Macroalgal influence on particulate organic matter sources and early transformation in an Arctic fjord

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Highlights

- Macroalgal-dominated sites were observed with higher labile surface particulate organic carbon and nitrogen signatures compared to adjacent waters.
- Biochemical and biomolecular composition indicated lateral transport from macroalgal-beds with conservative reorganization.
- Brandal was identified as a model site for future biogeochemical studies related to macroalgal expansion in Kongsfjorden.

Abstract

Accelerated Arctic warming is promoting the expansion of coastal macroalgal habitats; yet their influence on pelagic organic carbon cycling remains unresolved. This study investigates the influence of macroalgal beds on the biochemical composition of surface particulate organic matter (POM) in Kongsfjorden, Svalbard, during late summer 2023. Surface waters were sampled at four macroalgal-dominated sites (MDS) and from adjacent waters (Adj-W) located 500 m and 1500 m away. A multi-proxy approach integrating elemental composition, stable isotopes, biopolymeric fractions, monosaccharides, and amino acids was used to trace macroalgal contributions and their lateral redistribution. Concentrations of particulate organic carbon, nitrogen, carbohydrates, and proteins were consistently higher at MDS than in Adj-W, indicating localized enrichment of biochemically labile organic matter within macroalgal habitats. Molecular analyses further revealed elevated concentrations of macroalgal-associated sugars (glucose, galactose, fucose, mannuronic acid) and labile amino acids (Asp, Glu, Gly, Ser, Ala) reinforcing macroalgal-derived contributions to surface POM. While, $\delta^{13}C_{POC}$ showed minimal spatial variation (−26.8 to −29.1‰), the biochemical and molecular signatures indicated a decreasing macroalgal contribution towards Adj-W, along with internal reorganization, suggesting lateral transport of macroalgal-derived POM with selective early-stage transformation. Overall, these findings indicate that Arctic macroalgal beds act as dynamic coastal biogeochemical hotspots, redistributing and transforming organic carbon beyond their habitat.

Keywords: Arctic fjords; macroalgal-derived organic matter; coastal carbon cycling; lateral transport

1. Introduction

Accelerated warming of the Arctic has led to pronounced environmental changes, including a reduction in sea ice extent and thickness, intensified glacier melt, widespread permafrost thawing, and a shift toward more liquid precipitation (Dai et al., 2019; Rantanen et al., 2022). These changes are altering marine primary production (Attard et al., 2024), coastal carbon sources (Mathew et al., 2025), and nutrient dynamics within Arctic fjord systems (McGovern et al., 2020). Amid these environmental transformations, macroalgae have demonstrated ecological resilience and adaptability, enabling their expansion along Arctic coastlines (Assis et al., 2022). Recent estimates from species distribution modeling indicate a substantial increase in subtidal (45%) and intertidal (8%) brown macroalgal cover along the Arctic coastline over the past few decades (Krause-Jensen et al., 2020). This rapid and ongoing macroalgal expansion contributes substantially to coastal primary productivity and carbon dynamics in the Arctic (Attard et al., 2024; Krause-Jensen et al., 2020). Macroalgal biomass and condition are strongly shaped by local environmental variability, with runoff and site-specific forcing influencing kelp biochemistry and ecosystem functioning in Arctic coastal systems (Castro de la Guardia et al., 2025; Niedzwiedz et al., 2025). Comparable environment-driven changes in kelp biomass and distribution have been reported across the Arctic, including Greenland and the Canadian Arctic, indicating pan-Arctic rather than site-specific responses (Carlson et al., 2026; Filbee-Dexter and Wernberg, 2020; Krause-Jensen and Duarte, 2016). Kelp forest structure shifted markedly, with a reduced depth distribution, a declining abundance of several kelp species, and an increasing dominance of *Alaria esculenta*, driven primarily by rising turbidity and coastal darkening rather than temperature alone, thereby reshaping kelp biomass, demography, and ecosystem functioning in Kongsfjorden (Düsedau et al.,

2024). Field experiments have also shown that macroalgal blades can lose approximately 3% of their total area per day due to mechanical stress, physical abrasion against rocky substrates, seasonal increases in tissue brittleness, and biological weakening by epiphytes. Which, provide a substantial and continuous input of macroalgal-derived material to the coastal particulate organic matter (POM) pool (Buchholz and Wiencke, 2016).

Macroalgal beds contribute a significant amount of macroalgal-derived organic carbon, approximately 60% as particulate organic carbon (POC), and approximately 30% as dissolved organic carbon (DOC) (Kennedy and Blain, 2025; Pessarrodona et al., 2022) to the surrounding environment, and play a crucial role in supporting secondary production via detrital food web and coastal Arctic carbon cycling (Pedersen et al., 2021; Renaud et al., 2015; Simpkins et al., 2025). Macroalgal POM appears in multiple forms, including whole thalli and tissue fragments, and is often buoyant due to structural features such as pneumatocysts, allowing particles to stay suspended in surface waters (Carlson et al., 2026; Kennedy and Blain, 2025). This buoyancy promotes extensive lateral transport across coastal and fjord systems, effectively linking benthic macroalgal production with pelagic environments and shaping the spatial distribution of organic carbon (Carlson et al., 2026; van der Mheen et al., 2024). A substantial fraction of the carbon produced in macroalgal beds is exported to surrounding environments, with only about 2% remaining and settling at the site of production (Kennedy and Blain, 2025; Krause-Jensen and Duarte, 2016; Pessarrodona et al., 2022). Macroalgal POM undergoes microbial-mediated transformation and degradation during transit and thereby affects biogeochemical processes in macroalgal beds as well as adjacent waters (Adj-W) (Duarte et al., 2013; Krause-Jensen and Duarte, 2016; Ortega et al., 2019). Biochemical compositional and lipid biomarker studies have shown hints of macroalgal contribution to POM (Singh et al., 2024b) and sediments (Roy et al.,

2025) in Kongsfjorden. Similarly, studies from saline lake system demonstrate that microbial transformations of organic matter require high-resolution molecular proxies to distinguish carbon sources (Jiang et al., 2022; Yang et al., 2020). However, the spatial variability and magnitude of macroalgal-derived organic carbon contributions to POM along coastal gradients remain poorly understood.

To resolve the sources and transformation pathways better, and to understand how the expansion of macroalgal forests will influence Arctic coastal biogeochemistry, a systematic biochemical characterization of POM in and around macroalgal-dominated sites is necessary. Thus, the present study investigated the biochemical composition of POM from the surface waters of Kongsfjorden (Svalbard) at four macroalgal-dominated sites (MDS), and their respective adjacent waters (Adj-W) located 500 m and 1500 m from the MDS sites. Here, we addressed two key questions: *(i) To what extent do the biochemical characteristics of surface POM at MDS reflect inputs from macroalgal-derived organic matter? (ii) How does the biochemical composition of POM change from MDS to Adj-W, and (iii) What do these changes reveal about the lateral transport and early alteration of macroalgal-derived organic matter?*

Material and Methods

2.1 Sampling site and locations

Surface water samples were collected during late summer 2023 (September–October) from four MDS distributed along and across the Kongsfjorden coast using the workboat Teisten, with a Niskin sampler deployed at 3 m depth, as well as from adjacent locations (Adj-W) located 500 m and 1500 m away from each MDS site (Figs. 1A and 1B). The seawater was pre-filtered using a

200 µm mesh to remove larger particles. Seawater samples (3 L) were filtered using pre-combusted (4 hours at 450 °C) 0.7 µm pore size glass fiber filters (GF/F) to collect particulate matter. Immediately after filtration, the GF/F filters were stored at -80 °C until analysis. An aliquot of 100 mL seawater sample for dissolved nutrients analysis was collected in high-density polyethylene bottles from each sampling location and stored at -80 °C until analysis.

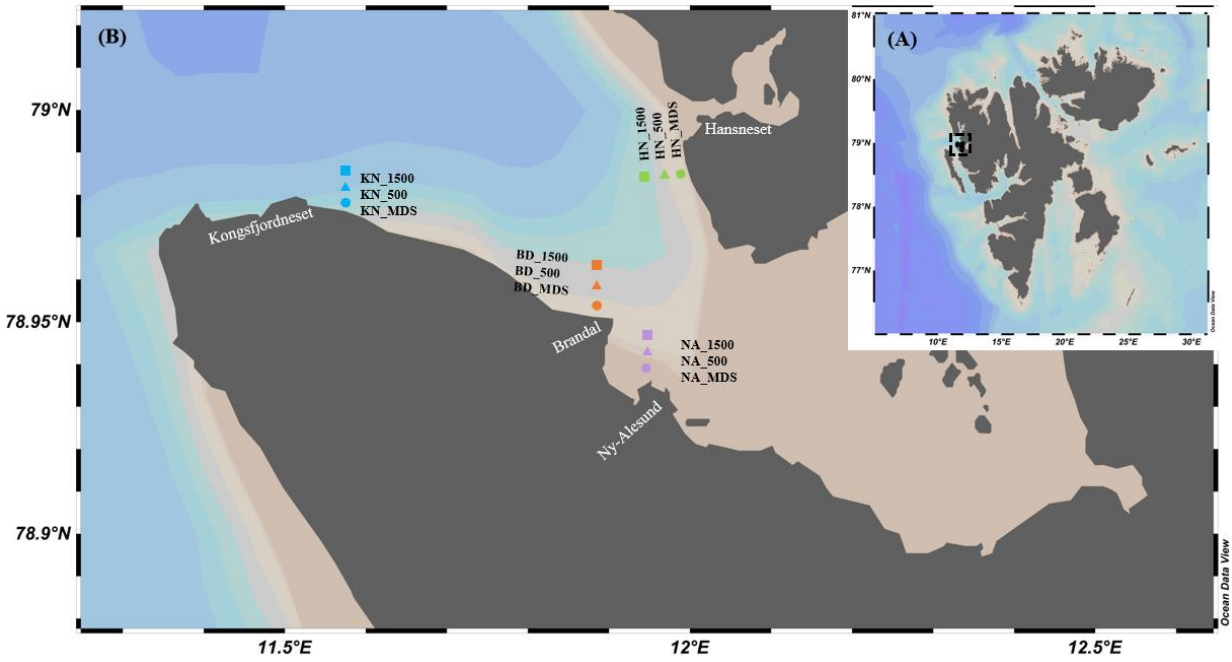


Figure 1. Study area and sampling locations in Svalbard (A) and the detailed map of sampling stations in Kongsfjorden (B) across nearshore macroalgal beds (MDS), mid-fjord (500 m), and offshore (1500 m) sites at BD, NA, KN, and HN.

2.2 Physicochemical characteristics of seawater

The vertical profiles of temperature, salinity, and turbidity at each sampling location were recorded using an SBE 911 plus instrument (Seabird Electronics Inc., USA). The concentrations of dissolved nutrients (nitrate, nitrite, silicate, and phosphate) were determined using a Seal AA3

analytical autoanalyzer with a standard deviation of ±1% and an R^2 value of >0.99 (Grasshoff et al., 2009). Chlorophyll *a* was extracted following (Singh et al., 2024a) with minor modifications. Briefly, GF/F filters were extracted in 90% acetone under low-light conditions by keeping them overnight at −20 °C. The pigment extracts were centrifuged (10,000×g, 4 °C, 10 min), filtered (0.2 µm PVDF), and analyzed using an Agilent 1200 HPLC with a ZORBAX 300 Extend-C8 column (1.1 mL min^{-1}, 40 °C). Pigments were separated using a reverse-phase methanol–ammonium acetate gradient and identified by comparing retention times and absorption spectra (250–850 nm) against a DHI chlorophyll-a standard.

2.3 Elemental and isotopic analyses of POM

Filters containing particulate matter were dried at 45 °C for 24 h, after which carbonates were removed by exposing the filters to fumes of 35% HCl for 6 h in a desiccator. The treated filters were then weighed and tightly packed into tin capsules for elemental and isotopic analyses (Jain et al., 2019; Singh et al., 2024b). Particulate nitrogen (PN), particulate organic carbon (POC), δ^{13}C-POC, and δ^{15}N-PN were measured at the Marine Stable Isotope Laboratory, National Centre for Polar and Ocean Research, Goa, India, using an elemental analyzer coupled to an isotope ratio mass spectrometer (EA-IRMS; Isoprime Vario Isotope Cube) operated in continuous-flow mode. External analytical precision for δ^{13}C and δ^{15}N was ±0.10‰ and ±0.14‰ (1σ), respectively, determined by repeated analysis of caffeine (IAEA-600) and ammonium sulphate (IAEA-N1) standards. δ^{13}C and δ^{15}N values are reported relative to VPDB and Air-N_2, respectively, with ammonium sulfate (IAEA-N1) used for normalization to Air-N_2. External precision for %C and %N was ±0.96% and ±0.95% (1σ), respectively, based on repeated measurements of sulfanilamide.

2.4 Biochemical analysis of POM

The dried, pre-weighed filters with POM were cut into smaller pieces using clean stainless-steel scissors and then used for further analysis. The total particulate carbohydrates (P-CHO), particulate proteins (P-PRT), and particulate lipids (P-LIP) were analyzed using the phenol-sulfuric acid (Dubois et al., 1956), Lowry (Upreti et al., 1988), and Phospho-Vanillin (Folch et al., 1957) methods, respectively, and as described earlier in (Singh et al., 2024b). Biopolymeric carbon (BPC) was determined as depicted by (Danovaro et al., 2001), using the sum of the carbon equivalents of P-CHO, P-PRT, and P-LIP (conversion factors of 0.4, 0.49 and 0.75, respectively).

2.5 Monosaccharide composition analysis of POM

For monosaccharide analysis, POM samples were acid-hydrolyzed and then analyzed using High-Performance Anion Exchange Chromatography coupled with a Pulsed Amperometric Detector (HPAEC-PAD) as described earlier by (Singh et al., 2024a). In brief, GF/F filters with POM were treated with 1 mL of 12 M H_2SO_4 at 25 °C for 2 h, diluted to 1.2 M with Milli-Q water, purged with N_2, sealed, and incubated at 100 °C for 4 h. After cooling, the internal standard (myo-inositol) was added, and the samples were neutralized with pre-combusted $CaCO_3$, centrifuged (6000 rpm, 10 min), and filtered (0.22 µm PTFE). The samples were analyzed using HPAEC-PAD (Metrohm 940 Professional IC Vario) equipped with an Au working electrode and Ag/AgCl reference electrode, on a Metrosep Carb 2 (250/4.0) coupled with a guard column at 30 °C. Sugars were separated using gradient elution (0.6 mL min^{-1}) with solvent A (1 mM NaOH, 1 mM sodium acetate) and solvent B (150 mM NaOH, 100 mM sodium acetate) over 120 min. Neutral sugars, amino sugars, and mannitol were resolved isocratically with solvent A, while acidic sugars were

separated using a solvent B gradient. Identification and quantification of monosaccharides were achieved using calibration with a mixture of sugar standards (Sigma).

2.6 Amino acid composition analysis of POM

For amino acid analysis, POM samples were acid-hydrolyzed using HCl and then analyzed using High-Performance Liquid Chromatography coupled with a Diode Array Detector (HPLC-DAD) using the method outlined by (Kim et al., 2024). GF/F filters with POM were cut into small pieces, placed in Pyrex tubes with 10 mL of 6 M HCl, purged with N_2, sealed, and hydrolyzed at 110 °C for 22 h. After cooling, nor-leucine was added as an internal standard. The hydrolysate was centrifuged, freeze-dried, reconstituted in 1 mL of Milli-Q water, vortexed, and filtered (0.22 µm). Amino acids were derivatized by sequentially mixing 2.5 µL borate buffer with 1 µL sample (0.5 min), followed by addition of 1 µL OPA reagent, mixing, and dilution with 15.5 µL of Milli-Q water in the HPLC (Agilent 1200) autosampler prior to injection. HPLC separation of the derivatized amino acids was carried out using a Zorbax AAA column (5 µm, 4.6 × 150 mm), a 20 µL injection volume, and a flow rate of 2 mL min^{-1}. Detection was performed using a DAD (Agilent) at 338 nm (reference 390 nm). The separation was carried out using gradient elution with mobile phase A (40 mM phosphate buffer, pH 8.2) and mobile phase B (acetonitrile: methanol:water, 45:45:10). Identification and quantification were performed using external calibration with a 17 amino acid standard mixture (Fig. S1: 10, 100, 250, 1000 pmol, Agilent, USA).

2.7 Statistical analysis

Statistical analysis was performed using R (version 4.6.0), prior to Analysis of variance (ANOVA) the assumption for normality and homogeneity of variance were assessed using Shapiro-Wilk and Levene's test (Table S1). Pearson correlation analysis was performed at a significance level of 0.05 to examine the relationship between the variables. Principal component analysis (PCA) was employed using the *vegan* and *factoextra* packages to visualize the biogeochemical gradient, and all plots were generated using *ggplot2*.

3. Results

3.1 Salinity, temperature, nutrients, and chl-a

Surface seawater salinity exhibited spatial variation, with the lowest salinity (27.4±0.0 psu) recorded at NA_1500 station, a site most influenced by glacier meltwater, and the highest salinity (31.6±0.1 psu) observed at KN_MDS, the outermost site under the influence of oceanic circulation (Table 1). Surface seawater temperature was lowest (4.2±0.0 °C) at NA_500 and highest at KN_MDS (5.5±0.0 °C). The lowest turbidity (2.1±0.1 NTU) was recorded at both BD_MDS and HN_MDS, while maximum turbidity (7.4±0.0 NTU) was observed at KN_MDS.

Nitrate varied from 0.05 µM (BD_MDS) to 0.80 µM (NA_1500) and showed an increasing trend from MDS to Adj-W for NA, BD, and HN (Table 1). The overall average nitrate concentrations were lower in MDS (0.39±0.23 µM) than in Adj-W (0.56±0.13 µM). Comparing different stations, the average nitrate concentration of all NA stations were high (0.66±0.12 µM), followed by KN (0.53±0.10 µM), HN (0.51±0.08 µM), and lowest at BD stations (0.30±0.22 µM). Nitrite concentration showed a similar pattern, with an increasing trend from MDS to Adj-W sites. However, phosphate concentrations showed minor differences (0.01 to 0.02 µM) among MDS and Adj-W sites.

Chlorophyll *a* (Chl *a*) concentrations ranged from 0.04 µg L^{-1} to 0.18 µg L^{-1} across all stations (Table 1) and with no clear trend in other photosynthetic pigments (Table S2). Similar to nitrate, Chl *a* showed an increasing trend from MDS to Adj-W sites at the NA, BD, and HN stations, while KN exhibited relatively low concentrations at both MDS and Adj-W sites. Overall, the average Chl *a* concentration was lower at MDS (0.07 µg L^{-1}) compared to Adj-W (0.08 µg L^{-1}). Among stations, BD stations recorded the highest average Chl *a* concentrations (0.11 µg L^{-1}), followed by HN and NA with 0.07 µg L^{-1}, whereas KN (0.04 µg L^{-1}) stations exhibited the lowest average concentrations.

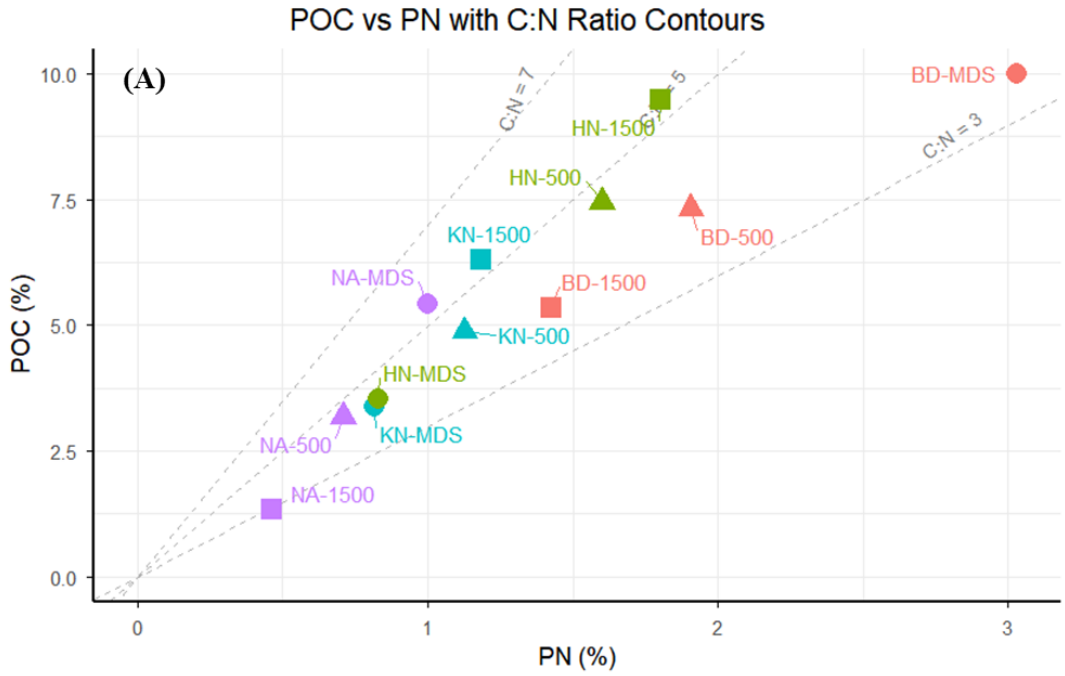
Table 1. Sampling stations and measured physicochemical parameters (temperature, salinity, nutrients, and chlorophyll a) across sampling stations.

Station	Station depth [m]	Temperature [°C]	Salinity [PSU]	Turbidity [NTU]	Nitrate (µM)	Phosphate (µM)	Nitrite (µM)	Chlorophyll a [µg L^{-1}]
NA_MDS	3.5	5.0±0.1	31.3±0.0	3.5±0.4	0.58	0.18	0.09	0.09
NA_500	122	4.2±0.0	30.1±1.3	5.0±0.1	0.61	0.17	0.11	0.04
NA_1500	300	5.2±0.1	27.4±0.0	2.9±0.4	0.80	0.20	0.11	0.08
BD_MDS	6.7	5.1±0.0	29.9±0.0	2.1±0.1	0.05	0.13	0.01	0.09
BD_500	146	4.7±0.3	30.3±0.1	2.9±0.1	0.39	0.15	0.04	0.18
BD_1500	362	5.4±0.0	30.9±0.6	4.4±0.3	0.45	0.15	0.06	0.05
KN_MDS	3.4	5.5±0.0	31.6±0.1	7.4±0.0	0.49	0.14	0.06	0.05
KN_500	216	5.0±0.5	29.5±0.1	3.1±0.4	0.65	0.16	0.08	0.06
KN_1500	240	4.5±0.0	29.8±0.0	2.9±0.1	0.45	0.14	0.07	0.05
HN_MDS	4.5	4.5±0.2	28.7±1.8	2.1±0.1	0.43	0.14	0.04	0.06
HN_500	76	4.3±0.0	29.8±0.0	3.8±1.7	0.58	0.13	0.05	0.06
HN_1500	315	4.3±0.0	29.8±0.3	3.8±0.5	0.52	0.13	0.07	0.09

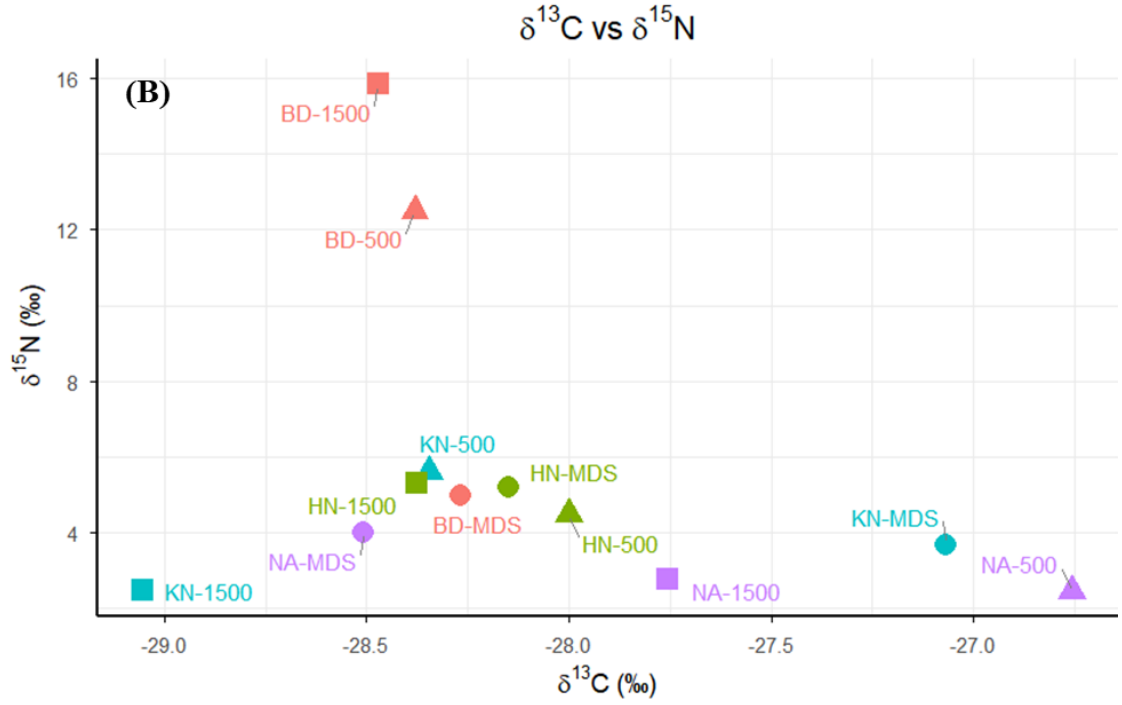
3.2 Elemental and stable isotopic composition

POC and PN concentrations varied over a wide range from 0.17 mg L^{-1} (KN_500) to 0.45 mg L^{-1} (BD_MDS) and from 0.04 mg L^{-1} (KN_500 and KN_1500) to 0.14 mg L^{-1} (BD_MDS), respectively (Fig. 2A). BD_MDS recorded the highest POC concentration (0.45 mg L^{-1}), followed by NA_MDS and HN_ MDS (0.32 mg L^{-1}), with the lowest POC at KN_MDS (0.21 mg L^{-1}). Overall average POC and PN concentrations were higher at MDS (0.32±0.10 and 0.08±0.04 mg L^{-1}, respectively) than at Adj-W (0.26±0.08 and 0.06±0.02 mg L^{-1}), respectively. Across stations, mean POC was highest at BD (0.37±0.10 mg L^{-1}), followed by HN (0.32±0.01 mg L^{-1}) and NA (0.24±0.07 mg L^{-1}), and lowest at KN (0.19±0.02 mg L^{-1}) (Fig. 2B). A similar pattern was observed for PN, with the highest values at BD (0.10 ± 0.03 mg L^{-1}), followed by HN (0.07±0.01 mg L^{-1}), NA (0.06±0.00 mg L^{-1}), and KN (0.04±0.01 mg L^{-1}). The POC/PN ratio ranged from 2.9 (NA_1500) to 5.4 (NA_MDS). The POC/PN ratio showed an increasing trend from MDS to Adj-W for all stations, except NA (Fig. 2C). The NA station showed a decreasing trend in POC/PN ratio from MDS (5.4) to Adj-W (2.9) with the highest change of 2.5.

The $\delta^{13}C$ and $\delta^{15}N$ values of POM varied from −26.8‰ (NA_500) to −29.1‰ (KN_1500) and from 2.5 (KN_1500) to 15.9 (BD_1500), respectively. Mean $\delta^{13}C$ values of all MDS stations (−28.0±0.64‰) were similar to those of Adj-W stations (−28.1±0.67‰). However, individually, KN showed a prominent decreasing trend in $\delta^{13}C$ (-27.1‰ to -29.1‰) and NA showed an increase of -28.5‰ to -27.5‰ from MDS to Adj-W, while HN and BD values were confined to a narrow range (-28.0‰ to -28.5‰). For $\delta^{15}N$, the overall average at MDS sites was lower (4.5 ± 0.73‰) than at Adj-W (6.4 ± 5.02‰). $\delta^{15}N$ value variations were minor (2.5‰ to 5.6‰) for the KN, HN, and NA stations, while the observed values for BD_500 (12.5‰) and BD_1500 (15.9‰) were quite high (Fig. 2B).


POC vs PN with C:N Ratio Contours
(A)
C:N = 7
C:N = 5
C:N = 3
BD-MDS
HN-1500
HN-500
BD-500
KN-1500
NA-MDS
BD-1500
KN-500
HN-MDS
KN-MDS
NA-500
NA-1500
POC (%)
PN (%)
10.0
7.5
5.0
2.5
0.0
0
1
2
3

255


δ13C vs δ15N
(B)
BD-1500
BD-500
KN-500
HN-MDS
HN-1500
BD-MDS
HN-500
KN-MDS
NA-MDS
NA-500
KN-1500
NA-1500
δ15N (‰)
δ13C (‰)
16
12
8
4
-29.0
-28.5
-28.0
-27.5
-27.0

256

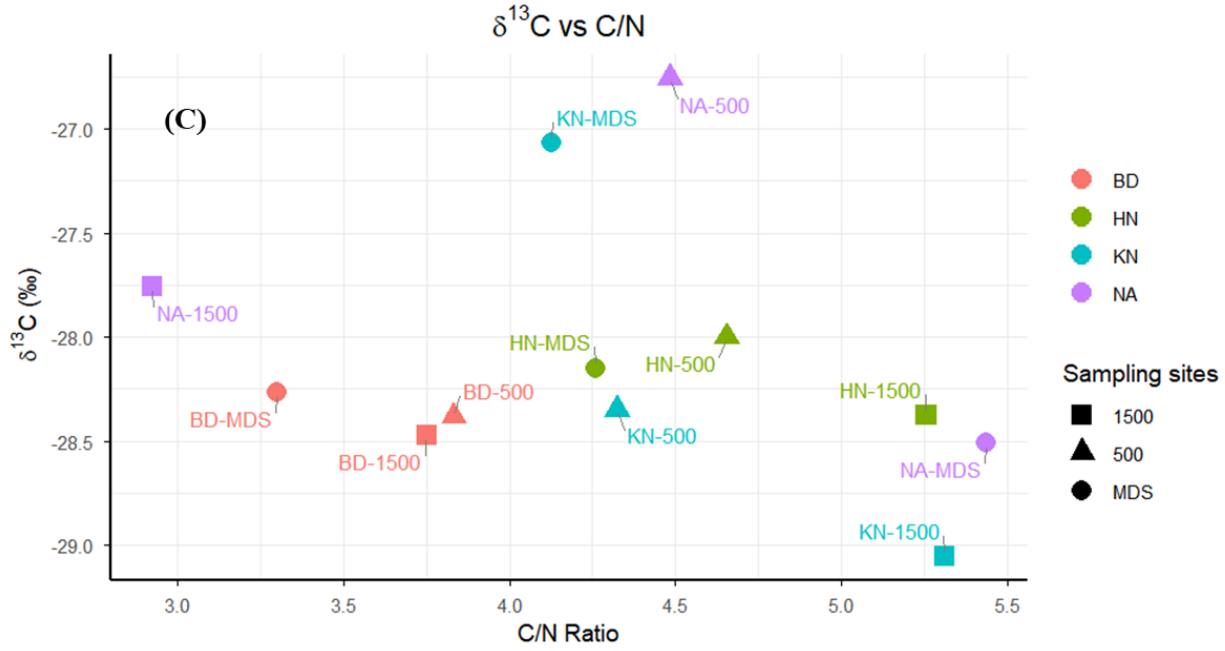


Figure 2. Relationship between Particulate Organic Carbon (POC %) and Particulate Nitrogen (PN %) relative to C/N ratio contours (A), dual isotope plot of $\delta^{13}C$ and δ15N signatures (B) and $\delta^{13}C$ versus C/N ratio in particulate organic matter (C)

3.3 Biochemical and biomolecular composition of POM

3.3.1 Concentrations of carbohydrates, proteins, and lipids

Particulate carbohydrate (PCHO) and proteins (PPRT) concentrations showed a decreasing trend from MDS (PCHO: 55.7 to 109.7 µg L^{-1}; PRT: 56.7 to 145.5 µg L^{-1}) to Adj-W (PCHO: 46.2 to 84.6 µg L^{-1}; PPRT: 32.1 to 94.4 µg L^{-1}) for all stations (Table 2). Unlike PCHO and PPRT, particulate lipids (PLIP) concentrations showed an increasing trend from MDS to Adj-W for NA (59.6 µg L^{-1} to 106.7 µg L^{-1}) and KN (51.6 µg L^{-1} to 70.9 µg L^{-1}), and a decreasing trend for BD (122.7 µg L^{-1} to 83.3 µg L^{-1}). For HN stations, HN_500 (118.1 µg L^{-1}) showed the highest PLIP concentrations, followed by HN_MDS (77.8 µg L^{-1}) and HN_1500 (47.5 µg L^{-1}). Among stations,

BD stations showed the highest average PCHO (90.7 µg L^{-1}), PPRT (105.4 µg L^{-1}), and PLIP (105.4 µg L^{-1}) concentrations.

Table 2. Concentrations of particulate biochemical components, including carbohydrates (P-CHO), proteins (P-PRT), and lipids (P-LIP), alongside their biopolymeric carbon equivalents (BPC-CHO, BPC-PRT, BPC-LIP) and total biopolymeric carbon (BPC) across the sampling stations.

Station	P-CHO (µg L^{-1})	P-PRT (µg L^{-1})	P-LIP (µg L^{-1})	BPC-CHO (µg L^{-1})	BPC-PRT (µg L^{-1})	BPC-LIP (µg L^{-1})	BPC (%)	BPC/POC (%)	Labile (%)
NA_MDS	67.7	61.1	59.6	27.1	29.9	44.7	31.7	31.7	17.8
NA_500	54.9	45.5	67.7	22.0	22.3	50.8	45.1	45.1	21.0
NA_1500	46.2	32.1	106.7	18.5	15.7	80.0	60.0	60.0	18.0
BD_MDS	109.7	145.5	122.7	43.9	71.3	92.0	46.3	46.3	25.7
BD_500	84.6	94.4	110.3	33.8	46.3	82.7	40.0	40.0	19.7
BD_1500	77.8	64.2	83.3	31.1	31.5	62.4	47.7	47.7	23.9
KN_MDS	55.7	56.7	51.6	22.3	27.8	38.7	42.2	42.2	23.8
KN_500	46.8	42.6	51.9	18.7	20.9	38.9	46.9	46.9	23.7
KN_1500	53.4	39.1	70.9	21.4	19.2	53.1	50.1	50.1	21.7
HN_MDS	78.6	97.0	77.8	31.4	47.5	58.3	43.4	43.4	25.0
HN_500	75.3	86.2	118.1	30.1	42.2	88.6	49.5	49.5	22.2
HN_1500	73.7	81.8	47.5	29.5	40.1	35.6	33.5	33.5	22.2

BPC_CHO: Biopolymeric carbon equivalent carbohydrate; BPC_PRT: Carbon equivalent bio-polymeric protein; BPC_LIP: Carbon equivalent bio-polymeric lipid

3.3.2 Biopolymeric vs. Non-Biopolymeric Carbon in POM

A consistent increase in BPC (%) from MDS to Adj-W was observed at NA and KN (Table 2 and Table S3). In contrast, BD exhibited lower BPC at BD_500 compared to both BD_MDS and BD_1500 (Table 2). For HN, BPC% was highest at HN_500 compared to HN_MDS and HN_1500. Overall, BPC_CHO and BPC_PPRT, representing labile components of POC, showed a consistent difference of 2-6% between MDS and Adj-W at individual sampling stations. The most significant variation occurred at BD sites, with BD_500 showing 19.6% of labile component contributions, followed by BD_1500 (23.9%) and BD_MDS (25.7%).

3.3.3 Monosaccharide composition of POM

Total monosaccharide concentrations at NA and BD declined from MDS to Adj-W (Fig. 3A and Table S3). In contrast, KN and HN exhibited increasing monosaccharide concentrations from MDS to Adj-W. Glucose (8.6 - 47.5 μg L^{-1}) and galactose (3.4 - 9.6 μg L^{-1}) dominated the monosaccharide pool and followed trends similar to total monosaccharides from MDS to Adj-W across stations. Station-wise, average monosaccharide concentrations were highest at BD (59.2 μg L^{-1}), followed by HN (47.9 μg L^{-1}), NA (32.0 μg L^{-1}), and KN (29.0 μg L^{-1}).

The mol% monosaccharide concentrations showed a consistent pattern across MDS and Adj-W for each station, with minor differences (Fig. 3B). However, BD and KN stations showed different compositions compared to NA and HN stations, mainly due to the contributions of glucosamine and rhamnose. Glucose, the dominant monosaccharide, exhibited a decreasing mol% trend from MDS to Adj-W at the BD station, whereas it showed an increasing mol% trend offshore at the other stations.

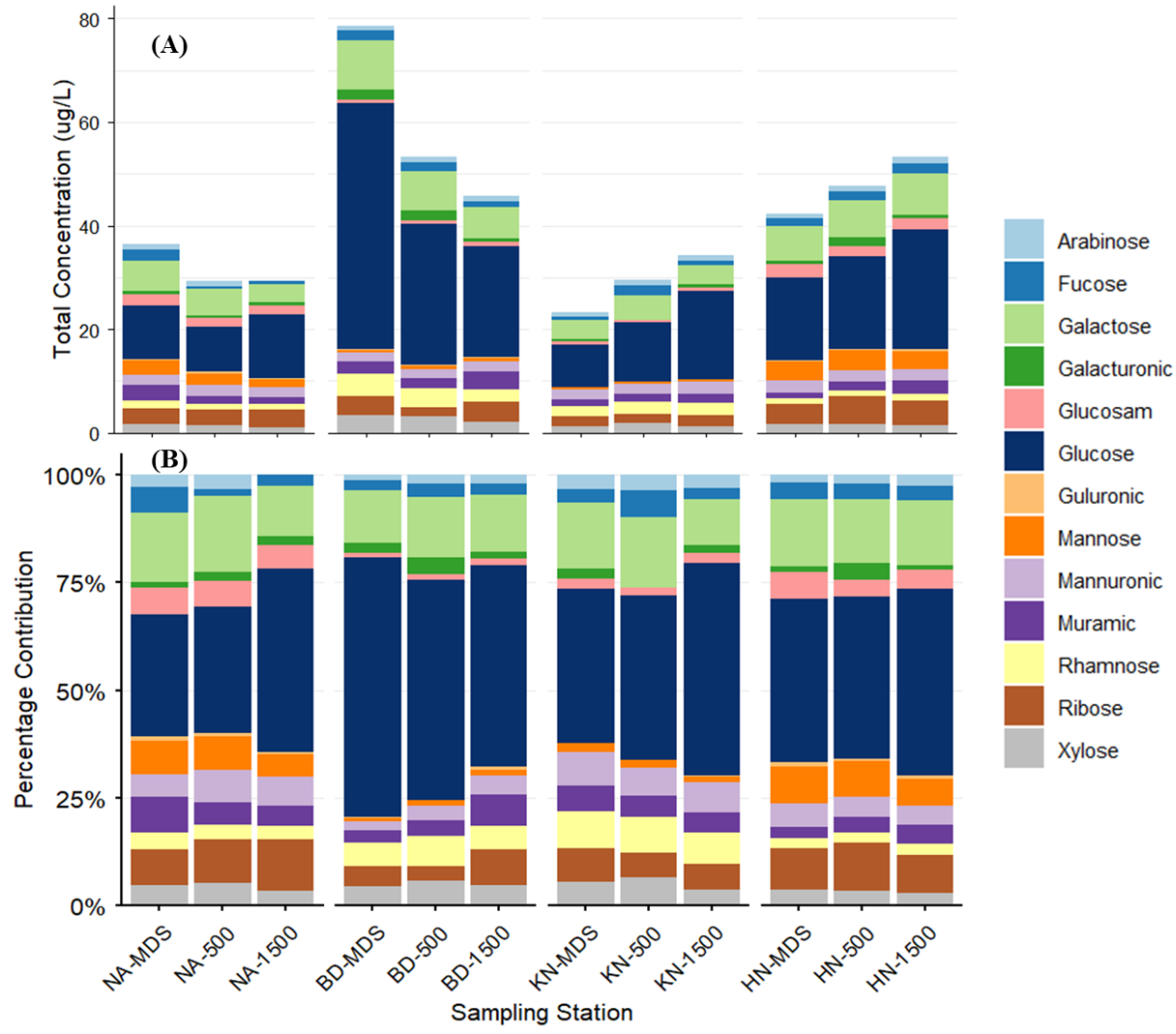


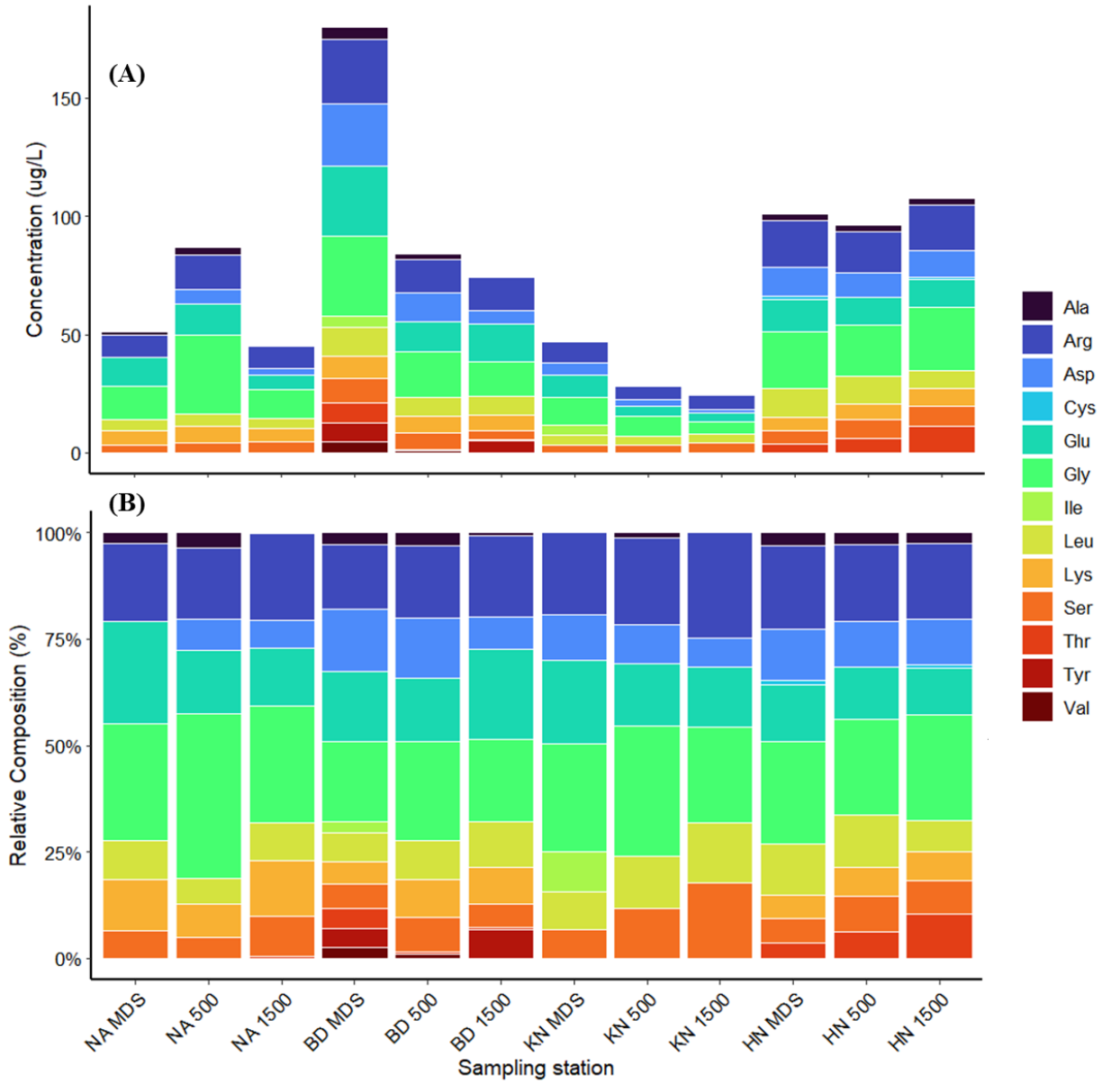
Figure 3. Spatial variation in monosaccharide composition of surface POM across fjord stations. (A) Concentrations (μg L^{-1}) and (B) relative percentage contributions of individual monosaccharides at macroalgal bed (MDS), 500 m, and 1500 m sites at NA, BD, KN, and HN.

3.3.4 Amino acid composition of POM

A clear decreasing trend in total amino acid concentrations from MDS to Adj-W was observed at BD and KN (Fig. 4A and Table S3). In contrast, concentrations at NA increased from NA_MDS to NA_500 further declined at NA_1500. At HN, total amino acid concentrations decreased

slightly from HN_MDS to HN_500 and then increased at HN_1500. Among stations, the average total amino acid concentrations were highest at BD (113 μg L^{-1}) followed by HN (101.6 μg L^{-1}), NA (61 μg L^{-1}) and KN (33.3 μg L^{-1}), also the average individual amino acid concentration were high in MDS than Adj-W (Table S4). The BD station showed the highest concentrations of individual amino acids, with Asp (26.1 μg L^{-1}), Glu (29.8 μg L^{-1}), Gly (33.9 μg L^{-1}), Arg (27.6 μg L^{-1}), and Lys (9.4 μg L^{-1}) peaking at the MDS and declining toward Adj-W (Asp: 5.6 μg L^{-1}; Glu: 15.9 μg L^{-1}; Gly: 14.4 μg L^{-1}; Arg: 14.4 μg L^{-1}; Lys: 6.5 μg L^{-1}). A similar decreasing pattern of the individual amino acids was observed for the KN station. Exceptions to the low individual amino acid concentrations at Adj-W (500 and 1500 m locations) included high Gly at NA_500 (33.5 μg L^{-1}), and high Gly (26.7 μg L^{-1}) and Arg (19.1 μg L^{-1}) at HN_1500.

Mol% concentrations of different amino acids indicated that Gly, Glu, and Arg were the dominant contributors across all sampling stations (Fig. 4B). The mol% concentration of Glu showed a decreasing trend from MDS to Adj-W at NA (24.1 % to 13.7%), KN (19.7% to 14.0%) and HN (13.3% to 10.9%) stations, whereas BD showed an increasing trend (MDS: 16.6%; Adj-W: 21.3%). In contrast, Gly and Arg exhibited similar spatial patterns across stations, with Gly showing its highest mol% contribution at the 500 m station at NA, BD, and KN, while Arg displayed a consistent increase from MDS to Adj-W across these stations.



329

330 **Figure 4.** Spatial variation in amino acid composition of surface POM across fjord stations. (A)

331 Concentrations (μg L^{-1}) and (B) relative percentage contributions of individual amino acids at

332 macroalgal beds (MDS), 500 m and 1500 m sites in NA, BD, KN, and HN.

333

334 **3.4 Statistical analysis**

Strong positive correlations were observed between PN and POC, PCHO, and PPRT ($r > 0.83$, $p<0.05$), with an exceptionally high correlation between PPRT and PCHO ($r = 0.96$, $p<0.05$) (Fig. S2A). In contrast, negative correlations were observed between BPC_LIP% and the non-BPC fraction ($r = -0.95$, $p<0.05$), and between nitrate and biochemical parameters (POC, PN, PCHO, PPRT) ($r < -0.66$, $p<0.05$). Despite consistent trends across parameters, ANOVA indicated no significant differences between MDS and Adj-W, suggesting gradual lateral transformations rather than abrupt distance-related changes, together with pronounced spatial heterogeneity among stations (Table S1).

Mannuronic acid (ManA) showed strong negative correlations with POC ($r = -0.79$) and PCHO ($r = -0.92$) (Fig. S2B). Glucose and galactose were negatively correlated with several compounds, including glucosamine ($r = -0.72$), mannose ($r = -0.70$), ribose ($r = -0.59$), and ManA ($r = -0.63$). Rhamnose exhibited pronounced negative relationships with guluronic acid (GulA; $r = -0.83$), glucosamine ($r = -0.76$), mannose ($r = -0.85$), and ribose ($r = -0.73$), whereas galactose was positively correlated with fructose ($r = 0.61$) and arabinose ($r = 0.58$). Strong positive associations were also observed among mannose, glucosamine ($r = 0.91$), and ribose ($r = 0.76$), with ribose additionally correlating positively with glucosamine ($r = 0.79$).

In PCA, the first two principal components explained 49.0% of the total variance, with PC1 and PC2 accounting for 30.1% and 18.9%, respectively (Fig. 5). PC1 was positively loaded by POC, PN, PCHO, PPRT, glucose, galactose, and labile amino acids (Asp, Glu, Thr), whereas negative PC1 loadings were associated with muramic acid, arabinose, fucose, and inorganic nutrients. Sample scores showed a spatial organization, with MDS plotting toward positive PC1 values and Adj-W progressively shifting toward negative PC1 values, which was seen more prominently for BD stations.

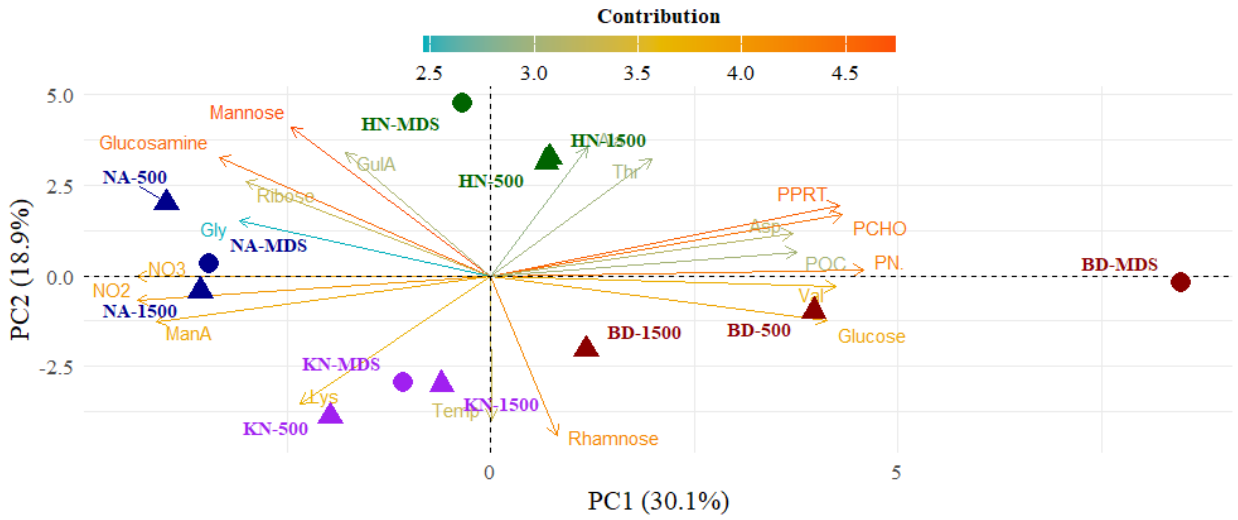


Figure 5. Principal Component Analysis (PCA) biplot of biogeochemical variables across different sample sites. The first two principal components (PC1 and PC2) account for 30.1% and 18.9% of the total variance, respectively. Individual samples are represented by colored shapes, categorized by site (e.g., NA, HN, KN, BD) and location (e.g., MDS, 500, 1500). Vectors (arrows) indicate the loadings of specific variables, including carbohydrates (e.g., Mannose, Glucose, Rhamnose), nutrients (NO^{2-}, NO^{3-}), and organic matter indicators (POC, PN, PCHO, PPRT). The color scale of the vectors represents the contribution of each variable to the principal components.

4. Discussion

The present study provides a multi-proxy assessment of POM in the surface waters of macroalgal beds in Kongsfjorden, integrating bulk biochemical, isotopic, biopolymeric composition, and molecular biomarkers. Elevated bulk (POC, PN, PCHO, and PPRT) and molecular (monosaccharides and amino acids) concentrations at MDS indicated that macroalgal beds act as localized sources of biochemically labile organic matter. The results demonstrated that macroalgal

beds imprint surface waters with distinct biochemical and molecular signatures that are redistributed across fjord-scale gradients. The PCA demonstrates that macroalgae influence surface POM along a continuous multivariate gradient rather than discrete habitat classes. The systematic offshore decline of these compounds, together with internal reorganization of the biopolymeric and molecular composition, shows that macroalgal-derived POM is efficiently exported and selectively transformed during lateral transport (Fig. 6).

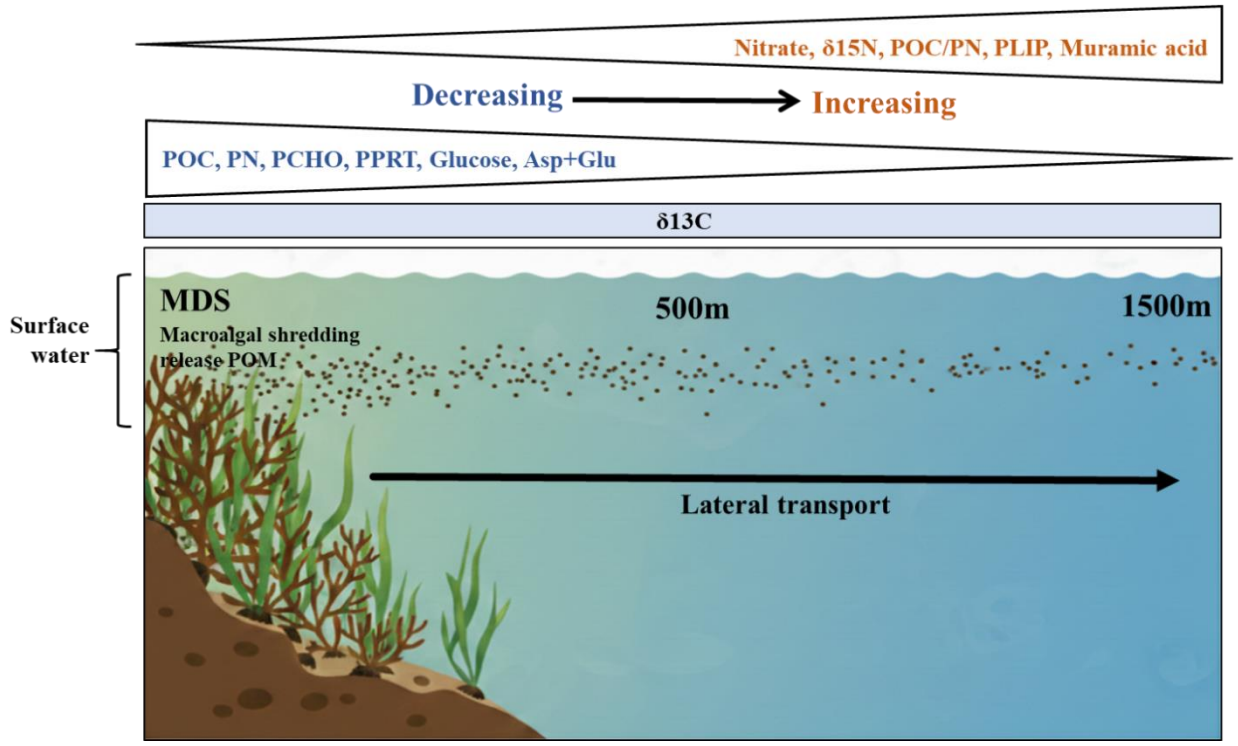


Figure 6. Schematic showing the biochemical nature of POM at macroalgal dominated sites and its transformation during lateral transport.

4.1 Influence of Macroalgal Beds on Surface POM Biochemical Composition

Macroalgal beds produce substantial organic carbon via photosynthesis, which enters surrounding waters (Chen et al., 2020; Filbee-Dexter et al., 2022; Pessarrodona et al., 2022; Watanabe et al.,

2020). The observed higher concentrations of POC and PN at MDS relative to Adj-W, together with consistently higher PCHO and PPRT, indicated localized enrichment of particulate matter near macroalgal beds. The inverse relationship of nitrate with POC, PN, PCHO, and PPRT ($r = -0.82$, $p < 0.05$) reflects biological assimilation of dissolved nutrients into the particulate pool, reinforcing the role of active coastal production in shaping POM composition along the fjord gradient. Macroalgal tissues are structurally rich in polysaccharides and contain substantial protein fractions, and the release of tissue fragments, sloughed material, and epiphyte-associated biomass (Kennedy and Blain, 2025; Watanabe et al., 2020) provides a direct pathway for incorporation of macroalgal carbon into surface POM contributing to Arctic coastal carbon cycling (Ager et al., 2023). Strong positive correlations ($r > 0.83$, $p < 0.05$) between PN and POC, PCHO, and PPRT indicate tightly coupled carbon and nitrogen incorporation during fresh organic matter production. The remarkably strong positive correlation between PPRT and PCHO ($r = 0.96$, $p < 0.05$) further indicates tightly coupled biological production and POM synthesis in macroalgal beds. The multivariate analysis of POM as resolved by PCA showed PC1 (30.1% variance) was dominated by PCHO, PPRT, PN, POC, glucose, and Asp and separated MDS from Adj-W along a continuous biochemical gradient, especially prominent for BD station (Fig. 5). The strong positive loadings of labile carbon and nitrogen compounds supported a distinct organic-rich biochemical state of surface POM at MDS.

Although macroalgal biomass and detritus are generally carbon-rich, three of the four stations (BD, KN, and HN) exhibited lower POC/PN ratios at the MDS sites than Adj-W. This pattern likely reflects contributions from fresh, nitrogen-rich organic matter produced within macroalgal habitats, possibly including phytoplankton, epiphytic microalgae, and benthic primary producers associated with kelp beds (Burfeid-Castellanos et al., 2021; Stanca and Parsons, 2021),

which could be re-suspended into surface waters and become part of POM. Kelp forest POM characteristics are highly variable depending on the water column conditions, which also influence contributions from macroalgal detritus and other autochthonous primary producers (Dyer et al., 2019). In favorable conditions, other primary producers may outweigh the stoichiometric signal of macroalgal tissue itself, resulting in relatively low POC/PN ratios of POM near macroalgal beds (Chen et al., 2020). Similarly, heterotrophic bacteria are typically richer in nitrogen and phosphorus than phytoplankton, and their colonization of particles can lower the bulk POC/PN ratio by contributing N-rich biomass (Jo et al., 2021). The subsequent increase in POC/PN ratios from MDS to Adj-W is consistent with preferential microbial degradation of labile nitrogen-rich compounds during lateral transport (Vidal et al., 2018), leading to relative enrichment of carbon-rich material with distance from source habitats.

$\delta^{13}C$ values of POM are widely used to trace organic matter sources (Gao et al., 2008; Pineault et al., 2013). Most macroalgae typically exhibit $\delta^{13}C$ values between −34.6‰ to −2.2‰ (Velázquez-Ochoa et al., 2022), though some brown macroalgal species show more negative signatures, ranging from −20‰ to −35‰ (Fredriksen, 2003). In Arctic coastal systems, marine phytoplankton-derived organic matter typically exhibits $\delta^{13}C$ values between −20‰ and −26‰, whereas terrestrial organic matter derived from C3 vegetation is generally more depleted, around −26‰ to −29‰ (Gao et al., 2008; Pineault et al., 2013). However, substantial overlap between marine and terrestrial isotopic ranges complicates source discrimination in Arctic fjord systems (Singh et al., 2024b). The similarity of $\delta^{13}C$ values between MDS and Adj-W indicates that macroalgal material does not dominate bulk POM isotopically; instead, it contributes substantially within a mixed particulate pool of macroalgal, phytoplanktonic, and terrestrial organic matter in Arctic fjords (Ørberg et al., 2023; Roy et al., 2025). This muted isotopic signal likely reflects that

macroalgal influence on surface POM is not solely derived from detached kelp tissue, but is also mediated by contributions from epiphytic and benthic microalgal production (Burfeid-Castellanos et al., 2021; Stanca and Parsons, 2021) and biochemically distinct macroalgal fractions, whose $\delta^{13}C$ values overlap those of pelagic organic matter.

$\delta^{15}N$ values of POM exceeding ~2‰ as observed in this study are consistent with marine nitrate-based production and microbial reworking, rather than atmospheric or N_2-fixation sources (Kuzyk et al., 2010), where intense benthic–pelagic coupling and rapid recycling of dissolved inorganic nitrogen promote isotopic enrichment of the available nitrogen pool (Elliott Smith and Fox, 2022). Reflecting the pattern more prominently, $\delta^{15}N$ value at BD_MDS (5.0‰), which was already high, further increased toward Adj-W (BD_500: 12.5‰, BD_1500: 15.9‰), indicating relatively fresher marine-derived organic matter within the macroalgal beds, which is transformed into relatively higher trophic contributions in surrounding waters.

4.2 Transformation of surface POM during lateral transport from macroalgal beds to adjacent waters

The biochemical composition of POM provides valuable insights into the nature of organic carbon and its benthic-pelagic coupling in macroalgal beds (Elliott Smith and Fox, 2022; Renaud et al., 2015). The observed systematic offshore changes in POM composition revealed both lateral transport and early transformation of macroalgal beds derived particles across the fjord (Vidal et al., 2018). The concentrations of PCHO and PPRT declined consistently from MDS to Adj-W, indicating progressive dilution of organic matter with distance sourced from macroalgal beds and associated autochthonous production (Ørberg et al., 2023; Smale et al., 2022; Simpkins et al., 2025). These labile compounds are preferentially consumed by particle-associated and free-living

455 microbes (Jain et al., 2019), serving as indicators of freshly produced, easily degradable organic
456 matter (Li et al., 2025). In contrast, PLIP generally increased offshore (except at BD), indicating
457 a relative enrichment of lipid-rich pelagic material and/or the preferential preservation of more
458 stable lipid compounds during transport. This pattern likely reflects selective microbial
459 degradation of labile carbohydrates and proteins during lateral transport, combined with mixing
460 with newly produced pelagic material (Li et al., 2025), highlighting dynamic compositional
461 transformation of POM from MDS to Adj-W.

462 The compositional shift in POM was further supported by changes observed in BPC
463 fractions. BPC represents the labile fraction of POM, mainly comprising proteins, carbohydrates,
464 and a lipid fraction, whereas the non-BPC fraction includes more refractory components such as
465 lignin, humic substances, black carbon, and cellulose (Fabiano et al., 1993; Lobbes et al., 2000;
466 Tselepides et al., 2000). Among BPC constituents, %BPC_lipid increased markedly from MDS
467 (17.8 ± 2.8%) to Adj-W (25.1 ± 8.6%), whereas the labile fraction (proteins and carbohydrates)
468 showed minor differences between MDS (23.1 ± 3.6%) and Adj-W (21.5 ± 2.5%). This pattern
469 suggests a relative enrichment of more stable organic matter within POC, accompanied by lateral
470 degradation of labile components, consistent with the observed decline in POC from MDS to Adj-
471 W. Further, the strong inverse relationship between %BPC_LIP and the non-BPC fraction ($r = -0.95$, $p < 0.05$) suggested biochemical reorganization of POM during lateral transport, consistent
473 with selective degradation and compositional restructuring rather than just uniform bulk loss. In
474 support, PCA also showed a progressive leftward shift from MDS to Adj-W along PC1 (Fig. 5)
475 demonstrating lateral export of POM from macroalgal beds to surrounding waters as a gradient,
476 consistent with progressive dilution and selective transformation during fjord-scale transport of
477 POM.

4.3 Molecular-level evidence for macroalgal imprint and early transformation of POM

Molecular fingerprints based on monosaccharides and amino acids offer direct insight into the origin, bioavailability, and early diagenetic transformation of organic matter (Grosse et al., 2021; Jo et al., 2022). Glucose is a common constituent of the macroalgal storage polysaccharide laminarin, while fucose, galactose, and uronic acids (glucuronic, mannuronic, and guluronic acids) are key monomers of structural polysaccharides such as alginates and fucans (Singh et al., 2024a). This carbohydrate pool of macroalgae is bound within structurally complex cell-wall polymers that are relatively resistant to microbial degradation (Kennedy and Blain, 2025). In contrast, phytoplankton cell walls and extracellular matrices are dominated by cellulose, and species-specific storage glucans, which are recycled relatively rapidly in surface waters (Biersmith and Benner, 1998). Glucose and galactose were observed to be the dominant monosaccharides throughout the samples, reflecting a shared baseline of organic matter likely derived from a mixture of macroalgal detritus, phytoplankton, and bacterial biomass (Li et al., 2025; Smale et al., 2022). However, the positive correlation of glucose with POC and PCHO indicated a relative enrichment of a labile, carbohydrate-rich organic matter pool at MDS where POC and PCHO were higher than Adj-W. On the other hand, the negative correlation between glucose and other monosaccharides such as galactose, mannose, mannuronic acid, ribose, and glucosamine reflected a relative increase in structurally complex, algal, microbial, and zooplankton-associated sugars during lateral transport and early diagenesis.

Amino acid distributions provide complementary evidence for POM source and lability patterns, as their composition reflects both the origin and degree of degradation (Grosse et al., 2021; Jo et al., 2022). The total amino acid concentrations observed in this study (24–180 $\mu g\ L^{-1}$) fall within the reported values from coastal Kongsfjorden (Zhu et al., 2016) and across Fram-Strait

(Grosse et al., 2021). The average total amino acids were higher at MDS (94.8 μg L^{-1}) than at Adj-W (68.4 μg L^{-1}), with BD exhibiting the highest average concentration (113.0 μg L^{-1}), indicating fresher, nitrogen-rich, proteinaceous POM in surface waters, along with elevated PPRT and low C:N ratios observed near macroalgal beds. At BD and KN, total amino acids drop by ~60–50% from MDS to Adj-W, indicating preferential microbial utilization of proteinaceous, N-rich material during lateral transport, consistent with the observed offshore increase in POC/PN and PLIP enrichment. NA and HN show mid-station or distal increases (NA_500, HN_1500), likely reflecting local resuspension or secondary production, supporting spatial heterogeneity as discussed before. The combined Asp + Glu content, reflecting the freshness of organic matter and the diagnostic Asp/Gly ratio, indicates the degradation state of organic matter (Machado et al., 2020; Yao et al., 2023). The decline in Glu, Asp, and Asp/Gly ratio, and the relative enrichment of Gly and Arg from MDS to Adj-W for most of the stations further provide molecular signatures for early-stage protein degradation and microbial reworking of macroalgal-derived POM during lateral transport.

Together, the coupled behavior of carbohydrates and amino acids demonstrated that macroalgal beds imprint surface POM with a distinct molecular signature that is progressively modified during fjord-scale export. These molecular patterns corroborate the bulk biochemical and isotopic evidences, indicating that macroalgal-derived organic matter is redistributed across coastal gradients while undergoing selective early transformation. The pronounced total monosaccharides and amino acid enrichment at BD (especially BD_MDS), which also exhibited the highest POC and PPRT concentrations, identifies this site as a biogeochemical hotspot of macroalgal influence, reinforcing the spatial coherence of macroalgal signatures across independent biochemical proxies.

4.4 Brandal (BD) as a biogeochemical hotspot of macroalgal influence in Kongsfjorden

BD station, among all studied stations, consistently emerged as an organic-rich site, showing characteristics of macroalgal-influenced surface POM, highlighting its role as a biogeochemical hotspot within Kongsfjorden. With the highest concentrations of POC, PN, PCHO, PPRT, total monosaccharides, and total amino acids, the BD station contributed the most in the PCA biplot (Fig. 5), which demonstrated local production and accumulation of biochemically labile organic matter within this macroalgal-dominated habitat. The strong gradient observed across PN, $\delta^{15}N$, C:N, PPRT, and amino acid composition from MDS to Adj-W at BD indicated nitrogen assimilation, dominance of fresh marine organic matter in macroalgal bed, and their progressive downstream alteration. At the molecular level also, BD_MDS was strongly enriched in glucose and other macroalgal sugars (fucose, galactose, mannuronic acid), with total monosaccharides and glucose declining offshore. Similarly, the offshore decrease in labile amino acids (e.g., Asp, Glu) provides a molecular signature for early degradation during export, indicating that the BD macroalgal bed is a major source of biochemically active POM and a key contributor to fjord-scale redistribution (van der Mheen et al., 2024).

Situated on the westernmost part of the south shore, BD is influenced by Atlantic water inflow, which creates relatively warmer and more saline conditions (Williams, 2017; Wilson, 2022; Woelfel et al., 2014), that support abundant micro-phytobenthic and benthic mosses (Woelfel et al., 2014). At BD, macroalgal cover is not higher than other sites, yet detritus accumulation is substantial, supporting elevated benthic faunal diversity. The presence of a deep trench, combined with storm-driven transport, concentrates detritus at BD (Schimani Katherina, 2019). Habitat heterogeneity further drives microbial community assembly and functional differentiation (Huang et al., 2026), reflected in high macroalgal detrital cover and meiofaunal

density (Schimani et al., 2022). Additionally, BD exhibits significantly lower turbidity than glacier-proximal sites, which prevents mineral masking of organic signatures and provides a stable light regime for primary producers (Bianchi et al., 2020). Collectively, these features make BD a retention zone for macroalgal detritus, acting as a biogeochemical hotspot and a critical repository for macroalgal-derived carbon. While Brandal represents a biogeochemical hotspot, its broader representativeness is constrained due to spatial variability in macroalgal structure and function across high Arctic fjords, driven by variation in latitude, ice scour, light availability, terrestrial runoff, and glacier-induced salinity and turbidity gradients (Bartsch et al., 2016). Thus, although Brandal provides a high-resolution case study, caution is required when extrapolating its biogeochemical fluxes to fjords characterized by intense glacial runoff, seasonal sea-ice cover, and a different community composition.

4.5 Implications of macroalgal-beds for Arctic coastal carbon cycling

Unlike previous studies on POM in Kongsfjorden that primarily used bulk isotopes (e.g., $\delta^{13}C$, $\delta^{15}N$) and their ratios for source apportionment (Kuliński et al., 2014; Singh et al., 2024b), our study advances biochemical perspective by integrating molecular level biomarkers (amino acids, sugars) with spatially resolution transect. This approach shift the focus from POM origin to its functional quality, enable differentiation between labile and refractory pools. Our study demonstrates that macroalgal-dominated sites in Kongsfjorden act as hotspots of labile and bioavailable organic matter, significantly shaping the composition and lability of POM in adjacent waters. The intermediate and variable patterns observed at the few stations highlight that the influence of MDS was not uniform but forms a gradient shaped by local hydrodynamics, freshwater inputs, and nutrient availability. The strong spatial heterogeneity observed, particularly

570 the emergence of Brandal as a biogeochemical hotspot, emphasizes that macroalgal impacts on
571 coastal carbon cycling are unevenly distributed within fjord systems. Such localized but persistent
572 sources of organic carbon from macroalgal-beds to surrounding waters and thereby dampening
573 seasonal variability in carbon availability (Norkko et al., 2007), enhancing benthic-pelagic food-
574 web stability and increase ecosystem resilience to interannual fluctuations in pelagic primary
575 production (Norkko et al., 2007; Renaud et al., 2015).

576 Although our study focused on surface waters, future research should include vertical
577 fluxes of POM near macroalgal beds and their coupling to hydrodynamics. Additionally, effects
578 of seasonal variability driven by glacial melt, riverine runoff, and episodic nutrient inputs at coast
579 are important as they can alter carbon concentrations and biochemical composition, particularly in
580 nearshore macroalgal habitats (Ager et al., 2023). Experimental studies at model sites like BD
581 could further help in elucidating the rates of labile carbon turnover, microbial utilization, and
582 nutrient remineralization at these sites. As macroalgal habitats are expanding under ongoing
583 warming, resolving the contribution of macroalgal biomass and beds-associated organic matter
584 dynamics in coastal biogeochemistry would be important for estimating Arctic carbon budgets and
585 ecosystem functioning.

586

587 **Conclusion**

588 The present study provides new insights into the role of Arctic macroalgal beds as active drivers
589 of coastal particulate organic matter dynamics in Kongsfjorden, an Arctic fjord. By integrating
590 bulk biogeochemical properties, stable isotopes, bio-polymeric composition, and molecular
591 biomarkers, we demonstrate that macroalgal habitats imprint surface waters with a distinct
592 biochemical and molecular signature. Elevated concentrations of POC, PN, carbohydrates,

proteins, monosaccharides, and amino acids at macroalgal-dominated sites indicate that macroalgal beds act as localized sources of biochemically labile organic matter to the overlying water column. Systematic offshore declines in bulk parameters, together with internal reorganization of bio-polymeric and molecular composition, reveal that macroalgal-beds derived POM is efficiently exported across fjord-scale gradients and undergoes selective early-stage transformation during lateral transport. The muted bulk isotopic gradients further indicate that macroalgal influence is expressed through continuous mixing and biochemical restructuring of a heterogeneous particulate pool rather than simple replacement of pelagic organic matter. A pronounced spatial gradient was observed across the stations, within which Brandal emerged as a distinct biogeochemical hotspot of macroalgal-associated organic matter dynamics, as supported by our multiproxy study. Overall, our findings show that macroalgal beds function as dynamic benthic–pelagic coupling zones that redistribute and transform organic carbon beyond their immediate habitat. As macroalgal cover continues to expand along Arctic coastlines under climate warming, their contribution to coastal carbon fluxes is likely to intensify, with important implications for Arctic carbon budgets and ecosystem functioning.

Data availability. The data are available in the Zenodo repository at: https://doi.org/10.5281/zenodo.18457176 (Jagtap et al., 2026).

Author contributions. ASJ and AS conceptualized the study with input from AJ. AS and AJ conducted the fieldwork, while laboratory analyses were performed by ASJ and NR. MT analyzed the elemental and isotopic data. All authors were involved in the interpretation of the results, the revision, and the writing of the final version of the paper.

Competing interests. The corresponding author has declared that none of the authors has any competing interests.

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