A Pan-Arctic Pigment Database for Phytoplankton and Sea-Ice Algae

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Abstract

Climate change has dramatically altered the Arctic seas with significant decrease in sea ice extent and thickness and warming water temperature. The ecological impacts of such change have been described for many parts of the Arctic Ocean, but long-term records of biological indicators are still missing. Among those, photosynthetic and accessory pigments are one of the key tools that aid quantification of phytoplankton and sea-ice algae biomass and characterisation of community composition. To address this gap, we present the first pan-Arctic compilation of in situ algal pigment data obtained exclusively by High-Performance Liquid Chromatography (HPLC), containing 10,798 samples collected across 77 Arctic research cruises between 2000 and 2024. As a result of large-scale collaborative effort, this database covers both open water and sea-ice environments across coastal, shelf and open domains. The database (https://doi.org/10.11583/DTU.29445104) includes measures of up to 26 pigments, with 8 major marker/accessory pigments being considered in this study, namely Alloxanthin (Allo), 19'-Butanoyloxyfucoxanthin (But-fuco), Chlorophyll a (Chl-*a*), Chlorophyll b (Chl-*b*), Fucoxanthin (Fuco), 19'-Hexanoyloxyfucoxanthin (Hex-fuco), Peridinin (Peri), and Zeaxanthin (Zea). This publicly available database provides crucial data that can be used to assess phytoplankton dynamics, validating remote sensing observations and can serve as a resource for future Arctic ecological- and modelling studies.

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1. Introduction

Climate change has disproportionately affected the Arctic, shown by drastic increases in temperature and ongoing sea-ice decline (England et al., 2021; Stroeve and Notz, 2018). Changing conditions in the Arctic have already altered the food web, with studies indicating further impacts in the near future (Ardyna and Arrigo, 2020; Arrigo and van Dijken, 2015; Flores et al., 2023; Freer et al., 2022; Quinlan et al., 2005). As the foundation of marine food webs, phytoplankton and sea-ice algae are critical for sustaining ecosystems and contribute to large parts of global primary production, leading to energy transfer across trophic levels and ultimately carbon sequestration (Falkowski, 1994; Serra-Pompei et al., 2022). Environmental heterogeneity and changes may alter community composition, with the potential to impact large-scale ecological processes. For example, in the Arctic and sub-Arctic regions, increased open water areas has led to a longer phytoplankton growing season likely associated with changes in community composition. Studies have demonstrated that climate change may favor increased biomass of smaller flagellated phytoplankton species, leading to reduced dominance of large diatoms species (Blais et al., 2017; Coupel et al., 2012; Vonnahme et al., 2025). This can impact the structure of the food web and overall carbon cycling by having an immediate effect on higher trophic levels, potentially influencing the abundance, distribution and feeding preferences of zooplankton (Campbell et al., 2009; Negrete-García et al., 2024).

Characterising phytoplankton community composition is therefore essential for better understanding ecosystem structure, dynamics and services, especially in the under-sampled Arctic seas, which have experienced the greatest impact of climate change in recent years (England et al., 2021). It is clear that long-term data on microalgae physiology and biomass are vital to enhance our ability to assess and detect spatial and temporal patterns in phytoplankton and sea-ice algae community structure and physiology in response to environmental change. Many studies have used pigment-based measurements, but datasets are often scattered across many sources. This makes it difficult to obtain, access and synthesize into a larger spatial and temporal scale. To address this gap, our paper provides baseline information regarding phytoplankton and sea-ice algae biomass and photosynthetic pigments in the Arctic Ocean aiming at providing a framework to support such large-scale Arctic algae studies across two decades of data.

Phytoplankton pigments, particularly chlorophyll a (Chl-*a*), drives photosynthesis by harvesting light and protecting the cells (Falkowski and Kiefer, 1985; Pereira and

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Gonçalves, 2022). Advances in pigments analysis through High-Performance Liquid Chromatography (HPLC) and ultra HPLC (UHPLC), have enabled precise identification and quantification of a suite of photosynthetic and photoprotective microalgal pigments. These pigments can serve as chemotaxonomic markers for major functional and taxonomic phytoplankton groups, including the commonly used diagnostic pigments, Alloxanthin (Allo), 19'-Butanoyloxyfucoxanthin (But-fuco), Chlorophyll *b* (Chl-*b*), Fucoxanthin (Fuco), 19'-Hexanoyloxyfucoxanthin (Hex-fuco), Peridinin (Peri), and Zeaxanthin (Zea) used in this study. Additionally and when available, the database presented in this paper also includes α-/β-carotene (αβ-Car), Bacteriochlorophyll a, Chlorophyllide *a* (Chlide *a*), Chl-*c*1, Chl-c1+*c*2, Chl-*c*3, Diadinoxanthin (Diadino), Diatoxanthin (Diato), Divinyl Chlorophyll a and b (DV-Chl-*a* and DV-Chl-*b*), Lutein (Lut), Neoxanthin (Neo), Pheophorbide *a* (Phide *a*), Pheophytin *a* (Phytin *a*), Prasinoxanthin (Pras) and Violaxanthin (Viola) (Jeffrey et al., 1999) (**Table 1**). These additional accessory pigments, some of which are also commonly used as marker pigments (Coupel et al., 2015a; Fragoso et al., 2017a), ~~can be used by~~enable phytoplankton to adapt and/or acclimate to various light regime changes that occur in the environment (Brunet et al., 2011). Variability in pigment composition can reflect strategies such as photoprotection, which involves the production of pigments that mitigate damage from excessive light and photo acclimation that refers to the ability of algae to adjust their pigment composition in response to light intensity changes that hereby can optimise photosynthetic efficiency (Bonilla et al., 2009; Gosselin et al., 2017).

Absorption and scattering of light by phytoplankton pigments and other cellular constituents influence the reflectance, which allow their detection by radiometers, making them an invaluable source for remote sensing applications (see overview in Bracher et al., 2017). Multispectral satellite sensors such as SeaWiFS, MODIS, MERIS and OLCI have paved the way and demonstrated the ability to distinguish phytoplankton functional types on large scales (Miller, 2004; Nieke et al., 2015). Recent development have focused on hyperspectral sensors, capable of measuring more narrow absorption and reflectance propertied, that can be missed by multispectral sensors (Hu, 2022). Successful applications include ENVISAT's Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) using the PhytoDOAS method (Bracher et al., 2009; Sadeghi et al., 2012) and the DLR Earth Sensing Imaging Spectrometer Mission (DESIS) using the WebAssembly System Interface (WASI) (Gege, 2004, 2014) by (Bracher et al., 2021). Most recently NASA's Plankton, Aerosol, Clouds, ocean Ecosystem (PACE) mission have been launched (Werdell et al., 2024) and the European Space Agency (ESA) is preparing the CHIME hyperspectral to be launched in the coming decade (Nieke et al., 2023).

Since satellites provide long-term synoptic observations of phytoplankton groups high-quality in situ pigment data is invaluable for product validation and algorithm refinement (Cetinić et al., 2024). Similarly, several studies based on self-organizing

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maps, spectral composition or machine-learning-based methods applied to satellite data have leveraged phytoplankton pigments to understand taxonomic shifts in phytoplankton communities (El Hourany et al., 2019, 2024; Hayward et al., 2025; Xi et al., 2020).

***Table 1**. Alphabetically ordered list of the major diagnostic pigments and additional accessory pigments considered in this study (including abbreviations, their full name and associated phytoplankton groups)* (Fragoso et al., 2017b; Jeffrey et al., 1999). *Notice that Dinoflagellates contains two types, reflecting different major pigments.*

Major diagnostic pigments		
Abbreviation	*Pigment name*	*Associated phytoplankton groups*
Allo	Alloxanthin	Cryptophytes
But-fuco	19'-Butanoyloxyfucoxanthin	Haptophytes, Pelagophytes
Chl-*a*	Chlorophyll *a*	All phytoplankton groups
Chl-*b*	Chlorophyll *b*	Green algae (chlorophytes and prasinophytes)
Fuco	Fucoxanthin	Diatoms, Pelagophytes, Dinoflagellates-2, Haptophytes (certain species of *Phaeocystis*)
Hex-fuco	19'-Hexanoyloxyfucoxanthin	Haptophytes, Dinoflagellates-2
Peri	Peridinin	Dinoflagellates-1
Zea	Zeaxanthin	Cyanobacteria, Green algae

Additional accessory pigments	
Abbreviation	*Pigment name*
αβ-Car	α-/β-carotene
Bacteriochlorophyll *a*	Bacteriochlorophyll *a*
Chlide *a*	Chlorophyllide *a*
Chl-c1	Chlorophyll c1
Chl-c1+c2	Chlorophyll c1+c2
Chl-c3	Chlorophyll c3
Diadino	Diadinoxanthin
Diato	Diatoxanthin
DV-Chl-*a*	Divinyl Chlorophyll *a*
DV-Chl-*b*	Divinyl Chlorophyll *b*
Lut	Lutein
Neo	Neoxanthin
Phide *a*	Pheophorbide *a*
Phytin *a*	Pheophytin *a*
Pras	Prasinoxanthin
Viola	Violaxanthin

While satellite data ~~are~~is becoming increasingly important, it remains limited by its ability to capture only the first optical depth under cloud- and ice-free conditions.

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In situ pigment data from the Arctic have compared to other parts of the world historically been limited due to the region's remoteness, harsh weather conditions and logistical challenges of conducting fieldwork in such remote regions. Advances in HPLC technology, together with standardised protocols (Hooker et al., 2005) and round-robins intercomparison of methodologies (Canuti, 2023), have contributed to the growing availability of pigment data globally, which also includes data from the Arctic and Sub-arctic regions (Kramer et al., 2022; Losa et al., 2017; Mattei and Scardi, 2021; Swan et al., 2016; Xi et al., 2023). Related efforts to obtain pigment data, such as those using UPLC methods (Hwang, 2025), also represent a valuable contribution, though they cannot be incorporated into the current database for inter-comparability reasons with HPLC-based measurements. Despite advances, spatial and temporal coverage across the Arctic remains uneven, underscoring persistent knowledge gaps, highlighting the need for coordinated, collective efforts to compile and expand existing data in this rapidly changing region.

To address this gap, we present the first pan-Arctic overview of phytoplankton and sea-ice algae pigment distributions, based on a comprehensive database of Arctic and sub-Arctic in situ pigment measurements collected between 2000 and 2024. The database is compiled from 77 cruises conducted across the Arctic Ocean, covering coastal, shelf, open-ocean and sea-ice domains (see **Table 2**). Importantly, this database represents a collective effort involving multiple institutions, research teams and international collaborations. By consolidating data from diverse sources, it provides a baseline for assessing long-term trends in phytoplankton pigments, communities and their ecological responses to environmental change. Additionally, such a database can support a pan-Arctic taxonomic characterisation of phytoplankton communities by employing pigment-based taxonomy techniques (Hayward et al., 2023, 2024; Vidussi et al., 2001; Wright and Jeffrey, 2006).

Methodology

2.1. Database Compilation

Phytoplankton and ice algae pigment data was compiled from 77 research cruises conducted between 2000 and 2024. The datasets were sourced from a combination of publicly available repositories (e.g., PANGAEA), institutional databases (e.g., NASA) and personal correspondence with scientists. Datasets were accompanied by relevant ancillary metadata, including information on sampling time, location and depth. A total of 10,798 pigment datapoints were compiled (**Table 2**). Where possible, cruise reports and original publications were consulted to verify the context and methods of data collection. Part of the data has already been published individually for the respective research cruises and/or projects, however, the compiled database presented in this article (including datasets not yet publicly available) has been stored in a public repository (https://doi.org/10.11583/DTU.29445104).

***Table 2**. Alphabetically ordered summary of Arctic and sub-Arctic* cruises *(= 77) with key dataset information such as year, sampling region(s) (as defined in section 3.1.), environment, sample count and associated DOI, where possible. Note that few samples were from melt-ponds, here assigned as ice samples.*

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Dataset	Year	Region(s)	Environment(s)	Number of Samples	DOI
ARA06B	2015	North Pacific Ocean, East Siberian Sea, Chukchi Sea, CAO	Water	112	https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00002844
ARA07B	2016	North Pacific Ocean, East Siberian Sea, Chukchi Sea	Water	50	
ARA08B	2017	North Pacific Ocean, East Siberian Sea, Chukchi Sea	Water	98	
ARA09B	2018	East Siberian Sea, Chukchi Sea	Water	110	
ARA10B	2019	North Pacific Ocean, East Siberian Sea, Chukchi Sea	Water	70	
ARA10B_Ice	2018	East Siberian Sea	Ice	65	
ARA11B	2020	North Pacific Ocean, East Siberian Sea, Chukchi Sea	Water	85	
AREX2000	2000	Norwegian Sea, Barents Sea, Fram Strait	Water	77	https://doi.org/10.48457/IOPAN.2025.523
AREX2001	2001	Norwegian Sea, Barents Sea, Fram Strait	Water	55	
AREX2002	2002	Norwegian Sea, Fram Strait	Water	20	
AREX2003	2003	Norwegian Sea, Barents Sea, Fram Strait	Water	50	
AREX2004	2004	Norwegian Sea, Fram Strait	Water	27	
AREX2005	2005	Norwegian Sea, Barents Sea, CAO, Fram Strait	Water	51	
AREX2014	2014	Norwegian Sea, Barents Sea, CAO, Fram Strait	Water	133	
AREX2019	2019	Barents Sea, CAO, Fram Strait	Water	113	
AREX2021	2021	Norwegian Sea, Barents	Water	59	

		Sea, Fram Strait			
AREX2022	2022	Norwegian Sea, Barents Sea, CAO, Fram Strait	Water	140	
Academik_Ioffe_2003	2003	Greenland Sea, Labrador Sea, Norwegian Sea	Water	34	
Arc2002	2002	Beaufort Sea, Chukchi Sea	Water	53	
Arc2004	2004	Beaufort Sea, Chukchi Sea	Water	90	
Arctic_Ocean_2024	2024	CAO	Ice, Water	61	https://doi.org/10.48457/IOPAN.2025.386
Arex2017	2017	CAO, Fram Strait	Water	33	
Assmy_ICE2010	2010	CAO	Water	42	
BODC/NERC_2001	2001	Greenland Sea	Water	169	http://doi.pangaea.de/10.1594/PANGAEA.793246
BODC/NERC_2002	2002			419	
BaySys	2018	Hudson Bay, Labrador Sea	Ice, Water	131	https://canwin-datahub.ad.umanitoba.ca/data/dataset/algal-pigments-icewater
Bracher2021_PS126	2021	Norwegian Sea, Fram Strait	Water	175	https://doi.pangaea.de/10.1594/PANGAEA.982954
Bracher_2017_PS106	2017	Norwegian Sea, Barents Sea, CAO, Fram Strait	Ice, Water	40	https://doi.org/10.1594/PANGAEA.899284
Bracher_2019_PS121	2019	Norwegian Sea, Fram Strait	Water	298	https://doi.org/10.1594/PANGAEA.941011
Bracher_2020_MSM93	2020	Norwegian Sea, Greenland Sea, Fram Strait	Water	219	
Bracher_2022_PS131_ATWAICE	2022	Norwegian Sea, Greenland Sea, CAO ,Fram Strait	Water	241	https://doi.pangaea.de/10.1594/PANGAEA.983242
Bracher_2023_PS136_HAUSGARTEN	2023	Norwegian Sea, Fram Strait	Water	137	https://doi.pangaea.de/10.1594/PANGAEA.983243
Bracher_2024_PS143.2	2024	Norwegian Sea, CAO, Fram Strait	Water	212	https://doi.pangaea.de/10.1594/PANGAEA.983244
CFL	2008	Beaufort Sea, Canadian Archipelago	Water	75	
DANA_ECOTIP_2021	2021	Baffin Bay, Labrador Sea	Water	16	https://doi.org/10.48457/IOPAN.2025.523
DSOS_GINR	2024	Baffin Bay, Labrador Sea	Water	234	
DiTuillio_2018	2018	CAO	Water	132	10.18739/A2028PD2H
DFO-Fragoso_2005	2005	Labrador Sea	Water	25	https://doi.pangaea.de/10.1594/PANGAEA.871872 For DFO-Fragoso (2005-2013), also see: https://waves-vagues.dfo-mpo.gc.ca/Library/354345.pdf
DFO-Fragoso_2006	2006	Labrador Sea	Water	12	
DFO-Fragoso_2007	2007	Labrador Sea	Water	32	
DFO-Fragoso_2008	2008	Labrador Sea	Water	25	
DFO-Fragoso_2009	2009	Labrador Sea	Water	26	
DFO-Fragoso_2010	2010	Labrador Sea	Water	27	
DFO-Fragoso_2011	2011	Labrador Sea	Water	33	
DFO-Fragoso_2012	2012	Labrador Sea	Water	30	
DFO-Fragoso_2013	2013	Labrador Sea	Water	27	

Fragoso_2014	2014	Greenland Sea, Labrador Sea	Water	16	
GreenEdge_Amundsen	2016	Baffin Bay, Labrador Sea	Water	589	10.17882/86417
Icescape_2010	2010	Chukchi Sea	Water	100	https://seabass.gsfc.nasa.gov/experiment/ICESCAPE
Icescape_2011	2011	Beaufort Sea, Chukchi Sea	Water	455	
Liu2015_PS93.2	2015	Norwegian Sea, Fram Strait	Water	241	
Liu_2016_PS99.1	2016	Norwegian Sea, Fram Strait	Water	96	https://doi.pangaea.de/10.1594/PANGAEA.905502
Liu_2016_PS99.2	2016	Fram Strait	Water	230	https://doi.pangaea.de/10.1594/PANGAEA.894874
Liu_2017_PS107	2017	Norwegian Sea, Fram Strait	Water	262	https://doi.pangaea.de/10.1594/PANGAEA.894860
MERIAN_ECOTIP2022	2022	Greenland Sea, Fram Strait	Water	40	https://doi.org/10.48457/IOPAN.2025.523
MOSAiC_Algal	2019, 2020	CAO, Fram Strait	Ice, Water	260	FYI samples: https://doi.pangaea.de/10.1594/PANGAEA.967448 SYI samples: https://doi.pangaea.de/10.1594/PANGAEA.967450 Open water samples: https://doi.org/10.1594/PANGAEA.955763
MOSAiC_SYI	2019, 2020	CAO	Ice	275	
MOSAiC_FYI	2019, 2020	CAO, Fram Strait	Ice	285	
MR17-05	2017	Beaufort Sea, North Pacific Ocean, Chukchi Sea	Ice, Water	74	https://www.godac.jamstec.go.jp/darwin_cruise/view/metadata?key=MR17-05C&lang=en
Malina	2009	Baffin Bay, Labrador Sea, Beaufort Sea, Canadian Archipelago, Laptev Sea, North Pacific Ocean, Chukchi Sea	Water	677	
Malina_Barge	2009	Beaufort Sea	Water	53	https://www.seanoe.org/data/00641/75345/
N-ICE2015	2015	CAO	Water	145	https://doi.org/10.21334/NPOLAR.2016.3EBB7F64
NunaWP4Mackenzie	2019	Beaufort Sea	Water	140	https://doi.org/10.1594/PANGAEA.937585
Thielecke_PS138_ArcWatch	2023	CAO	Ice, Water	151	
Peeken, PS74	2009	Norwegian Sea, Greenland Sea, Fram Strait	Water	130	
Peeken, PS76	2010	Norwegian Sea, Greenland Sea, Fram Strait	Water	549	

Peeken, PS78	2011	Fram Strait	Water	264	
Peeken, PS80	2012	Laptev Sea, CAO, Fram Strait	Water	576	
Peeken, PS85	2014	Fram Strait	Water	82	
Peeken, PS92	2015	CAO	Water	106	
Polarstern2003	2003	Greenland Sea, Norwegian Sea	Water	26	https://doi.org/10.48457/IOPAN.2025.523
SeaBASS_2004	2004	Beaufort Sea, Chukchi Sea	Water	59	
SeaBASS_2008	2008	Greenland Sea	Water	43	
SeaBASS_2013	2013	Baffin Bay, Labrador Sea, Norwegian Sea, Beaufort Sea, Barents Sea, East Siberian Sea, Canadian Archipelago, Chukchi Sea, Greenland Sea, Kara Sea	Water	77	
SubIce	2014	Chukchi Sea	Water	155	
Tara_Arctic	2013	Baffin Bay, Labrador Sea, Norwegian Sea, East Siberian Sea, Barents Sea, Canadian Archipelago, Greenland Sea, Kara Sea	Water	229	
Woodfjorden	2024	Fram Strait	Water	50	https://doi.org/10.48457/IOPAN.2025.504

2.2. Data Quality Measures

This dataset integrated HPLC pigment measurements from 77 research cruises, each carried out by laboratories using their own established laboratory procedures, including different HPLC set-ups, calibration standards and water filtration volume. Methodological descriptions associated with each dataset can be accessed through the provided DOIs in **Table 2** or by contacting the original data providers. To ensure consistency and comparability across sources, we applied a set of inclusion/exclusion criteria and harmonisation procedures to ensure data consistency and comparability across sources. Only datasets with measurements of seven out of the eight marker pigments described in **Table 1** were included in the database, allowing for reliable inter-sample comparison of pigment composition (criterion 1, see **Figure 1**). Although zeaxanthin is normally included in the analysis of phytoplankton functional types, it was excluded as a formal requirement in this database compilation because one source lacked measurement of this pigment and reliable distinction of green algae from other phytoplankton groups remain possible without zeaxanthin (see available pigments for each cruise in Supplementary **S1**). Zeaxanthin is also a major diagnostic pigment for

Synechococcus, which is largely absent from the Arctic region due to its thermal dependence on warmer waters (Six et al., 2021). Samples were excluded from the final database if they reported Chlorophyll (Chl-*a*) concentration of zero (criterion 2, see **Figure 1**), lacked measurements of the required marker pigments and/or were missing essential metadata such as geographic coordinates (criterion 3, see **Figure 1**).

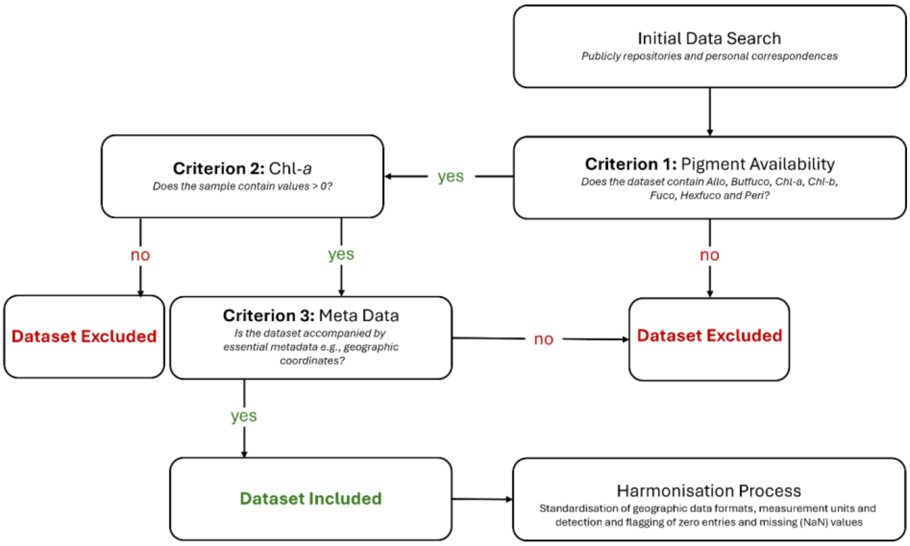

Figure 1. *Workflow diagram displaying the major decisions in the data compilation process.*

In addition to data filtering, multiple data harmonisation steps were also undertaken: longitudes reported in degrees East (0° to 360°E) were converted to signed longitude (-180° to 180°E/W) to ensure spatial compatibility with standard mapping tools ; datasets were also checked for true 0s and NaNs and that the distinction between these were standardised across datasets. This process required manual inspection of each dataset: If a pigment was entirely absent from a dataset, it was treated as NaNs (empty cells), whereas if a pigment was present but only had a single non-zero value reported, the remaining empty cells were interpreted as true 0s; finally, concentration units for accessory pigments and Chl-*a* were also standardised to the common unit, µg/L. There was ~~Considerable~~ considerable variability in methods used to calculate total Chl-*a* was observed across the database, and these methods ~~or~~ were not always reported. Consequently, ~~This~~ this parameter was ~~therefore~~ excluded. In addition, only a limited number of melt pond samples were available. These were therefore treated as part of the ice sample category, instead of a category by itself.

2.3. Limitations and Uncertainties of the Dataset

Despite efforts to minimize both limitations and uncertainties, this dataset consists of HPLC measurements from multiple laboratories. We acknowledge that methodological variability between laboratories exists and will introduce variability to the dataset. The following sections are provided to summarise the main known sources of limitations and uncertainties associated with compiling HPLC data from various laboratories, as well as general uncertainties inherent to pigments measurements.

Analytical

All datasets presented in this paper have followed standard protocols for HPLC analysis of phytoplankton pigments (see Supplementary Material S1). However, analytical uncertainties can arise from multiple stages of the workflow. As outlined by Wright & Jeffrey (2006), these can broadly be categorised into:

- **Collection and storage**
  Filtration volume, filter type and size, storage temperature and storage time
- **Extraction procedures**
  Sample disruption, duration and temperature, and choice of solvents
- **HPLC methods and techniques** (see review of HPLC pigment methods in Roy et al., 2011)
  Variations of column type and flow rate etc.
- **Peak detection, identification, integration and quantification**
  Differences in baseline correction, peak threshold, co-elution handling and pigment standards used for calibration

To minimize bias in each of these steps, substantial effort has been made through inter-comparability studies. Most notably are the SeaWiFS HPLC Analysis Round-Robin Experiments (SeaHarre-1 to SeaHarre-5) (Hooker et al., 2012) and HPLC/DAD intercomparison on phytoplankton pigments (HIP-1 to HIP-4) (Artuso, F et al., 2016; Canuti et al., 2016), which efforts has been to eliminate differences in pigment quantification across laboratories and quantify these uncertainties in terms of what can be expected, even when conducting analysis according to strict protocols.

Pigment-Specific

In addition to the analytical sources of uncertainties, pigment-specific sources also exist because of a varying degree of sensitivity to the above-described workflow. Any chosen HPLC method can therefore increase or reduce the variance experienced for a specific pigment. However, defining robust "uncertainty values" for each individual pigment remains a challenge across analytical methods. Recent inter-laboratory comparisons highlight this challenge, while also underscoring the need of such estimates in applications such as remote sensing validation (e.g., Canuti, 2023).

A main source of pigment-specific behavior comes from differences in the chemical stability of the pigments. This will affect their susceptibility to degradation, co-elution and extraction efficiency. For example, Chlorophylls (a, b, c_1 and c_2) are prone to degradation, particularly during storage and extraction, producing degradation products such as pheophytins and chlorophyllides. This can lead to biased and unprecise chlorophyll estimations as well as co-elution issues. This have often been reported for chlorophyll c_1 and chlorophyll c_2 as well as for the Fuco derivatives (But-fuco and Hex-fuco) (Roy et al., 2011; Simmons et al., 2016; Wright and Jeffrey, 2006; Zapata et al., 2000). Additionally, some chlorophyll degradation products, for example Phide *a* and Phytin *a*, can co-elute with carotenoids due to polarity changes (Mendes et al., 2007).

Finally, pigment concentration itself can be a major source of uncertainty. This is particularly true for low-abundance accessory pigments, which often approach the instrumental limits of detection (LOD) (Bidigare et al., 2002; Canuti, 2023; Canuti et al., 2016; Claustre et al., 2004; Hooker et al., 2005). For instance, when pigment concentrations fall below 0.01 mg m^{-3}, the relative standard deviation can reach up to nearly double that of pigments present at higher concentrations (Claustre et al., 2004).

3. Data Description

3.1. Sampling Coverage

To classify the sampling efforts across the Arctic and sub-Arctic seas into common groups, the study area was subdivided into 1~~5~~4 regions (**Figure 2**). A total of 10,095 water samples and 703 sea-ice samples were compiled and mapped according to their geographic location. Water samples displayed extensive sampling across most regions, while ice samples were comparatively sparse and primarily concentrated in the Central Arctic Ocean (CAO), Canadian Archipelago and Hudson Bay. These samples originate from a limited number of cruises and are not consistently represented throughout the years. Regional sampling frequencies are summarised in **Figure 2**, highlighting the dominance of water samples and the uneven spatial distribution of sea-ice samples.

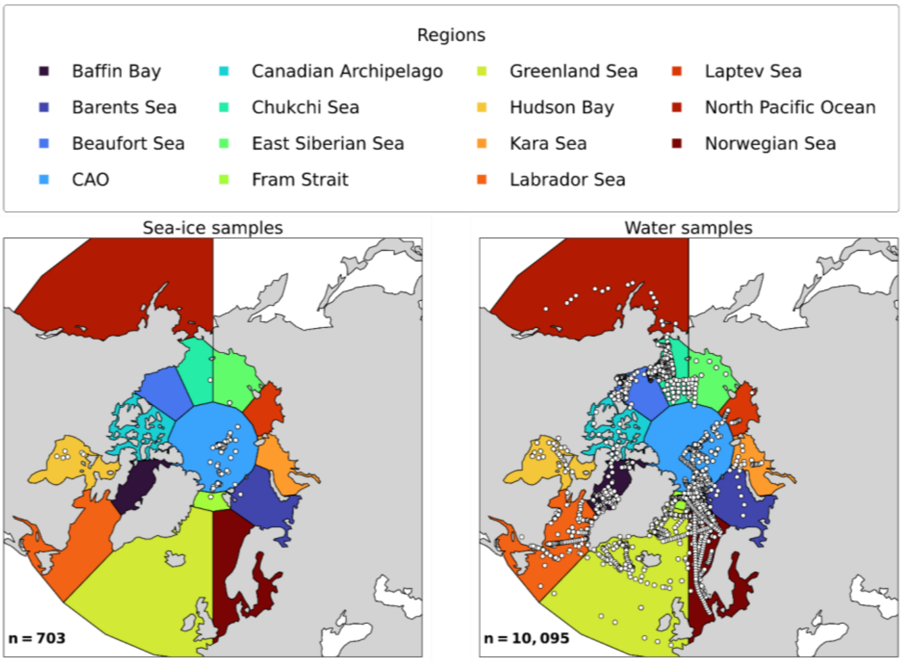

***Figure 2**. Map showing the spatial distribution of water and sea-ice samples across 15~~4~~ defined regions of the Arctic and sub-Arctic seas. Each point represents an individual sampling location. ~~and is colored according to the year of collection.~~*

Overall, the water sample collection also varied substantially across years, with higher coverage in 2002, 2009, 2016 and 2020 (**Figure 3**). These periods correspond to large-scale, multidisciplinary campaigns such as MALINA (Coupel et al., 2015b), GreenEdge (Bruyant et al., 2022; Massicotte et al., 2020), the AR7W transect during the MOSAiC cruise and others, including global initiatives such as the International Polar Year (IPY). Additionally, the MAREDAT pigment database represents a major synthesis effort (Peloquin et al., 2013) (see **Table 1**).

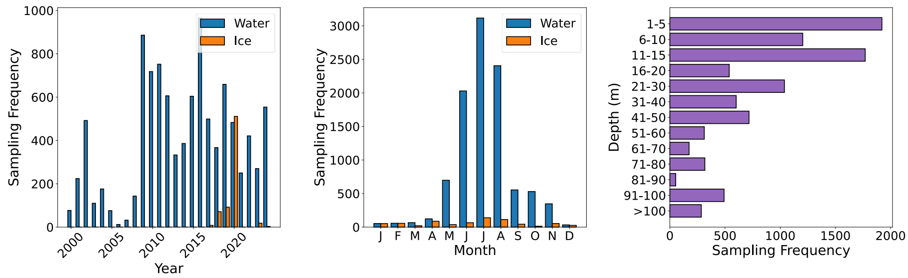

Figure 3. *(Left) yearly sampling frequency for water column and sea-ice samples, (middle) monthly sampling frequency and (right) number of water samples observations per depth bin. Note that for sea-ice samples, the vertical distribution is not presented due to inconsistencies in the ice core sampling methods among the different campaigns.*

Seasonally, sampling frequency was the highest in spring and summer (May-August). Sampling frequency was lower in September, followed by a notable secondary drop in December. The lowest sampling frequency is observed during winter and early spring (December-March), when there is extensive sea ice extent. Sampling frequency also varied vertically in the water column (**Figure 3**). Most samples were collected within the upper 1-15 meters range. Sampling frequency consistently declines from 21-30 meters onward, before a slight increase in the 91-100 meters range.

3.2. Pigment Distribution

Pigment concentration in water and sea-ice samples exhibited considerable variability in the biomass and composition of algal communities as well as in the spatiotemporal structure of the database (**Table 3**). In addition, the observed variability can also be attributed to adaptive pigment strategies.

Since direct comparison of absolute pigments concentrations between sea-ice and water samples should be interpreted with caution, only a brief description of absolute pigment concentration is provided for context (**Table 3a**). Chl-*a*, the primary indicator of phytoplankton and sea-ice algae biomass, had a mean concentration of 0.997 µg/L in water samples and 0.639 µg/L in sea-ice samples although the highest individual values in both environments point to episodic blooms. These values represent the mean of all individual concentration measurements in the compiled dataset. The highest concentration across the database, 32.76 µg/L, was recorded in the Chukchi Sea originating from the Ice Scape dataset in August 2010. In general, such high concentrations are rare, with the majority of samples falling below 0.5 µg/L across seasons. Overall, concentrations were highly variable with 90% of values falling between 0.017 and 3.789 µg/L in water samples and between 0.022 and 0.292 µg/L in sea-ice samples (**Table 3a**). It should be recognised that there is a potential bias when comparing open-water and bulk-ice samples due to neglect of the dilution of pigments when bulk sea-ice cores are melted, which can underestimate concentrations from sympagic algae (Chamberlain et al., 2022; Gradinger, 2009; Miller et al., 2015).

In terms of the relative ratios to Chl-*a* (**Table 3b and Figure 4**) the database also showed marked seasonal variability. Among the eight analysed marker pigments, Fuco consistently had the highest ratios, particularly during winter months, followed by a decline through summer and early autumn. The Fuco-derivatives, But-fuco and Hex-fuco, both considered diagnostic markers of haptophytes, had a stable distribution throughout the year, aside from notable peaks in November. ~~Additionally, Hex-fuco had a higher overall proportion than But-fuco, implying higher proportion of dinoflagellates.~~

The ratio of Allo, a distinct marker pigment of cryptophytes, started to increase in late winter, prior to the main growing season. Peri~~d~~, which is a marker pigment of dinoflagellates, had low overall ratios. These ratios increased during summer, peaking in October, before they exhibited a sharp decline toward the onset of December. As expected, Zea and Chl-*b* were relatively aligned throughout most of the year, consistent with their shared role as a marker pigment of green algae. However, a marked dissimilarity in their patterns occurred in November, when Chl-*b* declined while Zea increased.

For the sea-ice samples, the only accessory pigments with high ratios are Fuco and Chl-*b*.

These differences suggest distinct pigment signatures between sea-ice and water samples, underscoring the importance of expanding sea-ice sampling efforts to better capture algae dynamics in this environment.

Table 3. *Summary of 5th, 95th, mean, median and std statistics across all cruises (= 77), for (a) pigment concentration categorized by sample type and (b) relative ratio of accessory pigments vs. Chl-a, For detailed pigment information by individual cruises, see Supplementary* ***Table S1****. For detailed information about all pigments across environments, see Appendices* ***Table A1***

(a)	Water Samples (µg/L)					Sea-ice Samples (µg/L)				
Parameter / Pigment	5th percentile	95th percentile	Mean	Median	Std	5th percentile	95th percentile	Mean	Median	Std
Allo	0.000	0.061	0.014	0.003	0.031	0.000	0.016	0.004	0.000	0.020
But-fuco	0.000	0.080	0.020	0.007	0.040	0.000	0.005	0.001	0.000	0.008
Chl-*a*	0.017	3.789	0.997	0.417	1.855	0.022	2.292	0.639	0.179	1.746
Chl-*b*	0.000	0.207	0.059	0.033	0.091	0.000	0.158	0.037	0.000	0.109
Fuco	0.003	1.493	0.357	0.106	0.853	0.000	1.392	0.367	0.063	1.120
Hex-fuco	0.000	0.434	0.092	0.019	0.180	0.000	0.011	0.002	0.000	0.010

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Peri	0.000	0.105	0.021	0.001	0.072	0.000	0.057	0.016	0.000	0.078
Zea	0.000	0.030	0.008	0.001	0.025	0.000	0.009	0.003	0.000	0.022

(b)	**Water Samples (ratio)**					**Sea-ice Samples (ratio)**				
Parameter / Pigment	5th percentile	95th percentile	Mean	Median	Std	5th percentile	95th percentile	Mean	Median	Std
Allo vs Chl-*a*	0.000	0.078	0.100	0.009	1.634	0.000	0.034	0.006	0.000	0.021
But-fuco vs Chl-*a*	0.000	0.160	0.263	0.024	4.663	0.000	0.013	0.003	0.000	0.030
Chl-*b* vs Chl-*a*	0.000	0.358	1.094	0.077	15.482	0.000	0.414	0.087	0.000	0.138
Fuco vs Chl-*a*	0.068	0.666	2.504	0.290	26.620	0.000	0.741	0.428	0.443	0.235
Hex-fuco vs Chl-*a*	0.000	0.489	0.681	0.080	9.694	0.000	0.007	0.004	0.000	0.018
Peri vs Chl-*a*	0.000	0.118	0.221	0.004	5.792	0.000	0.150	0.028	0.000	0.109
Zea vs Chl-*a*	0.000	0.056	0.056	0.003	1.062	0.000	0.027	0.005	0.000	0.021

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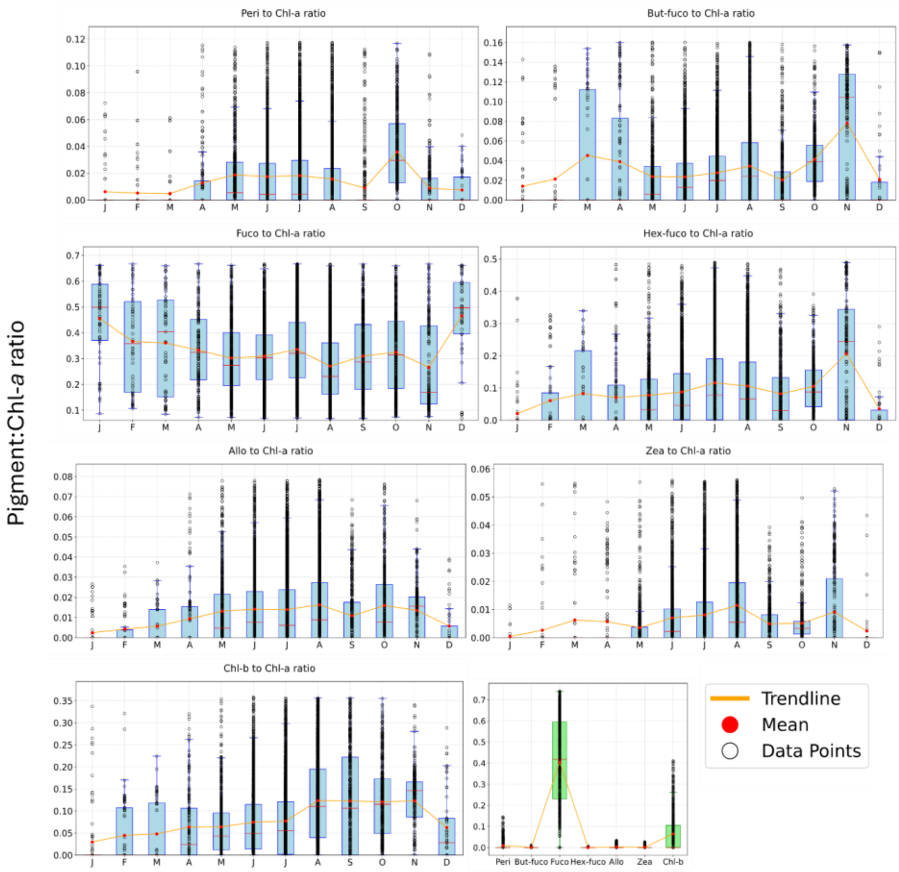

***Figure 4**. Display of the seasonal variation of individual accessory pigment concentration to Chl-a ratio. Water samples are shown as monthly ratios in **blue** and sea-ice samples are shown overall across months per pigment in **green**. Only values within 5th to 95th percentile are included. Data points are displayed as open circles, the mean ratio for each month is shown as a red dot and an orange line connects means.*

Spatial and Temporal Dynamics

In our dataset, Chl-*a* exhibited strong spatial and temporal (seasonal) and inter-annual variability, reflecting the dynamic nature of phytoplankton and sea-ice algae in polar and subpolar environments. Elevated concentrations were observed in areas such as the Fram Strait, Barents Sea, Beaufort Sea, Chukchi Sea and Labrador Sea (**Figure 5**). However, as the database is opportunistic by nature, covering only discrete regional samplings, spatial and seasonal comparisons should be made with caution.

In spring, the Labrador Sea recorded the seasonal maximum (18.75 µg/L), with the highest values occurring mostly in surface waters (0-5 meters). As previously mentioned, summer exhibited the maximum database record for Chl-*a*. Contrary to spring, highest averages were found between 16-30 meters. By autumn, Chl-*a* had declined across most regions. However, localised high biomass persisted in some areas such as Beaufort Sea, Chukchi Sea and Fram Strait. Winter Chl-*a* was generally low.

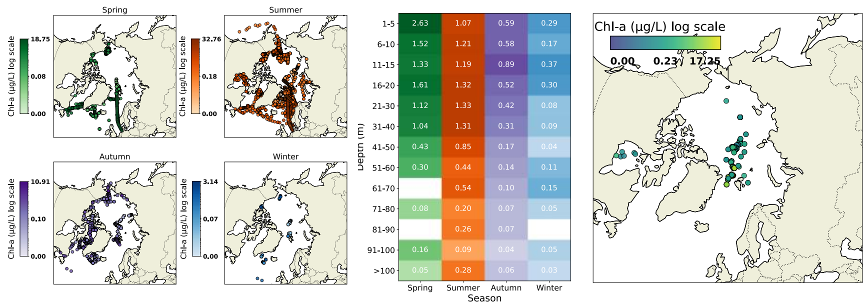

Figure 5. *(a) Spatial distribution of all measured Chl-a water samples in each season, shown as subplots for spring, summer, autumn and winter. Color mapping uses logarithmic scale, but the values themselves are not log-transformed. (b) Mean Chl-a concentration as function of depth range (rows) and season (columns). Color indicates the average value for each depth/season bin. Missing color indicates that data is not available. (c) Spatial distribution of all measured Chl-a for sea-ice samples.*

The concentration frequency distribution plots of water samples (**Figure 6**, blue plots) showed that both Chl-*a*, Chl-*b* and Fuco exhibited approximately log-normal distribution, with peak concentrations near central values and tails on either side. This interpretation was supported by the log-normal distribution of data. However, formal normality tests such as Kolmogorov-Smirnov (K-S test) indicated significant deviations from perfect log-normality, likely due to large sample size and/or the presence of outliers (see Appendices **Figure A1**). In contrast, pigments such as Zea, Peri ~~d~~ and the Fuco derivatives exhibited more variable distributions and greater heterogeneity among samples. The histograms for the sea-ice samples (**Figure 6**, grey plots), had much more variability in the distribution of concentrations. This is likely also related to smaller sample size for sea-ice samples.

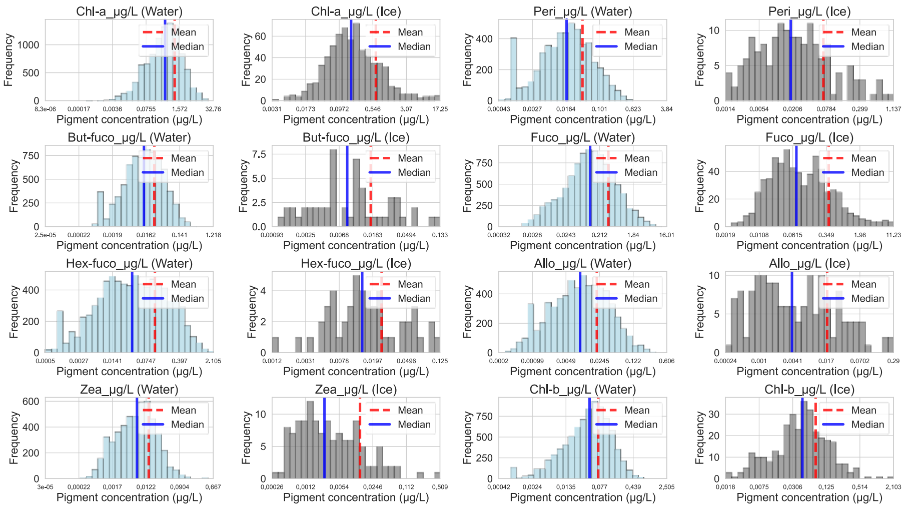

Figure 6. *Frequency histograms displaying log-scaled pigment concentrations. Water samples are shown in blue and sea-ice samples are shown in grey. x-axis represents actual pigment concentrations. Note the different ranges for y-axis comparing water and sea-ice samples.*

4. Data Availability

All datasets used in this paper have been compiled into a single repository, accessible using DOI: https://doi.org/10.11583/DTU.29445104 (Heidemann et al., 2026).

5. Conclusions

Photosynthetic and accessory pigments serve as indicators of community structure and biomass, and are important oceanographic variables for understanding ocean ecology, as they can also support assessment of biogeochemical cycling. Yet, datasets reporting concentrations of those pigments remain sparse in the Arctic region. To address this gap, we compiled, filtered, standardised and harmonised 10,798 pigment samples from HPLC, including water (n = 10,095) and sea-ice samples (n = 703), collected during 77 research cruises spanning from 2000 to 2024 across 15~~4~~ defined Arctic and sub-Arctic regions. Sampling frequency varied by year, with peak efforts in 2002, 2009, 2016 and 2020. These years correspond to major multidisciplinary research projects and international initiatives such as the International Polar Year (IPY). Seasonally, most samples were collected during spring and summer months in the upper water column.

Within the available dataset, Chl-*a* was found in higher concentrations in sea-ice samples compared to water samples, on average. However, for accessory pigments, concentrations were generally found to be lower in sea-ice samples. Despite this, the highest concentration of Chl-*a* across the dataset, 32.76 µg/L, was recorded for a water sample in the Chukchi Sea. Other areas that exhibited elevated Chl-*a* concentrations were spread across the Arctic marginal seas such as the Fram Strait, Barents Sea, Beaufort Sea and Labrador Sea. Interestingly, among the eight marker pigments, Fuco consistently had the highest pigment to Chl-a ratios, particularly during winter months, followed by a decline through summer and early autumn. For the sea-ice samples, the only accessory pigments with high ratios were Fuco and Chl-*b*.

Our comprehensive phytoplankton and sea-ice algal HPLC-based pigment dataset provides valuable insights into the research effort in the Arctic Ocean. Furthermore, it offers important observations on spatial and temporal patterns of primary producers supporting large-scale environmental research in the Arctic across over two decades of sampling efforts.

Appendices

Table A1. *Pigment concentration statistics for all included measured pigments, separated by sample type and summarised across all cruises. For each pigment and environment, the table reports the 5th percentile, 95th percentile, mean, median and standard deviation (Std).*

	Water Samples (µg/L)					**Sea-ice Samples (µg/L)**				
Parameter / Pigment	5th percentile	95th percentile	Mean	Median	Std	5th percentile	95th percentile	Mean	Median	Std
Chl *c*3	0.000	0.232	0.054	0.014	0.116	0.000	0.051	0.014	0.000	0.053
Chl *c*1*c*2	0.000	0.652	0.146	0.048	0.295	0.000	0.365	0.101	0.035	0.254
Chl c1	0.000	0.031	0.009	0.000	0.061	0.000	0.000	0.000	0.000	0.007
Chlide *a*	0.000	0.062	0.015	0.000	0.078	0.000	0.007	0.002	0.000	0.022
Peri	0.000	0.105	0.021	0.001	0.072	0.000	0.057	0.016	0.000	0.078
Phide *a*	0.000	0.132	0.028	0.000	0.147	0.000	0.437	0.132	0.000	0.821
But-fuco	0.000	0.080	0.020	0.007	0.040	0.000	0.005	0.001	0.000	0.008
Fuco	0.003	1.493	0.357	0.106	0.853	0.000	1.392	0.367	0.063	1.120
Neo	0.000	0.022	0.005	0.000	0.010	0.000	0.014	0.002	0.000	0.010
Pras	0.000	0.053	0.011	0.000	0.025	0.000	0.005	0.001	0.000	0.006
Viola	0.000	0.027	0.007	0.002	0.012	0.000	0.034	0.010	0.000	0.049
Hex-fuco	0.000	0.434	0.092	0.019	0.180	0.000	0.011	0.002	0.000	0.010
Diadino	0.000	0.232	0.058	0.020	0.108	0.000	0.239	0.052	0.000	0.208
Allo	0.000	0.061	0.014	0.003	0.031	0.000	0.016	0.004	0.000	0.020
Diato	0.000	0.025	0.005	0.000	0.016	0.000	0.063	0.010	0.000	0.036
Zea	0.000	0.030	0.008	0.001	0.025	0.000	0.009	0.003	0.000	0.022
Lut	0.000	0.011	0.003	0.000	0.012	0.000	0.025	0.009	0.000	0.069
bacterio chl *a*	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
DV Chl *b*	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.000
Chl-*b*	0.000	0.207	0.059	0.033	0.091	0.000	0.158	0.037	0.000	0.109
DV Chl *a*	0.000	0.000	0.001	0.000	0.007	0.000	0.000	0.000	0.000	0.000
Chl-*a*	0.017	3.789	0.997	0.417	1.855	0.022	2.292	0.639	0.179	1.746
Phytin *a*	0.000	0.034	0.007	0.000	0.047	0.000	0.000	0.007	0.000	0.048
alphabetaCar	0.000	0.067	0.018	0.006	0.032	0.000	0.085	0.017	0.000	0.064

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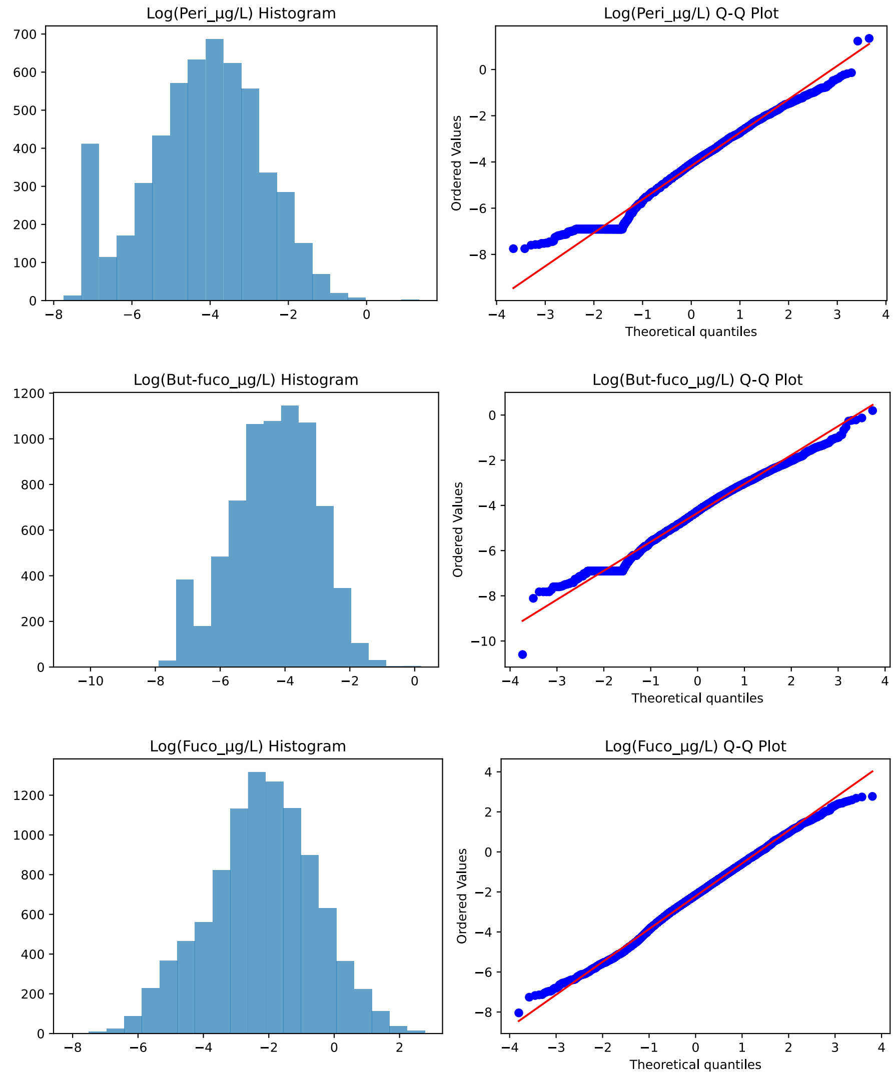
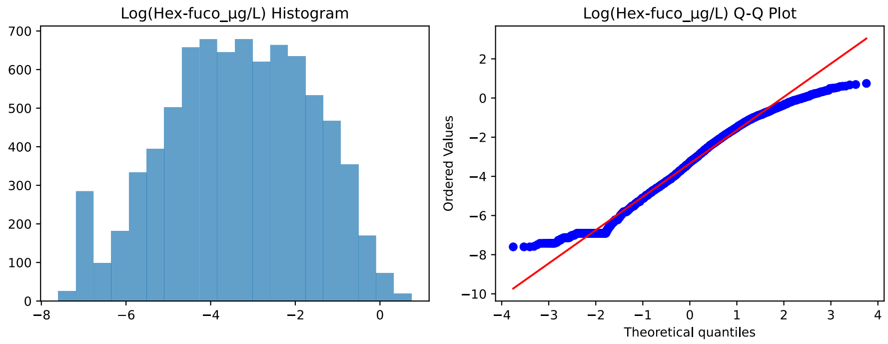
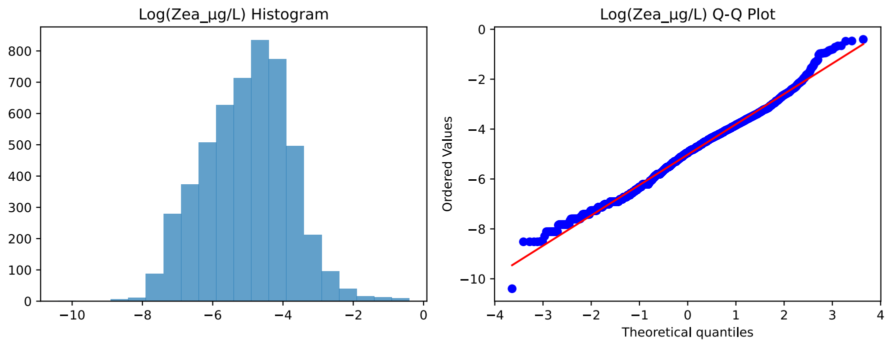
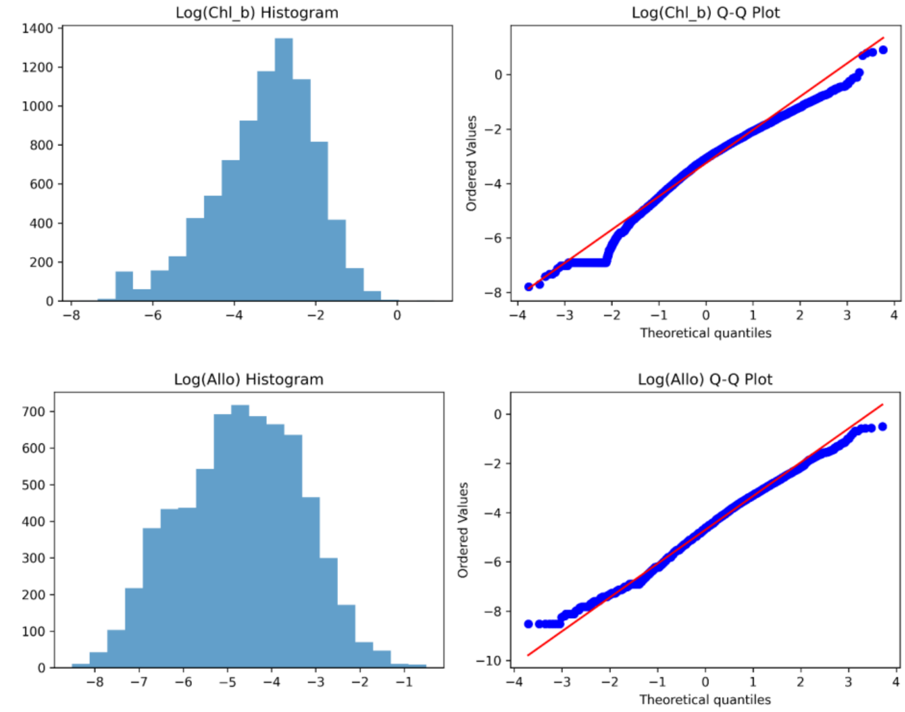
Figure A1. *Histogram and Q-Q plots performed for each marker pigment on standardised and log-transformed data. For each pigment, a histogram and a Q-Q plot are visualized to assess normality. All Kolmogorov-Smirnov (K-S) p-values were below 0.05 test, indicating that the data deviates from a normal distribution.*




Log(Hex-fuco_µg/L) Histogram
Log(Hex-fuco_µg/L) Q-Q Plot
Ordered Values
Theoretical quantiles


Log(Zea_µg/L) Histogram
Log(Zea_µg/L) Q-Q Plot
Ordered Values
Theoretical quantiles



Author contributions

ACH consolidated the data, harmonized and standardised the dataset, performed the data analysis, generated plots and developed the manuscript.

AH conceived the study idea, provided relevant expertise, contributed data, facilitated key contacts and data sources and contributed to revising and improving the data analysis and manuscript.

RG-A provided relevant expertise and contributed to conceiving the study idea, revising and improving the data analysis and manuscript.

PA, AB (Astrid Bracher), GC, GD, KDD, AF, GMF, JH (Jacob Høyer), MI, AJ, TJP, PK, YL, MAVL, AM (Atsushi Matsuoka), AM (Alenya Merz), CJM, EO, IP, MP, JSE, JS, AT, GV, HX and EJY contributed data, provided relevant expertise and revised the manuscript.

AB (Atreya Basu) and JH (Jiwoon Hwang) provided relevant expertise and revised the manuscript.

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