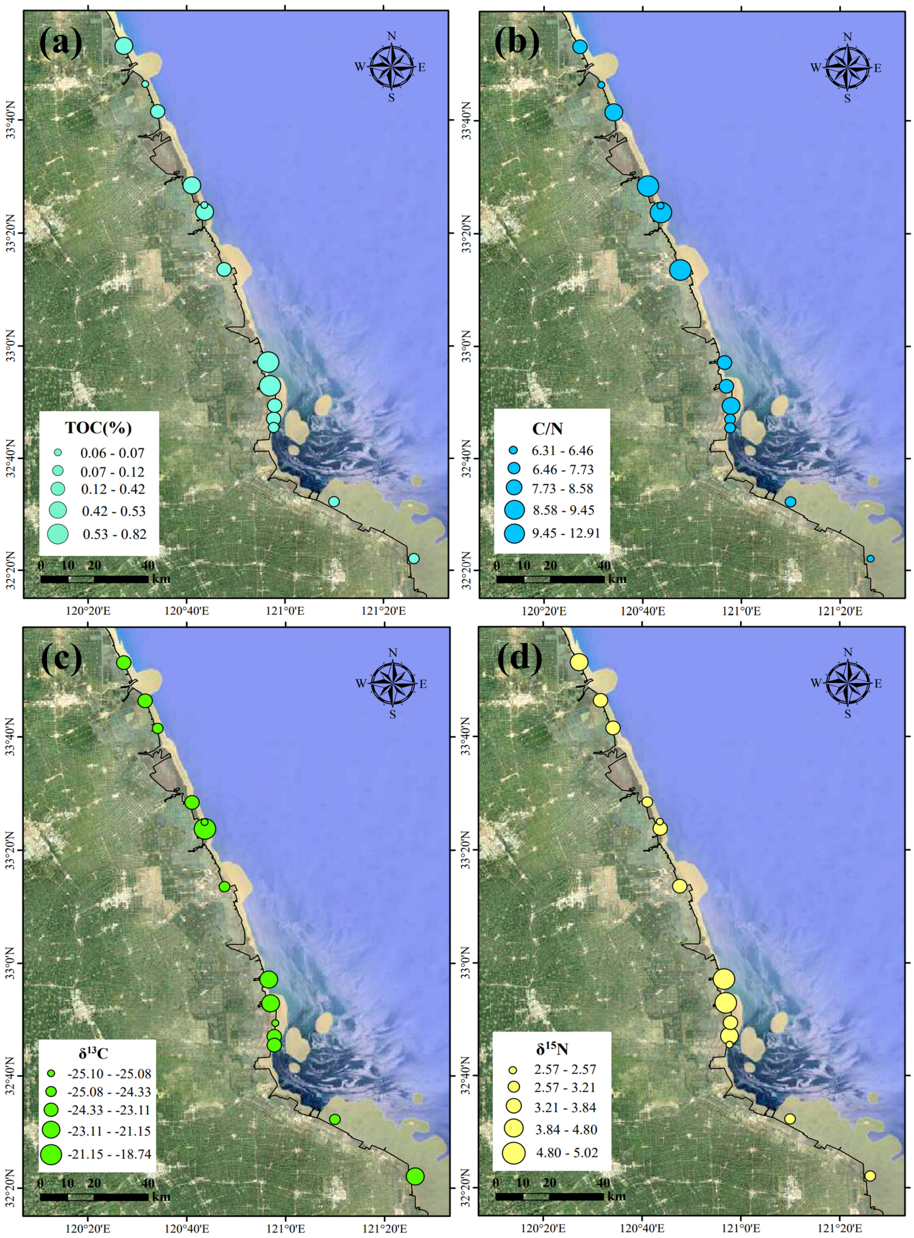

FIGURE 4
Spatial distribution of TOC **(A)**, C/N **(B)**, δ^{13}C **(C)** and δ^{15}N **(D)** in surface sediments.

showed a decreasing trend from north to south. The C/N values of the surface sediments in the northern part of the study area were higher, with the highest value at site N4 (12.91), followed by sites N6 and N7. Lower C/N values were in the south-central part of the study area, with the lowest value at the southernmost site N14 (6.47) (Figure 4B). The C/N ratio of the sediments fluctuated slightly, with a coefficient of variation at 23.11%.

The δ^{13}C values of the surface sediments of the Jiangsu coastal tidal flats ranged from -25.11‰ to -18.75‰, with a mean value of -23.23‰ (Figure 5B). The δ^{13}C values in the central part of the study area were slightly higher than those in the northern and southern areas. In particular, the value at site N6 was the highest (-18.75‰), followed by that at site N9. Site N5, which was the closest to site N6, had the lowest δ^{13}C value (-25.11‰) (Figure 4C). Overall, the δ^{13}C values in the study area were relatively stable, with a coefficient of variation at -7.56%.

The δ^{15}N values of surface sediments in the Jiangsu coastal tidal flats ranged from 2.57‰ to 5.02‰, with a mean value of 3.73‰ (Figure 5C). The δ^{15}N values at the radial sand ridge in the central part of the study area were significantly higher than those in other areas, ranging from 3.78‰ to 4.80‰, followed by the area near the Sheyang estuary, ranging from 3.62% to 4.62%. In contrast, the δ^{15}N value in the Rudong region at the southern end of the study area was low, with the lowest value of 2.57‰ (Figure 4D). As a whole,

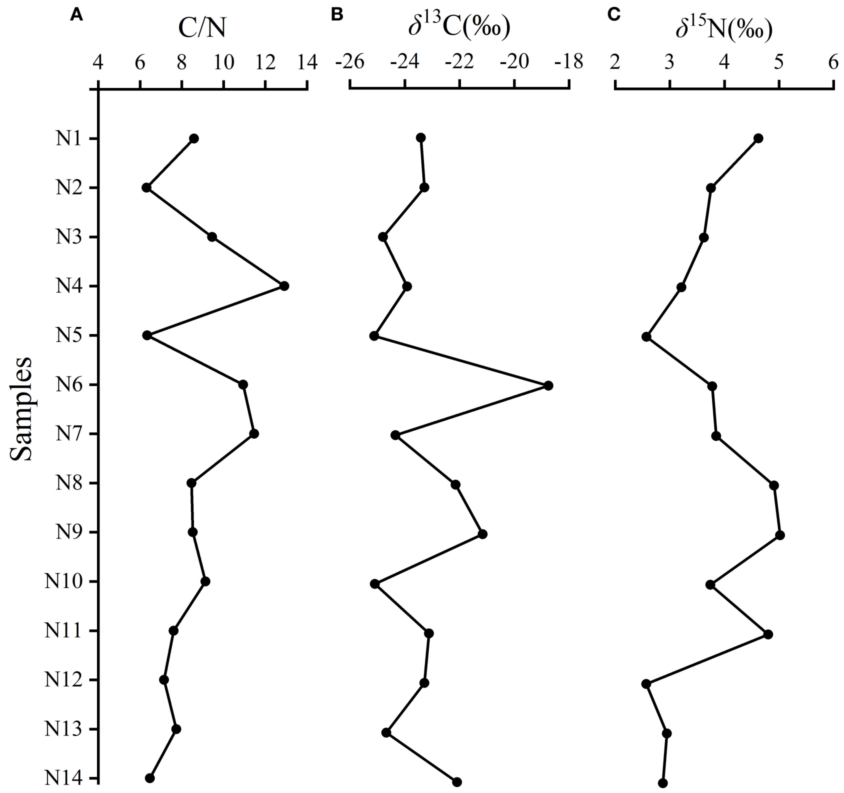

FIGURE 5
Distributions of C/N **(A)**, δ^{13}C **(B)** and δ^{15}N **(C)** in surface sediments of Jiangsu coastal tidal flats.

the δ^{15}N values in the central and northern parts of the study area were generally higher than those in the south. It fluctuated more significantly with a coefficient of variation at 22.69%.

3.3 Grain size of sediment

The surface sediment composition of the coastal tidal flats in Jiangsu was dominated by silt, followed by sand grains, with less clay content (Figure 6). The average grain size (Mz) of the surface sediments from the 14 sampling sites ranged from 3.03Φ to 7.25Φ, and the average contents of sand grains, silt and clay were 27.44 ± 5.44%, 60.88 ± 3.60% and 11.68 ± 0.61%, respectively. In terms of the spatial distribution, the sediment grain size in the northern part of the study area (Region I and Region II) was significantly smaller than that in the southern part, especially at the N1 and N2 stations located at the northern end of Yancheng. In addition, the composition of different sediment samples varied greatly. Sand grains were mainly distributed in the southern part of the study area (Region IV), with a minimum value of 1.7%, a maximum value of 48.5%, and a coefficient of variation at 88.21%. Silt and clay were mainly distributed in the central and northern parts of the study area (Regions I and III), with contents ranging from 3.6% to 85.34% and from 4.8% to 33.3%, respectively. Their coefficients of variation were 32.34% and 69.65%, respectively. The grain size skewness values of the surface sediments in the Jiangsu coastal tidal flats ranged from -0.40 to 0.51, with a mean value of 0.08, showing a trend from negative to positive skewness. The sorting coefficient fluctuations were highly apparent, and the sorting degree ranged from good to poor, with a mean value of 2.49 ± 1.31.

4 Discussion

4.1 Sources of organic carbon in the surface sediments of nearshore tidal flats in Jiangsu

4.1.1 Qualitative analysis of organic carbon sources in sediments

Generally, stable carbon isotope tracing and C/N values are practical tools for identifying the source of organic carbon in tidal and salt marsh sediments (Zhou et al., 2006). They are frequently employed for identifying the source of organic carbon in intertidal sediments (Cook et al., 2004). In coastal tidal ecosystems, there are significant differences in the chemical composition and stable isotope composition of organic matter from terrestrial and marine sources. Due to the differences in δ^{13}C and C/N values between marine algae and terrestrial vascular plants, which contain significant amounts of cellulose, these values have been frequently utilized as markers to efficiently differentiate organic matter sources in aquatic ecosystems (rich in carbon). In contrast, marine algae have no cellulose and are rich in protein (rich in nitrogen) (Liu et al., 2020). Therefore, in this study, the δ^{13}C and C/N values were

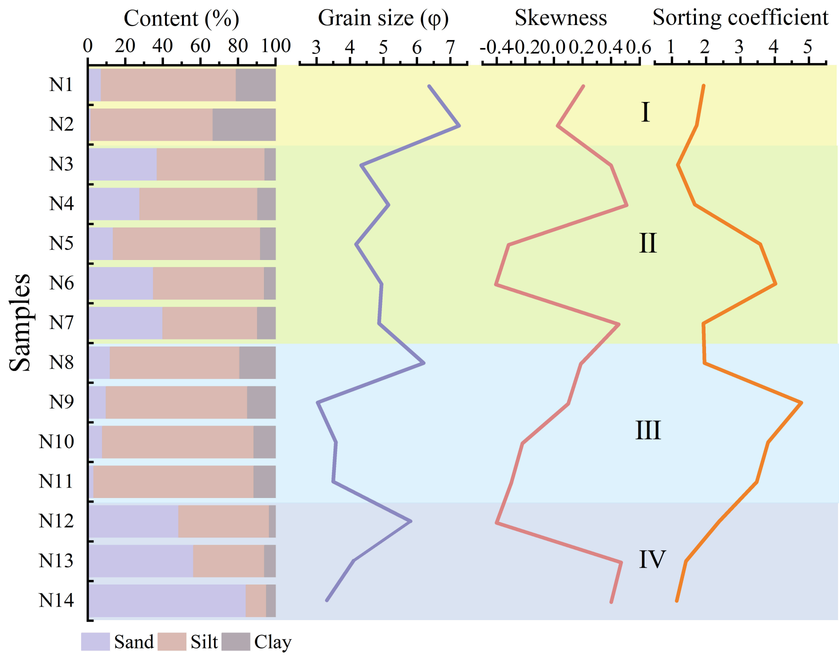

FIGURE 6
Grain size composition and grain size parameter variation of surface sediments.

combined to investigate the possible sources of organic carbon in Jiangsu's surface sediments of the nearshore tidal flats.

Determination of the most comment elements is essential for analyzing each source's contribution proportion. The range of end-member values obtained by different scholars is different. Consequently, when employing $\delta^{13}C$ and C/N values to assess the contribution of each source of organic carbon, the end member's values should be determined based on both previous findings and the specific conditions of the study area. The large size of terrestrial vegetation, such as *Spartina alterniflora* and *Phragmites australis* in the coastal tidal flats of Jiangsu constitutes an essential source of internal input of organic carbon (Liu et al., 2011). The runoff from the Yangtze River and the abandoned Yellow River deposit a large amount of suspended sediment in the coastal tidal flats of Jiangsu Province. Studies show that the Yangtze River and the abandoned Yellow River provide approximately 10×10^8 tons and 5×10^8 tons of sediment, respectively, to the ocean every year (Wang et al., 2013). In addition, industrial and agricultural activities, domestic sewage and aquaculture drainage constitute remote terrestrial sediments with runoff. The ^{13}C *in situ* labeling method indicates that benthic microalgae are stable and continuous sources of sediment organic carbon (Oakes et al., 2012). Their primary productivity in the Yangtze estuary accounts for approximately 16.5% of the total tidal flat productivity (Shang et al., 2009). Benthic microalgae may be a vital ex situ marine source of sediment organic carbon. Therefore, combined with the research status of the Jiangsu coastal zone, this study selected C3 plants, C4 plants, the abandoned Yellow River estuary, the Yangtze River estuary and marine benthic microalgae as end members for qualitative analysis. In Table 1, the values of each end member are displayed.

Figure 7 shows that the sediment organic carbon in the study area originates from the mixed input of terrestrial and marine phases, where the terrestrial phase accounts for a larger proportion, with the characteristics of nearshore sea-land interaction. The abandoned Yellow River estuary (AHH), the Yangtze River estuary (CJ), C3 plants, C4 plants, and marine benthic microalgae

TABLE 1 Different $\delta^{13}C$ and C/N values of end members.

End-members	$\delta^{13}C$ (‰)	C/N
Abandoned Yellow River estuary (Qi et al., 2021)	24.0 ± 0.3	8.1 ± 2.1
Yangtze River Inlet (Wu et al., 2018; Sun et al., 2021)	-26.4 ± 0.8	7.6 ± 0.5
C3 plant (Yu et al., 2010; Lu et al., 2013)	-28.9 ± 0.5	18.0 ± 7.3
C4 plant (Lu et al., 2013)	-15.3 ± 4.2	15 ± 4.6
benthic microalgae (Shang et al., 2009; Quan et al., 2012)	-19.9 ± 0.9	5.1 ± 0.2

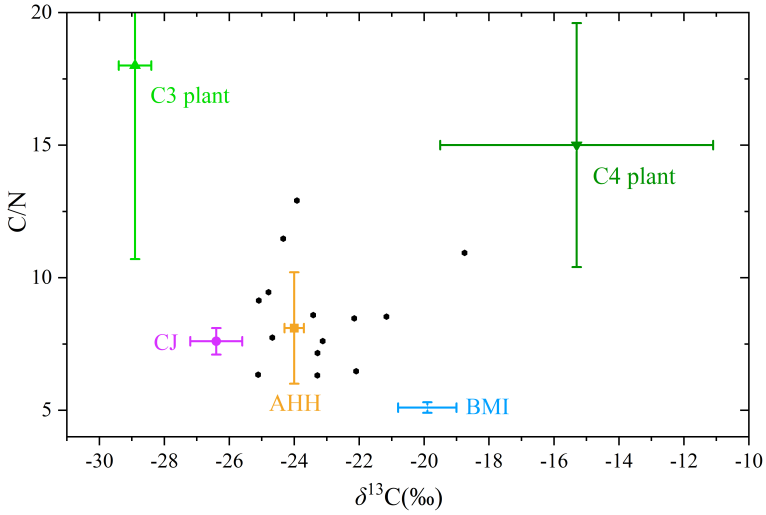

FIGURE 7
The diagram of C/N-δ^{13}C of sediment in the Jiangsu coastal tidal flat and potential sources. The references of the source data are the same as those in Table 1. The vertical and horizontal lines in different colors indicate the ranges of C/N and δ^{13}C, respectively.

(BMI) are the primary sources of organic carbon in the coastal sediments of Jiangsu. The δ^{13}C values of the surface sediments in the study area were distributed mainly near the abandoned Yellow River estuary and benthic microalgae, but the C/N values of the sediments were much higher than those of benthic microalgae. TN mostly includes total organic nitrogen (TON) and total inorganic nitrogen (TIN). At the same time, clay minerals can adsorb TIN in the sediment in the form of NH^{4+}, resulting in a reduction in TN content in the measured samples, thus making the sediment C/N values high and inaccurate (Hu et al., 2006; Hu et al., 2012; Liu et al., 2020). Moreover, the sediment δ^{13}C and C/N values in the study area were distributed in a small regional range but were not highly concentrated. The results indicated that the composition of organic carbon sources was consistent among the 14 sites, but the contributions of each source were different.

4.1.2 Quantitative analysis of sediment organic carbon sources

Based on the results of the qualitative analysis, C3 plants, C4 plants, the abandoned Yellow River estuary, Yangtze River inlet and marine benthic microalgae were taken as the leading end members, and the contribution proportion of each end member in the surface sediments of the coastal tidal flats of Jiangsu was calculated by the MixSIAR model (Figure 8). The results showed that the contribution proportions of suspended sediments carried by the Yangtze River inlet and the abandoned Yellow River estuary to the organic carbon in the surface sediments of Jiangsu coastal tidal flats ranged from 13.2% to 53.1% and 12.5% to 25.1%, respectively, with mean values of 28.1% and 19.3%, respectively, and the sum of the contribution proportions of both to each point ranged from 29.7% to 69.9%, with a mean value of 47.4%. The contribution of benthic

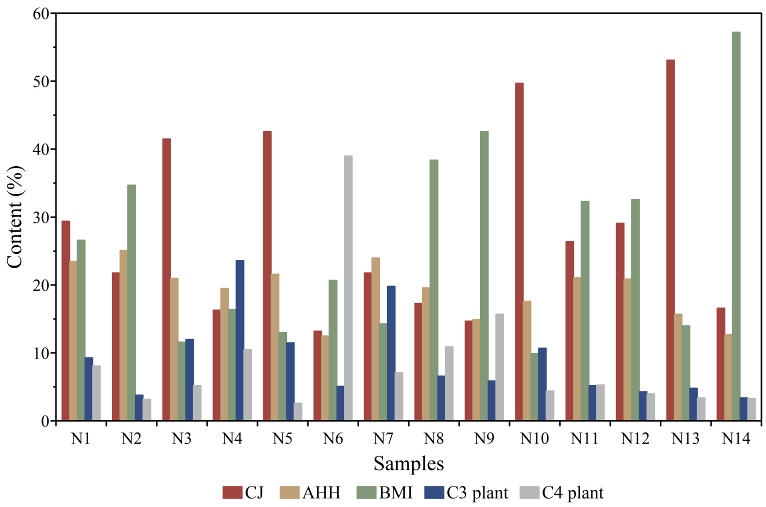

FIGURE 8
Relative percentages of organic carbon from different sources in surface sediments of Jiangsu coastal tidal flats.

microalgae ranged from 9.9% to 57.2%, with a mean value of 26%; the contribution of C3 plants to each site ranged from a minimum of 3.4% to a maximum of 23.6%, with a mean value of 9%. In comparison, the contribution of C4 plants reached a maximum value of 39%, with a mean value of 8.8%. The calculation results showed that the contribution percent of each end member to the organic carbon fluctuated wildly in the coastal tidal flat sediments of Jiangsu.

The main sources of organic carbon in the coastal tidal flat sediments in Jiangsu were the Yangtze River estuary and the abandoned Yellow River estuary, and the organic matter had strong terrigenous characteristics. This is mainly because the runoff from the Yangtze River carried a large amount of suspended sediment into the sea and contributed to the organic carbon source of the surface sediment of the coastal tidal flat. Studies have shown that fine sediment from the estuary of the Yangtze River could be transported northward to the tidal flat at approximately 35°N (Liu et al., 2007; Lu et al., 2019).The abandoned Yellow River delta is a delta formed after the Yellow River took over the Huai River, which is in a state of perennial erosion and an essential source of sediment for the nearshore tidal flats in Jiangsu (Zhou et al., 2014). The contribution of the Yangtze River estuary to organic carbon in the southern part (N10~N13) of the study area is greater than that of the abandoned Yellow River estuary. This may be because the distance between this region and the Yangtze River is relatively small, and terrigenous organic matter can be added through the northern branch of the Yangtze River (Zhang W.G. et al., 2012).

The average contribution of marine benthic microalgae to organic carbon in the coastal tidal flats of Jiangsu was significantly lower than that of the abandoned Yellow River estuary and the Yangtze River estuary. This may be due to the resuspension and transport caused by hydrodynamic processes, so the *in situ* accumulation is insignificant (Oakes et al., 2012). Under the hydrodynamic action of the Kuroshio and the Yellow Sea warm current, marine plankton can be carried to the South Yellow Sea (Komorita et al., 2021). Under the influence of the semidiurnal tidal current of the Yellow Sea, marine plankton move toward the tidal flats near Jiangsu at high tide and in the opposite direction at low tide. Since the speed and duration of the waves are more significant at rising tide than at falling tide, some of the marine plankton will remain in the tidal flats of Jiangsu after the falling tide (Chen et al., 2011). Except for the tides, the Subei Coastal Current, which moves south or north depending on the season, can also bring coastal marine plankton to the study area from both directions. In addition, in the tidal flat middle area with relatively limited suspended sediment replenishment and in the mudflats, the contribution of marine benthic microalgae to organic carbon in surface sediments is high. However, in the growth area or edge of *Spartina alterniflora*, vegetation is an essential source of organic carbon and profoundly affects the distribution of organic carbon.

4.2 Influencing factors of TOC distribution in surface sediments of Jiangsu coastal tidal flats

4.2.1 Sediment grain size

Studies have shown that sediment grain size is an important factor controlling the content and distribution of TOC in the surface sediments of coastal tidal flats (Liu et al., 2020). As a result of Pearson correlation analysis, the correlation coefficient between TOC content and mean grain size in the surface sediments of Jiangsu coastal tidal flats was $r_1 = 0.732$ at $p < 0.05$, and the correlation coefficient between TOC content and clay content was $r_2 = 0.714$ at $p < 0.01$. Both r_1 and r_2 ranged from 0.6 to 0.8, respectively, and were strongly positively correlated, which indicated that the finer the sediment was, the higher the TOC content. This result showed that the organic carbon in the surface sediment of the tidal flats near Jiangsu is more likely to be enriched in fine-grained material.

The internal reasons for this phenomenon were analyzed from carbon income and expenditure. On the one hand, the large specific surface area of fine-grained sediments provides good binding points for organic matter and has a strong adsorption capacity for organic carbon, thus increasing carbon income (Keil et al., 1994). On the other hand, fine-grained sediments have small voids, insufficient oxygen exchange, and poor water and air permeability, which weakens the respiration process of sediments and effectively slows the degradation rate of organic matter, thus reducing carbon expenditure (Wang et al., 2009). Therefore, the enrichment of fine-grained sediments often occurs with high TOC content. In contrast, due to the poor water holding capacity and carbon adsorption capacity of coarse particles, the productivity of salt marsh vegetation such as *Spartina alterniflora* is low, which generally reduces its TOC content (Mao et al., 2015).

4.2.2 Hydrodynamics

There was a positive correlation between TOC and fine grained sediments, meaning the factors controlling TOC distribution should be similar to those affecting the distribution of fine grained sediments. Hydrodynamics is the driving force of sediment transport (Ramaswamy et al., 2008). Fine particles in sediments are lighter than coarse particles and are transported farther under hydrodynamic action (Zhang C et al., 2012), thus affecting the distribution of fine particles in the surface sediments of the coastal tidal flat in Jiangsu. Moreover, the positive correlation between TOC and fine-grained sediments also indicates that hydrodynamic sorting is essential in controlling the distribution of organic matter along the Jiangsu tidal flats (Liu et al., 2020; Ogrinc et al., 2005).

Sediment transport in the nearshore tidal flats of Jiangsu is mainly influenced by tidal waves. The East China Sea advancing tidal wave moves northward from the mouth of the Yangtze River and reflects off the southern coast of the Shandong Peninsula; thus, the rotating tidal wave of the South Yellow Sea is formed (Xing et al., 2012). The nontidal point of this rotating tide is located in the abandoned Yellow River delta area. The two major tidal wave systems converge in the sea off the Jianggang area in the middle of the Jiangsu nearshore tidal flats and form a tidal pattern with convergent and divergent tides (Xu et al., 2016). The average tidal range is centered on the Jianggang area and decreases to the north and south (Zhang and Zhang, 1996). Therefore, the convergence of the two tidal waves near the Jianggang area strengthens the tidal energy aggregation, thus enhancing the hydrodynamics of the radial sand ridge. This is not conducive to the deposition of finer particles, however, as these hydrodynamics make the sediment material particles at this location (N9~N11) coarser than those in the northern and southern areas.

In addition, Lu et al. (2019) suggested that the fine-grained sediment from the Yangtze estuary could move northward with runoff to the vicinity of the tidal flats at 35° N. Tianning Li et al. hypothesized that under the influences of the Yangtze flushing water and the north Jiangsu current, the coarse fraction with low organic matter content along the Jiangsu tidal flats was mainly deposited in the northern and southern parts of the tidal flats, while the fine-grained fraction with high organic matter content continued to move forward (Zhang W. G. et al., 2012). As a result, fine-grained sediments rich in organic matter will be deposited in the central part of the Jiangsu tidal flats, while coarse-grained sediments will be deposited in the northern and southern regions. The sediments in the northern part of the study area (central Jiangsu tidal flats) are mostly fine-grained. In contrast, the sediments in the southern part of the study area (south Jiangsu tidal flats) are mostly coarse-grained, which is consistent with the above results. In addition, the Sheyang River estuary, where sites N1 and N2 were located, has a wide river surface. Its shore section is mainly composed of fine-grained sediment discharged from the abandoned Yellow River. The riverbed material is primarily composed of silt, which is mainly influenced by the unidirectional flow of seawater. The transport dynamics are relatively weak, so the sediment particles are rather fine, making it easier to enrich organic carbon.

4.2.3 Vegetation

The natural vegetation of the Jiangsu coastal tidal flats is basically coastal saline vegetation. As an important carbon component in the surface sediment, it profoundly affects the burial and distribution of organic carbon. According to the vegetation distribution recorded during sampling, the sampling sites with high organic carbon content were all located in or near the growth area of *Spartina alterniflora* vegetation (N1, N3, N4, N6~N11), especially at N8 and N9. These two sites were located near the mouth of the Dongtai River, where *Spartina alterniflora* grew densely and had high biomass. Nearly 30% of the organic carbon in the surface sediment was contributed by vegetation. The sampling sites with low organic carbon content (N2, N5, N12~N14) had almost no vegetation growth around them, and were typical mudflats. Their organic carbon contents were low and mainly derived from nutrients in seawater and other organisms such as benthic microalgae. Thus, the distribution and coverage of vegetation is also a significant factor affecting the TOC content of surface sediments.

There are two mechanisms by which vegetation influences the TOC content of surface sediments in coastal tidal flats in Jiangsu Province. First, through the vegetation's high primary productivity, it directly fixes carbon in the environment during the growth process. Then, apoplastic material and root secretions are degraded into humus through the microbial action cycle, which directly affects the sediment TOC content (Xu et al., 2008). The second mechanism is to weaken the seawater dynamics through its well-developed root system, causing the beach sediment to solidify and deposit a large amount of fine particulate matter, indirectly affecting the sediment TOC content (Chen et al., 2007). In addition, for protection and siltation promotion, Jiangsu introduced *Spartina alterniflora Loisel* in the early 1980s. Compared with C3 plants such as *Phragmites australis*, *Spartina alterniflora* has higher photosynthetic efficiency and frequency of tidal invasion, which is conducive to rapid sedimentation and siltation of fine-grained sediments (Cheng et al., 2008), and thus has a higher organic carbon burial capacity. It has been shown that the burial rate of organic carbon in the tidal flats of Wanggang in northern Jiangsu Province was seven times higher than that before the introduction of *Spartina alterniflora* (Huang et al., 2018).

4.2.4 Other influencing factors

The TOC content in the surface sediments of coastal tidal flats in Jiangsu may also be subject to climate change and human activities, which directly or indirectly affect the carbon burial capacity of sediments. Among them, climate change generally plays a role at larger spatial scales. It has been noted that as regional scales shrink, the link between climate variables and organic carbon typically weakens (Wang et al., 2010). The impact of human activities on organic carbon is mainly manifested in the degradation of wetlands caused by land use development and river input changes due to dam retention in reservoirs (Zhang et al., 2015). In locations with significant anthropogenic disturbance, there is less organic carbon storage per unit area (Song et al., 2018). Jiangsu is one of the major coastal agricultural provinces in China, consuming 3×10^6 tons of chemical fertilizers per year. Since 2008, the average consumption intensity of chemical fertilizers in the province has reached 453.7 kg/hm^2, which is much higher than the national average of 335.3 kg/hm^2 (Liu et al., 2016; Wang et al., 2020). Agricultural fertilizers can be carried directly by surface runoff, thus affecting the content and spatial distribution of organic carbon in the coastal tidal flats of Jiangsu Province. The δ^{15}N value of nitrogen fertilizer in China were low, −6‰ to 4‰ (Li et al., 2016), while the δ^{15}N value of wastewater and domestic sewage were both above 10‰ (McKinney et al., 2001; Ruiz-Fernandez et al., 2002). The lower δ^{15}N values (2.57-3.85 ‰) in the sediment of the northern and southern mud regions indicate the influence of agricultural fertilizers (Figure 5). In addition, the δ^{15}N value of sites N1, N8, N9 and N11 were near 5‰, which might have been related to domestic sewage and wastewater inputs.

5 Conclusion

In this study, the carbon and nitrogen contents, C/N ratios and stable isotopes for 14 surface sediment samples from the coastal tidal flats of Jiangsu Province were analyzed, and the following results were obtained.

(1) There was a significant positive correlation between the TOC and the TN ($R^2 = 0.925$, P<0.01), demonstrating that most of the nitrogen in the sediments was organic. Spatially, vegetation-covered or margin areas had significantly higher TOC and TN contents than mudflats.

(2) The organic carbon sources of sediments in the coastal tidal flats of Jiangsu were a mixture from the abandoned Yellow River estuary, Yangtze River inlet, C3 plants, C4 plants and marine benthic microalgae. Using the Bayesian mixture model (MixSIAR) to quantify the proportions of each source's contribution to the organic carbon of surface sediments, it was found that the suspended sediments carried by the Yangtze River estuary and the abandoned Yellow River estuary contributed the most to the organic carbon of sediments in the nearshore tidal flats of Jiangsu.

(3) The organic carbon content was considerably correlated with the mean sediment grain size and clay content of the nearshore tidal flats of Jiangsu, which indicated that sediment grain size and hydrodynamics were essential factors controlling the distribution of organic carbon in the coastal tidal flats of Jiangsu. Additionally, the distribution of sediment organic carbon was also related to tidal vegetation, climate change and human activities. This study provides a solid foundation for the creation of carbon sink measures in nearshore tidal flats.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

RZ: Conceptualization, Formal analysis, writing, reviewing and editing. XD: Investigation, Formal analysis, Methodology. QL: reviewing and editing. MX: Investigation and editing. YZ: reviewing, investigation and editing. All authors contributed to the article and submitted and approved the submitted section.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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