Differences in the Composition, Source, and Stability of Suspended Particulate Matter and Sediment Organic Matter in Hulun Lake, China

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Research Article

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Differences in the composition, source, and stability of suspended particulate matter and sediment organic matter in Hulun Lake, China

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Abstract: Sediment (SOM) and suspended particulate (SPOM) organic matters are two important organic matters in water. Their occurrence, migration and transformation, and stability have important effects on the environmental behaviors of carbon, nitrogen, phosphorus, and other pollutants in a water environment. The content, composition, fluorescence characteristics, source, and stability of SOM and SPOM in Hulun Lake, a typical lake in cold and arid region of China, were compared by sequential extraction, three-dimensional fluorescence spectroscopy, parallel factor technique, carbon–nitrogen ratio, and stable carbon isotope. SOM and SPOM in north and west were higher than those in east and south. The average content of SPOM (24.70 ± 4.63 g/kg) was slightly higher than that of SOM (23.04 ± 10.27 g/kg), but the difference was not significant. Humin was the dominant component in SOM and SPOM, accounting for 73.7% and 61.2%, respectively. Humus was the main fluorescence component of water-extractable organic matter in SOM and SPOM, accounting for 79.9% and 70.4%, respectively, of the total fluorescence intensity. SOM and SPOM were derived from terrestrial sources with relative contribution rate of about 70%. SPOM was more influenced by autochthonous sources and had significantly lower humification degree and stability than SOM. Effects of climate changes on migration, transformation, stability, and bioavailability of organic matters and endogenous pollutants closely related to organic matters in lakes of cold and arid regions should be paid attention in the future.

Keywords: lake in a cold and arid area, Hulun Lake, sediment organic matter (SOM), suspended particulate organic matter (SPOM), source, stability

1. Introduction

Organic matter exists widely in all kinds of water environments and is one of the important chemical components in a water environment. Organic matter participates in the material circulation of the aquatic environmental food web and affects the occurrence, migration, transformation, cycle, and biological availability, and toxicity of water environment pollutants, including nitrogen, phosphorus, heavy metals, and toxic and harmful organic matters (Guo et al. 2020; Shah et al. 2021; Slukovskii et al. 2020; Yao et al. 2020). Organic matters in a lake water environment have complex and diverse compositions and structures and can be divided into dissolved (DOM), suspended particulate (SPOM), and sediment (SOM) organic matters in accordance with different attached media (Chen et al. 2021; Verdugo et al. 2004). The mutual transformation among DOM, SPOM, and SOM can be realized through physical, chemical, and biological functions along with the migration, transformation (He et al. 2016; Toosi et al. 2014), and changes in the environmental characteristics of pollutants combined with organic matters and remarkably influences the environmental quality and ecological health of water (Kurek et al. 2021; Tang et al. 2021). The stabilities of SOM and SPOM make an important contribution to the occurrence of DOM and carbon burial in the lake (Chmiel et al. 2016; Lü et al. 2019; Wang et al. 2021b). However, studies comparing the occurrence and stability of SPOM and SOM in lakes and the changes and mechanism of migration, transformation, occurrence, and bioavailability of biogenic elements and pollutants during the migration and transformation processes among SOM, SPOM, and DOM are few.

The lake ecosystem in cold and arid regions is fragile because of its special geographical location and basin climate. This ecosystem is minimally affected by human activities and sensitive to climate change, human interference, and environmental change (Li et al. 2021; Ma et al. 2013; Song et al. 2020; Zhang et al. 2015). Therefore, once the human interference intensity increases or the climate and environment change significantly, the water ecological environment of lakes in the cold and arid region may be seriously and irreversibly damaged. The occurrence, migration, transformation, and sedimentary evolution of organic matters in lakes are bound to change. Thus, the cold and arid regions are ideal study areas for observing the burial, migration, and transformation behaviors and the influencing factors of lake carbon. However, historical data and research of lake organic matters in cold and arid regions are insufficient. Hence, a systematic, comprehensive, and in-depth understanding of the occurrence, transformation and transport, deposition, and evolution of organic matters in

lakes in cold and arid regions as well as the response process and mechanism to climate change and water environment change are lacking, which remarkably restricts the protection and management of lake water environment in cold and arid regions, and relevant research should be carried out.

The Hulun Lake is a typical lake in the Inner Mongolia–Xinjiang Lake region located in the cold and arid region of China and is the largest lake in north China (Xie et al. 2021). Hulun Lake plays an irreplaceable role in adjusting regional climate, conserving water resources, preventing desertification, protecting biodiversity, and maintaining the ecological balance of Hulunbuir Grassland and the ecological security of northern China (Liu and Yue 2017). The contents, components, fluorescence characteristics, sources, and stabilities of SOM and SPOM in Hulun Lake are studied by the combined use of sequential extraction method, three-dimensional fluorescence excitation emission matrix spectrum–parallel factor method (EEMs-PARAFAC), carbon-nitrogen ratio (C/N), and stable carbon isotope ($\delta^{13}C$).

2. Materials and Methods

2.1 Study area

Hulun Lake (48.55°–49.33°N, 116.97°–117.81°E) is also known as Dalai Lake. The Hulun Lake basin (including Halaha and Hailar River Basins) is located in China and Mongolia and has an area of 2.92×10^5 km^2, of which the area in China is 1.08×10^5 km^2, accounting for 37% of the total area (Wang et al. 2020). The length, width, circumference, and average water depth of Hulun Lake is 93 km, 32 km, 447 km, and 5.7 m, respectively (Li et al. 2019). The temperature of the Hulun Lake Basin varies considerably at different times throughout the year. The highest temperature is observed in summer for a short time, and low temperature occus in winter with the ice-forming period lasting for six months (Ao et al. 2020). The dominant wind in the basin is northwest wind, with an average annual wind speed of 4.2 m/s (Zhang et al. 2018). The main land use type in the basin is grassland, with an area of 20 393.57 km^2, among which the natural grassland area is as high as 20 132.69 km^2, accounting for 81% of the total area of the basin (Wang et al. 2021a).

2.2 Sediment and suspended particle sample collection

Twelve surface sediment and suspended particle samples were collected from Hulun Lake in July 2019 (**Fig. 1**). At each sampling point, 40 L of the overlying water sample 0.5 m away from the water surface was collected in a clean plastic bucket. After being transported back to the laboratory, water was filtered by a glass fiber filter membrane (GF/F, Φ = 47 mm, Whatman, UK), which was burned at 450 °C for 3 h in advance. After the filter membrane was freeze-dried, suspended particle samples were obtained and stored in a clean sample bag. Surface sediment samples were collected using the Beeker cylindrical sampler (NL, Φ = 12 cm, Eijkelkamp, 04.23; SA, the Netherlands) and stored in clean polythene sampling bags in the dark. Sediment samples were freeze-dried

after being transported back to the laboratory and sifted through a sieve (100 mesh, 0.149 mm). The prepared sediment samples were stored in clean polythene bags.

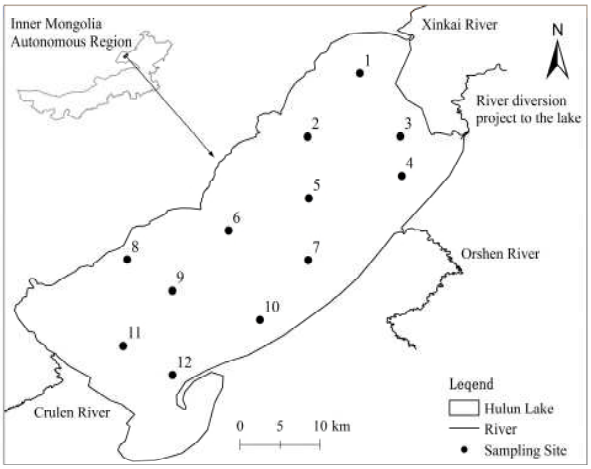

Fig. 1 Sampling sites and location of sediments and suspended particles of Hulun Lake.

2.3 Experimental methods

2.3.1 C/N

Sample pretreatment before total organic carbon (TOC) analysis: An appropriate amount of sediment or suspended particle samples were weighed and placed into a centrifuge tube and added with 20 mL HCl (3 mol/L) to react fully for the removal of inorganic carbon. Samples were washed with ultrapure water to neutral, freeze-dried, ground, and passed through a 100-mesh (0.15 mm) nylon sieve. Pretreated samples were stored in clean polythene bags.

Sample pretreatment before total organic nitrogen (TON) analysis (Zhang et al. 2018): An appropriate amount of sediment or suspended particle samples were weighed into a centrifuge tube and added with sufficient amounts of 2 mol/L KCl and 0.5 mol/L HCl to react fully for the removal of inorganic nitrogen. Samples were washed with ultrapure water to neutral, ground, freeze-dried, and passed through a 100-mesh (0.15 mm) nylon sieve. Pretreated samples were stored in clean polythene bags.

The contents of TOC and TON were determined using the Elementar (elementar vario MACRO cube, Elementar Analysensysteme GmbH, Germany). C/N was the ratio of TOC to TON.

2.3.2 Sequential extraction of organic matter components

The chemical components of SOM and SPOM included water-extracted organic matter (WEOM), humic acid (HA), fulvic acid (FA), and humin (HM), and the contents of each component were determined using the sequential extraction method (Zhang et al. 2017).

Step 1: Dry sediment or suspended particle sample (1 g) was placed into a 100 mL centrifuge tube and added with 50 mL ultrapure water. The tube was oscillated in a water bath at 25 °C for 1 h and then centrifuged. The supernatant was filtered with 0.45 μm membrane (the same as below) to obtain the WEOM extract.

Step 2: The residue obtained in step 1 was cleaned with saturated NaCl and added with 50 mL NaOH (1 mol/L)–$Na_4P_2O_7$ (0.1 mol/L) mixed solution. The pH of the mixture was adjusted to 13 by using 0.1 mol/L HCl. The tube was oscillated at 25 °C for 1 h and centrifugated to separate the supernatant and residue.

Step 3: The residue obtained in step 2 was cleaned with saturated NaCl and dried at 55 °C to obtain HM.

Step 4: The supernatant (20 mL) obtained in step 2 was collected, and its pH was adjusted to 1.0–1.5 by using H_2SO_4 (0.5 mol/L). The solution was kept in a 60 °C water bath for 1.5 h, allowed to stand for 8 h, centrifuged, and filtered to obtain the FA extract.

Step 5: The residue on the filter paper after filtration in step 4 was dissolved in warm NaOH (0.05 mol/L) solution to obtain the HA extract.

After measuring the dissolved organic carbon (DOC) concentration in WEOM, FA, and HA extracts by using an automatic total organic carbon tester (TOC-V, SHIMADZU, Japan), the contents of WEOM, FA, and HA in sediments and suspended particles were further calculated in accordance with the mass of the sediments. The HM content (g/kg) was the difference between the TOC content and the total contents of WEOM, FA, and HA.

2.3.3 EEM data of WEOM

The WEOM extract in section 1.3.2 was subjected to ultraviolet-visible (UV–VIS) spectrophotometry (D5000, hash, USA) at the wavelength range of 200–700 nm (1 nm intervals, medium speed). Ultrapure water was used for the baseline correction of absorbance measurements. A fluorescence analyzer (Hitachi, F7000, Japan) was used to scan the fluorescence spectrum of WEOM to obtain the EEM data. A 150 W xenon lamp was used as the excitation source, and the PMT voltage was set to 400 V. The excitation (λ_{Ex}) and emission (λ_{Em}) wavelengths were set to 210–450 and 250–530 nm, respectively, and the wavelength increment, slit width, and scanning speed were set to 2 nm, 10 nm, and 12000 nm/min, respectively. The calibration methods of EMM data and the determination of fluorescence components by the PARAFAC technology were performed by referring to the methods of Wang et al (2018). The fluorescence intensities (F_{max}) of individual components were used to represent their relative concentrations in the extract, and the total fluorescence intensity (F_t) of WEOM was the sum of all components. F_t was calculated using Eq. (1):

$$F_t = \sum_{1}^{n} F_{max(n)}, \quad (1)$$

where n is the number of the fluorescence components of WEOM in SOM or SPOM, and $F_{max(n)}$ (R.U.) is the relative intensity of the nth component of WEOM in SOM or SPOM.

The humification index (HIX) is the ratio of the peak area in the λ_{Em} range of 435–480 nm to the peak area in the λ_{Em} range of 300–345 nm at λ_{Ex} of 255 nm (Huguet et al. 2009).

2.3.4 $\delta^{13}C$

The sediment and suspended particle samples were pretreated by adding HCl (3 mol/L) to react fully for the removal of inorganic carbon. A proper amount of pretreated sample and 2–3 g CuO wire were placed into a quartz tube that was preheated at 850 °C for 2 h in a muffle furnace. The tube was then welded, sealed in a high-vacuum system, and burned at 850 °C for 5 h in a muffle furnace, and the CO_2 was purified in a vacuum system (Liang et al. 2014). The $\delta^{13}C$ was analyzed using an isotope mass spectrometer (MAT252, Finnigan Mat, Germany) with the Pee Dee Belemnite of Cretaceous in South Carolina, USA as the standard, and the analytical error was 0.2‰. The $\delta^{13}C$ values were calculated using Eq. (2):

$$\delta^{13}\mathrm{C} = (\frac{R_t}{R_s} - 1) \times 1000‰, \quad (2)$$

where R_t is the ratio of natural abundance of ^{13}C to ^{12}C of the sample, and R_s is the ratio of natural abundance of ^{13}C to ^{12}C of the standard.

2.3.5 Relative contribution of organic matter sources

The relative contribution rates of terrestrial and autochthonous sources for SOM and SPOM were calculated using end-member mixing models through the following equations (Wang et al. 2021a):

$$C = C_T + C_A, \quad (3)$$

$$N = N_T + N_A, \quad (4)$$

$$R_T = C_T / N_T, \text{ and} \quad (5)$$

$$R_A = C_A / N_A. \quad (6)$$

where C is the TOC content in sample; C_T and C_A are the TOC contents from terrestrial and autochthonous sources, respectively, in the sample; N is the TON content of sediment or suspended particle sample; N_T is the TON content of terrestrial organic matters in the sample; N_A is the TON content of autochthonous matters in the sample; R_T is the C/N value of terrestrial organic matters; and R_A is the C/N value of autochthonous organic matters.

The values of N_T, N_A, C_T, and C_A were calculated by Eqs. (3)–(6):

$$N_T = (C - R_A \times N) / (R_T - R_A), \quad (7)$$

$$N_A = (C - R_T \times N)/(R_A - R_T), \quad (8)$$

$$C_T = R_T \times (C - R_A \times N)/(R_T - R_A), \text{ and} \quad (9)$$

$$C_A = R_A \times (C - R_T \times N)/(R_A - R_T). \quad (10)$$

N_T, N_A, C_T, and C_A were calculated by substituting the values of R_A, R_T, C, and N into Eqs. (7)–(10), and the relative contribution rates of terrestrial and autochthonous sources were calculated by Eqs. (11) and (12):

$$P_T = C_T / C, \text{ and} \quad (11)$$

$$P_A = C_A / C. \quad (12)$$

P_T and P_A are the relative contribution rates of terrestrial and autochthonous sources, respectively.

P_T and P_A based on $\delta^{13}C$ were calculated using Eqs. (13) and (14) (Koszelnik et al. 2018):

$$\delta^{13}C = \delta^{13}C_T \times P_T + \delta^{13}C_A \times P_A, \text{ and} \quad (13)$$

$$P_T + P_A = 1. \quad (14)$$

$\delta^{13}C_T$ is the $\delta^{13}C$ value of terrestrial organic matters in sample, and $\delta^{13}C_A$ is the $\delta^{13}C$ value of autochthonous organic matters in sample.

2.4 Statistical analysis

Three parallel analyses were performed for all measured indices, and test results were expressed as the average value of three parallel analyses (error range of the results of the three analyses < 5%).

The distribution map of sampling sites was drawn using the ArcGIS 10.2. Figures about the contents, composition, fluorescence intensity, and fluorescence components of the WEOM of SOM and SPOM and the C/N and $\delta^{13}C$ values of sediment and suspended particle samples were created using the Surfer 14.0 software.

The minimum, maximum, mean, and standard deviations of the analytical indices were determined using the SPSS 19.0 software. The correlation and significance analyses between two data sets were performed using the Pearson correlation coefficient method and ANOVA, respectively, in the SPSS 19.0 software.

3 Results and Discussion

3.1 Contents and compositions of SOM and SPOM in Hulun Lake

The contents of SOM and SPOM in Hulun Lake were characterized using the TOC concentrations in suspended particles and sediments, respectively. SOM and SPOM contents range from 4.79 g/kg to 34.95 g/kg (mean = 23.04 ± 10.27 g/kg) and from 16.19 g/kg to 31.49 g/kg (24.70 ± 4.63 g/kg), respectively (**Fig. 2**). The average content of SPOM was slightly higher than that of SOM, but the difference was not significant ($P > 0.05$).

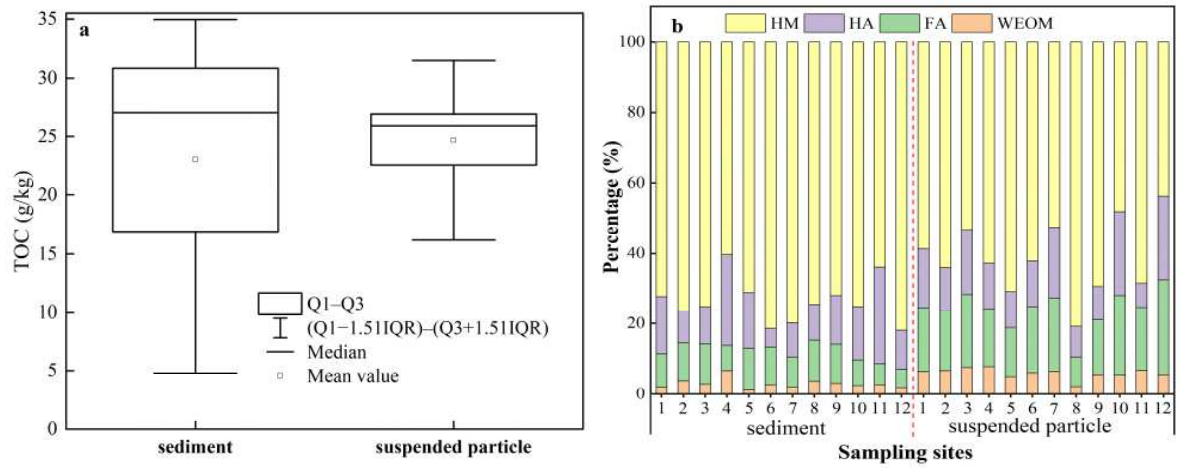

Fig. 2 (a) Contents of total organic carbon (TOC) in sediments and suspended particles and (b) compositions of sediment (SOM) and suspended particulate (SPOM) organic matters in Hulun Lake. Q1: first quartile, Q3: third quartile, IQR: interquartile range, HM: humin, HA: humic acid, FA: fulvic acid, WEOM: water-extractable organic matter.

The contents of SOM and SPOM in the north and west were higher than those in the east and south. The spatial distribution characteristics of SOM and SPOM in Hulun Lake were affected by the land use around the lake, dominant wind direction, and sediment particle size distribution. The grass shoreline in the northwest of Hulun Lake is 150 km long (Song et al. 2011), and animal husbandry is developed. In addition, the perennial prevailing wind in the basin is northwest wind, which leads to a large amount of hay, animal manure, or soil from the semiarid grassland in the northwest into the lake followed by the surface runoff formed by wind or rainfall. According to statistics, the annual amount of hay into the Hulun Lake is about 3348 t (frozen period: 1580 t, nonfrozen period: 1768 t) (Zhang et al. 2019b). The decomposition and settlement of hay can introduce a large amount of dissolved and particulate organic matters. While the east bank of Hulun Lake is the lakeside dune zone, the organic matter input is less than that of the west lake. In addition, the sediments in southeastern part are sandy sediments with large particle size, whereas the sediments in the northwestern part are silts with small particle size. Most organic matters (more than 85%) are distributed in fine particles, and the lowest proportion is distributed in coarse particles (Shang et al. 2013). The median grain size (D_{50}) of surface sediments in Hulun Lake was significantly negatively correlated with TOC content ($D_{50} = -2.7197\text{TOC} + 104.38$, $R^2 = 0.6505$, $P<0.01$). Hence, the SOM contents in the north and west lake areas with small sediment particle size were higher than those in the east and south lake areas with large sediment particle size. Hulun Lake is a shallow lake with a wide lake surface and an average water depth of 5.7 m. Under the disturbance of wind and waves, the sediment resuspension is also one source for SPOM (Ao et al. 2020; Liu et al. 2019b). Thus, the spatial distribution of SPOM is also affected by the SOM distribution.

SOM and SPOM consist of four chemical components, i.e., WEOM, HA, FA, and HM. Among these components, WEOM is soluble in water, an active component in SOM and SPOM, and has the highest bioavailability and the lowest proportion (Li et al. 2018; Ni et al. 2021; Zhang et al. 2021). The WEOM contents in SOM and SPOM were 0.15–1.34 and 0.45–2.28 mg/kg, respectively, and had mean values of 0.63 ± 0.35 and 1.49 ± 0.50 g/kg, respectively. WEOM took 3.0% and 6.0% of SOM and SPOM, respectively. HM is not soluble in acid or alkali and is difficult to decompose (Pham et al. 2021; Zhang et al. 2019a). HM is the most stable form of SOM and SPOM. The HM contents in SOM and SPOM were 2.89–26.73 and 7.32–22.33 g/kg, respectively, and had mean values of 17.31 ± 7.81 and 15.33 ± 4.36 g/kg, respectively. These mean values accounted for 73.7% and 61.2%, respectively, of the total amount of SOM and SPOM, respectively. FA and HA can be dissolved in acid or alkali, and their stabilities are between those of WEOM and HM. The contents of FA in SOM and SPOM ranged from 0.32 g/kg to 3.87 g/kg and from 1.72 g/kg to 5.61 g/kg, respectively, and accounted for 9.2% and 18.1%, respectively, of the total amounts of SOM and SPOM, respectively. The contents of HA in SOM and SPOM ranged from 1.24 g/kg to 5.32 g/kg and from 1.77 g/kg to 5.40 g/kg, respectively, and accounted for 14.2% and 14.8% of the total amount of SOM and SPOM, respectively. The relative ratios of the components (WEOM:FA:HA:HM) in SOM and SPOM were 1.0:3.6:4.5:27.4 and 1.0:2.9:2.3:10.3, respectively. HM was the dominant component of SOM and SPOM in Hulun Lake.

3.2 Fluorescence components of WEOM in SPOM and SOM in Hulun Lake

WEOM takes the smallest proportion in SOM and SPOM but is the most active component and is most easily used by microorganisms. WEOM contains different fluorescence components with different characteristics in structure, humification degrees, and sources (Derrien et al. 2019; Han et al. 2021; Liu et al. 2019a). Therefore, further analysis of the fluorescence composition of WEOM can further understand the composition, source, and biodegradability of SOM and SPOM. The WEOM fluorescence spectra of SOM and SPOM in Hulun Lake reflected humus- and protein-like fluorescence peaks. The three-dimensional fluorescence spectra of EEM were analyzed using the PARAFAC, and 4 and 3 fluorescence components with single-emission wavelength were determined. As shown in **Table 1**, the four fluorescence components of WEOM in SOM included 1 terrigenous fulvic acid-like component C1, 2 terrigenous humic acid-like components C2 and C3, and 1 tryptophan-like component C4 formed by biodegradation. The three fluorescence components of WEOM in SPOM included fulvic acid-like component C1′, terrigenous humic acid-like component C2′, and tryptophan-like component C3′.

Table 1 WEOM components of SOM and SPOM in Hulun Lake.

Organic matter	Component	Ex_{max} (nm)	Em_{max} (nm)	Description
SOM	C1	238	410	fulvic acid-like fluorescence
	C2	276	490	humic acid-like fluorescence
	C3	252,362	454	humic acid-like fluorescence
	C4	220,276	340	tryptophan-like fluorescence
SPOM	C1′	244	434	fulvic acid-like fluorescence
	C2′	272, 368	480	humic acid-like fluorescence
	C3′	224, 276	346	tryptophan-like fluorescence

Ex_{max}: maximum excitation wavelength, Em_{max}: maximum emission wavelength, C1: component 1 of SOM, C2: component 2 of SOM, C3: component 3 of SOM, C4: component 4 of SOM, C1′: component 1 of SPOM, C2′: component 2 of SPOM, C3′: component 3 of SPOM.

The total fluorescence intensity of WEOM in SOM (F_t-SOM) ranged from 0.87 R.U. to 5.45 R.U. (mean = 2.74 ± 1.33 R.U), and humus-like components (C1 + C2 + C3) took 79.9% of F_t-SOM (**Fig. 3a**). The total fluorescence intensity of WEOM in SPOM (F_t-SPOM) ranged from 1.60 R.U. to 4.68 R.U. (mean = 3.64 ± 0.88 R.U.), and humus-like components (C1′ + C2′) took 70.4% of F_t-SPOM (**Fig. 3b**). Humus-like components were the dominant fluorescence components for WEOM in SOM and SPOM, but the proportion of humus-like components in SOM was slightly higher than that in SPOM.

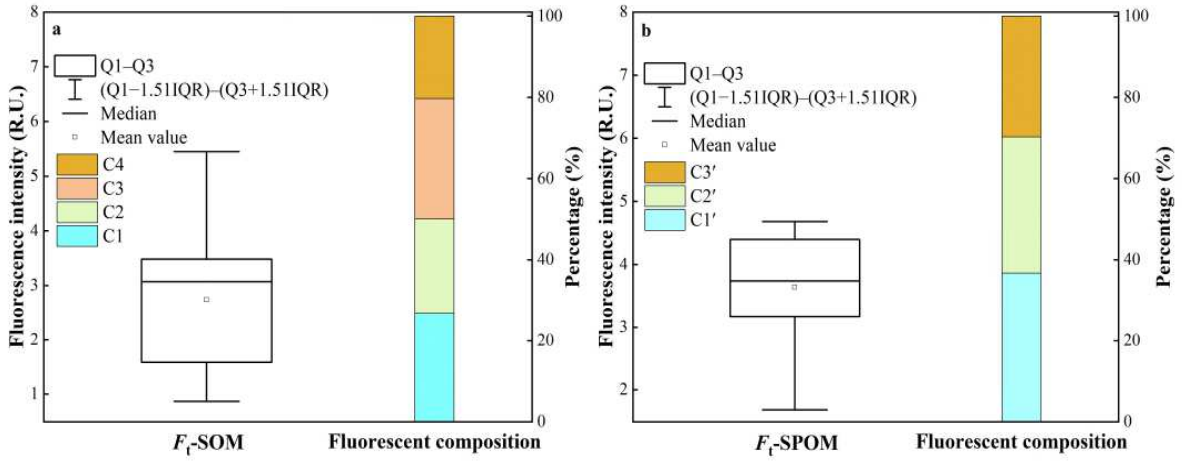

Fig. 3 Total fluorescence intensities (F_t) and fluorescent compositions of WEOM in (a) SOM and (b) SPOM organic matters in Hulun Lake.

3.3 Sources of SPOM and SOM in Hulun Lake

The organic matter carriers from different sources have different ranges of C/N and $\delta^{13}C$ and are conservative in the physical mixing process (Yu et al. 2010). The combination of C/N and $\delta^{13}C$ can effectively distinguish the

source of organic matter (Pan et al. 2019; Yu et al. 2010). The C/N values of aquatic phytoplankton range from 4 to 10 (Meyers 1994), and the $\delta^{13}C$ values usually range from −42‰ to −24‰ (Liu et al. 2021). The C/N of most terrestrial higher plants is > 20 (Meyers 1994), and the C/N and $\delta^{13}C$ values of C3 plants range from 20 to 80 and from −32‰ to −22‰, respectively (Kendall et al. 2001; Ogrinc et al. 2008). The values of C/N and $\delta^{13}C$ for C4 plants generally range from 40 to 80 and −16‰ to −9‰, respectively (Kendall et al. 2001). The C/N values of organic matters from terrestrial soils range from 8 to 15 (Ogrinc et al. 2008), and their $\delta^{13}C$ values are similar to those of terrestrial plants. C/N is less than 8, indicating large lake aquatic biomass, high primary productivity, and high proportion of autochthonous sources. The C/N is between 8 and 15, indicating that SOM and SPOM are influenced by terrestrial and autochthonous sources. C/N is greater than 15, indicating that SOM and SPOM come from terrestrial input. The C/N ranges of surface sediments and suspended particles in Hulun Lake were 8.37–15.39 (mean = 12.21 ± 2.01) and 7.53–15.20 (mean = 11.33 ± 2.55), respectively. The values of $\delta^{13}C$ in sediments and suspended particles ranged from −27.78‰ to −26.25‰ (mean = −27.18‰ ± 0.52‰) and from −27.20‰ to −26.10‰ (mean = −26.57‰ ± 0.43‰), respectively. According to the relationship of C/N and $\delta^{13}C$ of different end-member substances proposed by Meyers (1994) as shown in **Fig. 4**, SOM and SPOM in Hulun Lake were influenced by the joint effects of autochthonous and terrestrial sources, and the influence of autochthonous inputs on SPOM might be greater than that on SOM.

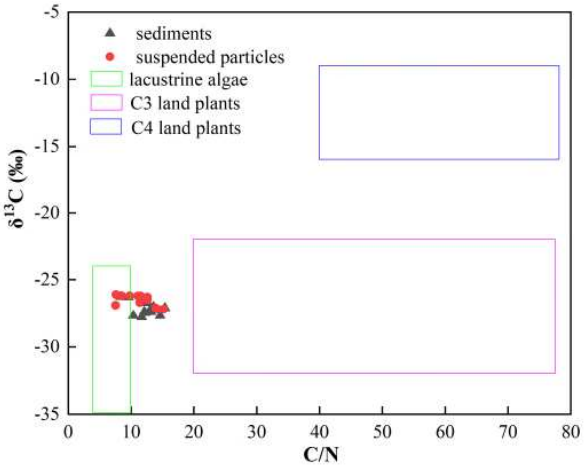

Fig. 4 Carbon-nitrogen ratio (C/N) and stable carbon isotope ($\delta^{13}C$) values of lacustrine algae, C3 land plants, C4 land plants, and sediments and suspended particles in Hulun Lake.

The relative contributions of terrestrial (P_t) and autochthonous (P_a) sources were estimated using two end-member mixing models based on C/N and $\delta^{13}C$, respectively, to further analyze the relative contributions of autochthonous and terrestrial sources to SOM and SPOM in Hulun Lake (**Table 2**).

Table 2 Relative contributions of terrestrial (P_t) and autochthonous (P_a) sources of SOM and SPOM in Hulun Lake.

	Item	Calculated by C/N			Calculated by $\delta^{13}C$		
		C/N	P_a (%)	P_t (%)	$\delta^{13}C$ (‰)	P_a (%)	P_t (%)
SOM	Min	8.37	12.8	40.5	−27.78	14.3	55.6
	Max	15.39	59.5	87.2	−26.25	44.4	85.7
	Mean	12.21 ± 2.01	29.3 ± 13.4	70.7 ± 13.4	−27.18 ± 0.52	26.2 ± 10.3	73.8 ± 10.3
SPOM	Min	7.53	10.6	34.8	−27.20	17.5	59.4
	Max	15.20	65.2	89.4	−26.10	40.6	82.5
	Mean	11.33 ± 2.55	32.8 ± 18.8	67.2 ± 18.8	−26.57 ± 0.43	31.1 ± 9.3	68.9 ± 9.3

The P_t values of SOM and SPOM estimated by C/N were 70.7% ± 13.4% and 67.2% ± 18.8%, respectively, and the *P*a values of SOM and SPOM were 29.3% ± 13.4% and 32.8% ± 18.8%, respectively. The P_t values of SOM and SPOM estimated by $\delta^{13}C$ were 73.8% ± 10.3% and 68.9% ± 9.3%, respectively, and the *P*a values of SOM and SPOM were 26.2% ± 10.3% and 31.1% ± 9.3%, respectively. The estimation results of the two methods were basically consistent, and SPOM was relatively more affected by autochthonous sources than SOM, and this finding was consistent with the results of preliminary judgment. These results might be because samples were collected in July when the cyanobacterial bloom occurred in Hulun Lake area in summer. During the sampling period, the chlorophyll a concentration ranged from 4.37 mg/m^3 to 60.56 mg/m^3 (mean = 18.39 mg/m^3). Therefore, planktonic algae contribute a certain amount of SPOM as a part of suspended particles.

3.4 Stabilities of SPOM and SOM in Hulun Lake

The organic matters in a lake water environment exist in forms of DOM, SOM, and SPOM, which can transformed into one another through physical and chemical processes, such as adsorption–desorption, dissolution, condensation, redox, photochemistry, and biological processes of phytoplankton and large and medium-sized aquatic plants and microorganisms (He et al. 2016; Wu et al. 2008) (**Fig. 5**). The stabilities of SOM and SPOM directly affect the migration and transformation of organic matters and pollutants and the environmental toxicities of the pollutants in different media in the lake water environment (Hu et al. 2019; Lipczynska-Kochany 2018; Miller et al. 2020). Relatively stable SOM and SPOM are not easy to biodegrade, which is conducive to carbon deposition and accumulation, and the risk of rerelease and biotoxicity of the pollutants combined with them are relatively small. By contrast, poor stabilities of SOM and SPOM are not conducive to the deposition and accumulation of carbon, and the ecological risks of combined pollutants are relatively high. Therefore, evaluating the stabilities of SOM and SPOM is important in lake water environment protection. The stabilities of SOM and SPOM were evaluated on the basis of source, composition, The percentage of HA in humus acid (PQ value), and HIX value of organic matters.

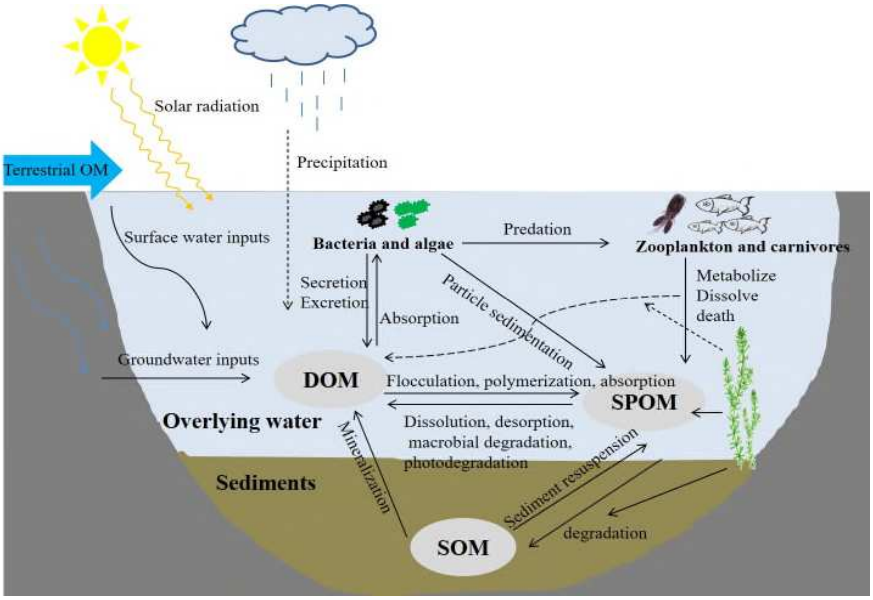

Fig. 5 Occurrence, migration, and transformation of organic matters in a lake environment. OM: organic matter.

SOM and SPOM in Hulun Lake came from terrestrial sources, and the contribution rate of terrigenous source was about 70%. Organic matters from terrigenous sources are humus-like matters, and the humification degrees are high. In terms of composition, the predominant component of SOM and SPOM in Hulun Lake was HM, which is difficult to degrade. HM accounted for 73.7% and 61.2% of the total amount of SOM and SPOM, respectively, and its maximum values could reach 81.9% and 80.9%, respectively. However, WEOM accounted for only 3.0% and 6.0% of the total amount of SOM and SPOM, respectively. In addition, the fluorescence components of WEOM were humus-like components, which had a large molecular weight and were relatively difficult to degrade, whereas tryptophane-like components with small molecular weight and easy to biodegrade accounted for less than 30%. The results of the composition survey were in good agreement with the results of source identification. HIX can also reflect the humification degree of WEOM. HIX < 4 indicates low humification degree of WEOM, and HIX of 4–10 means the strong humification degree of WEOM and that WEOM is difficult to biodegrade (Huguet et al. 2009). The HIX values for WEOM in SOM and SPOM of Hulun Lake ranged from 4.21 to 8.54 (mean = 6.40) and from 4.07 to 7.40 (mean = 6.09), respectively. The HIX values were all in the range of 4 to 10, indicating that the WEOM in SOM and SPOM of Hulun Lake had a strong humification degree and were difficult to biodegrade. Compared with those of Taihu Lake, with the same area and eutrophication level as Hulun Lake, the HIX values of WEOM in SOM and SPOM of Hulun Lake were significantly ($P < 0.05$) higher (Wang et al. 2018), indicating significantly higher humification degrees (**Table 3**).

Table 3 Humification index (HIX) values of WEOM in SOM and SPOM of Hulun and Taihu Lakes.

Lake	HIX	Min	Max	Mean	SD

Hulun Lake	SOM	4.21	8.54	6.40	1.29
	SPOM	4.07	7.40	6.09	0.85
Taihu Lake	SOM	2.37	3.68	3.02	0.08
	SPOM	2.81	5.32	4.04	0.15

Min: minimum value, Max: maximum value, SD: standard deviation.

The PQ value can also be used to characterize the stabilities of SOM and SPOM (Bulosan-Atendido et al. 2005; Satisha and Devarajan 2005; Yang et al. 2019; Zhang et al. 2020). A high PQ value results in complete humification process of organic matters, stable organic matters, accumulation of organic matters in sediments and suspended particles, and low contribution to the carbon cycle. By contrast, a low PQ value results in poor stability of organic matters, recycling of organic carbon, and increased contribution to the carbon cycle. PQ values were calculated using Eq. (15):

$$PQ = \mathrm{HA}/(\mathrm{WEOM}+\mathrm{HA}+\mathrm{FA}). \quad (15)$$

The PQ values of SOM and SPOM in Hulun Lake ranged from 0.29 to 0.76 (mean = 0.52 ± 0.13) and from 0.22 to 0.46 (0.37 ± 0.07), respectively. The PQ values of SPOM were significantly lower than those of SOM ($P < 0.01$). The comprehensive evaluation results of source, component, and HIX and PQ values showed that the stability of SPOM in Hulun Lake was significantly lower than that of SOM. As one of the important forms of organic matters in the lake water environment, SPOM plays an important role in carbon cycle and pollutant migration and transformation in the lake (He et al. 2021a, b; Hu et al. 2019; Lehmann et al. 2004). Compared with SOM, SPOM is more likely to be transported in water bodies. For shallow lakes, under the effects of wind disturbance and hydrodynamic force, the frequency of migration and transformation between SPOM, DOM, and SOM is increased, and the mechanism is complex. The results of this study indicated that the stability of SPOM in Hulun Lake was significantly lower than that of SOM, which might be because algae was one of the important sources of SPOM during the cyanobacterial outbreak in July. The main components of algal organic matters are protein-like substances with low humification degree and high bioavailability (Lee et al. 2016; Nicolau et al. 2015; Villacorte et al. 2013). In recent years, the climate of Hulun Lake shows a trend of warming and drying, and bloom outbreaks have become normal in summer (Bao et al. 2021; Chen et al. 2012). With increasing temperature, the area of the bloom increases, and the duration of the bloom is prolonged, which may contribute to SPOM. Studies showed that the release effects of SOM and SPOM were enhanced, and stabilities deteriorate with increasing temperature (Gudasz et al. 2010; Lipczynska-Kochany 2018). This finding may be a common phenomenon in other lakes located in cold and arid regions. Therefore, studies on the occurrence characteristics of organic matters in different media, and the migration and transformation of organic matters and endogenous pollutants, which are

closely related to the environmental behavior of the organic matters, in different types of lakes in China especially for the lakes in cold and arid regions under climate change are important for lake environmental protection. Moreover, these areas should be further studied in the future.

4. Conclusion

The occurrence, sources, and stabilities of SOM and SPOM in Hulun Lake were investigated and compared. Results showed that SOM and SPOM were different in content, chemical composition, fluorescence composition of WEOM, source, and stability.

The average content of SPOM in Hulun Lake was slightly higher than that of SOM, but no significant difference was observed. The contents of SOM and SPOM showed a spatial distribution, i.e., higher in the north and west than in the east and south, due to the influences of land use, dominant wind direction, and sediment grain size distribution. The dominant component of SOM and SPOM was HM. The average proportion of HM in SOM was 73.7%, which was higher than that in SPOM (61.2%). The proportions of WEOM in SOM and SPOM were the smallest, but the WEOM proportion in SPOM was higher than that in SOM. The dominant fluorescence component of WEOM in SOM and SPOM was the humus-like component.

According to the analysis results of C/N and $\delta^{13}C$, SOM and SPOM were influenced by terrestrial and autochthonous sources but came from terrestrial input. The relative contribution rate of terrestrial source was about 70%. SOM was more affected by terrestrial source than SPOM.

The SOM and SPOM in Hulun Lake had stronger humification degrees than those in Taihu Lake and were not easy to biodegrade. Moreover, the stability of SPOM was significantly lower than that of SOM, which might be affected by the cyanobacterial bloom in summer. In recent years, the climate of Hulun Lake showed a trend of warming and drying, and the normal occurrence of cyanobacterial bloom might have a remarkable influence on the stability of SOM and SPOM. In the future, the studies on the occurrence, migration, and transformation characteristics and stability of organic matters and endogenous pollutants in different media in lake water environment in cold and arid regions under climate change should be strengthened.

Declarations

- **Ethics approval and consent to participate:** Not applicable.
- **Consent for publication:** Not applicable.

- **Availability of data and materials:** The datasets used and/or analyzed in the study are available from the corresponding author upon reasonable request.
- **Competing interests:** The authors declare no competing interest.
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- **Authors' contributions:** Wenwen Wang collected and analyzed samples and was a major contributor in writing the manuscript. Junyi Chen collected and analyzed the samples. Shuhang Wang formulated the sampling and experimental schemes. Wei Li checked the quality of the paper. All authors read and approved the final manuscript.

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