People's Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

National Higher School of Marine Sciences and Coastal Management

Graduation thesis for obtaining the Degree of Marine Sciences Engineer

Option: aquaculture management

Theme:

Phytoplankton and Aquaculture Sustainability: Biological Indicators for the Sustainable Management of Farming Areas

Presented by:

- **MESSAOUI Yousra**

Defended on 27 /06/2026, before the jury composed of:

Mr. DILMI Ammar	Assistant Professor	President
Ms. CHABET DIS Chalabia	Research Professor A	Examiner
Ms. MESLEM Nabila	Senior Lecturer B	Supervisor
Ms. HAMMADI Ouahiba	PhD student	Co Supervisor

Academic Year 2025/2026

Acknowledgement

بِسۡمِ ٱللَّهِ ٱلرَّحۡمَٰنِ ٱلرَّحِيمِ

«وَآخِرُ دَعْوَاهُمْ أَنِ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ»

First and foremost, I thank God for giving me the strength and courage to write this.

This degree has tears in it, prayers on it, and God all over it. It has been a long path of self-discovery, where I learned that true capacity is defined not just by knowledge, but by the courage to keep moving forward and not listening to the rejection so you will achieve anything that life throws your way.

To my mother and father

جزاكما الله عني خير الجزاء

Who made sure I graduated, Thank you for your unconditional love and your infinite patience. Every success I have achieved bears your mark. Thank you for teaching me that true value is built through effort, consistency, and the ability to rise above every difficulty.

To my sister Wissam

Who shared the weight of this journey with me, I'm so grateful for your presence by my side, and thanks to my brothers for the pure love.

To my late grandfather and grandmother

You are held forever in the safest place of my heart. Your legacy remains the quiet, guiding force behind every step I take. May this work serve as a lasting Sadaqah jariyah for both of you.

To my friends

***Rania**, who carried so much of this burden with me, and **Aya**, Thank you for being there for me and for all memories we made together.*

***Rahma**, **Chaima** and her **son**, and **Nour el Houda**, **Ilhem,Rosa,Amira** .Thank you for sharing this path with me and for your support that made me smile even when I was tired.*

*And thanks to the member of jury, **my supervisor**, **MS.chalabia** and **MR.Dilmi** for provides us with positive energy, the guidance and evaluation.*

To ILYES REDJEB

Thank you for your love, your kindness, and your respect, for your focus on my safety, comfort and motivation throughout this journey.

this success and degree is as much yours as it is mine.

Abstract

This study was conducted at the Ain Taya aquaculture site, in the coastal waters east of Algiers, over two seasonal field campaigns, in February and May 2026, with the objective of assessing the environmental influence of floating fish cages on the surrounding Aïn Taya coastal waters and phytoplankton community structure. Five sampling stations were established around the farm, and five parameters were measured: total suspended solids, dissolved inorganic nutrients (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}, SiO_4^{4-}), chlorophyll-a concentration, phytoplankton taxonomic composition, and ecological diversity indices. Results show a measurable nitrogen enrichment gradient centered on ST01, the cage center, most pronounced in May when nitrate concentration reached 0.8097 µmol/L, indicating an early stage of eutrophication near the cage structures. The phytoplankton community was dominated by diatoms throughout both campaigns, with Skeletonema sp. reaching 45,640 cells L^{-1} at ST01 in May. Diversity indices indicate a reduction in biological diversity at nutrient-enriched stations, with a Simpson dominance index of D = 0.789 at ST01 in May, reflecting near-monoculture bloom conditions. One potentially harmful species, Alexandrium sp., was detected at ST03 during May. Taken together, the results confirm that the Ain Taya aquaculture installation exerts a detectable but spatially limited environmental influence on the coastal waters of this southwestern Mediterranean site under current operating conditions.

Keywords: aquaculture, phytoplankton, ecological diversity, eutrophication, Aïn Taya coastal waters, southwestern Mediterranean.

Résumé

Cette étude a été menée sur le site d'aquaculture d'Aïn Taya, dans les eaux côtières situées à l'est d'Alger, durant deux campagnes saisonnières : février et mai 2026, afin d'évaluer l'impact environnemental des cages flottantes sur la qualité des eaux côtières d'Aïn Taya et la communauté phytoplanctonique côtière. Cinq stations d'échantillonnage ont été établies autour des structures, et cinq paramètres ont été mesurés : les matières en suspension (MES), les nutriments inorganiques dissous (NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}, SiO_4^{4-}), la concentration en chlorophylle-a, la composition taxonomique du phytoplancton et les indices de diversité écologique. Les résultats montrent un enrichissement en azote mesurable au niveau de la cage centrale (ST01), particulièrement prononcé en mai, où la concentration en nitrates a atteint 0,8097 µmol/L, traduisant un début d'eutrophisation à proximité des structures. La communauté phytoplanctonique est dominée par les diatomées, en particulier Skeletonema sp. dont la densité cellulaire a atteint 45 640 cellules L^{-1} à ST01 en mai. Les indices de diversité révèlent une réduction de la diversité biologique aux stations enrichies en nutriments, avec un indice de Simpson D = 0,789 à ST01 en mai, traduisant des conditions proches d'une efflorescence monospécifique. Une espèce potentiellement toxique, Alexandrium sp., a été détectée à ST03 en mai. L'ensemble des résultats confirme que l'installation aquacole d'Aïn Taya exerce une influence environnementale détectable mais spatialement limitée sur ce site de la Méditerranée sud-occidentale, dans les limites actuelles de production.

Mots-clés : aquaculture, phytoplancton, diversité écologique, eutrophisation, eaux côtières d'Aïn Taya, Méditerranée sud-occidentale

ملخص

أُجريت هذه الدراسة في موقع الاستزراع المائي بعين طاية، شرق مدينة الجزائر العاصمة، خلال حملتين ميدانيتين موسميتين، في فيفري وماي 2026، بهدف تقييم التأثير البيئي لأقفاص تربية الأسماك العائمة على المياه الساحلية لعين طاية وعلى بنية مجتمع العوالق النباتية. تم تحديد خمس محطات لأخذ العينات حول المزرعة، وقيست خمسة معايير: المواد العالقة الكلية، المغذيات اللاعضوية الذائبة (النترات، النتريت، الأمونيوم، الفوسفات، السيليكات)، تركيز الكلوروفيل-أ، التركيب التصنيفي للعوالق النباتية، ومؤشرات التنوع الإيكولوجي. أظهرت النتائج تدرجًا قابلًا للقياس في إغناء المياه بالنيتروجين يتمركز عند المحطة رقم واحد، أي مركز الأقفاص، وكان الأكثر وضوحًا في شهر مايو حيث بلغ تركيز النترات 0.8097 ميكرومول في اللتر، وهو ما يعكس بداية ظاهرة التخثث بالقرب من هياكل التربية. سيطرت الدياتومات على مجتمع العوالق النباتية خلال الحملتين، حيث سُجّل نوع السكيليتونيما بكثافة بلغت 45640 خلية في اللتر عند المحطة رقم واحد في مايو. تشير مؤشرات التنوع إلى انخفاض في التنوع البيولوجي في المحطات الغنية بالمغذيات، بمؤشر سيطرة سيمبسون بلغ 0.789 عند المحطة رقم واحد في مايو، ما يعكس ظروفًا شبه أحادية النوع. كما تم رصد نوع واحد يُحتمل أن يكون ضارًا، هو الأليكسندريوم، عند المحطة رقم ثلاثة خلال مايو. وإجمالاً، تؤكد النتائج أن منشأة الاستزراع المائي بعين طاية تُحدث تأثيرًا بيئيًا قابلًا للرصد لكنه محدود مكانيًا على المياه الساحلية لعين طاية، الواقعة في جنوب غرب البحر الأبيض المتوسط، في ظل ظروف الإنتاج الحالية.

الكلمات المفتاحية: الاستزراع المائي، العوالق النباتية، التنوع الإيكولوجي، التخثث، المياه الساحلية لعين طاية، جنوب غرب البحر الأبيض المتوسط.

TABLE OF CONTENTS

Acknowledgement 2
Abstract 3
Résumé 5
ملخص 6
TABLE OF CONTENTS 7
List of figures 9
List of tables 11
List of Abbreviations 13
..... 1
INTRODUCTION 1
CHAPTER I. GENERAL BACKGROUND 4
I.1. Coastal Ecosystems and Aquaculture 5
I.2. Water Quality and Nutrient Dynamics 5
I.3. Phytoplankton Dynamics 6
I.3.1. Chlorophyll-a as a Proxy for Biomass 6
CHAPTER II. MATERIALS AND METHODS 9
II.1. Study Area 10
II.1.1. Geographical and Topographic Context 10
II.1.2. Bathymetry and Substrate 11
II.2. Sampling Stations 12
II.3. Sampling Strategy and Field Campaigns 13
II.3.1. Water Sampling and In-Situ Measurements 13
II.3.2. Sample Collection and Preservation 15
II.3.3. Transport Conditions 16
II.4. Laboratory Procedures 16
II.4.1. Total Suspended Solids (TSS) 16
II.4.2. Chlorophyll-a Extraction 18
II.4.3. Dissolved Inorganic Nutrient Analysis 19
II.5. Phytoplankton Identification and Statistical Analysis 20
II.5.1. Taxonomic Identification the Utermöhl Method 20
II.5.2. Ecological Diversity Indices 22

.....24
CHAPTER III. RESULTS AND DISCUSSION.....24
III.1. Total Suspended Solids (TSS).....25
III.1.1. February 2026, Winter Campaign.....25
III.1.2. May 2026, Spring Campaign.....26
III.1.3. Seasonal Comparison and Discussion.....27
III.2. Dissolved Inorganic Nutrients.....29
III.2.1. Nitrates (NO_3^-).....30
III.2.2. Nitrites (NO_2^-).....31
III.2.3. Ammonium (NH_4^+).....31
III.2.4. Phosphates (PO_4^{3-}).....32
III.2.5. Silicates (SiO_4^{4-}).....32
III.2.6. General Discussion of Nutrient Results.....33
III.3. Chlorophyll-a Concentrations.....34
III.3.1. February 2026: Winter Campaign.....34
III.3.2. May 2026, Spring Campaign.....35
III.3.3. Seasonal Comparison and Trophic Assessment.....38
III.4. Phytoplankton Community Structure.....39
III.4.1. February 2026, Winter Campaign.....41
III.4.1.1. Relative Frequency and Abundance, February 2026.....43
III.4.1.2. Ecological Diversity Indices, February 2026.....44
III.4.2. May 2026, Spring Campaign.....45
III.4.2.1. Harmful Algal Bloom Species, May 2026.....47
III.4.2.2. Relative Frequency and Relative Abundance, Both Campaigns.....48
III.4.2.3. Ecological Diversity Indices. May 2026.....49
III.4.3. Seasonal Comparison and Community Dynamics.....50
III.4.4. General Discussion of Phytoplankton Results.....51
CONCLUSION.....54
BIBLIOGRAPHICAL REFERENCES.....57
APPENDICES.....59

List of figures

Figure I.1. Simplified flowchart showing how nutrient inputs from aquaculture can stimulate phytoplankton growth, leading to environmental outcomes like oxygen changes and algal blooms (author's schematic, based on Boudouresque, 2004; Nefraoui et Tabi, 2015). Page 20

Figure II.1. Satellite image showing the location of the commune of Ain Taya. Page 24

Figure II.2. Satellite image showing the location of the farm and the livestock area. Page 24

Figure II.3. Spatial distribution of the five sampling stations at the Ain Taya aquaculture site. Page 26

Figure II.4. the Niskin bottle water sampler illustrating the messenger trigger mechanism and the closed sampling chamber used for subsurface water collection at 5 m depth. Page 27

Figure II.5. A plankton net size of 20 µm. Page 28

Figure II.6. Laboratory preparation of sample bottles and filtration funnels. Page 29

Figure II.7. Insulated iceboxes used for sample preservation and transport. Page 30

Figure II.8. Gravimetric filtration apparatus and analytical balance for TSS pre-weighing . Page 31

Figure II.9. Filter drying in the oven at 105°C and final gravimetric mass determination . Page 31

Figure II.10. Inverted microscope workspace and Utermöhl sedimentation chamber setup. Page 34

Figure III.1. Comparison of total suspended solid (TSS) concentrations (mg/L) at the five sampling stations during the February and May 2026 campaigns. Page 42

Figure III.2. Dissolved inorganic nutrients concentrations measured at the five stations during February 2026. Page 43

Figure III.3. Dissolved inorganic nutrients concentrations measured at the five stations during May 2026. Page 43

Figure III.4. Chlorophyll-a concentrations (µg/L, logarithmic scale) at the five sampling stations during the February and May 2026 campaigns at the Ain Taya aquaculture site. Dashed line indicates the hypereutrophic threshold (75 µg/L) according to Vollenweider et al. (1998).

Page 50

Figure III.5. Photomicrographs of phytoplankton taxa observed under the inverted microscope (Utermöhl method, ×400 magnification) at the Ain Taya aquaculture site. Page 54

Figure III.6. Composition and cell density (cells L^{-1}) of the phytoplankton community at the five sampling stations during the February 2026 campaign at the Ain Taya aquaculture site.

Page 56

Figure III.7. Composition and cell density (cells L^{-1}) of the phytoplankton community at the five sampling stations during the May 2026 campaign at the Ain Taya aquaculture site. Page 60

Figure III.8. Relative frequency (FR, %) of phytoplankton taxa recorded across both sampling campaigns (n = 10 samples: 5 stations × 2 campaigns) at the Ain Taya aquaculture site. Page 62

Figure III.9. Comparison of the Shannon-Weaver diversity index (H') and Simpson dominance index (D) at the five sampling stations between the February and May 2026 campaigns at the Ain Taya aquaculture site. Page 65

List of tables

Table I.1. Comparative characteristics of diatoms and dinoflagellates in coastal Mediterranean waters (author's schematic, based on Illoul, 1987). Page 22

Table II.1. Characteristics and GPS coordinates of the five sampling stations at Ain Taya. Page 26

Table II.2. Summary of sampling campaigns, dates, and parameters measured. Page 27

Table III.1. TSS concentrations (mg/L) at the five sampling stations, February 2026 campaign. Page 39

Table III.2. TSS concentrations (mg/L) at the five sampling stations May 2026 campaign. Page 40

Table III.3. Raw absorbance readings and chlorophyll-a concentrations at the five stations, February 2026. Page 48

Table III.4. Raw absorbance readings and chlorophyll-a concentrations at the five stations, May 2026. Page 49

Table III.5. Comparison of final chlorophyll-a concentrations(µg/L) and trophic status between the two campaigns. Page 51

Table III.6. Phytoplankton taxa identified at the Ain Taya. Page 53

Table III.7. Phytoplankton cell densities (cells L^{-1}) at the five sampling stations, February 2026 campaign. Page 55

Table III.8. Ecological diversity indices calculated for the phytoplankton community at the five sampling stations, February 2026. Page 58

Table III.9. Phytoplankton cell densities (cells L^{-1}) at the five sampling stations, May 2026 campaign. Page 59

Table III.10. Relative frequency (FR %) of phytoplankton taxa recorded across both sampling campaigns. Page 62

Table III.11. Ecological diversity indices calculated for the phytoplankton community at the five sampling stations — May 2026. Page 63

List of Abbreviations

A664: Absorbance measured at 664 nm.

A750: Absorbance measured at 750 nm (turbidity correction).

AFNOR : Association Française de Normalisation.

AR : Relative Abundance.

D: Simpson Dominance Index.

DIN: Dissolved Inorganic Nitrogen.

DSP : Diarrhetic Shellfish Poisoning.

ENSSMAL : École Nationale Supérieure des Sciences de la Mer et de l'Aménagement du Littoral.

FR: Relative Frequency.

GF/C: Glass Fibre filter grade C (Whatman, 1.2 µm porosity).

GF/F: Glass Fibre filter grade F (Whatman, 0.7 µm porosity).

H': Shannon-Weaver Diversity Index.

HAB: Harmful Algal Bloom.

J': Pielou's Evenness Index.

N: Cell concentration (cells per litre).

NF EN 872: French/European standard for TSS gravimetric analysis.

NH_4^+: Ammonium.

NO_2^-: Nitrite.

NO_3^-: Nitrate.

PFE : Projet de Fin d'Études.

PO_4^{3-} : Orthophosphate.

PSP: Paralytic Shellfish Poisoning.

S: Species Richness.

SARL : Société à Responsabilité Limitée.

SiO_4^{4-} : Silicate.

ST01: Sampling Station 01 (cage centre).

ST02: Sampling Station 02 (north, 50 m from cages).

ST03: Sampling Station 03 (east, 50 m from cages).

ST04: Sampling Station 04 (west, 50 m from cages).

ST05: Sampling Station 05 (control, 100 m from cages).

TSS: Total Suspended Solids.

µg/L: Micrograms per litre.

µmol/L: Micromoles per litre.

INTRODUCTION

In recent years, marine aquaculture in Algeria has experienced significant expansion, becoming a key pillar of the national strategy to strengthen food security (Taguemount et al., 2023). This growth has been accompanied by a marked increase in intensive fish farming systems, particularly floating cage installations along the coast (MPRH, 2008; Taguemount et al., 2023). However, the proliferation of these structures in sensitive coastal areas such as Aïn Taya raises notable environmental concerns. Floating cages act as anthropogenic point sources of nutrient enrichment, releasing uneaten feed and metabolic waste directly into the water column, which can induce localized eutrophication and alter the surrounding pelagic ecosystem (Messaoudene et Loubar, 2009; Beveridge, 2004). Similar impacts have been documented at other Mediterranean cage-farming sites, where sea-cage aquaculture was shown to significantly affect phytoplankton community structure and water quality in adjacent waters (Ben Souissi et al., 2017; Challouf et al., 2017). Given these risks, establishing a regular monitoring program is essential to evaluate the environmental impact of aquaculture activities on the marine environment in a rigorous and reproducible way (FAO, 2006).

Coastal marine ecosystems are inherently dynamic, and their ecological equilibrium is highly sensitive to fluctuations in nutrient input (Boudouresque, 2004). Within this context, phytoplankton communities play a fundamental role, forming the base of the marine food web as primary producers (Boudouresque, 2004). Phytoplankton biomass, commonly estimated through chlorophyll-a concentration, is a robust and widely accepted bio-indicator for assessing the trophic status and overall ecological health of aquatic environments, particularly in the vicinity of aquaculture zones (Messaoudene et Loubar, 2009; Vollenweider et al., 1998). This approach has been applied successfully in other Mediterranean and Algerian coastal contexts: Challouf et al. (2017) used chlorophyll-a and phytoplankton parameters to characterize nutrient enrichment near cage farms in Monastir Bay, Tunisia, while Ben Souissi et al. (2017) documented shifts in phytoplankton community composition near a sea-cage farm in the south-western Mediterranean. In the Algerian context specifically, several studies have examined phytoplankton dynamics along the coast, including work on the Bou-Ismaïl Bay aquaculture zone (Messaoudene et Loubar, 2009; Tlidjane, 2013), the Cap Caxine area (Illoul, 1987), and broader surveys of Algerian coastal phytoplankton diversity (Nefraoui et Tabi, 2015; Djerioui, 2015). More recently, Boufeniza (2021) modeled phytoplankton dynamics along the Algiers coast using satellite imagery and water color analysis, offering a complementary large-scale perspective to the localized field-based approach adopted here. These studies collectively support the use of phytoplankton as a sensitive early-warning indicator of aquaculture-derived eutrophication, though findings vary depending on hydrodynamic conditions, farming intensity, and site-specific

characteristics underscoring the need for site-specific monitoring rather than generalized assumptions.

Despite this growing body of literature, site-specific data on the Aïn Taya aquaculture zone remain limited since the foundational work conducted in the neighboring Bou-Ismaïl Bay by Messaoudene et Loubar (2009), leaving open questions about how phytoplankton dynamics at Aïn Taya have evolved as cage farming activity has intensified. Addressing this gap is essential both for local environmental management and for contributing comparative data to the broader Mediterranean literature on aquaculture impacts (Ben Souissi et al., 2017; Challouf et al., 2017).

The primary objective of this study is therefore to assess the environmental sustainability of the aquaculture site at Aïn Taya by characterizing the spatial distribution of phytoplankton biomass in its surrounding waters. More specifically, this study aims to quantify chlorophyll-a concentrations across a gradient of distances from the floating cages, and determine whether a significant nutrient-enrichment gradient exists between stations located near the cages and reference stations further away, following the trophic classification approach proposed by Vollenweider et al. (1998). To achieve this, five sampling stations were selected along a distance gradient from the cage structures, allowing spatial comparison of phytoplankton biomass. Water samples were collected in situ using Niskin bottles, and chlorophyll-a concentrations were subsequently quantified in the laboratory using standard spectrophotometric methods (Jeffrey et Humphrey, 1975; Messaoudene et Loubar, 2009).

This thesis is organized into three main chapters. The first chapter reviews the existing literature on the interactions between aquaculture activities and phytoplankton ecology. The second chapter details the materials and methods used during the field campaigns and laboratory analyses. The third chapter presents and discusses the empirical results, benchmarking our findings against published Algerian and Mediterranean reference studies, including Messaoudene et Loubar (2009), Boufeniza (2021), Challouf et al. (2017), and Belkacemi et Meddahi (2021).

CHAPTER I. GENERAL BACKGROUND

I.1. Coastal Ecosystems and Aquaculture

The Algerian coastline stretches along the Mediterranean Sea for approximately 2148 km (APS, 2023) and is characterized by a narrow continental shelf and a relatively high level of biological diversity. Mediterranean coastal ecosystems are known to be fragile environments, highly sensitive to human pressures, particularly in semi-enclosed coastal areas (Boudouresque, 2004).

In recent years, marine aquaculture has been developed in Algeria as a national response to the progressive decline of wild fish stocks and to support food security objectives (MPRH, 2008; Taguemount et al., 2023). Floating cage systems, such as those installed at Ain Taya along the Algerian coast, represent the most common production model adopted in Algerian marine aquaculture.

However, these installations are not without environmental consequences. Fish farming activities continuously release organic matter into the surrounding water column, mainly through uneaten feed and fish excretion. These inputs tend to modify the local sediment composition and increase nutrient concentrations near the farm (Messaoudene F. et Loubar S., 2009). In coastal zones with limited water circulation, such as Ain Taya, these effects can be considerably amplified, making regular environmental monitoring a necessity rather than an option (Boudouresque, 2004; Nefraoui H. et Tabi N.E.Y., 2015).

I.2. Water Quality and Nutrient Dynamics

Sustainable aquaculture relies inherently on the capacity of the aquatic environment to assimilate and process the organic load generated by farming operations. Water quality is determined by a complex interplay of physical, chemical, and biological parameters, including temperature, salinity, dissolved oxygen, pH, and nutrient concentrations. Among these, nitrogen (N) and phosphorus (P) represent the most critical factors in fish farming, serving as the primary drivers of biological shifts in the surrounding ecosystem (Nefraoui H. et Tabi N.E.Y., 2015).

In aquaculture, the accumulation of these nutrients, particularly in zones with poor water mixing, can lead to eutrophication. This process involves an excess of organic matter that stimulates uncontrolled algal blooms, followed by oxygen depletion as the biomass decomposes (Boudouresque, 2004). In cage farming systems, the accumulation of nitrogenous waste compounds, particularly ammonium, depends on the balance between biological production and the assimilative capacity of the receiving water body (Beveridge, 2004).

These chemical shifts are not confined to the water column; they trigger an almost immediate biological response. As nitrogen and phosphorus concentrations rise in the vicinity of the cages, phytoplankton rapidly uptakes this nutrient surplus, leading to accelerated growth. This direct

coupling between nutrient input and phytoplankton dynamics forms the core mechanism that this study aims to investigate at the Ain Taya site (Boudouresque, 2004; Nefraoui, 2015).

Figure I.1. Simplified flowchart showing how nutrient inputs from aquaculture can stimulate phytoplankton growth, leading to environmental outcomes like oxygen changes and algal blooms (author's schematic, based on Boudouresque, 2004; Nefraoui et Tabi, 2015).

I.3. Phytoplankton Dynamics

Phytoplankton consists of microscopic photosynthetic organisms that form the base of the marine food web. Due to their rapid turnover rates and direct physiological dependence on dissolved nutrients and light, these communities respond swiftly to fluctuations in water quality (Boudouresque, 2004). Consequently, monitoring phytoplankton dynamics in the vicinity of fish farms provides a sensitive, early-warning indicator of the aquaculture footprint (Boudouresque, 2004). Such shifts in community structure (discussed further in section I.3.2) provide an early signal of changing environmental conditions near aquaculture installations.

I.3.1. Chlorophyll-a as a Proxy for Biomass

Chlorophyll-a is the primary photosynthetic pigment present in all phytoplankton cells, and its concentration in water is widely used as a reliable proxy for estimating total algal biomass. Standard determination involves filtering a known volume of water through glass fiber filters, extracting the pigment in acetone, and measuring the absorbance spectrophotometrically. The resulting values provide a rapid and standardized estimate of algal abundance within a given water mass (Jeffrey et Humphrey, 1975).

Chlorophyll-a concentrations naturally fluctuate with oceanographic conditions. In the Algerian Basin, strong seasonal and spatial variations have been documented, with biomass peaks generally associated with nutrient-rich upwelling events or freshwater discharges (Boufeniza, 2021; Messaoudene F. et Loubar S., 2009). In the vicinity of aquaculture installations, a localized increase in chlorophyll-a near the cages is often interpreted as a direct response to nutrient enrichment from feed waste and fish excretion. When sustained over time, these elevated chlorophyll-a levels can signal the onset of eutrophication, as the decomposition of excess algal biomass consumes dissolved oxygen and threatens the balance of the local ecosystem (Messaoudene F. et Loubar S., 2009).

For a more precise assessment of phytoplankton productivity, chlorophyll-a measurements can be converted into carbon biomass estimates, providing a more robust representation of actual biological production and enabling more rigorous comparisons between sampling stations and periods(Messaoudene F. et Loubar S., 2009).

I.3.2. Taxonomic Diversity and Trophic Status

Assessing phytoplankton biomass alone is insufficient to fully characterize the trophic state of a coastal ecosystem. Species composition and community structure offer complementary insights that are often more sensitive to environmental fluctuations than total cell abundance (Nefraoui H. et Tabi N.E.Y., 2015; Magurran, 2004).

In Mediterranean coastal waters, a healthy and undisturbed system is typically characterized by a diverse phytoplankton community in which diatoms (Bacillariophyceae) dominate, particularly during spring and autumn. Their proliferation is favored by the cool, nutrient-rich, and well-mixed conditions characteristic of these seasons. Conversely, when water stratification intensifies and nutrient inputs remain elevated, dinoflagellates (Dinophyceae) tend to increase in abundance relative to diatoms. This functional shift is widely considered an indicator of environmental enrichment or anthropogenic stress (Illoul, 1987; Boufeniza, 2021). Research in Algerian coastal waters has documented marked dinoflagellate dominance during stratification periods, a condition that significantly heightens the risk of harmful algal blooms (Illoul, 1987; Boufeniza, 2021).

Along the Algerian coast, potentially harmful algal species (HABs), including *Alexandrium* spp. and *Dinophysis* spp., have been recurrently recorded (Djerioui, 2015). These organisms are of direct concern for aquaculture operations, as certain species produce potent phycotoxins that accumulate in filter-feeding bivalves, such as mussels and clams, posing severe risks to both the farmed stock and human consumers (Smayda, 1997; Djerioui, 2015) .

To quantify the structural equilibrium of the phytoplankton community, ecological diversity indices are routinely applied. The Shannon-Weaver index (H') measures overall diversity by integrating species richness and the evenness of individual distribution. Pielou's evenness index (J') evaluates how uniformly individuals are distributed among the identified species; a low J' value indicates that one or a few species dominate the assemblage, a pattern frequently associated with organic pollution or nutrient enrichment. Additionally, the Simpson index (D), or its complement (1-D), provides a robust measure of dominance within the community (Nefraoui

H. et Tabi N.E.Y., 2015; Magurran, 2004).The key ecological and physiological differences between these two dominant phytoplankton groups are summarized in Table I.1.

Table I.1. Comparative characteristics of diatoms and dinoflagellates in coastal Mediterranean waters (author's schematic, based on Illoul, 1987).

Trait or Ecological Role	Diatoms(Bacillariophyceae)	Dinoflagellates(Dinophyceae)
Cell structure	Silica shell (frustule).	Cellulose plates or no rigid shell.
Mobility	Non-motile (carried by currents).	Motile (Flagella).
Preferred environment	Cool, nutrients-rich, mixed waters.	Warm, stratified, calm waters.
Bloom period	Spring and autumn.	Summer or during enrichment periods.
Ecological role	Base of the food web.	Some species produce toxins.
Response to nutrients	Rapid growth when nutrients increase.	Can persist when nutrients stay high.

When chlorophyll-a concentrations are integrated with species composition and ecological diversity indices, a comprehensive assessment of the trophic state becomes achievable. For instance, elevated chlorophyll-a values, when coupled with diatom dominance and low evenness (J'), collectively provide a robust signal of localized nutrient enrichment in the vicinity of aquaculture operations (Nefraoui H. et Tabi N.E.Y., 2015; Challouf et al., 2017).

CHAPTER II. MATERIALS AND METHODS

This chapter describes the methods used to assess the environmental impact of the aquaculture site at Ain Taya. The study is structured around three primary stages: the characterization of the study site, the implementation of a field sampling strategy spanning two seasonal campaigns, and the application of standardized laboratory analysis protocols. This approach aligns with the technical recommendations of Messaoudene F. et Loubar S., 2009 for aquaculture environmental monitoring and Nefraoui H. et Tabi N.E.Y., 2015 for phytoplankton diversity assessment.

II.1. Study Area

Ain Taya was selected for this study due to its direct relevance to the development of marine aquaculture in Algeria and the presence of an active floating cage installation. The Algerian coastline, stretching approximately 2148 km along the Mediterranean Sea (APS, 2023), constitutes an ecologically fragile zone where coastal anthropogenic activities exert continuous pressure on marine biodiversity (Boudouresque, 2004). Situated east of the Bay of Algiers, Ain Taya provides a representative framework for investigating the localized environmental impacts of cage farming within a semi-open coastal ecosystem.

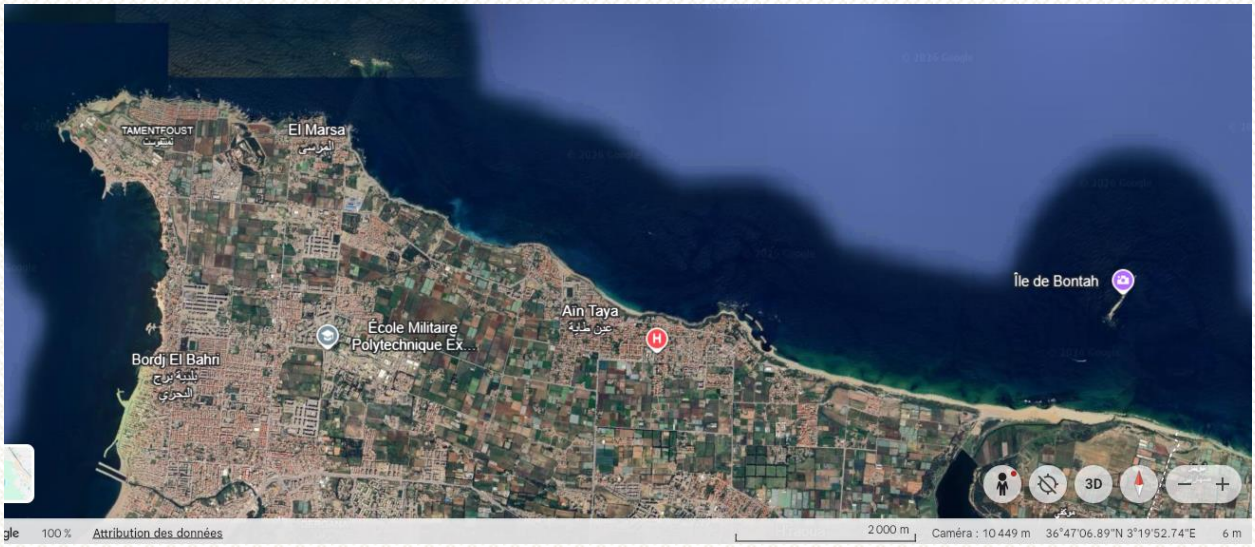


Figure II.1. Satellite image showing the location of the commune of Ain Taya .

II.1.1. Geographical and Topographic Context

The study area is located at Sercouf Beach (locally designated as Ain Chorb), within the municipality of Ain Taya, approximately 25 km northeast of Algiers. This site hosts the floating-cage concession of Aquasparidae, a marine finfish aquaculture enterprise farming gilthead seabream (Sparus aurata) and European seabass (Dicentrarchus labrax) at Ain Taya.

From a geomorphological and topographical perspective, the coastal zone features two distinct marine terraces. The upper terrace, situated at elevations between 30 and 43 m above sea level, demonstrates long-term Quaternary tectonic uplift, whereas the lower terrace slopes down toward the modern shoreline. Geographically, this coastal stretch forms part of the western margin of the Bay of Zemmouri. The central coordinates of the experimental site are positioned at approximately 36°47'50" N and 3°18'54" E.

Figure II.2. Satellite image showing the location of the farm and the livestock area .

II.1.2. Bathymetry and Substrate

The seafloor morphology at Ain Taya aligns with the general features of the central Algerian margin, characterized by a relatively narrow continental shelf (Boudouresque, 2004). Within the sampling stations, the bathymetry 5m . This specific depth range directly governs the hydrodynamic dispersion and settling dynamics of particulate organic waste released from the aquaculture cages before its accumulation on the seabed (Messaoudene F. et Loubar S., 2009).

Two distinct benthic substrate zones characterize the study area. A nearshore rocky strip extends from the coastline to approximately 500 m offshore. Beyond this boundary, the seabed undergoes a sedimentological transition toward coarse sand. The aquaculture infrastructures, encompassing both longlines and floating cages, are securely anchored within this sandy-bottom zone (Messaoudene F. et Loubar S., 2009).

II.2. Sampling Stations

Five sampling stations were established to capture the spatial gradient of the farm's potential environmental influence. The design allows direct comparison between the area under the cages and the surrounding reference environment (Messaoudene F. et Loubar S., 2009).

- ST 01 (farm centre): positioned at the heart of the cage system, at 30 m depth.
- ST 02 (North): located 50 metres north of the cages, at 5 m depth.
- ST 03 (East): located 50 metres east of the cages, at 5 m depth.
- ST 04 (West): located 50 metres west of the cages, at 5 m depth.
- ST 05 (control): located 100 metres from the cages, at 5 m depth, used as a reference point with no direct cage influence.

Table II.1. Characteristics and GPS coordinates of the five sampling stations at Ain Taya.

Station	Location	Distance from cages(m)	Coordinates(N)	Coordinates(E)	Depth (m)
ST 01	Center of cages	0	36°48’31”	3°19’48.57”	5m
ST 02	North	50	36°48’06.57”	3°19’43.73”	5m
ST 03	East	50	36°48’03.50”	3°19’42.74”	5m
ST 04	West	50	36°48’02.50”	3°19’35.57”	5m
ST 05	Control	100	36°48’04.04”	3°19’33.44”	5m

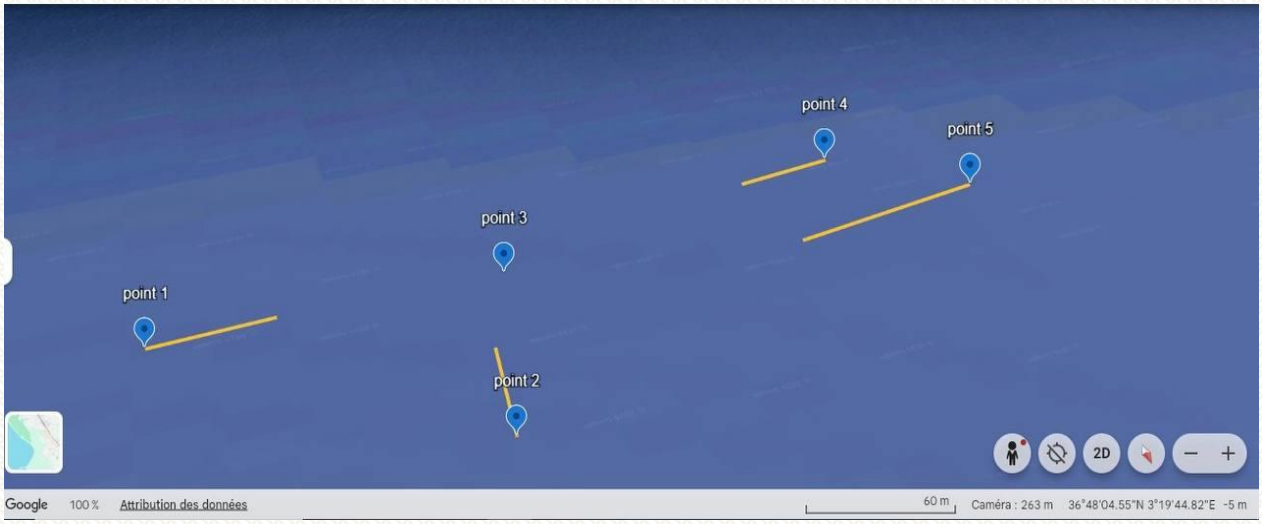


Figure II.3. Spatial distribution of the five sampling stations at the Ain Taya aquaculture site.

II.3. Sampling Strategy and Field Campaigns

To capture the seasonal variability of phytoplankton dynamics and physicochemical water quality indicators, two field campaigns were conducted across the 2025–2026 annual cycle at the Ain Taya site:

- Winter Campaign (February 18, 2026): Characterized by minimum annual water temperatures, intense vertical mixing of the water column, and reduced baseline biological activity.
- Spring Campaign (May 5, 2026): Characterized by progressive thermal warming, initiation of water column stratification, and heightened phytoplankton productivity.

This dual-season experimental design allows comparison of contrasting hydrological conditions to better understand how seasonal changes affect the farm's environmental impact. Field operations were carried out aboard a motorized vessel equipped with a Hanna GPS receiver to ensure precise positioning of the sampling stations during both campaigns. In addition to the parameters listed above, it was not possible to measure physical and chemical water-column parameters (temperature, salinity, pH, etc.) during these two campaigns, due to the unavailability of a multi-parameter probe.

II.3.1. Water Sampling and In-Situ Measurements

Water samples were collected at 5 m depth using a 5 L Niskin bottle. The triggering mechanism involves a weighted messenger dropped along the hydrographic cable, which hermetically seals the bottle at the target depth, ensuring an undisturbed sample. The 5 m depth stratum was selected to target the upper mixed layer within the euphotic zone, where optimal irradiance

drives primary productivity and where nutrient inputs from the fish cages are expected to be most concentrated before dispersing through the water column.

Figure II.4. the Niskin bottle water sampler illustrating the messenger trigger mechanism and the closed sampling chamber used for subsurface water collection at 5 m depth.

To complement the discrete water collection, qualitative phytoplankton samples were gathered using a standard plankton net with a 20 µm mesh size. The net was towed horizontally within the subsurface layer at a constant low speed for approximately 5 min at each sampling station. This operational design specifically aims to concentrate larger microphytoplankton cells and colonial morphotypes that are typically underrepresented or excluded within small-volume Niskin bottle aliquots.

Upon retrieval, the concentrated plankton slurry was recovered from the cod-end collector, transferred into pre-labelled amber glass bottles, and immediately fixed with Lugol's iodine solution at a final concentration of 1 mL per 100 mL of sample. These net-haul samples were dedicated to taxonomic identification and checking species diversity (floristic analysis). Conversely, the quantitative assessment of cell abundance and population density was performed exclusively on the Niskin bottle samples following the standardized Utermöhl sedimentation method (Messaoudene F. et Loubar S., 2009).

Figure II.5. A plankton net size of 20 µm.

II.3.2. Sample Collection and Preservation

At each of the five stations, four types of samples were collected per campaign:

- Chlorophyll-a Aliquots**:** water collected in opaque polyethylene bottles to prevent photo-degradation of pigments. Kept in darkness throughout transport.
- Phytoplankton identification samples: 500 mL volumes immediately fixed with Lugol's iodine solution at a concentration of approximately 1 mL per 100 mL of sample. Lugol's solution preserves cell morphology and causes flagella to contract, which facilitates sedimentation during counting (Messaoudene F. et Loubar S., 2009).
- TSS samples: collected in clean plastic bottles for gravimetric analysis.
- Nutrient samples (dissolved inorganic nutrients): collected in one clean plastic bottle per station without prior filtration and immediately frozen at −20°C for preservation. Analysis of nitrates (NO_3^-), nitrites (NO_2^-), ammonium (NH_4^+), phosphates (PO_4^{3-}), and silicates (SiO_4^{4-}) was carried out at the ENSSMAL chemistry laboratory, using standard colorimetric methods (Aminot et Chaussepied, 1983).

Figure II.6. Laboratory preparation of sample bottles and filtration funnels.

II.3.3. Transport Conditions

Throughout transit to the ENSSMAL laboratory, all sample containers were secured within an isothermal container maintained at approximately 4°C using pre-chilled ice packs. Careful precautions were taken to protect the chlorophyll-a bottles from any light exposure, the Lugol-fixed phytoplankton aliquots were preserved under continuous cold and dark conditions; this specialized transport protocol was sufficient to maintain complete cellular integrity over the short transit window, which ranged between 1 and 2 hours (Messaoudene F. et Loubar S., 2009; Rodier et al., 2005). Upon arrival at the laboratory facilities, the non-filtered nutrient aliquots were immediately transferred to a deep-freezer unit (-20 °C) to arrest any ongoing biological uptake or nutrient transformation.

Figure II.7. Insulated iceboxes used for sample preservation and transport

II.4. Laboratory Procedures

II.4.1. Total Suspended Solids (TSS)

Total Suspended Solids represent the total particulate matter retained on a filter after passing a known volume of water through it. This parameter reflects the organic and inorganic load in the water column, which is particularly relevant near fish cages where uneaten feed and faecal matter continuously enrich the surrounding environment.

The analysis followed the gravimetric protocol standardised under NF EN 872 (AFNOR, 2005). Whatman GF/C glass fibre filters were rinsed with distilled water, dried in an oven at 105°C for two hours, and weighed to the nearest 0.0001 g to obtain the initial mass (m_i). 250mL of

seawater, pre-screened through a 5 mm sieve to remove coarse particles, was then filtered under vacuum through each prepared filter.

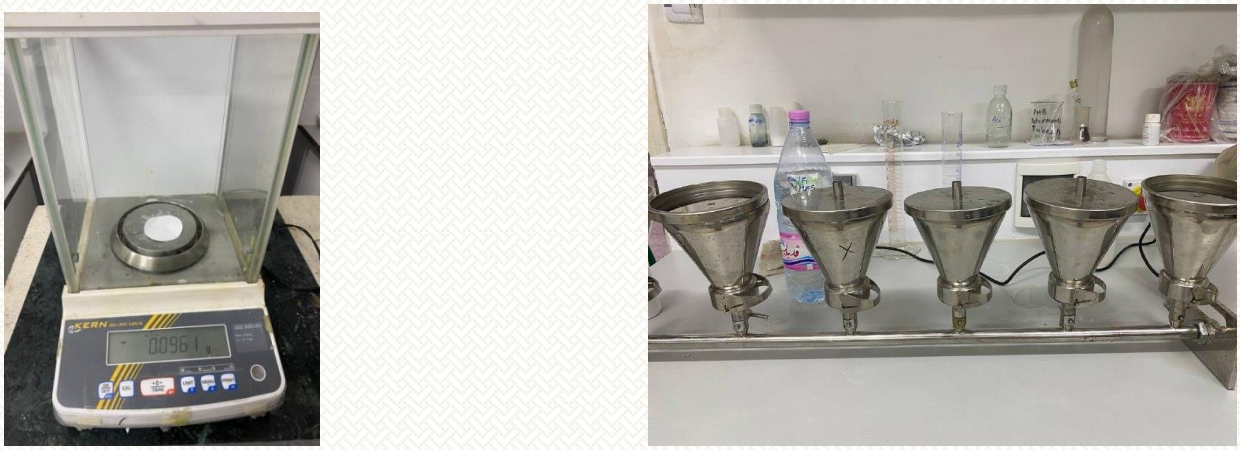


Figure II.8. Gravimetric filtration apparatus and analytical balance for TSS pre-weighing

After filtration, the filters were returned to the oven at 105°C until constant mass was reached, generally after 12 hours, then weighed again to obtain the final mass (mf). The TSS concentration was calculated using the following formula:

$$\mathbf{TSS\ (mg/L) = (mf - m_i) \times 1000 / V}$$

For samples with a high particulate load, such as those collected at ST01 and ST04, which were the stations closest to the cage structures and most exposed to suspended organic matter, centrifugation at 4000–5000 rpm for 10 minutes was applied as an alternative, with the recovered pellet dried and weighed under the same conditions (AFNOR, 2005).

Figure II.9. Filter drying in the oven at 105°C and final gravimetric mass determination

II.4.2. Chlorophyll-a Extraction

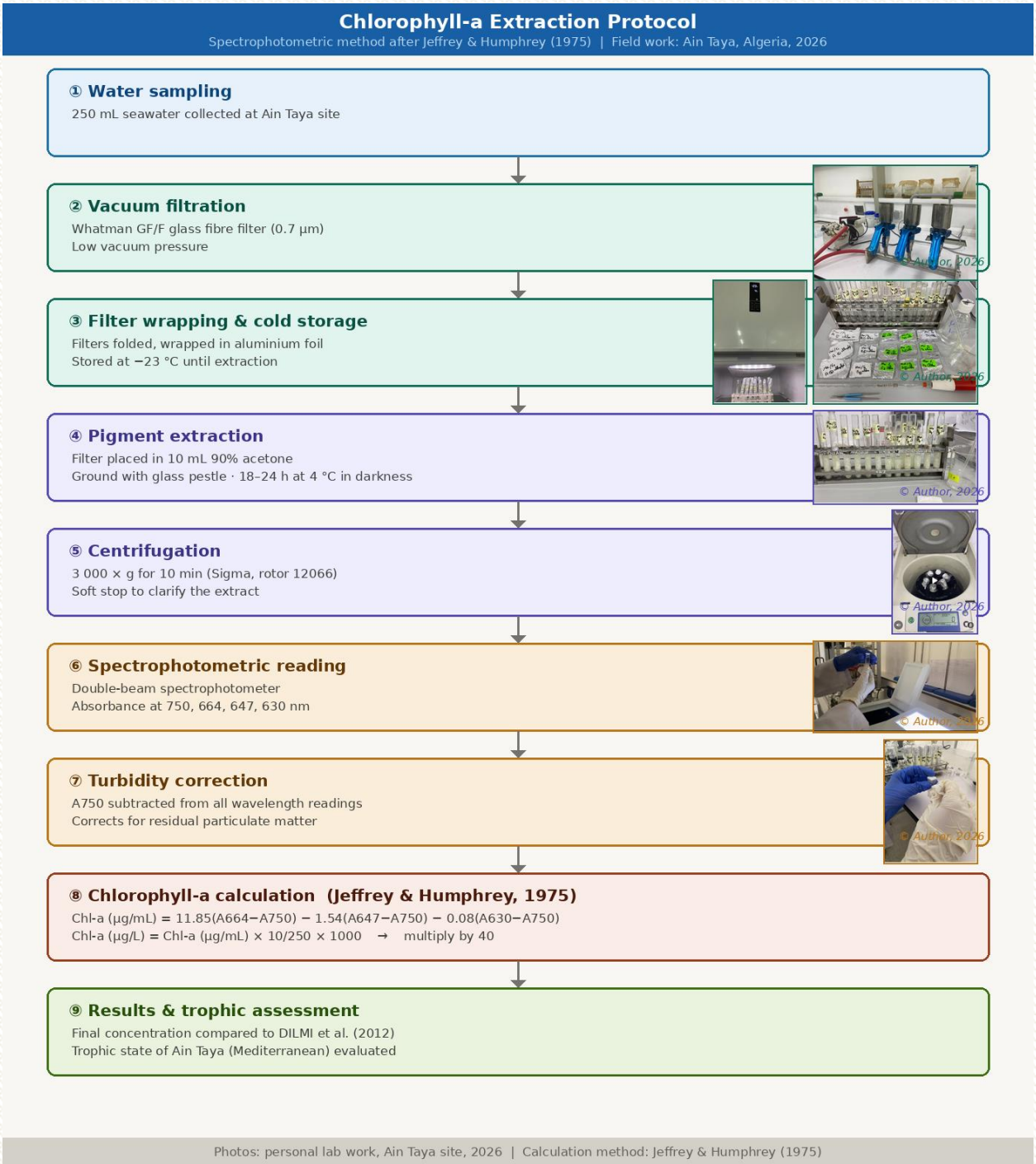
The extraction and quantification of chlorophyll-a (Chl-a) followed the spectrophotometric method of Jeffrey and Humphrey (1975), a standard reference protocol widely utilized in Mediterranean oceanographic studies. For each sample, a 250mL aliquot of seawater was filtered under low vacuum pressure, through Whatman GF/F glass fiber filters (0.7 µm porosity). Upon filtration, the filters were carefully folded, wrapped in aluminum foil to prevent photo-oxidation, and stored at (- 4°C) until processing. Each filter was subsequently transferred into a glass centrifuge tube containing 10 mL of 90% aqueous acetone. Mechanical homogenization was performed using a glass pestle to disrupt the cell walls and optimize pigment extraction efficiency. The resulting macerate was incubated for 12 to 24 hours at (- 4°C) in complete darkness to ensure complete pigment leaching. Following incubation, the extract was centrifuged at 3,000 × (Relative Centrifugal Force) for 10 min to clear residual turbidity. Absorbance values were recorded using a double-beam spectrophotometer at optical wavelengths of 750, 664, 647, and 630 nm. The absorbance at 750 nm was systematically subtracted from the readings at 664, 647, and 630 nm to correct for non-specific background turbidity. The concentration of Chl-a within the acetone extract was determined using the Jeffrey et Humphrey (1975) trichromatic equation:

$$\textbf{Chl-a (µg/mL)} = 11.85\,(A664 - A750) - 1.54\,(A647 - A750) - 0.08\,(A630 - A750)$$

The final concentration in the water sample (µg/L) was obtained by applying the volume correction factor:

$$\textbf{Chl-a (µg/L)} = \textbf{Chl-a (µg/mL)} \times \textbf{V acetone (mL)} / \textbf{V filtered (mL)}$$

where **V** acetone = 10 mL and **V** filtered = 250 mL, giving a conversion factor of 10/250 = 0.04 $\mathbf{L^{-1}}$ equivalent (i.e., multiply µg/mL by 40 to obtain µg/L). The absorbance at 750 nm was subtracted from all readings prior to calculation to correct for residual turbidity in the extract.



II.4.3. Dissolved Inorganic Nutrient Analysis

Dissolved inorganic nutrients were measured at the ENSSMAL chemistry laboratory using a SKALAR San++ continuous flow analyzer (Skalar Analytical, Breda, Netherlands), according to the automated colorimetric protocols described by Aminot et Chaussepied (1983). This continuous flow system enables the simultaneous spectrophotometric determination of multiple micro-nutrient fractions with high analytical reproducibility and low detection limits. Prior to analysis, the cryopreserved seawater samples were thawed at room temperature (20-22°C). To isolate the strictly dissolved phase and eliminate any residual micro-particulate matter that might

scatter light or interfere with the colorimetric pathways, each thawed aliquot was filtered through a 0.45 µm cellulose acetate membrane filter immediately before system injection. Five primary inorganic nutrient fractions were systematically monitored, with all final concentrations expressed in micromoles per liter (µmol/L):

- Nitrates (NO_3^-): Determined via automated cadmium reduction to nitrites (NO_2^-), followed by azo dye diazotization and spectrophotometric detection at 540nm.
- Nitrites (NO_2^-): Determined directly through sequential reaction with sulfanilamide and N-(1-naphthyl)ethylenediamine dihydrochloride under acidic conditions, yielding a pink azo dye measured at 540 nm.
- Ammonium (NH_4^+): Quantified using the Berthelot-indophenol blue reaction pathway, wherein ammonium reacts with phenol and hypochlorite in an alkaline medium to generate an indophenol blue complex recorded at 630 nm.
- Orthophosphates (PO_4^{3-}): Determined via the phosphomolybdenum blue method, involving the reaction of orthophosphate ions with ammonium molybdate and antimony potassium tartrate under acidic conditions, with the resulting complex read at 880 nm.
- Dissolved Silicates (SiO_4^{4-}): Measured through the formation of a silicomolybdate complex via reaction with ammonium molybdate in an acidic medium, subsequently reduced to molybdenum blue and quantified at 810 nm. To ensure rigorous quality control (QC), all sample extractions were processed in technical duplicates. Multipoint linear calibration curves were dynamically established at the beginning of each analytical run using certified multi-element standard solutions. High-purity deionized water reagent blanks were systematically interspersed within each carousel sequence to correct for baseline drift and background reagent absorbance.

II.5. Phytoplankton Identification and Statistical Analysis

The identification and counting of phytoplankton are essential for understanding the structure of the community. A high biomass might hide a very low diversity, which is often a sign of a disturbed environment.

II.5.1. Taxonomic Identification the Utermöhl Method

Quantitative assessment of phytoplankton cell abundance and population density was performed using the standardized Utermöhl sedimentation method (Utermöhl, 1958), implemented in accordance with European quality guidelines (NF EN 15204). Prior to chamber filling, the 500 mL Lugol-fixed sample was gently homogenized by repeated inversion. A 50 mL aliquot was subsequently dispensed into a composite cylindrical settling chamber (comprising a sedimentation tube and a thin-bottom plate holder). The sample was left undisturbed for 24 hours on a vibration-free surface to allow complete gravitational settling of all micro-algal cells, satisfying the standard requirement of at least 3 to 4 hours of settling time per 10 mm of fluid column height. Following complete sedimentation, the taxonomic enumeration and quantitative

counting were carried out using an Leica inverted microscope, calibrated for Utermöhl counts equipped with phase-contrast optics and brightfield illumination. Cells were counted across random fields of view or fixed transects at 400 magnifications, depending on cell size and background density, to achieve a representative evaluation of the micro-algal community structure near the aquaculture cages.

Figure II.10. Inverted microscope workspace and Utermöhl sedimentation chamber setup

For the identification of diatoms and dinoflagellates, the taxonomic guide of Illoul (1987) was used as primary references. Identification relied on morphological features including the shape of the theca, the structure of the frustule, the presence and arrangement of flagella, and the overall cell geometry.

Counting strategies were adapted based on cell density to keep the error below 20%:

Observed density	Strategy	Justification
Very low	Full chamber	Avoids underestimation of rare species
Moderate (>100 ind.)	Half chamber	Statistically reliable extrapolation
High	Transects	Good spatial representation
Bloom (>100 ind./field)	10-12 Random fields	Standard quantitative approach

The concentration was calculated using the formula:

$$\mathbf{N = n\ (S/s*V)}$$

Where **N** = cells/L, **n** = cells counted, **S** = chamber area, **s** = observed area, **V** = volume (L)

II.5.2. Ecological Diversity Indices

To characterize the phytoplankton community structure across the five sampling stations, several mathematical descriptors were computed. These indices convert abundance data into ecological values that are easy to interpret, following specialized frameworks for Algerian coastal and aquaculture ecosystems (Nefraoui H. et Tabi N.E.Y., 2015; Magurran, 2004).

- Species Richness (S): Defined as the total number of distinct taxonomic units identified within a single sample. While elevated richness traditionally denotes highly stable environments, variations in S near aquaculture concessions can highlight transitional ecological states or structural shifts induced by localized nutrient inputs.

- Shannon-Weaver Diversity Index (H'): Measures the structural complexity and entropy of the community based on the relative abundance of each taxon. It was calculated as follows:

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

  Where :

  p_i : represents the proportion of individuals belonging to the i^{th} species ($p_i = n_i / N$).

  High H' values reflect a well-balanced, mature ecosystem, whereas depressed values signal community stress or the ecological dominance of opportunistic taxa thriving under eutrophic conditions.

- Pielou's Evenness Index (J'): Quantifies the equitability of individual distribution among the co-occurring species, calculated as:

$$J' = \frac{H'}{H'_{max}} = \frac{H'}{ln_s}$$

- Simpson's Dominance Index (D) and Gini-Simpson Index (1-D): Measures the probability that two randomly selected individuals from a sample belong to the exact same taxon:

$$D = \sum_{i=1}^{S} p_i^2$$

The complementary Gini-Simpson index (1-D) was utilized to evaluate community evenness. This metric is highly sensitive to dominant species shifts, making it an excellent diagnostic tool for detecting early-stage micro-algal bloom conditions (Magurran, 2004).

- Occurrence and Relative Abundance Dynamics

To assess the spatial distribution and ubiquity of specific taxa, two semi-quantitative parameters were established:

1. Frequency of Occurrence (F_o, %): Also referred to as Relative Frequency *(FR)* in traditional ecological frameworks, this metric determines the spatial ubiquity or recurrence of a specific taxon across the study area. It was calculated as the percentage of total analyzed samples in which the species was detected:

$$F_o = \left(\frac{N_{presence}}{N_{total}}\right) \times 100$$

Where $N_{presence}$ is the number of samples where the species was recorded, and N is the total number of samples collected during the campaign (N = 5 stations × 1 depth = 5 samples per campaign).

2. Relative Abundance (A_r, %): Alternatively designated as *AR* or *relative proportion*, this index expresses the numerical weight and structural dominance of each species within the total community. It was calculated as follows:

$$A_r = \left(\frac{n_i}{N}\right) \times 100$$

Where :

$\mathbf{n_i}$ represents the cell density (cells/L) of the $\mathbf{i^{th}}$ species at a given station, and **N** represents the cumulative cell density of all identified phytoplankton species at that same station.

Together, these ecological indicators provide a robust baseline for evaluating the "biological footprint" of the floating cage installation and assessing whether the Aïn Taya site is approaching its ecological carrying capacity (Nefraoui H. et Tabi N.E.Y., 2015).

CHAPTER III. RESULTS AND DISCUSSION

III.1. Total Suspended Solids (TSS)

Total suspended solid concentrations were determined at the five sampling stations during both campaigns following the gravimetric protocol NF EN 872 (AFNOR, 2005). For each station, three replicates were analysed and the mean value was retained. Results are expressed in mg/L and presented in Tables III.1 and III.2.

III.1.1. February 2026, Winter Campaign

During the February campaign, TSS concentrations ranged from 28.0 mg/L at ST01 (cage centre) to 120.0 mg/L at ST03 (East). The lowest value was recorded directly under the farm structures, while the highest particulate load was found at the eastern station. This spatial pattern suggests that during winter, the dominant current direction at the site transports suspended particles eastward from the cage area rather than allowing them to accumulate beneath the farm itself. Under winter conditions, the absence of thermal stratification and the presence of stronger vertical mixing limit the settling of fine particles near the cage structures, allowing the particulate plume to be dispersed laterally by local currents (Messaoudene F. et Loubar S., 2009). ST04 (West) and ST05 (Control) both recorded an identical value of 80.0 mg/L, suggesting comparable hydrodynamic exposure on both the western and control sides of the site during winter, independent of direct cage proximity. ST02 (North) recorded 40.0 mg/L, the second lowest value of the campaign, indicating limited northward particle transport at this season. The relatively large range between stations in February from 28.0 to 120.0 mg/L reflects the spatially heterogeneous hydrodynamic conditions typical of Algerian coastal waters during winter, where current-driven transport can create localised zones of particle accumulation even within a small study area (Messaoudene F. et Loubar S., 2009).

Table III.1. TSS concentrations (mg/L) at the five sampling stations, February 2026 campaign (V filtered = 250 mL)

Station	PI (g)	PF (g)	MES (mg/L)
ST01 (Centre)	0,093	0,100	**28,0**
ST02 (North)	0,060	0,070	**40,0**
ST03 (East)	0,090	0,120	**120,0**
ST04 (West)	0,090	0,110	**80,0**
ST05 (Control)	0,090	0,110	**80,0**

III.1.2. May 2026, Spring Campaign

During the May campaign, TSS concentrations ranged from 68 mg/L at ST04 (West) to 104.0 mg/L at ST05 (Control). The spatial distribution was relatively homogeneous across the four farm-adjacent stations (ST01 to ST04), with values between 68 and 76.0 mg/L, while the control station recorded the highest concentration of the campaign. This unexpected result at ST05 may reflect the contribution of allochthonous inputs from the surrounding coastal zone during spring, including terrigenous runoff following seasonal rainfall events common along the Algerian coast during this period, which can significantly increase the particulate load beyond the direct influence zone of the farm (Boudouresque, 2004).

ST01 (cage centre) recorded 76.0 mg/L in May, which is notably higher than its February value of 28.0 mg/L. This increase of 48.0 mg/L between the two campaigns at the cage centre is consistent with intensified biological activity and particle production near the structures during the spring period, when elevated temperatures accelerate fish metabolism, feed consumption, and the microbial degradation of organic matter (Messaoudene F. et Loubar S., 2009). The similarity in TSS concentrations between ST02, ST03, and ST04 in May suggests that the particulate load was more uniformly distributed around the farm during spring, likely due to reduced current velocities under stratified conditions limiting long-range lateral transport.

Table III.2. TSS concentrations (mg/L) at the five sampling stations, May 2026 campaign (V filtered = 250 mL)

Station	PI(g)	PF(g)	MES (mg/L)
ST01 (Centre)	0,096	0,115	**76,0**
ST02 (North)	0,095	0,113	**72**
ST03 (East)	0,096	0,113	**68**
ST04 (West)	0,096	0,113	**68**
ST05 (Control)	0,130	0,156	**104,0**

III.1.3. Seasonal Comparison and Discussion

- The TSS values recorded at Ain Taya during both campaigns are broadly consistent with those reported at comparable Algerian coastal aquaculture sites, where particulate loads in the range of 20–100 mg/L have been documented around cage structures during productive seasons (Messaoudene F. et Loubar S., 2009; Tlidjane, 2013). In contrast, the Tunisian reference study of Challouf et al. (2017) recorded substantially lower suspended matter near cage structures in Monastir Bay, reaching only 28.6 mg/L in autumn and 6.5 mg/L in winter, well below the values observed at Ain Taya during both campaigns. This difference may reflect the distinct hydrodynamic conditions, stocking densities, and seasonal dynamics between the two sites, as TSS levels in cage aquaculture environments are known to vary considerably depending on local current patterns and farm management practices (Beveridge, 2004). At the international level, Beveridge (2004) notes that well-managed Mediterranean cage farms typically generate measurable TSS increases above background levels within a limited radius of the cages, a pattern that aligns with our data. No specific regulatory threshold for TSS has been established under current Algerian aquaculture legislation (MPRH, 2008); however, the FAO (2006) recommends maintaining TSS below 80 mg/L in the immediate vicinity of cage installations to avoid chronic gill irritation in farmed fish and to preserve the self-purification capacity of the receiving water body. Under this guideline, the values recorded at ST01 in May (76.0 mg/L) and at ST05 (104.0 mg/L) approach or exceed this threshold, warranting periodic monitoring of the particulate load at this site.

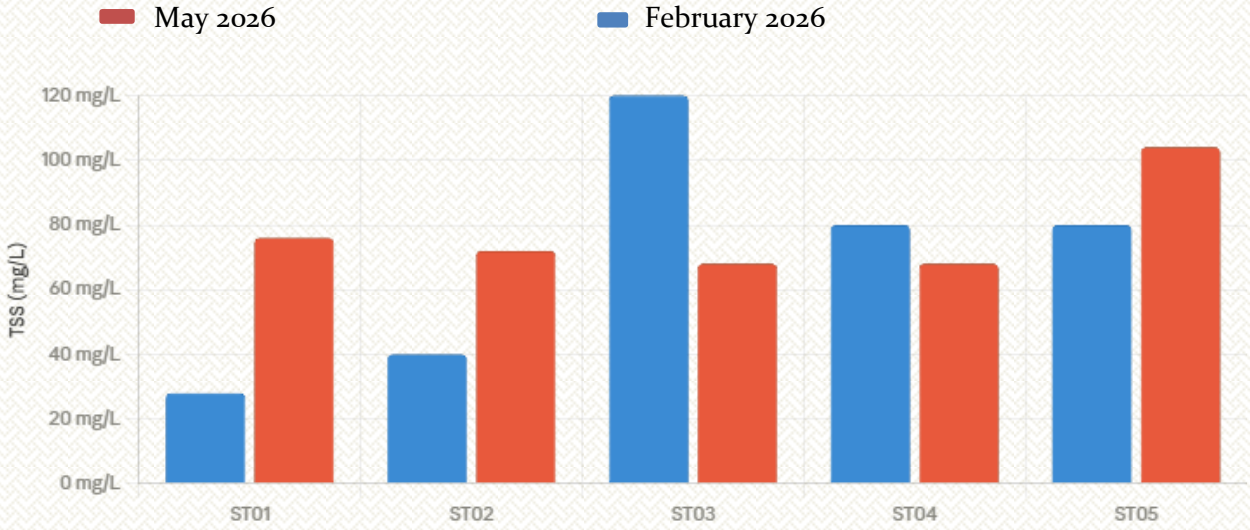


Figure III.1. Comparison of total suspended solid (TSS) concentrations (mg/L) at the five sampling stations during the February and May 2026 campaigns at the Ain Taya aquaculture site.

Taken together, the TSS results from both campaigns indicate a moderate but consistent particulate load throughout the study area, with site-wide mean values of 69.6 mg/L in February and 77.6 mg/L in May. These concentrations fall within ranges typically reported for coastal

Mediterranean waters influenced by aquaculture activities, which vary depending on farm intensity and the local hydrodynamic regime (Messaoudene F. et Loubar S., 2009; Challouf et al., 2017).

At the Algerian scale, Tlidjane (2013) similarly documented seasonal variation in suspended solid concentrations around a fish farm at Bou-Ismail Bay. Belkacemi et Meddahi (2021) similarly reported elevated suspended matter along the eastern Algiers coast during spring, linked to both natural particle resuspension and biological production. These comparisons confirm that the particulate loads recorded at Ain Taya fall within the range expected for Algerian coastal aquaculture sites, and do not represent an exceptional level of contamination under current operating conditions.

The seasonal contrast between campaigns is moderate for TSS compared to the dramatic differences observed for chlorophyll-a, which suggests that the suspended particulate pool at this site is influenced by multiple sources beyond the farm itself, including natural marine particles, phytoplankton cells, and resuspension of bottom sediments during energetic winter conditions. The most notable seasonal change was recorded at ST01 (cage centre), where TSS increased from 28.0 mg/L in February to 76.0 mg/L in May (+48.4 mg/L), confirming the farm's direct contribution to the particulate load during the biologically active spring season. The highest value of the entire study was recorded at ST05 in May (104.0 mg/L), which reinforces the interpretation that coastal runoff and regional particle inputs play a significant role in determining TSS concentrations at this site, independent of the farm's direct influence.

At the national legislative level, Algerian law n° 03-10 of 19 July 2003 relative to the protection of the environment within the framework of sustainable development establishes the general principle that aquatic ecosystems must be protected against any form of pollution likely to alter water quality (Art. 49), and prohibits the discharge of polluting effluents into marine waters under Algerian jurisdiction (Art. 52). However, no executive decree currently in force in Algeria sets specific numerical threshold values for suspended particulate matter, dissolved inorganic nutrients, or chlorophyll-a concentrations in marine coastal or aquaculture monitoring areas. In the absence of national-specific standards, the technical guidelines of the FAO (2006) and the trophic classification of Vollenweider et al. (1998) are used as the operative reference framework throughout this study, as is common practice in published Algerian aquaculture environmental assessments (Messaoudene F. et Loubar S., 2009; Tlidjane, 2013).

III.2. Dissolved Inorganic Nutrients

The concentrations of dissolved inorganic nutrients: nitrates (NO_3^-), nitrites (NO_2^-), ammonium (NH_4^+), phosphates (PO_4^{3-}), and silicates (SiO_4^{4-}), were determined at the five sampling stations during both campaigns using a SKALAR automatic flow analyser, following standard colorimetric methods (SKALAR, 2000; EPA, 1974). Results are expressed in µmol/L.

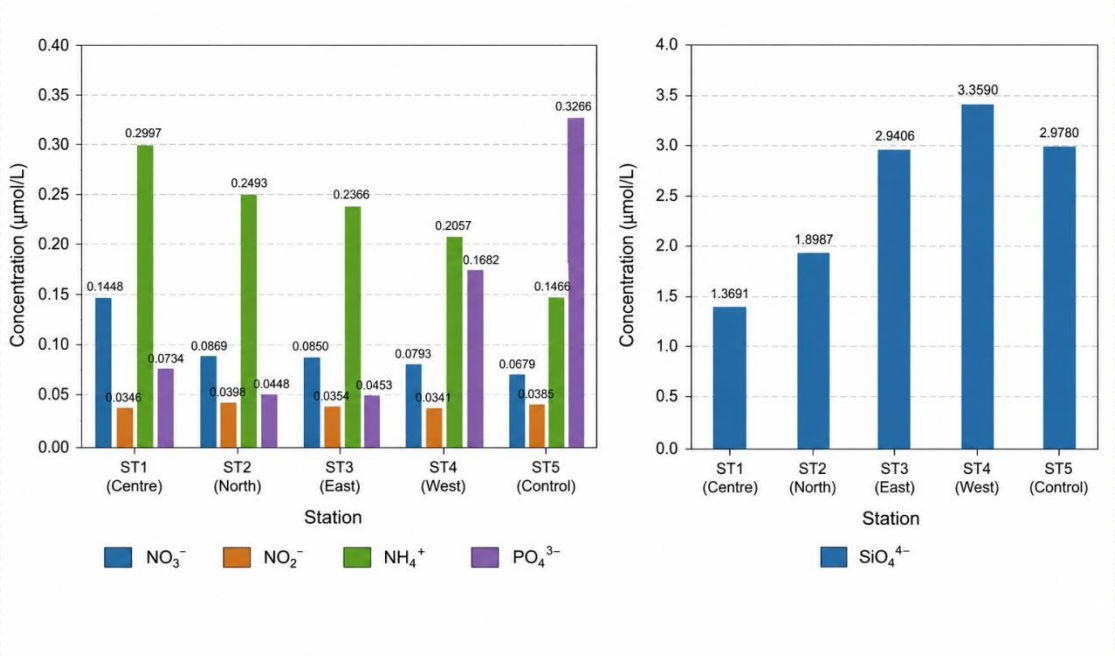


Figure III.2. Dissolved inorganic nutrients concentrations measured at the five stations during February 2026.

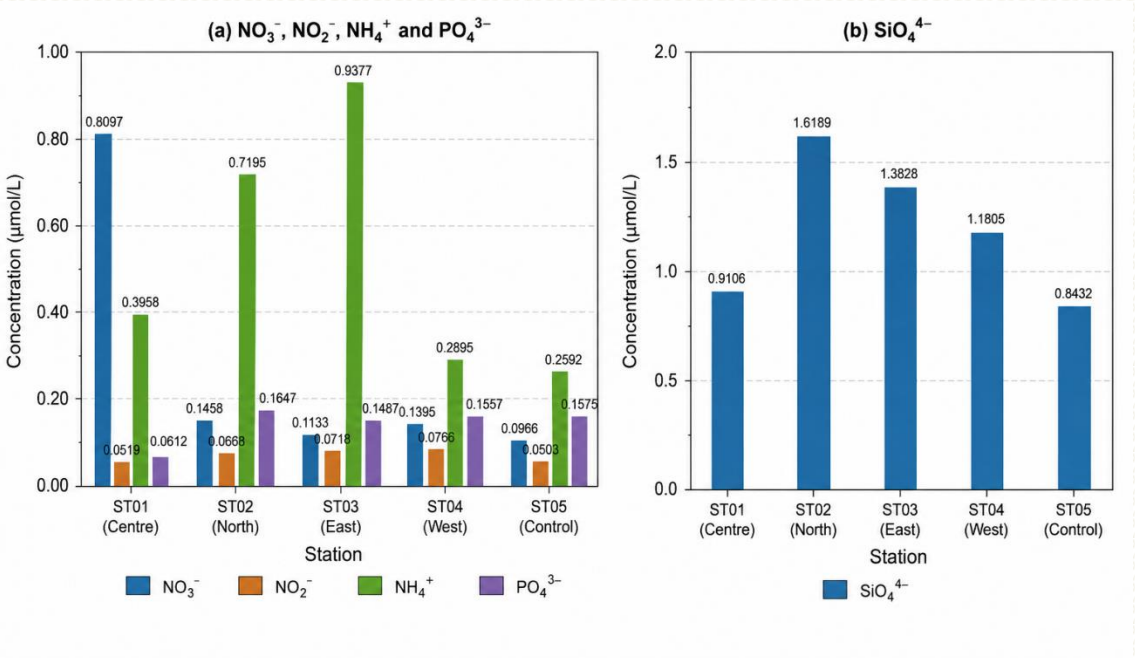


Figure III.3. Dissolved inorganic nutrients concentrations measured at the five stations during May 2026.

III.2.1. Nitrates (NO_3^-)

Nitrate concentrations in February ranged from 0.0679 µmol/L at the control station to 0.1448 µmol/L at Station ST01, the cage centre. This spatial gradient, with the highest value directly under the farm structures, reflects the continuous input of nitrogenous waste from fish excretion and uneaten feed, which undergoes bacterial nitrification in the water column to produce nitrates (Nefraoui H. et Tabi N.E.Y., 2015). However, all February values remained low overall, consistent with the reduced biological activity and stronger water mixing typical of winter conditions in the Aïn Taya coastal waters (Messaoudene F. et Loubar S., 2009).

In May, nitrate concentrations increased substantially at all stations, with **ST01** recording the highest value of the entire study at 0.8097 µmol/L. This a more than fivefold increase between February and May at the cage centre confirms that spring warming and thermal stratification limit the dilution of nutrients released by the farm, allowing them to accumulate in the surface layer. The control station ST05 recorded 0.0966 µmol/L in May, which represents the natural background level of the Ain Taya coastal zone during this season.

These values remain below the concentrations reported by Messaoudene F. et Loubar S., 2009 at the same site during the 2009 sampling period, which suggests that nutrient loading from the farm may have stabilised or that the current stocking density generates a lower organic output than previously observed. These values remain well below the 12.4 µmol/L nitrate concentrations reported near cage structures by Ben Souissi et al. (2017) in Tunisia, a point developed further in section III.2.6.

III.2.2. Nitrites (NO_2^-)

Nitrite concentrations were low at all stations during both campaigns, ranging from 0.0341 to 0.0398 µmol/L in February and from 0.0503 to 0.0766 µmol/L in May. Nitrites are intermediate products of the nitrogen cycle, formed during the bacterial oxidation of ammonium and rapidly converted to nitrates under oxygenated conditions. Their low and relatively uniform concentrations across stations suggest that nitrification processes were functioning normally at this site during both campaigns (Aminot et Chaussepied, 1983).

The slight increase observed in May compared to February, particularly at ST03 (0.0718 µmol/L) and ST04 (0.0766 µmol/L), may reflect a higher rate of ammonium oxidation driven by warmer water temperatures and increased bacterial activity in spring. These values remain well within ranges typically reported for non-polluted Mediterranean coastal waters (Challouf et al., 2017).

III.2.3. Ammonium (NH_4^+)

Ammonium concentrations in February ranged from 0.1466 µmol/L at ST05 to 0.2997 µmol/L at ST01. The spatial gradient was clear and consistent: the highest value was recorded at the cage centre (ST01), decreasing progressively toward the control station. Ammonium is the primary nitrogen form excreted directly by fish through gill diffusion and metabolic waste, and its elevated concentration at ST01 confirms that the cage structures represent an active point source of dissolved inorganic nitrogen in the water column (Aminot et Chaussepied, 1983). In February, the relatively modest concentrations across all stations suggest that natural dilution and bacterial nitrification processes were sufficient to process the farm's ammonium output under the well-mixed winter conditions prevailing at this time of year.

In May, ammonium concentrations increased at all stations and displayed a modified spatial pattern. ST03 recorded the highest value of the entire study (0.9377 µmol/L), followed by ST02 (0.7195 µmol/L) and ST01 (0.3958 µmol/L). This shift in the spatial gradient, where the eastern and northern stations recorded higher ammonium than the cage centre itself, is an important observation. It suggests that by May, the thermal stratification of the water column reduced vertical mixing and allowed ammonium to accumulate preferentially in the surface layer at stations positioned downflow from the cages. The lower value recorded at ST01 relative to ST02 and ST03 in May may reflect active phytoplankton uptake at the cage centre, where the intense Skeletonema sp. bloom documented in the phytoplankton results (45,640 cells L^{-1}) would have consumed dissolved ammonium rapidly as a preferred nitrogen source (Illoul, 1987; Nefraoui H. et Tabi N.E.Y., 2015). This interpretation is supported by the coincidence of the highest

ammonium values with the stations recording intermediate phytoplankton densities, where uptake was less intensive.

The overall seasonal increase in ammonium between February and May is consistent with increased fish metabolism at higher water temperatures and with the reduced nitrification capacity of warmer, stratified waters. These findings broadly agree with Messaoudene F. et Loubar S., 2009 at the same site, who also reported elevated ammonium concentrations near the Ain Taya cages.

III.2.4. Phosphates (PO_4^{3-})

Phosphate concentrations showed an unexpected spatial pattern during February, with the lowest values recorded near the cages (0.0448–0.0734 µmol/L at ST01–ST03) and the highest value at the control station ST05 (0.3266 µmol/L). This inverse gradient is unusual for a farm-impacted site and may reflect active uptake of phosphates by the phytoplankton bloom at ST02 (which recorded 11.75 µg/L chlorophyll-a in February), depleting the dissolved phosphate pool near the cage area faster than it is replenished by farm inputs (Boudouresque, 2004).

In May, phosphate concentrations were more uniform across stations, ranging from 0.0612 µmol/L at ST01 to 0.1647 µmol/L at ST02. The increase between February and May at most stations is consistent with the seasonal intensification of organic matter decomposition and remineralisation of phosphorus from settling organic particles, a pattern also documented by Messaoudene F. et Loubar S., 2009 at the same site. The Redfield ratio (N:P = 16:1) provides a useful reference for interpreting these results: during February, the N:P ratio at ST01 was approximately 6.52 (using DIN = NO_3^- + NO_2^- + NH_4^+ = 0.4791 µmol/L and PO_4^{3-} = 0.0734 µmol/L), indicating strong nitrogen limitation relative to Redfield balance. In May, the ratio at ST01 shifted to approximately 21:1 (DIN = 1.2574 µmol/L, PO_4^{3-} = 0.0612 µmol/L), moving closer to Redfield balance and reflecting the nitrogen enrichment contribution of the farm during the productive season. This seasonal shift in the N:P ratio aligns with the stimulation of diatom growth documented in the phytoplankton results, indicating that the farm alters not only absolute nutrient concentrations but also the stoichiometric balance of the dissolved inorganic nutrient pool.

III.2.5. Silicates (SiO_4^{4-})

Silicates are essential for the construction of diatom frustules and their concentration directly influences the development of siliceous phytoplankton communities. In February, silicate concentrations were the highest of all nutrients measured, ranging from 1.3691 µmol/L at ST01 to 3.3590 µmol/L at ST04. The higher values at the peripheral stations compared to the cage

centre suggest that silicates were being consumed by the diatom community growing near the farm, particularly at ST01 and ST02 which showed the highest chlorophyll-a values in February.

In May, silicate concentrations decreased at all stations compared to February, dropping to values between 0.8432 µmol/L at ST05 and 1.6189 µmol/L at ST02. This seasonal decline is consistent with the intense phytoplankton growth of spring, during which diatoms incorporate large quantities of dissolved silica into their cell walls. The depletion of silicates by late spring is a process frequently described in Mediterranean coastal waters and often associated with the transition from diatom to dinoflagellate dominance later in the productive season (Illoul, 1987; Nefraoui H. et Tabi N.E.Y., 2015). The low silicate concentration at ST01 in May (0.9106 µmol/L), combined with the extremely high chlorophyll-a recorded there, is consistent with intense diatom growth having consumed much of the available silica earlier in the season.

III.2.6. General Discussion of Nutrient Results

Taken together, the nutrient data confirm that the aquaculture installation at Ain Taya exerts a measurable influence on the dissolved inorganic chemistry of the surrounding water, particularly for nitrogen compounds. The enrichment signal is clearest for nitrates and ammonium at the cage centre in both campaigns, and becomes more spatially dispersed in May due to the combined effects of thermal stratification and current-driven transport.

Despite the clear farm influence, all nutrient concentrations recorded at this site remain well below the thresholds associated with severe eutrophication in Mediterranean coastal waters. The Algerian Basin is generally classified as mesotrophic, with nutrient concentrations naturally low compared to more enclosed or heavily urbanised coastal zones (Boufeniza, 2021).The Ain Taya site appears to sit at the interface between natural mesotrophic conditions and localised farm-driven enrichment, a pattern that requires continued monitoring to prevent a transition toward persistent eutrophic conditions, especially during the productive spring season.

At the Algerian coastal scale, available published studies on marine aquaculture sites focus primarily on phytoplankton community structure and do not systematically report dissolved inorganic nutrient concentrations, making direct numerical comparison difficult. In this context, the FAO (2006) guidelines and the Mediterranean reference values reported by Ben Souissi et al. (2017) in Tunisia represent the most appropriate benchmarks for situating the nutrient data recorded at Ain Taya.

Situating these results within published reference frameworks is essential to assess the significance of the observed enrichment.. Regarding recommended thresholds for aquaculture

environments, the FAO (2006) considers dissolved inorganic nitrogen concentrations below 5 µmol/L as acceptable in cage farming areas, and notes that concentrations above 20 µmol/L present a risk of triggering uncontrolled algal growth. All values recorded during this study remained well below both thresholds. At the Mediterranean scale, fish excretion in cage farms is known to release a substantial proportion of nitrogen as ammonium, which is rapidly oxidized to nitrate and assimilated by phytoplankton and bacteria. This process is consistent with the nitrate and ammonium gradients observed between ST01 and the peripheral stations at Ain Taya during both campaigns. These comparisons confirm that the site is not currently approaching a critical enrichment threshold, but underscore the importance of continued monitoring as the farm expands production capacity.

At the regional level, Rebbah et al. (2025), studying the Beni Haroun Dam in northeastern Algeria, recorded phosphate (PO_4^{3-}) concentrations reaching 0.72 mg/L and ammonium values up to 0.29 mg/L — concentrations substantially higher than those recorded at Ain Taya during both campaigns, which reflects the more enclosed freshwater dam environment and the absence of marine dilution capacity. Despite this difference in absolute concentrations, the authors documented a similar pattern of elevated nutrient availability driving increased phytoplankton abundance, dominated by Cyanobacteria and Dinoflagellata — a nutrient-mediated community response analogous to the diatom proliferation observed at Ain Taya under farm-enriched conditions.

III.3. Chlorophyll-a Concentrations

Chlorophyll-a concentrations were determined at all five stations during both campaigns using the spectrophotometric method of Jeffrey et Humphrey (1975). Results are expressed in µg/L and presented in Tables III.3 and III.4.

III.3.1. February 2026: Winter Campaign

Chlorophyll-a concentrations recorded during the February campaign were low across all five stations, ranging from 0.34 µg/L at ST04 to 11.75 µg/L at ST02. According to the trophic classification of Vollenweider et al. (1998), four stations fell within the oligotrophic to mesotrophic range, which matches the typical winter conditions of the western Mediterranean, where low water temperature, reduced light intensity, and strong vertical mixing limit phytoplankton growth (Boudouresque, 2004).

The highest concentration of the February campaign was recorded at ST02 (11.75 µg/L) rather than at ST01, the cage centre (1.22 µg/L). This unexpected spatial pattern suggests that during

winter, local hydrodynamic conditions redistributed nutrients away from the cage centre toward the northern sector of the site. In the absence of thermal stratification, horizontal dispersion dominates over vertical accumulation, allowing nutrient-enriched water to spread laterally before phytoplankton can develop at the source point. This pattern is plausible in winter surveys of Mediterranean aquaculture sites, where current direction can outweigh cage proximity in determining local chlorophyll-a distribution.

Stations ST03, ST04, and ST05 recorded very low concentrations (3.75, 0.34, and 4.48 µg/L respectively), confirming that the farm's influence on phytoplankton biomass was minimal during this period. These values are comparable to those reported by Messaoudene F. et Loubar S., 2009 at the same site during winter 2009.

Table III.3. Raw absorbance readings and chlorophyll-a concentrations at the five stations, February 2026 (V filtered = 250 mL, V acetone = 10 mL).

Station	A750	A664	A647	A630	A664−A750	A647−A750	A630−A750	Chl-a (µg/mL)	Chl-a (µg/L)
ST01 (Centre)	0.030	0.033	0.033	0.035	0.003	0.003	0.005	0.0305	1.22
ST02 (North)	0.022	0.048	0.031	0.027	0.026	0.009	0.005	0.2938	11.75
ST03 (East)	0.030	0.039	0.038	0.037	0.008	0.006	0.007	0.0938	3.75
ST04 (West)	0.059	0.060	0.061	0.063	0.001	0.002	0.004	0.0085	0.34
ST05 (Control)	0.012	0.022	0.016	0.015	0.010	0.004	0.003	0.1121	4.48

III.3.2. May 2026, Spring Campaign

The May campaign revealed a dramatically different picture. Concentrations increased sharply at all stations compared to February, ranging from 3.52 µg/L at ST03 to 583.91 µg/L at ST01.

Three of the five stations exceeded the hypereutrophic threshold of 75 µg/L defined by Vollenweider et al. (1998), confirming that the farm exerts a strong environmental influence during the productive spring season.

ST01, positioned at the centre of the floating cages, recorded the highest concentration of the entire study (583.91 µg/L).The A750 reading at this station was 0.514, indicating exceptionally

high water turbidity consistent with dense algal biomass and suspended organic particles. This value signals a condition of hyper-eutrophication directly under the farm structures, where the continuous release of organic waste from fish excretion and uneaten feed, combined with the favourable spring conditions of increasing temperature and light availability, triggered an intense phytoplankton bloom confined to the cage area. Such extreme chlorophyll-a values near cage centres have been linked to the accumulation of ammonium and phosphate in stratified surface waters, a process that becomes particularly pronounced when vertical mixing is reduced during spring warming (Nefraoui H. et Tabi N.E.Y., 2015; Boufeniza, 2021).

ST04 recorded the second highest concentration (143.65 µg/L), suggesting significant lateral dispersion of nutrient-enriched water from the cages in a westward direction, likely driven by the dominant current patterns at the site during this season. ST02 followed with 84.25 µg/L, confirming that enrichment also extended northward from the farm. Comparing these values to the Tunisian cage farm study of Challouf et al. (2017) in Monastir Bay, where maximum chlorophyll-a near cage structures reached only 4.28 µg/L, the Ain Taya concentrations are substantially higher, which may reflect the semi-enclosed nature of the site and the limited water renewal capacity at this location during spring.

ST05, the control station located 100 metres from the cages, recorded 11.36 µg/L, a value classified as eutrophic but close to the natural spring background of the Aïn Taya coastal waters. This concentration is consistent with the mesotrophic to slightly eutrophic conditions documented for Algerian coastal waters during spring (Boufeniza, 2021; Messaoudene F. et Loubar S., 2009), confirming that ST05 effectively represents the ambient environmental state beyond the direct influence of the farm.

ST03 recorded the lowest chlorophyll-a value of the May campaign (3.52 µg/L), despite having shown the highest ammonium concentration across the entire site (0.9377 µmol/L) during the same period. This apparent contradiction is explained by the time lag between nutrient transport and phytoplankton response. The dominant current likely carried dissolved ammonium from ST01 to ST03 rapidly through advection, but phytoplankton cells require 24 to 48 hours to complete one division cycle. Algal biomass therefore did not have sufficient time to accumulate at ST03 before sampling, unlike at ST04 and ST02, where prolonged nutrient exposure had already sustained measurable phytoplankton growth. This decoupling between dissolved nutrient concentration and chlorophyll-a biomass is a well-documented feature of dynamic coastal environments, where advection operates faster than biological turnover (Boudouresque, 2004).

Table III.4. Raw absorbance readings and chlorophyll-a concentrations at the five stations, May 2026 (V filtered = 250 mL, V acetone = 10 mL).

Station	A750	A664	A647	A630	A664−A750	A647−A750	A630−A750	Chl-a (µg/mL)	Chl-a (µg/L)
ST01 (Centre)	0.514	1.871	1.433	1.357	1.357	0.919	0.843	14.58	583.91
ST02 (North)	0.081	0.277	0.210	0.303	0.196	0.129	0.222	2.11	84.25
ST03 (East)	0.075	0.083	0.079	0.082	0.008	0.004	0.007	0.0881	3.52
ST04 (West)	1.021	1.326	1.031	1.115	0.3055	0.010	0.094	3.597	143.65
ST05 (Control)	0.054	0.080	0.069	0.068	0.026	0.015	0.014	0.284	11.36

The chlorophyll-a concentrations recorded at ST01 (583.91 µg/L) and ST04 (143.65 µg/L) during the May campaign are acknowledged as exceptionally high relative to typical Mediterranean coastal values. The calculations are mathematically correct, following the Jeffrey and Humphrey (1975) equation with the standard conversion factor (×10 mL ÷ 0.25 L = ×40). However, the elevated A750 readings at ST01 (0.514) and ST04 (1.021) indicate that the acetone extracts retained significant residual turbidity after centrifugation, likely due to the high particulate load in the water near the cage structures during spring. Standard spectrophotometric practice requires A750 to remain below 0.05; values above this threshold reduce the reliability of the turbidity correction and may inflate the corrected absorbances at 664 nm, directly driving the chlorophyll-a estimate upward. The high values at ST01 and ST04 should therefore be interpreted as a combined signal of real biological enrichment and methodological interference from sample turbidity. Re-centrifugation at 4000–5000 rpm or a second filtration step through a 0.2 µm membrane before reading would have reduced this interference. These results are retained as the actual laboratory output, but this limitation is fully acknowledged in the interpretation.

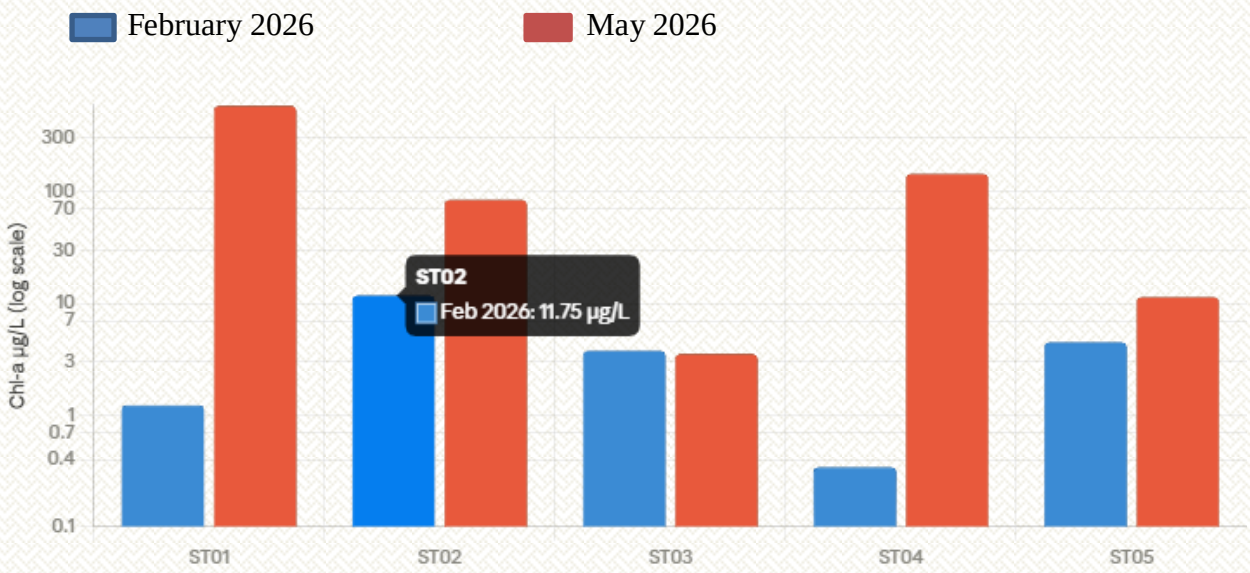


Figure III.4. Chlorophyll-a concentrations (µg/L, logarithmic scale) at the five sampling stations during the February and May 2026 campaigns at the Ain Taya aquaculture site. Dashed line indicates the hypereutrophic threshold (75 µg/L) according to Vollenweider et al. (1998).

III.3.3. Seasonal Comparison and Trophic Assessment

The contrast between the two campaigns is striking. February values remained below 12 µg/L at all stations, while May values reached up to 583.91 µg/L at the cage centre, a difference of several orders of magnitude at ST01 alone, though this contrast should be interpreted with caution given the methodological limitations associated with the elevated A750 readings at that station, as discussed above. This seasonal amplification of the farm's environmental footprint is driven by the combination of three converging factors in spring: increased biological productivity, reduced vertical mixing, and sustained nutrient loading from the cages.

The trophic status assessment (Table III.5) shows that in February, all stations were either oligotrophic or mesotrophic, indicating that the farm had a limited effect on the ecosystem during winter. By May, three stations had reached hypereutrophic conditions and only ST03 remained oligotrophic. This transition from a predominantly healthy winter state to a spatially differentiated eutrophic spring state is a pattern consistent with the seasonal dynamics of Mediterranean cage aquaculture sites, where the productive season concentrates the environmental impact into a relatively short period of high biological activity (Boudouresque, 2004; Illoul, 1987).

The persistence of low chlorophyll-a at ST03 throughout both campaigns, combined with the extreme values at ST01 and ST04, suggests that the farm's environmental influence is directional rather than radially symmetrical. Continued monitoring across additional seasons and years

would be needed to confirm whether this spatial pattern is consistent or varies with interannual changes in current direction and thermal stratification at the Ain Taya site.

Table III.5. Comparison of final chlorophyll-a concentrations (µg/L) and trophic status between the two campaigns.

Station	February 2026	May 2026	Variation	Trophic status (May)
ST01 — Centre	1.22	583.91	×478	Hypereutrophic
ST02 — North	11.75	84.25	×7.2	Hypereutrophic
ST03 — East	3.75	3.52	×0.94	Oligotrophic
ST04 — West	0.34	143.65	×423	Hypereutrophic
ST05 — Control	4.48	11.36	×2.5	Eutrophic

Trophic status classification based on Vollenweider et al. (1998): oligotrophic < 2 µg/L; mesotrophic 2-8 µg/L; eutrophic 8-75 µg/L; hypereutrophic > 75 µg/L

Comparing these findings with studies carried out in Algeria and the broader Mediterranean region provides important context for interpreting the magnitude of the Ain Taya trophic signal. Studies in the southwestern Mediterranean indicate that the Algerian Basin is generally oligotrophic to mesotrophic, with low surface chlorophyll-a concentrations offshore and somewhat higher values in productive coastal zones during spring (Boufeniza, 2021). The concentrations recorded at ST01 (583.91 µg/L) and ST04 (143.65 µg/L) in May thus represent a major enrichment above the regional background, directly attributable to the farm's nutrient output under stratified spring conditions. At the national level, The reference study of Challouf et al. (2017) in Monastir Bay, Tunisia, reported maximum chlorophyll-a concentrations not exceeding 4.28 µg/L near cage structures under oligotrophic conditions, confirming that the values recorded near the Ain Taya cages are substantially above those of comparable southern Mediterranean cage farms. For reference, the FAO (2006) recommends that chlorophyll-a in cage aquaculture monitoring areas should not persistently exceed 10 µg/L at reference stations a threshold that ST05 (11.36 µg/L in May) slightly surpassed, suggesting that the farm's influence extends to the control station during the productive season and that this station may need to be repositioned further from the cages in future monitoring campaigns.

III.4. Phytoplankton Community Structure

The phytoplankton community was analysed at the five sampling stations during both seasonal campaigns using the Utermöhl sedimentation method. A total of fifteen taxa were identified

across both campaigns, belonging to two major taxonomic groups: diatoms (Bacillariophyceae) and dinoflagellates (Dinophyceae). The complete species list, along with their group affiliation and HAB status, is presented in Table III.6. Results are reported in terms of cell densities (cells L^{-1}), relative abundance, relative frequency, species richness, and diversity indices.

Table III.6. Phytoplankton taxa identified at the Ain Taya aquaculture site during February and May 2026, with taxonomic group and HAB status.

Species	Group	HAB	Occurrence	Toxin / Risk
Chaetoceros sp.	Diatom	No	Feb + May	—
Skeletonema sp.	Diatom	No	Feb + May	—
Coscinodiscus sp.	Diatom	No	Feb + May	—
Navicula sp.	Diatom	No	Feb only	—
Nitzschia sp.	Diatom	No	Not detected	—
Rhizosolenia sp.	Diatom	No	Not detected	—
Thalassiosira sp.	Diatom	No	May only	—
Leptocylindrus sp.	Diatom	No	Feb + May	—
Asterionellopsis sp.	Diatom	No	May only	—
Dinophysis caudata	Dinoflagellate	Yes (DSP)	Not detected	Diarrhetic Shellfish Poisoning
Alexandrium sp.	Dinoflagellate	Yes (PSP)	May only	Paralytic Shellfish Poisoning
Ceratium fusus	Dinoflagellate	No	Feb only	—
Tripos furca	Dinoflagellate	No	May only	—

Protoperidinium sp.	Dinoflagellate	No	Feb + May	—
Noctiluca scintillans	Dinoflagellate	No	Not detected	—

DSP: Diarrhetic Shellfish Poisoning; PSP: Paralytic Shellfish Poisoning.

Note: *Nitzschia* sp., *Rhizosolenia* sp., *Dinophysis* caudata, and *Noctiluca* scintillans were included in the identification list based on their documented occurrence in the Bay of Algiers (Illoul, 1987; Djerioui, 2015) but were not detected at any station during either campaign.

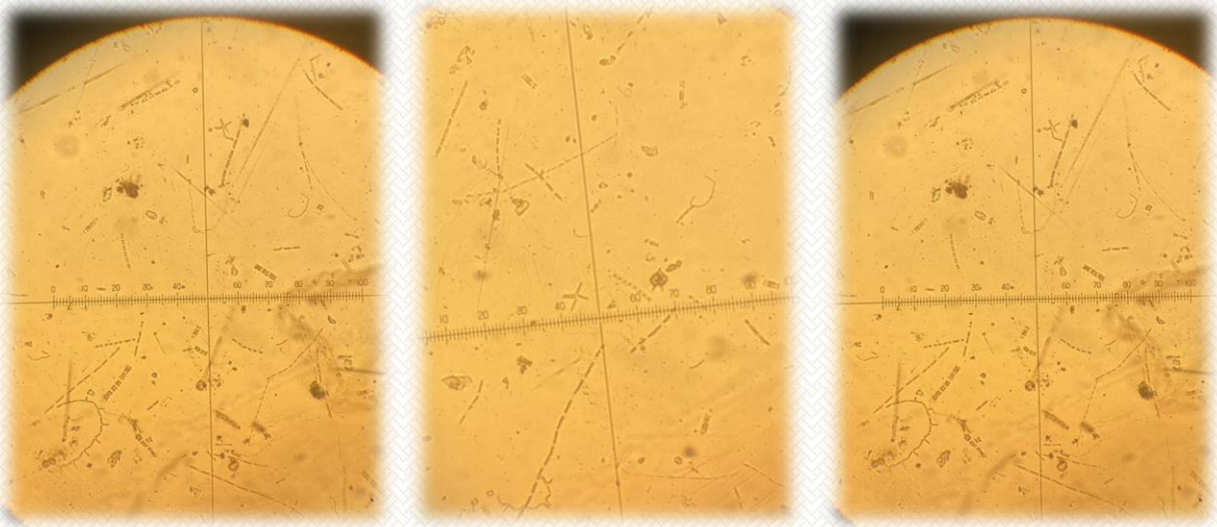


Figure III.5. Photomicrographs of phytoplankton taxa observed under the inverted microscope (Utermöhl method, ×400 magnification) at the Ain Taya aquaculture site.

III.4.1. February 2026, Winter Campaign

During the February campaign, phytoplankton abundance was low across all stations, which is consistent with the winter oligotrophic conditions of the western Mediterranean where reduced light intensity and strong vertical mixing limit algal growth (Illoul, 1987; Messaoudene F. et Loubar S., 2009). The full sedimentation chamber was scanned at each station, as the low cell density required complete observation to avoid underestimation of rare taxa. Using a sedimentation volume of 50 mL and a multiplication factor of 20 (full chamber), cell densities ranged from 440 cells L^{-1} at ST03 to 1,100 cells L^{-1} at ST02.

Table III.7. Phytoplankton cell densities (cells L^{-1}) at the five sampling stations, February 2026 (sedimentation volume: 50 mL; full chamber; multiplication factor: 20).

Species / Station	ST01 (Centre)	ST02 (North)	ST03 (East)	ST04 (West)	ST05 (Control)
Chaetoceros sp.	20	—	—	20	100
Skeletonema sp.	540	800	380	520	680
Coscinodiscus sp.	100	300	40	40	100
Navicula sp.	100	—	20	—	—
Leptocylindrus sp.	—	—	—	20	40
Ceratium fusus	40	—	—	—	—
Protoperidinium sp.	—	—	—	—	—
TOTAL	800	1100	440	600	920

Diatoms dominated the community at all five stations during this campaign, accounting for 95% or more of total cell abundance. Skeletonema sp. was by far the most abundant taxon, representing 67.5% of the total count at ST01, 72.7% at ST02, 86.4% at ST03, 86.7% at ST04, and 73.9% at ST05. This Skeletonema sp. dominance in winter matches a well-documented feature of Mediterranean coastal phytoplankton, where this small chain-forming diatom responds rapidly to nutrient inputs under cool, well-mixed conditions (Illoul, 1987; Boufeniza, 2021). *Coscinodiscus* sp was the second most abundant taxon at ST02 (300 cells L^{-1}), where its presence alongside the high Skeletonema density is consistent with the elevated chlorophyll-a concentration recorded at that station (11.75 µg L^{-1}).

Ceratium fusus was detected exclusively at ST01 (40 cells L^{-1}). Given the extremely low cell density recorded, corresponding to approximately two cells counted in the settling chamber, this observation should be interpreted with caution. *Ceratium fusus* is a species known for its broad physiological tolerance, capable of persisting across a range of hydrodynamic and trophic conditions. Its sporadic occurrence at the cage centre is therefore more plausibly explained by random sampling variation or individual cell advection from adjacent water masses than by any

structural or ecological effect of the cage installation. Indeed, floating cage structures in open coastal environments are known to intensify local water turbulence through drag forces and fish movement, conditions that are unfavourable to dinoflagellate persistence. Under winter conditions, the absence of thermal stratification further precludes the formation of any micro-stratified layer beneath the structures. No potentially harmful species (HAB taxa) were detected during the February campaign.

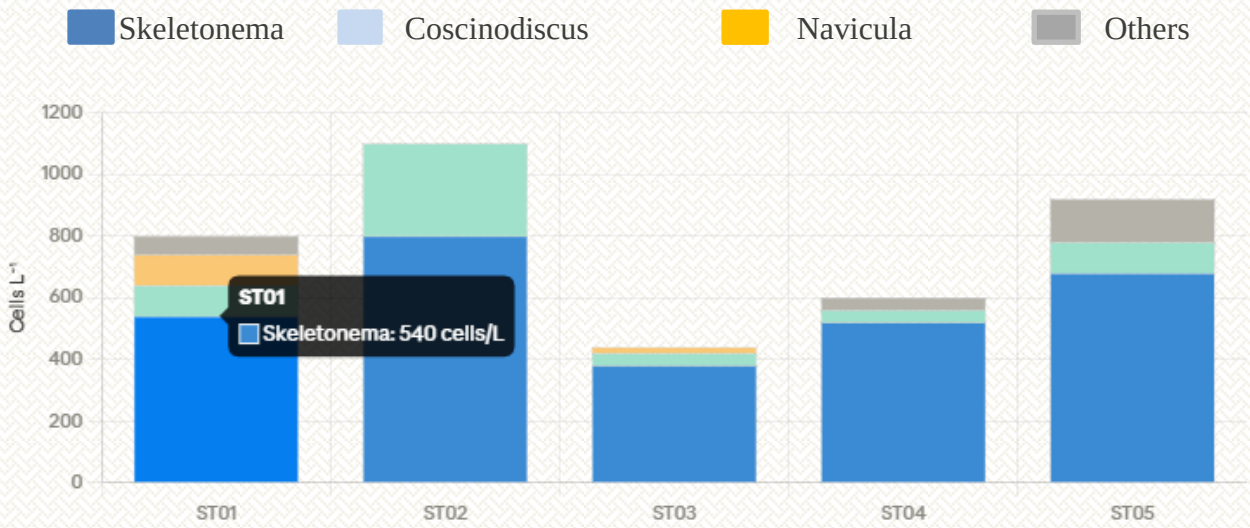


Figure III.6. Composition and cell density (cells L^{-1}) of the phytoplankton community at the five sampling stations during the February 2026 campaign at the Ain Taya aquaculture site.

III.4.1.1. Relative Frequency and Abundance, February 2026

Skeletonema sp. and *Coscinodiscus* sp. were the most consistently recorded taxa, present at all five stations (FR = 100%). *Navicula* sp. was recorded at two stations (FR = 40%), while *Chaetoceros* sp. *and Leptocylindrus* sp. were each recorded at one station (FR = 20%). *Ceratium fusus* was recorded at one station (FR = 20%), while *Tripos furca* was also recorded at one station (FR = 20%).This low frequency of most taxa reflects the sparse community typical of winter conditions in the Aïn Taya coastal waters.

III.4.1.2. Ecological Diversity Indices, February 2026

Table III.8. Ecological diversity indices calculated for the phytoplankton community at the five sampling stations, February 2026.

Index	ST01 (Centre)	ST02 (North)	ST03 (East)	ST04 (West)	ST05 (Control)
Species richness (S)	5	2	3	4	4
Shannon-Weaver (H')	1.027	0.586	0.485	0.531	0.842
Pielou's evenness (J')	0.638	0.845	0.442	0.383	0.608
Simpson index (D)	0.490	0.603	0.756	0.758	0.572
1 – D	0.510	0.397	0.244	0.242	0.428

Species richness in February was low across all stations, ranging from S = 2 at ST02 to S = 5 at ST01. The highest diversity was recorded at ST01 (H' = 1.027), which is explained by the co-occurrence of four diatom taxa and one dinoflagellate (Ceratium fusus).

Despite its higher abundance, ST02 recorded the lowest species richness (S = 2), with only *Skeletonema* sp. and *Nitzschia* sp. present. Pielou's evenness index was highest at ST02 (J' = 0.845), reflecting a relatively balanced distribution between the two co-occurring species. This high evenness value is ecologically consistent: with only two taxa sharing abundance in a roughly 73/27 ratio, no single species achieves absolute dominance, and the community remains proportionally well-distributed. At ST03 and ST04, low J' values (0.442 and 0.383) indicate that *Skeletonema* sp. overwhelmingly dominated, with little contribution from the other taxa.

The Simpson dominance index confirmed the pattern observed with Shannon-Weaver. The highest dominance (D = 0.758 at ST04, D = 0.756 at ST03) corresponds to strong *Skeletonema* sp dominance, while ST01 displayed the lowest dominance (D = 0.490), consistent with a more evenly distributed community. Overall, the February diversity indices reflect a winter assemblage characterised by low richness and moderate to high dominance by a single diatom species, a pattern that matches nutrient-driven diatom blooms commonly reported in the western Mediterranean during the cold season (Nefraoui H. et Tabi N.E.Y., 2015; Illoul, 1987).

III.4.2. May 2026, Spring Campaign

The May campaign revealed a dramatic increase in phytoplankton abundance at all stations compared to February. The half-chamber counting strategy was applied at all five stations due to the high cell densities observed, using a sedimentation volume of 50 mL and a multiplication factor of 40. Total cell densities ranged from 13,360 cells L^{-1} at ST03 to 45,640 cells L^{-1} at ST01, representing increases of up to 57-fold relative to the February values at the same stations. This seasonal explosion in cell numbers reflects the combined effect of spring warming, increased light availability, reduced vertical mixing, and nutrient accumulation in the stratified surface layer, conditions known to favour intense diatom proliferation in Mediterranean coastal zones (Boudouresque, 2004; Illoul, 1987).

Table III.9. Phytoplankton cell densities (cells L^{-1}) at the five sampling stations, May 2026 (sedimentation volume: 50 mL; half chamber; multiplication factor: 40).

Species / Station	ST01 (Centre)	ST02 (North)	ST03 (East)	ST04 (West)	ST05 (Control)
Asterionellopsis sp.	360	40	120	240	360
Chaetoceros sp.	400	—	160	—	—
Skeletonema sp.	40440	33200	8000	28720	26720
Coscinodiscus sp.	520	1720	240	240	400
Thalassiosira sp.	1320	8760	3600	4640	3480
Leptocylindrus sp.	2400	1680	1200	1640	1520
Alexandrium sp.	—	—	40	—	—
Tripos furca	—	160	—	—	—
Protoperidinium sp.	200	—	—	80	40
TOTAL	45,640	45,560	13,360	35,560	32,520

Note:Tripos furca (formerly Ceratium furca, sensu Illoul, 1987)

Skeletonema sp. remained the dominant taxon in May, but its dominance intensified substantially. At ST01, it accounted for 88.6% of total cell abundance (40,440 cells L^{-1}), while at ST02 its contribution reached 72.9% (33,200 cells L^{-1}). The elevated abundance of Skeletonema sp. at the cage centre is consistent with the hypereutrophic chlorophyll-a value recorded there (583.91 μg L^{-1}), and confirms that the intense nutrient enrichment from fish waste and uneaten feed stimulated a localised diatom bloom directly beneath the farm structures. The same pattern has been documented in other cage aquaculture studies in the Mediterranean, where Skeletonema spp. commonly bloom in response to elevated dissolved inorganic nitrogen concentrations (Nefraoui H. et Tabi N.E.Y., 2015).

Thalassiosira sp. emerged as the second most abundant taxon in May, with densities ranging from 1,320 cells L^{-1} at ST01 to 8,760 cells L^{-1} at ST02. The markedly higher Thalassiosira density at ST02 compared to ST01 is noteworthy: while Skeletonema sp. appeared to dominate near the nutrient source at the cage centre, *Thalassiosira* sp. may be competitively favoured at slightly lower nutrient concentrations, exploiting the more dispersed nutrient gradient at the northern station. *Leptocylindrus* sp. was consistently present across all five stations (1,200–2,400 cells L^{-1}), suggesting it can sustain moderate growth throughout the site regardless of the local nutrient gradient. *Asterionellopsis* sp. also appeared for the first time in May, present at all stations (40–360 cells L^{-1}), which is consistent with its preference for spring conditions in Algerian coastal waters (Illoul, 1987).

The dinoflagellate contribution remained minimal throughout May, representing less than 0.5% of total cell abundance at all five stations. Diatoms overwhelmingly dominated the community (99.6–99.9%), while dinoflagellates and other minor groups accounted for the remaining 0.1–0.4%, confirming that the spring bloom at Aïn Taya was driven entirely by siliceous forms. This near-exclusive diatom dominance suggests that silicate concentrations, though declining from February to May, remained sufficient to support diatom growth throughout the spring campaign (Illoul, 1987; Boufeniza, 2021). The low dinoflagellate proportion also indicates that the site had not yet undergone the functional community shift toward dinoflagellate dominance that typically follows silicate exhaustion in the late spring or summer (Illoul, 1987; Nefraoui H. et Tabi N.E.Y., 2015).

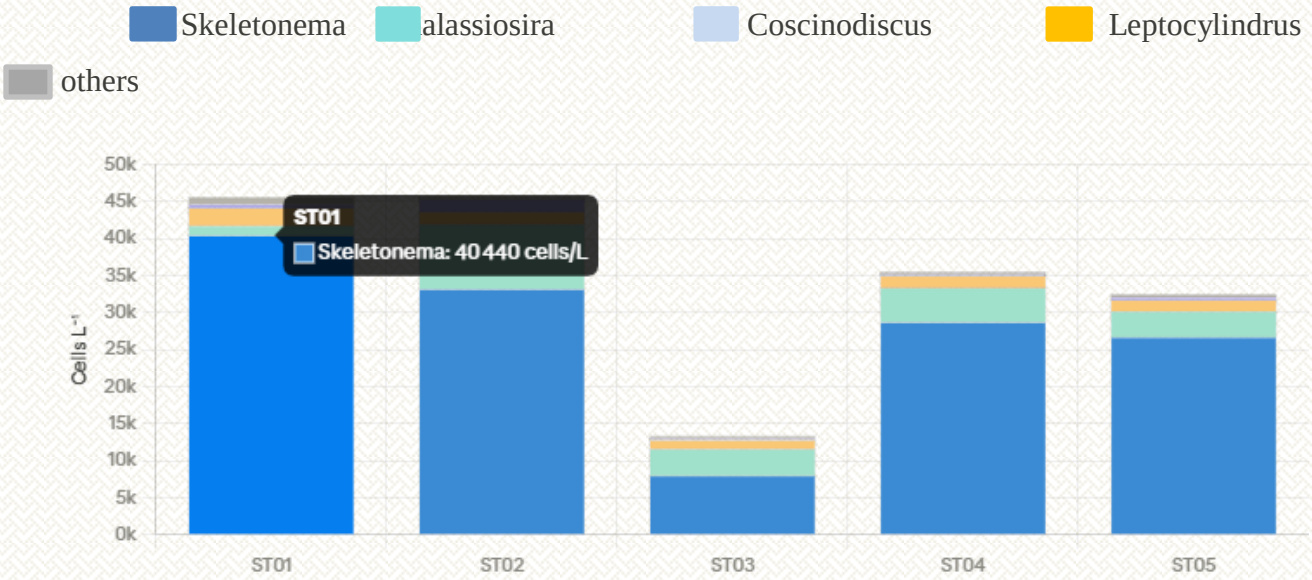


Figure III.7. Composition and cell density (cells L^{-1}) of the phytoplankton community at the five sampling stations during the May 2026 campaign at the Ain Taya aquaculture site.

III.4.2.1. Harmful Algal Bloom Species, May 2026

One potentially harmful species, *Alexandrium* sp., was detected at ST03 at a low density of 40 cells L^{-1} during the May campaign. Alexandrium species produce saxitoxins responsible for Paralytic Shellfish Poisoning (PSP), which can accumulate in filter-feeding organisms such as mussels and clams farmed at the Orca Marine installation (Djerioui, 2015; Smayda, 1997). Although the density recorded was far below the alert thresholds typically used in shellfish aquaculture monitoring programmes — usually set at several hundred to several thousand cells L^{-1} , the detection of this genus at ST03 merits attention. ST03 is positioned at the eastern edge of the study area, where offshore dilution conditions limit nutrient accumulation, and the isolated occurrence of *Alexandrium* sp. at this station may reflect advective transport from adjacent coastal waters rather than in situ bloom development.

Dinophysis caudata, which was included in the species identification list following its known occurrence in the Bay of Algiers (Djerioui, 2015), was not detected at any station during either campaign. Its absence does not preclude its presence at other times of year, as Dinophysis spp. typically peak during the warmer months of summer and early autumn in the western Mediterranean. No other HAB taxa were detected during either sampling period.

III.4.2.2. Relative Frequency and Relative Abundance, Both Campaigns

Table III.10. Relative frequency (FR, %) of phytoplankton taxa recorded across both sampling campaigns (n = 10 samples: 5 stations × 2 campaigns).

Species	Group	Occurrences	FR (%)
Skeletonema sp.	Diatom	10/10	100.0
Coscinodiscus sp.	Diatom	10/10	100.0
Leptocylindrus sp.	Diatom	7/10	70.0
Asterionellopsis sp.	Diatom	5/10	50.0
Chaetoceros sp.	Diatom	5/10	50.0
Thalassiosira sp.	Diatom	5/10	50.0
Protoperidinium sp.	Dinoflagellate	3/10	30.0
Navicula sp.	Diatom	2/10	20.0
Alexandrium sp.	Dinoflagellate	1/10	10.0
Ceratium fusus	Dinoflagellate	1/10	10.0
Tripos furca	Dinoflagellate	1/10	10.0
Nitzschia sp.	Diatom	0/10	0.0
Rhizosolenia sp.	Diatom	0/10	0.0
Dinophysis caudata	Dinoflagellate	0/10	0.0
Noctiluca scintillans	Dinoflagellate	0/10	0.0

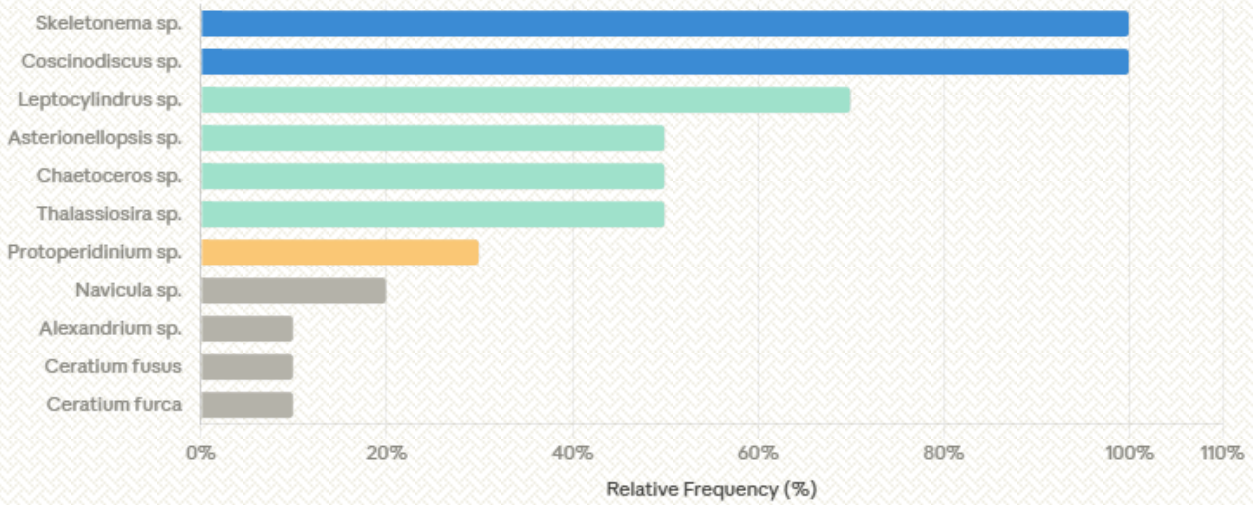


Figure III.8. Relative frequency (FR, %) of phytoplankton taxa recorded across both sampling campaigns (n = 10 samples: 5 stations × 2 campaigns) at the Ain Taya aquaculture site.

Skeletonema sp and *Coscinodiscus* sp were the only taxa recorded at all ten sampling occasions, giving them a relative frequency of 100%. This ubiquity reflects their capacity to persist across both seasonal and spatial gradients at the Ain Taya site. *Leptocylindrus* sp was the third most frequent taxon (FR = 70%), present at seven out of ten samples. *Asterionellopsis* sp, *Chaetoceros* sp, and *Thalassiosira* sp. each achieved FR = 50%, as they were restricted to the May campaign but present at all five stations during that period.

III.4.2.3. Ecological Diversity Indices. May 2026

Table III.11. Ecological diversity indices calculated for the phytoplankton community at the five sampling stations, May 2026.

Index	ST01 (Centre)	ST02 (North)	ST03 (East)	ST04 (West)	ST05 (Control)
Species richness (S)	7	6	7	6	6
Shannon-Weaver (H')	0.519	0.819	1.062	0.661	0.656
Pielou's evenness (J')	0.267	0.457	0.546	0.369	0.366
Simpson index (D)	0.789	0.571	0.440	0.672	0.689

1 – D	0.211	0.429	0.560	0.328	0.311

Species richness increased in May compared to February at all stations, ranging from S = 6 at ST02, ST04, and ST05, to S = 7 at ST01 and ST03. This increase reflects the appearance of new taxa: *Asterionellopsis* sp, *Thalassiosira* sp, *Chaetoceros* sp. (at certain stations), and the dinoflagellates *Tripos furca* and *Alexandrium* sp. that were absent or below detection limits in winter. However, despite the higher species richness, Shannon-Weaver diversity declined sharply at most stations in May. The lowest H' value of the entire study was recorded at ST01 (H' =0.519), directly under the cage centre, where *Skeletonema* sp. constituted 88.6% of total abundance. This extreme dominance by a single species reduces the effective diversity regardless of the number of taxa present, and represents a textbook example of competitive exclusion driven by nutrient over-enrichment (Magurran, 2004; Nefraoui H. et Tabi N.E.Y., 2015).

Pielou's evenness followed a consistent spatial pattern in May. The lowest J' value was recorded at ST01 (J' = 0.267), where the concentration of nutrient inputs from the cages created conditions most favourable to *Skeletonema* sp. growth, to the detriment of other taxa. ST03 recorded the highest evenness of the May campaign (J' = 0.546), consistent with its lower nutrient load, lower chlorophyll-a concentration (3.52 µg L^{-1}), and more balanced species distribution. The Simpson dominance index reinforced this picture: D = 0.789 at ST01 (the highest value of the entire study) indicates that nearly 79% of randomly sampled cell pairs would belong to the same species, confirming near-monoculture conditions at the cage centre during spring.

III.4.3. Seasonal Comparison and Community Dynamics

The seasonal comparison reveals a consistent and ecologically meaningful pattern across the five stations. While species richness increased slightly from February to May at all locations, reflecting the appearance of additional taxa under favourable spring conditions, diversity as measured by H' declined at two of the five stations: most markedly at ST01 (from H' = 1.027 in February to H' = 0.519 in May), and at ST05 (from H' = 0.842 to H' = 0.656).

This inverse relationship between richness and diversity is explained by the unequal redistribution of abundance in May, where the rapid proliferation of *Skeletonema* sp. under conditions of high nutrient availability caused a dramatic reduction in the proportional representation of all other taxa.

The most ecologically meaningful trend is observed at ST01, where the Simpson dominance index rose from D = 0.490 in February to D = 0.789 in May. A value of D = 0.789 is well above values typically associated with algal bloom conditions in Algerian coastal aquaculture zones

(Nefraoui, 2015). Shannon-Weaver diversity declined from H' = 1.027 in February to H' = 0.519 in May at ST01, confirming near-monoculture conditions at the cage centre during the spring bloom.

In contrast, ST03 displayed the opposite trajectory: H' remained low in February (H' = 0.485) but increased to the highest value of the May campaign (H' = 1.062), while J' also increased (from 0.442 to 0.546) and D decreased (from 0.756 to 0.440).

The control station ST05 recorded moderate and relatively stable index values across both campaigns (H' = 0.842 in February, H' = 0.656 in May; D = 0.572 in February, D = 0.689 in May), suggesting that the farm's biological influence extended to this station in May

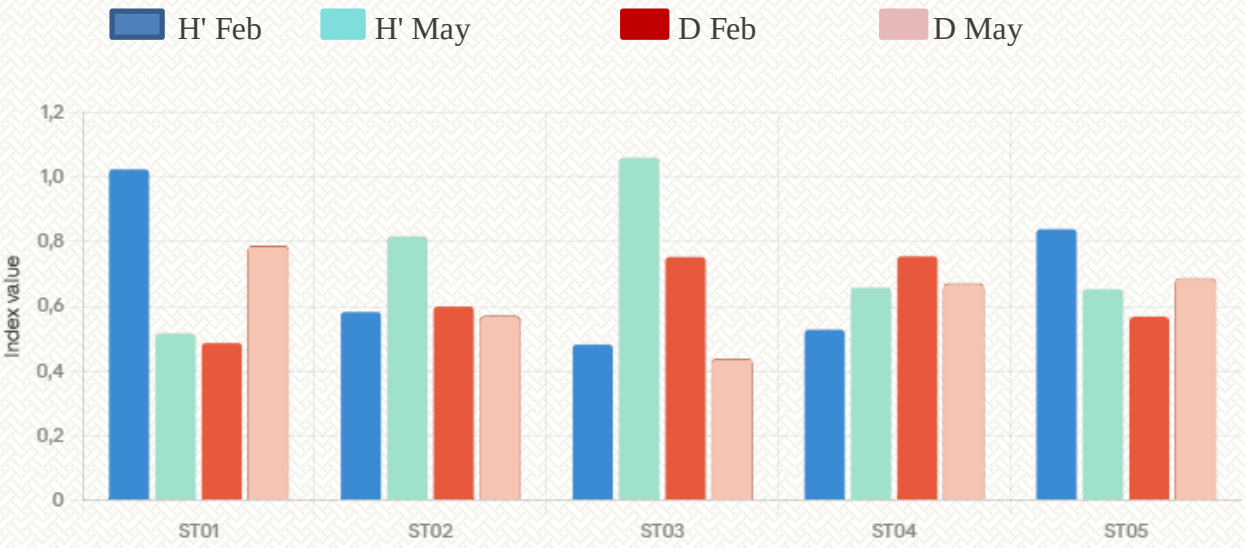


Figure III.9. Comparison of the Shannon-Weaver diversity index (H') and Simpson dominance index (D) at the five sampling stations between the February and May 2026 campaigns at the Ain Taya aquaculture site.

III.4.4. General Discussion of Phytoplankton Results

Taken together, the phytoplankton results from both campaigns provide a coherent picture of the biological response of the Ain Taya coastal ecosystem to aquaculture-driven nutrient enrichment. Diatoms, and in particular Skeletonema sp., dominated the community throughout the study period, a pattern in line with the documented structure of the Algerian coastal phytoplankton during spring and winter (Illoul, 1987). The intensity of this dominance, however, increased dramatically in May at the nutrient-enriched stations, transitioning from a moderately diverse winter assemblage to a nearly monospecific bloom at the cage centre.

The ecological indices revealed that the farm's biological impact is not uniform across the site. A clear spatial gradient was identified in May, with the strongest ecological disturbance signal highest Simpson dominance (D = 0.789), lowest Shannon diversity (H' = 0.519), lowest evenness (J' = 0.267) concentrated at ST01, directly under the cage structures. This gradient weakened with distance from the cages, with ST03 remaining relatively unaffected and displaying community structure closer to a natural spring assemblage. The directional nature of this impact, already evident in the chlorophyll-a and nutrient data, is further supported by the diversity indices: the western and northern stations (ST04 and ST02) showed stronger enrichment signals than the eastern and control stations (ST03 and ST05), consistent with the dominant current patterns at this site during the spring campaign.

The detection of *Alexandrium* sp. at ST03, though at low density, reinforces the importance of continued phytoplankton monitoring at the Ain Taya site. In shellfish aquaculture systems where mussels and clams filter large volumes of water and can accumulate algal toxins rapidly even low *Alexandrium* densities represent a precautionary trigger for increased monitoring frequency. The absence of *Dinophysis* caudata and *Noctiluca* scintillans during both campaigns suggests that the site had not yet developed conditions favouring these large-celled, bloom-forming dinoflagellates, but their known occurrence in Algerian coastal waters (Djerioui, 2015) warrants continued vigilance, particularly in summer when thermal stratification intensifies.

The diversity values recorded at Ain Taya can be compared to those reported in other Algerian and Mediterranean aquaculture studies to assess the relative degree of community disturbance. Nefraoui H. et Tabi N.E.Y., 2015 reported markedly lower Shannon-Weaver diversity at stations directly influenced by cage structures compared to undisturbed reference stations in Algerian shellfish and fish farming areas, a pattern consistent with the H' = 0.519 recorded at ST01 in May in the present study. The Simpson dominance index of D = 0.789 at ST01 exceeds the levels that Nefraoui H. et Tabi N.E.Y., 2015 associates with algal bloom conditions in Algerian aquaculture zones, confirming that the cage centre reached a biologically disturbed state during the spring campaign. At the Algerian coastal level, Nefraoui H. et Tabi N.E.Y., 2015 studying phytoplankton dynamics along the Algerian coast, documented that diatom-dominated communities with reduced Shannon diversity are characteristic of nutrient-enriched coastal zones, a pattern directly comparable to the H' = 0.519 recorded at ST01 in May in the present study.

Within the Algerian context, Nefraoui H. et Tabi N.E.Y., 2015 documented that phytoplankton assemblages along the Algerian coast are dominated by dinoflagellates followed by diatoms, with Chlorophyceae, Euglenophyceae, and Cryptophyceae as minor groups. In contrast, the diatom dominance observed at Ain Taya, particularly the monoculture bloom of Skeletonema sp. at ST01 in May, reflects the nutrient-enriched and well-mixed conditions specific to the cage-influenced zone, where silica availability and dissolved inorganic nitrogen favour fast-growing diatoms over motile dinoflagellates. Belkacemi et Meddahi(2021) similarly reported diatom

dominance (Bacillariophyceae, 59.7%) along the eastern Algiers coast during spring, consistent with the seasonal pattern observed at our site. At the international level, Challouf et al. (2017) in Monastir Bay identified 106 phytoplankton taxa versus the 15 taxa identified in this study, a difference primarily attributable to the much greater sampling duration (12 months versus 2 campaigns) and spatial coverage (11 versus 5 stations) of the Tunisian study, rather than to inherent differences in habitat diversity. Rebbah et al. (2025) at Beni Haroun Dam recorded genera including Oscillatoria, Anabaena, and Ceratium. freshwater and brackish taxa not observed at the marine Ain Taya site. This confirms that, while the underlying nutrient-enrichment mechanism may be comparable, the resulting community composition differs fundamentally between continental (freshwater/brackish) and marine systems.

CONCLUSION

This study was conducted at the Aquasparidae floating-cage aquaculture site in Ain Taya, east of Algiers, over two seasonal campaigns in February and May 2026, with the objective of assessing the environmental influence of the farm's floating fish cages on the surrounding coastal water quality and phytoplankton community. Five parameters were monitored at five stations positioned around the cages: total suspended solids, dissolved inorganic nutrients, chlorophyll-a concentration, phytoplankton taxonomic composition, and ecological diversity indices.

The results demonstrate that the Aquasparidae installation exerts a measurable but spatially limited influence on its coastal environment. A consistent nitrogen enrichment gradient was observed around the cage centre (ST01), with nitrate and ammonium concentrations reaching their highest values at this station during both campaigns. The enrichment signal was far more pronounced in May, when nitrate concentration at ST01 reached 0.8097 µmol/L, roughly a fivefold increase relative to February, reflecting increased fish metabolism at higher water temperatures and reduced dilution under stratified spring conditions.The phytoplankton community was dominated by diatoms throughout both campaigns, with *Skeletonema* sp. as the consistently dominant taxon. Fifteen taxa were identified in total across the study. The spring campaign revealed a substantial increase in cell density at all stations, with ST01 reaching

45,640 cells L^{-1}. This increase in abundance was accompanied by a marked reduction in community diversity at the nutrient-enriched stations: the Shannon-Weaver index at ST01 fell from H' = 1.027 in February to H' = 0.519 in May, while the Simpson dominance index rose from D = 0.490 to D = 0.789, indicating near-monoculture conditions at the cage centre during the spring bloom.One potentially harmful species, *Alexandrium* sp., was detected at ST03

during the May campaign, at a low density of 40 cells L^{-1}. Although this density remains far below levels of immediate concern, its presence justifies continued phytoplankton toxin monitoring, particularly to protect the shellfish farming activity at the site.Chlorophyll-a concentrations showed the strongest seasonal contrast of all parameters measured, rising from below 12 µg/L at every station in February to a maximum of 583.91 µg/L at ST01 in May. The control station, ST05, also recorded a modest increase to 11.36 µg/L in May, suggesting that its current position 100 metres from the cages may not fully capture background conditions once the farm reaches peak biological activity in spring.Taken together, these results show that the Aquasparidae site produces a detectable seasonal environmental signal, characterised by elevated

nutrients, high phytoplankton biomass, and reduced community diversity concentrated near the cages, which attenuates with distance and does not currently indicate a severe ecological

disturbance. The pronounced seasonal amplification of this signal between winter and spring, together with the detection of a harmful algal species, nonetheless indicate that the site should continue to be monitored as production levels evolve. As perspectives for future work, this study recommends extending the monitoring programme to include summer and autumn campaigns; incorporating physicochemical parameters such as temperature, salinity, and dissolved oxygen; applying multivariate statistical analysis to help separate farm-derived from natural sources of nutrient variability; and conducting sediment analysis beneath the cages to assess the installation's benthic impact.

BIBLIOGRAPHICAL REFERENCES

AFNOR, 2005. NF EN 872 .Qualité de l'eau .Détermination des matières en suspension,Méthode par filtration sur filtre en fibre de verre. AFNOR, Paris : 14 p.

Agence Presse Service (APS), 2023. Le littoral algérien passe de 1 622 km à 2 148 km. Dépêche APS, 26 juin 2023, Alger.

Aminot A. et Chaussepied M., 1983. Manuel des analyses chimiques en milieu marin. CNEXO, Éditions Jouve, Paris : 395 p.

Belkacemi A. et Meddahi M., 2021. Biodiversité et composition du phytoplancton et du microphytobenthos de la côte Est Algéroise. Mémoire de master, option Biologie Marine, ENSSMAL, Alger : 93 p.

Ben Souissi J., Laabir M., Yahia M.N.D. et Ben Souissi A., 2017. Phytoplankton community and water quality assessment near a sea-cage fish farm in the south-western Mediterranean. Aquacult. Environ. Interact., 9 : pp 273–288. DOI : 10.3354/aei00213.

Beveridge M.C.M., 2004. Cage Aquaculture. 3rd ed. Blackwell Publishing, Oxford : 380 p.

Boudouresque C.-F., 2004. Marine biodiversity in the Mediterranean: status of species, populations and communities. Sci. Rep. Port-Cros Natl. Park, 20 : pp 5–146.

Boufeniza R.L., 2021. Évaluation de la couleur et de la qualité biologique des eaux marines de la côte algéroise à partir de l'imagerie satellite et modélisation du phytoplancton marin. Thèse de doctorat 3ème cycle LMD, ENSSMAL, Alger : 202 p.

Challouf R., Hamza A., Mahfoudhi M., Ghozzi K. et Bradai M.N., 2017. Environmental assessment of the impact of cage fish farming on water quality and phytoplankton status in Monastir Bay (eastern coast of Tunisia). Aquaculture International, 25 : pp 2275–2292. DOI : 10.1007/s10499-017-0187-1.

Djerioui A., 2015. Contribution à l'étude du phytoplancton nocif dans des zones confinées de la région d'Alger port et plage d'Eldjamila, port et plage de Sidi fredj. Mémoire de master, ENSSMAL, Alger : 110 p.

EPA, 1974. Methods for Chemical Analysis of Water and Wastes. Environmental Protection Agency, Cincinnati : 491 p.

FAO, 2006. Environmental impact assessment and monitoring in aquaculture. FAO Fisheries and Aquaculture Technical Paper, 527. FAO, Rome : 648 p.

Illoul H., 1987. Contribution à l'étude qualitative, quantitative et structurelle des populations phytoplanctoniques au large du Cap Caxine. Mémoire de Magister, ENSSMAL (Ex-ISMAL), Alger : 98 p.

Jeffrey S.W. et Humphrey G.F., 1975. New spectrophotometric equations for determining chlorophylls a, b, c1 and c2 in higher plants, algae and natural phytoplankton. Biochem. Physiol. Pflanz., 167 : pp 191–194.

Magurran A.E., 2004. Measuring Biological Diversity. Blackwell Publishing, Oxford : 256 p.

Messaoudene F. et Loubar S., 2009. Contribution à l'étude des sites à potentialités aquacoles en Baie de Bou-Ismail : paramètres physico-chimiques et peuplement phytoplanctonique. Mémoire de fin d'études en Sciences de la Mer, option Aquaculture, ENSSMAL, Alger : 72 p.

MPRH, 2008. Schéma directeur de développement des activités de la pêche et de l'aquaculture, **Horizon 2025**. Ministère de la Pêche et des Ressources Halieutiques, Alger : 87 p.

Nefraoui H. et Tabi N.E.Y., 2015. Dynamique et diversité du phytoplancton de la côte Algérienne. Mémoire de master, ENSSMAL, Alger : 85 p.

Rebbah A.C., Bouchareb N., Lalaoui M. et al, 2025. Impact of physico-chemical parameters on the spatial distribution of phytoplankton in Beni Haroun Dam (Mila, Northeastern Algeria). Egyptian Journal of Aquatic Biology and Fisheries, 29 (4) : pp. 969–988. DOI : 10.21608/ejabf.2025.442612.

République Algérienne Démocratique et Populaire, 2003. Loi n° 03-10 du 19 juillet 2003 relative à la protection de l'environnement dans le cadre du développement durable. Journal Officiel de la République Algérienne Démocratique et Populaire, n° 43, 20 juillet 2003.

Rodier J., Bazin C., Broutin J.P., Chambon P., Champsaur H. et Rodi L., 2005. L'analyse de l'eau : eaux naturelles, eaux résiduaires, eau de mer. 8ème éd. Dunod, Paris : 1383 p.

Skalar Analytical, 2000. San Continuous Flow Analyser Operator Manual. Skalar Analytical B.V., Breda : 210 p.

Smayda T.J., 1997. Harmful algal blooms: their ecophysiology and general relevance to phytoplankton blooms in the sea. Limnol. Oceanogr., 42 (5) : pp 1137–1153.

Taguemount A., Kherici N., Bouaicha N. et Benali I., 2023. Aquaculture in Algeria: current status and considerations for commercial development. Asian J. Fish. Aquat. Res., 25 (5) : pp 53–68.

Tlidjane I., 2013. Contribution à l'étude qualitative, quantitative et structurelle des populations de phytoplancton de la Baie de Bou-Ismail, cas du site « le vivier ». Mémoire d'Ingénieur d'État en Sciences de la Mer, option Aquaculture, ENSSMAL, Alger : 93 p.

Utermöhl H., 1958. Zur Vervollkommnung der quantitativen Phytoplankton-Methodik. Mitt. Int. Ver. Theor. Angew. Limnol., 9 : pp 1–38.

Vollenweider R.A., Giovanardi F., Montanari G. et Rinaldi A., 1998. Characterization of the trophic conditions of marine coastal waters with special reference to the NW Adriatic Sea: proposal for a trophic scale, turbidity and generalized water quality index. Environmetrics, 9 (3) : pp 329–357.

APPENDICES

Appendice I. Simplified Protocol for Chlorophyll-a Analysis

The following protocol was used for the extraction and spectrophotometric determination of chlorophyll-a at ENSSMAL laboratory, based on the Jeffrey et Humphrey (1975) equations.

Materials required: GF/F glass fibre filters (0.7 µm porosity), vacuum filtration pump, amber-coloured glass tubes, 90% acetone (10 mL per sample, approximately 170–180 mL total for 5 stations across 3 campaigns plus blanks), centrifuge, double-beam spectrophotometer (664 nm, 647 nm, 630 nm, 750 nm), pipettes and graduated glassware, refrigerator (4°C, in darkness).

Steps:

Step 1 – Filtration: Filter 250 mL of seawater under low vacuum through a pre-labelled GF/F filter.

Step 2 – Preservation: Fold the filter, wrap it in aluminium foil and store at 4°C until extraction.

Step 3 – Extraction: Place the filter in a glass tube with 10 mL of 90% acetone. Leave in the refrigerator for 12 to 24 hours in complete darkness.

Step 4 – Clarification: Centrifuge at 3,000 g for 10 minutes to obtain a clear extract.

Step 5 – Blank preparation: Fill a cuvette with pure 90% acetone (no sample) and set the spectrophotometer to zero. This blank corrects for the absorbance of the solvent and the cuvette itself.

Step 6 – Spectrophotometric reading: Measure the absorbance of the extract at 750 nm, 664 nm, 647 nm and 630 nm. Subtract the 750 nm value from each reading to correct for turbidity.

Step 7 – Calculation: Apply the Jeffrey et Humphrey (1975) equations to obtain the chlorophyll-a concentration in µg/L.

Example of blank correction: if A664 (sample) = 0.420 and A664 (blank) = 0.020, then corrected A664 = 0.400. Apply the same correction at 647 nm and 630 nm before using the equations.

Appendice II. Protocol for Total Suspended Solids (TSS) – Gravimetric Method (NF EN 872)

Materials required: analytical balance (precision 0.01 g), 5 mm sieve, Whatman GF/C glass fibre filters, Büchner funnel and filtration flask, vacuum pump, oven set at 105°C, distilled water.

Steps:

Step 1 – Filter preparation: Rinse the GF/C filter with distilled water. Dry in the oven at 105°C for 2 hours. Weigh to 0.01 g precision → this is the initial mass (m^I).

Step 2 – Filtration: Pass 250 mL of pre-screened water (5 mm sieve) through the prepared filter under vacuum.

Step 3 – Drying and weighing: Place the filter in the oven at 105°C until constant mass is reached (approximately 12 hours). Weigh again → this is the final mass ($m\dot{f}$).

Step 4 – Calculation: TSS (mg/L) = ($m\dot{f} – m^I$) × 1000 / V, where V is the filtered volume in mL.

Note: For highly turbid waters (e.g., at stations closest to the cage structures such as ST01 and ST04), centrifugation at 4000–5000 rpm for 10 minutes may be used as an alternative, recovering the pellet and drying it under the same conditions (AFNOR, 2005).

Appendice III. Utermöhl Counting Sheet – Phytoplankton Cell Enumeration

Utermöhl (1958) was used for the enumeration and identification of phytoplankton cells. The counting sheet below summarises the multiplication factors used at ENSSMAL, depending on the sedimentation volume and the area observed under the inverted microscope.

Sedimentation volumes and corresponding multiplication factors: for a 50 mL chamber, the factor for a half-chamber count is 40 (full chamber: 20); for 25 mL, it is 80 (full: 40); for 10 mL, it is 200 (full: 100); for 2 mL, it is 1000 (full: 500).

Micrometric calibration (2 mm calibration slide, 1 division = 0.01 mm): at ×10 objective: 100 divisions = 1990 µm; at ×20 objective: 100 divisions = 500 µm; at ×40 objective: 80 divisions = 200 µm.

General counting formula: $N = (n \times S) / (s \times V)$, where N is the number of cells per litre, n is the number of cells counted, S is the total surface area of the chamber, s is the surface area observed, and V is the volume sedimented in litres.

Counting strategy: when cell density is low (fewer than 100 individuals of the target species in the entire chamber), the entire chamber floor should be scanned. When density is high, count along transects or fields at ×200 to ×400 magnification and calculate the mean. Always aim to count at least 100 cells of the dominant species to keep the counting error below 20%.


ENSSMAL
LCVRM
CIAMEL
banbiom
Pelagos
Certificate Of Participation
This certificate is awarded to
Messaoui Yousra, Meslem Nabila and Hammadi Ouahiba
In recognition of their participation in the 2nd edition of the conference entitled
"Anthropogenic Interactions with the Sea and the Coastal Zone:
Observation And Ecosystem-Based Management"
Held on June 8th 2026 with a poster entitled "Phytoplankton and Aquaculture Sustainability: Biological Indicators for the Sustainable Management of Farming Areas".
The Director of LCVRM
فريمس سمير
مدير مخبر بحث
Laboratoire CVRM ENSSMAL
The Director of ENSSMAL
الأستاذ: مزوار خوضير
مكلف بتسيير الشؤون إدارة المدرسة