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SUBJECT

Study of the Bioaccumulation of trace metals by the Main Small Pelagic Species Along the Algerian Coast

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Thesis Defense held on July 10th, 2025, in front of the examination committee composed of:

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Dedication

I dedicate this work, first and foremost, to **my younger self**
Thank you for your patience, your will to keep going, and your quiet courage.
You held on when it was hard, you turned your fears into strength, and your pain into resilience.
Be proud, one of our dreams has just come true.

I dedicate this work to **my beloved parents**,
The ones who may not have given me life, but who gave me something even greater:
The meaning of life.
You raised me with love, taught me values, and inspired me to become the best version of myself.
For everything you've done, I am endlessly thankful.

I also dedicate this work to the memory of **my biological father**
You are no longer here, but I carry your presence with me every step of the way.
I hope you're proud of the woman I've become.

To my dear nieces, **Wiam and Bouchra**
You are pure joy in my life.
I dream of seeing you grow, thrive, and reach heights far beyond my own.

To my precious friends **Abir, Zaina, Houda, Shanna, Selma, Mélissa and Manel my sweet little one,**
Thank you for standing by me through both the light and the dark.
Your presence gave strength to every step of this journey.

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May your passion lead you far.
Believe in yourselves, and don't stop until your dreams become your reality.

To my **IEMC classmates**
I hope we meet again, not just as graduates, but as fulfilled individuals, proud of what we've become.

And finally, to everyone who helped me near or far, with words or silence, with gestures or presence
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This success carries a part of each of you

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This journey has been a true odyssey, and it is with immense joy that I share today the fulfillment of this dream turned into reality. Thank you to everyone who contributed, near or far, to this wonderful adventure!

List of Acronyms

°C: Degrees Celsius

‰: Parts per thousand

AAS: Atomic Absorption Spectrometry

Ad: Adult

Ag: Silver

AW: Atlantic water

Cd: Cadmium

Ch: Child

cm/s: Centimeters per second

cm: Centimeter

cm^3: Cubic centemeter

CNL: National coastal center

CNRDPA: National Center for Research and Development of Fisheries and Aquaculture

Co: Cobalt

Cr: Chromium

CRL: Consumption rate limit

CTF: Cape tres Forcas

Cu: Copper

D.W: Dry weight

E: East

EDI: Estimated dietary intake

ENSSMAL: National Higher School of Marine Sciences and Coastal Management

FAO: Food and Agriculture Organization

Fe: Iron

FIGIS: Fisheries Global Information System

FL: Fork length

g: Gram

HI: Hazard index

Hg: Mercury

HgS: Mercury sulfide

ICES: International Council for the Exploration of the Sea

Kg: Kilogram

Km: Kilometer

LIW: Levantine Intermediate Water

Lm: Length at first maturity

m/s: Meters per second

m: Meter

MAW: Modified Atlantic Water

mm: Millimeter

Mn: Manganese

Mo: Molybdenum

MPRH: Ministry of Fisheries and Marine Resources

MREE: Rare Earth Elements

N: North

ng: Nanogram

Ni: Nickel

ONS: National Statistics Office

Pb: Lead

pg: Picogram

pH: Potential of hydrogen

ppt: Parts per thousand

PSU: Practical Salinity Unit

S: South

Se: Selenium

SL: Standard length

TF: Transfer factor

THQ: Target hazard quotient

Ti: Titanium

TL: Total length

UNDPA: United Nations Department of Political Affairs

USA: United states of Ameria

USNWC: United States Naval Weather Center

V: Vanadium

W.W: Wet weight

W: West

WWF: World Wide Fund for Nature

Zn: Zinc

μg/L: Micrograms per liter

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Introduction

INTRODUCTION

Marine pollution has emerged as one of the most pressing environmental challenges of our time, intensifying over recent decades as a direct consequence of expanding human activities. Among the myriad pollutants threatening our oceans, trace metals stand out as particularly worrisome due to their high toxicity, persistence, resistance to degradation, and their alarming ability to bioaccumulate and biomagnify through marine food webs (Gusso Choueri et al., 2015; Storelli et al., 2005). Once introduced into the marine environment via urban runoff, industrial discharges, or agricultural effluents, these metals tend to accumulate in sediments and living organisms, posing significant ecological threats to marine life and serious health risks to humans who consume contaminated seafood (Gutiérrez et al., 2018; Cinnirella et al., 2013; Galgani et al., 2011).

The Mediterranean Sea, a semi-enclosed basin, is especially vulnerable to chemical pollution. Its limited water exchange and densely populated coastlines create a ‘trap’ where contaminants, including trace metals, build up over time, degrading marine habitats and compromising the safety of seafood (Romeo et al., 2015). Algeria’s coastline, stretching over 1,200 kilometers, is increasingly under pressure from rapid coastal urbanization, intense maritime traffic, and the discharge of untreated waste (Refes, 2011; Benzohra & Millot, 1995).

While considerable research has focused on metal contamination in bottom-dwelling fish and benthic invertebrates, small pelagic fish species have received far less scientific attention despite their crucial ecological roles, commercial importance, and widespread consumption, particularly in Mediterranean countries like Algeria, Tunisia, and Egypt (Tsikliras & Antonopoulou, 2006). Species such as *Sardinella aurita* and *Sardina pilchardus* are among the most heavily fished and consumed along the Algerian coast, forming the backbone of the regional fisheries economy. Thanks to their abundance, short lifespans, low trophic positions, and constant exposure to coastal waters, these species serve as excellent sentinels for monitoring environmental metal pollution.

Furthermore, the buildup of trace metals in both edible tissues (like muscle) and key metabolic organs (such as liver, gills, and gonads) of these fish represents a tangible health risk for consumers. Regular monitoring of these contaminants is therefore vital, not just for environmental risk assessment, but also for food safety and the sustainable management of marine resources (Storelli et al., 2005, Gabr & Gab-Alla, 2008).

In light of these considerations, the present study sets out to assess the bioaccumulation of selected trace metals (including Cd, Pb, Cu and Zn) in small pelagic fish species essentially: *Sardina pilchardus, Sardinella aurita, Boops boops, Engraulis encrasicolus*, *Trachurus trachurus*, and *Trachurus mediterraneus* collected from various fishing zones along the Algerian coast. Specifically, it investigates how metal accumulation varies according to fishing area, species, biochemical composition and across different organs (muscle and gills). The research also aims to provide a toxicological and health risk assessment of the fish samples in relation to international safety standards.

The thesis is structured as follows:

- Chapter I offers a comprehensive overview of trace metals in the marine environment, discussing their sources, pathways, bioavailability, and toxicological impacts, along with a detailed introduction to the studied fish species.
- Chapter II presents a description of the Algerian coast, highlighting its physical, biological, and anthropogenic characteristics relevant to the study.
- Chapter III details the materials and methods, including sampling strategy, laboratory analyses, and the protocols used for metal quantification and biological assessment.
- Chapter IV reports and discusses the results, examining metal concentrations in relation to biological and spatial variables, and evaluating potential health risks.

The thesis concludes with a summary of key findings and perspectives for future research.

Chapter I

Literature review

CHAPTER I: LITERATURE REVIEW

I.1 General Overview of metals in aquatic ecosystems

I.1.1 General Overview of Trace Metals

A metal is a chemical element, usually present in an ore, characterized by its specific luster, high electrical and heat conductivity, hardness, and malleability. Metals easily form alloys by their combination with other elements, as it has always been employed by humans since antiquity.

Heavy metals as a term refers to naturally occurring metallic elements, metals or, in some cases, metalloids characterized by high density, usually greater than 5 g/cm^3. However, this term is commonly used in a non-scientific and non-regulatory context (Miquel, 2001).

Heavy metals are ubiquitous in all environmental compartments, though usually present in trace quantities (Namr et al., 2006). The elements are hence referred to as "trace metals."

In seawater, metals can be present in ionic, dissolved, colloidal complexes, organometallic compounds, or adsorbed on organic or inorganic particulate matter.

While certain metals are essential for biological processes (trace elements), the majority have the ability to behave as environmental contaminants when their concentrations reach critical levels, which depend upon the physicochemical properties (speciation) of the element. Iron (Fe), copper (Cu), zinc (Zn), nickel (Ni), cobalt (Co), vanadium (V), selenium (Se), molybdenum (Mo), manganese (Mn), chromium (Cr), and titanium (Ti) are some of these(Bendjeddou, 2013).

On the contrary, certain metals have no known biological purpose and can be toxic, such as mercury (Hg), lead (Pb), cadmium (Cd), and silver (Ag).

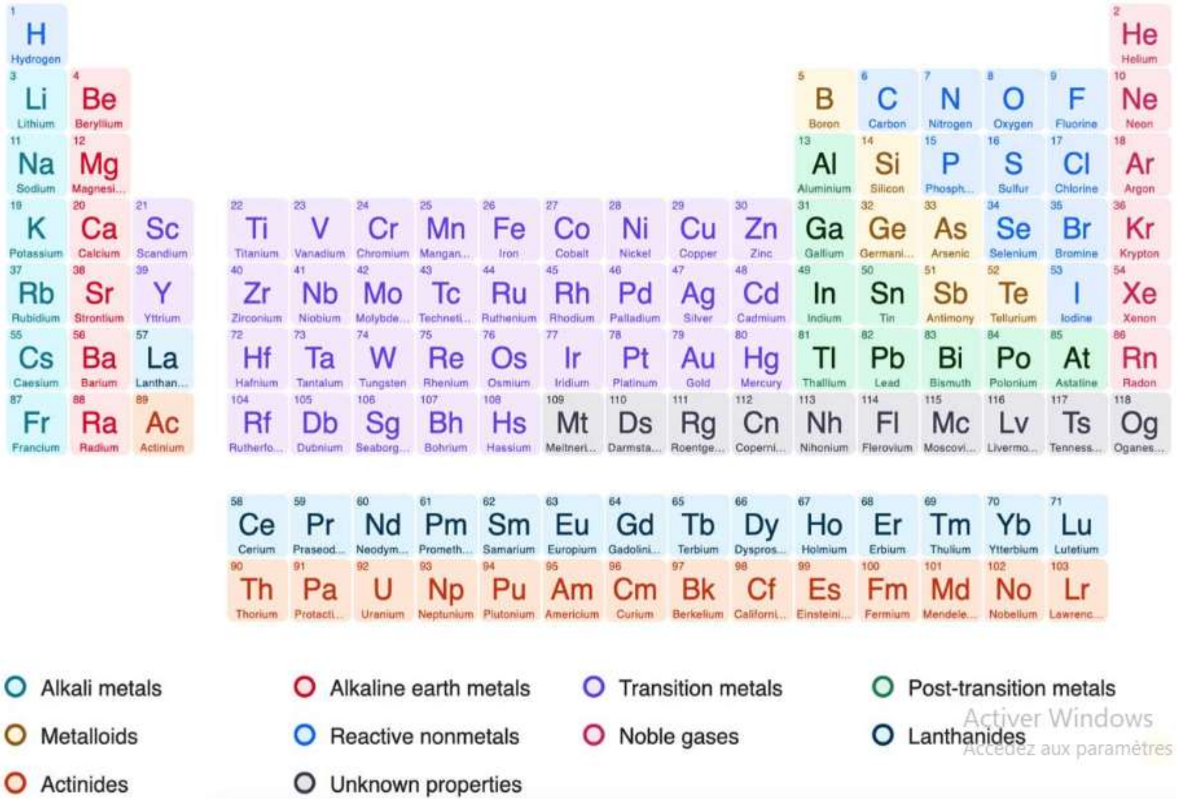


Figure 1 : Periodic Table of Elements
Source: https://www.daviddarling.info/encyclopedia/P/periodic_table.html

I.1.1.1 Physico-Chemical Properties of the Studied Metals

I.1.1.1.1 Non-Essential (Toxic) Elements

I.1.1.1.1.1 Lead (Pb)

Lead (Pb) is a naturally occurring metal that exists in its principal forms dissolved, colloidal, and particulate. It has high affinity for particulate matter with only an approximate 10% of lead in dissolved phase in the ocean. Lead adsorption on particulates is pH-dependent and increases with rising pH levels (Cossa et al., 1993; Marchand et Kantin, 1997). Lead tends to develop compounds with two or more elements and strongly binds with soil particles, settling predominantly in the upper levels of the soil (Gupta et al., 2008). Through soil erosion, lead-containing particles can be washed away by rainfall into water bodies and lakes, contributing to its level in these water bodies (Abadin et al., 2007).

I.1.1.1.1.2 Cadmium (Cd)

Cadmium (Cd) is a highly toxic element that is listed as a priority pollutant due to its environmental persistence and non-biodegradability. As a non-essential metal for biological systems, it has utmost importance in the areas of ecotoxicology and toxicology (Patel et al., 2021; Tian et al., 2021). Cd is present naturally in trace levels in the aquatic ecosystem (0.002–0.015 μg/L in uncontaminated rivers, to 2–3 μg/L or higher in surface water of the impacted environments); however, it is particularly present in commodities production and processing of industrialization, as well as in agricultural, mining, and chemical activities, where it is released or mobilized into the aquatic ecosystem in large amounts, causing threats to aquatic ecosystems (Delahaut et al., 2020; Lacave et al., 2020).

Elemental cadmium is not toxic to living organisms by nature but becomes hazardous when it is ionized to Cd^{2+}, which is biologically very toxic.

I.1.1.1.2 Essential elements (oligo-elements)

I.1.1.1.2.1 Copper (Cu)

Copper is a naturally occurring metal that is spread throughout the environment and is a ubiquitous contaminant in industrial effluents, primarily in mining and metallurgical process effluents (Aksu & Donmez, 2000; Savvaidis et al., 2003). Copper, being an essential micronutrient, acts as an essential component of numerous metalloenzymes and proteins (Lontie, 1984). However, at high levels, particularly in its free-ionic state, copper is cytotoxic to microbes and significantly affects microbial cell viability (Domek, 1984).

I.1.1.1.2.2 Zinc (Zn)

Zinc is a trace element involved in numerous metabolic processes, especially as a coenzyme. In the marine environment, it is present in various chemical forms, including hydrated ions ($Zn(H_2O)_2^{+n}$), complexes with organic ligands such as fulvic and humic acids, and as adsorbed species on particulate matter.

Similar to copper, zinc is an biologically important metal that is required in trace amounts by a very large number of marine organisms. However, although it is not a priority pollutant, elevated concentrations can disrupt physiological processes, most notably suppressing oyster reproduction and larval development (Bendjeddou, 2013).

I.1.2 Sources of contamination in marine environment

Water body contamination by trace metals is a result of various inputs, primarily categorized as natural or anthropogenic. Trace metals can enter sea environments through geological processes, atmospheric and riverine fluxes, and human involvement (Figure 2).

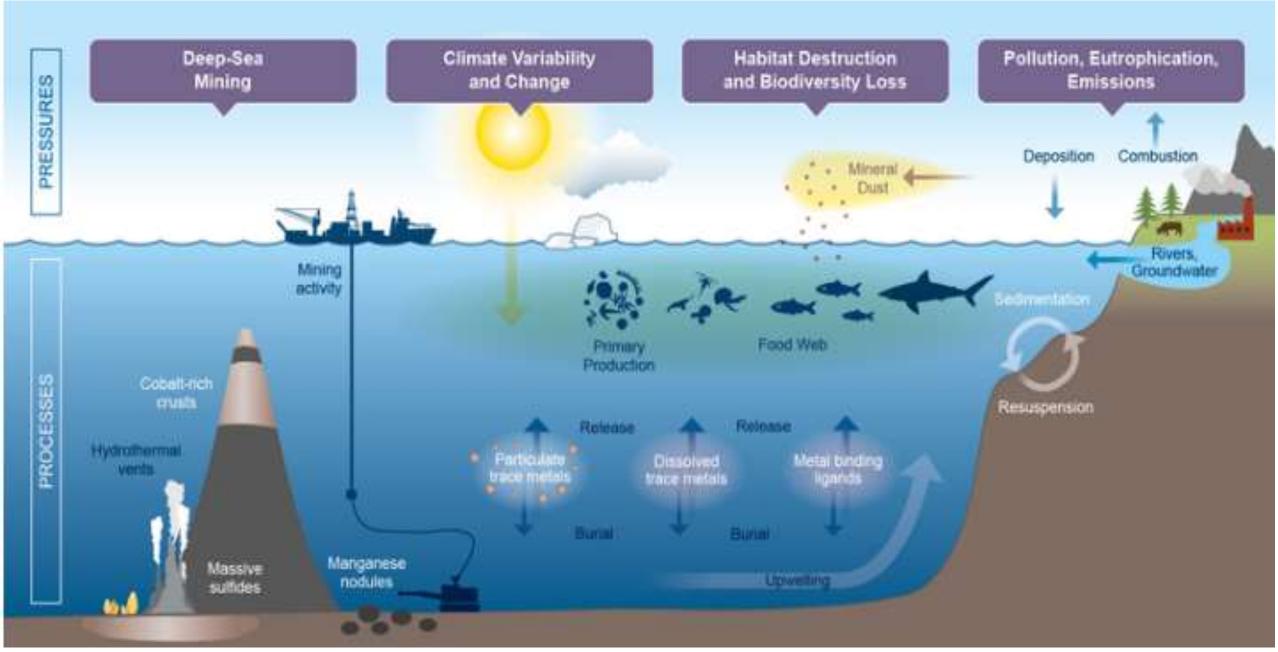


Figure 2 : Anthropogenic and Natural Pressures Driving Trace Metal Contamination in the Marine Environment

Source : https://www.geomar.de/en/research/irf/metals-in-the-ocean

I.1.2.1 Natural sources

I.1.2.1.1 Geological and Hydrological sources

Trace metals naturally exist in the Earth’s crust and find their way into water bodies through rock weathering, erosion, and mineral dissolution. Geological material releases metallic constituents into the environment when they come into contact with water and oxygen (Gilmour & Riedel, 2009). These levels are typically low and nonhazardous and even serve as needed nutrients for biological development. However, sometimes naturally occurring geological concentrations become toxic.

In addition, volcanic processes on land and in the deep ocean, and hydrothermalism, are significant input factors for trace metal concentration in deep ocean waters. Groundwater transport in aquifers and soil horizons prior to surfacing also contributes to the movement of trace elements into surface water bodies (de Souza Machado et al., 2016; Michael et al., 2005; Taniguchi et al., 2002).

I.1.2.1.2 Atmospheric and Riverine Inputs

Atmospheric deposition, including airborne particles and dust from various sources, introduces trace metals into aquatic environments. The particles can travel hundreds of miles before they settle in estuaries and coastal waters. Similarly, riverine inputs, resulting from weathering, leaching of the land, and erosion of rocks, contribute to trace metal loads on coastlines. Atmospheric and riverine inputs can either be natural or result from anthropogenic sources (Förstner and Wittmann, 2012).

I.1.2.2 Anthropogenic sources

For thousands of years, human activities have been the cause of mobilizing trace metals from geological reservoirs to surface ecosystems. Sources of anthropogenic trace metal pollution may be localized or diffuse and affect aquatic ecosystems, terrestrial systems, and the air (Förstner & Wittmann, 2012).

Major sources include mining, metal smelters, burning of fossil fuels, industrial and agricultural processes, and shipping. Trace metals released into the air ultimately settle and get redeposited into watersheds, and in turn, impact natural water systems (Gilmour & Riedel, 2009). Disturbance of metal-enriched ore through industrial mining and land-use alteration intensely accelerates the trace metal entry rate into the marine system (Förstner & Wittmann, 2012).

I.1.3 Metal Contaminants in Marine environment

I.1.3.1 Transport and Biogeochemical Cycling in Coastal Waters

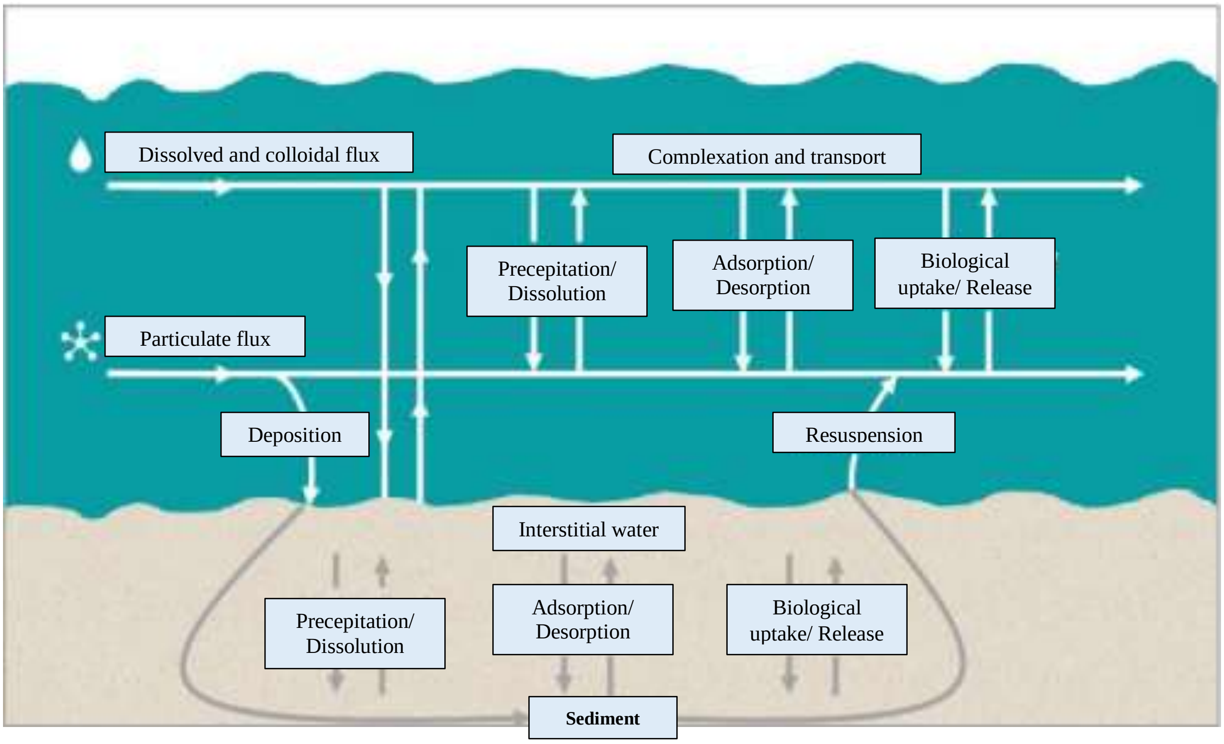


Figure 3 : Biogeochemical interactions ruling trace metal transfers in aquatic environments (adapted from Morrison et al., 1989)

Once introduced into estuarine and coastal systems, trace metals are subjected to complex biogeochemical cycles. These involve surface-to-deep-water transport by vertical processes, dilution, and reactions with sediment and organic matter. In addition, hydrodynamical processes, such as deep- and surface-water circulation, play a major role in transporting and distributing these elements within marine environments (Gaulier, 2020).

I.1.3.2 Trace Metal Contamination in Marine Sediments

One of the main sources of trace metal pollution sinks is marine sediments, especially in coastal regions that experience significant human stress. Because of its great potential for adsorption and interaction with other sediment constituents, these metals, which come from industrial effluents, urban wastewaters, and river transportation, preferentially settle in the fine fraction of sediment. Numerous physicochemical factors, such as grain size, organic matter content, and the redox state of the sediment–water border, influence the distribution and accumulation of trace metals (Atroune & Boutaleb, 2012).

Following deposition, the metals may become immobile by trapping in mineral phases or complexation with inorganic or organic ligands. However, sediments are not passive sinks. By altering the pH, redox potential, sediment resuspension, or bioturbation, the trace metals may be remobilized back into the water column above the sediment. This dynamic activity stresses the duality of marine sediments: they function both as long-term pollutants and secondary sources, increasing metal bioavailability and ecological risk (Atroune & Boutaleb, 2012).

I.1.3.3 Trace metal accumulation in marine biota

The contamination of marine ecosystems by trace metals is a less visible but highly active form of contamination that strongly affects both ecosystems and human health. These contaminants enter aquatic systems through industrial effluent, atmospheric deposition, and riverine inputs, ultimately accumulating within food webs. The biosphere, which comprises the lithosphere, atmosphere, and hydrosphere, encompasses the homeostatic balance necessary for life. However, industrialization and human activities have introduced contaminants that disrupt this equilibrium, necessitating continuous monitoring of air, water, and land content to locate and contain environmental deterioration (Athar & Vohora, 2001).

Trace metal accumulation in fish is a complex process regulated by various physiological parameters like age, developmental stages, and rate of metabolism (Khansari et al., 2005). Metal deposit location in an organism is dependent on exposure pathway, the metal exposed, and the species' physiological characteristics (Abida Begum et al., 2009). Aside from bioaccumulation, heavy metal toxicity also has the capacity to cause enormous behavioral derangements, such as disrupted locomotion, hence enhanced susceptibility to predation. Additionally, prolonged exposure has been linked to structural deformities, particularly vertebral deformation, thus adding more threats to individual survival and population stability in general (Gabr & Gab-Alla, 2008).

Polluted sediments also create a severe risk through exposure of benthic fauna such as worms, crustaceans and insects to poisonous metal levels. These pollutants can bioconcentrate in the tissue of the fauna, which subsequently is transferred to higher trophic levels through feeding interactions. This is a series of occurrences that describe how contaminants become concentrated and moved through ecosystems.

I.1.3.3.1 Bioaccumulation

Bioaccumulation refers to the process by which organisms absorb, store, and amass organic and inorganic contaminants from their surrounding environment. The process is a consequence of a complex interaction among several factors like pathways of absorption, excretion, passive removal, and metabolic transformations. Bioaccumulation in fish occurs by two primary routes of uptake: direct absorption of waterborne contaminants and ingestion of food particles that have already been contaminated (Streit, 1998) (Figure 4).

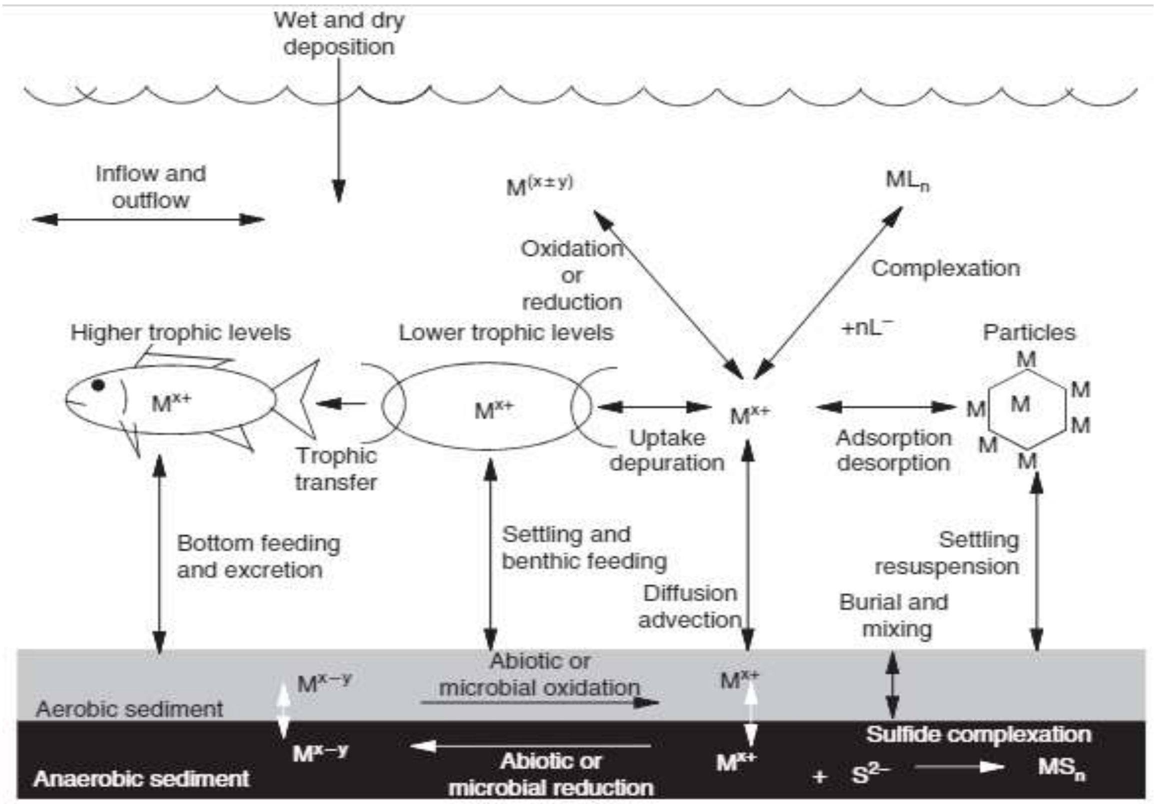


Figure 4 : Some of the major processes affecting the behavior of trace element cycling between water, sediments, and organisms (adapted from Gilmour & Riedel, 2009)

I.1.3.3.2 Bioconcentration

Bioconcentration is the accumulation of direct uptake of a chemical by an organism from the abiotic surrounding environment into a higher concentration within the organism than in the external medium (Rand, 1995). The original design of this concept was meant for describing the aquatic system behavior of hydrophobic organic chemicals and has been extended to encompass organic compounds and trace elements in various environmental matrices since then. For soil and sediment systems, bioconcentration of trace elements refers to the net accumulation within or on an organism of trace elements from porewater alone. Thus, when calculating bioconcentration in such a case, the appropriate reference concentration would be that of the trace element in porewater and not its total concentration in sediment or soil (McGeer et al., 2004).

I.1.3.3.3 Biomagnification

Biomagnification is an increase in concentration within an organism from one lower trophic level to a higher trophic level within the same food web due to bioaccumulation via the diet. Biomagnification can be measured relative to whole-body, tissue/organ-specific, or, where relevant, to lipid content. Organ- and tissue-specific issues of biomagnification for trace elements are problematic since the partitioning of trace elements to target organs (e.g., liver, kidney, brain) can be extremely species-variable and thus may not properly represent general biomagnification in the food chain (McGeer et al., 2004; Gray, 2002).

I.1.3.3.4 Bioavailability

Bioavailability defines the extent to which chemical substances are available to be absorbed by organisms and exert possible toxic effect (Alexander, 2000). The ability of pollutants to penetrate biological systems is influenced by numerous factors, including the organism type, exposure pathway, exposure time, and environmental factors like soil conditions (Peijnenburg & Jager, 2003). As a critical parameter, bioavailability controls the mobility and ecological impact of metal elements, and it is a valuable indicator for environmental hazard assessment. Aquatic organisms, including fish, ingest pollutants directly from contaminated water and indirectly through the food chain (Zhu et al., 2023).

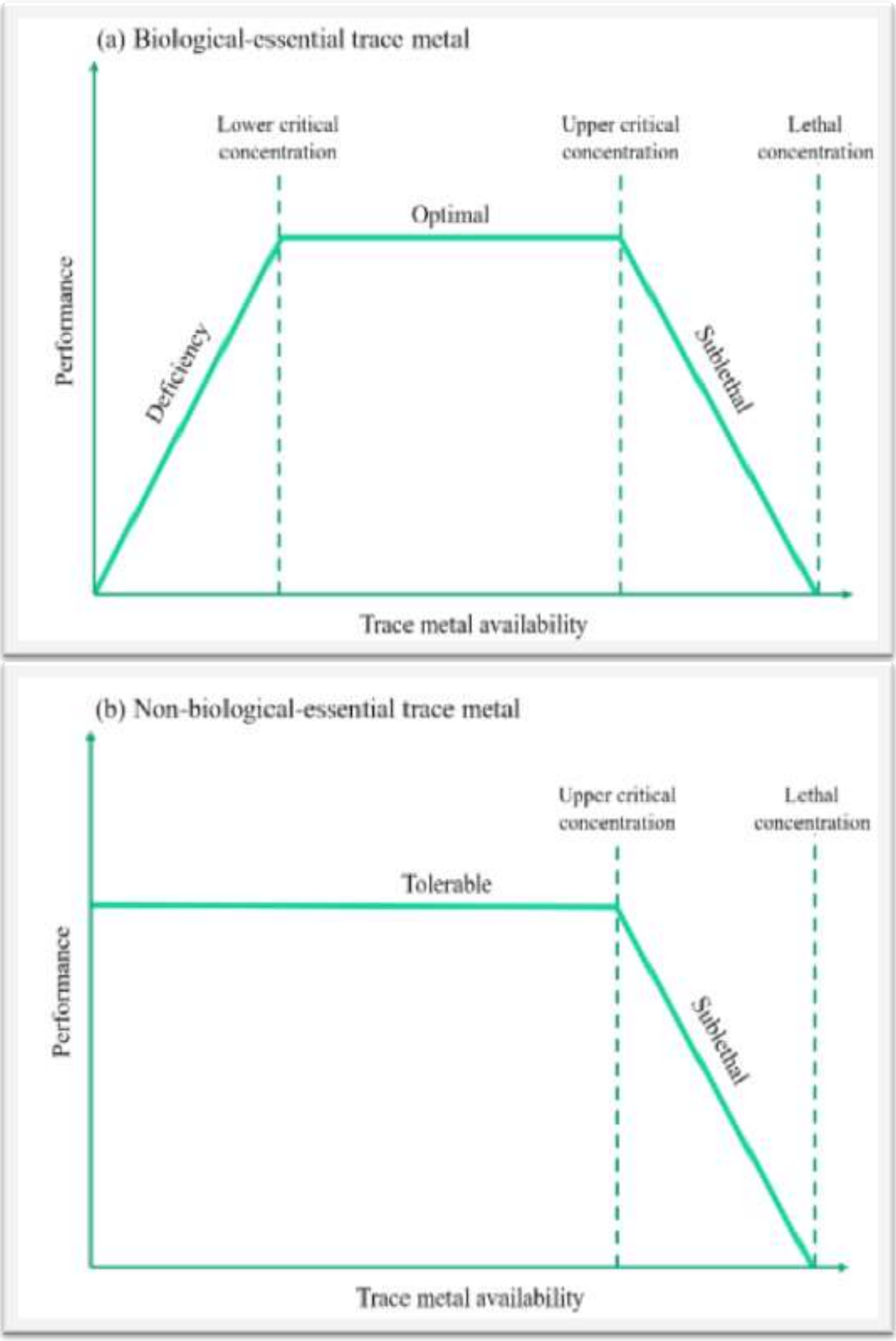


Figure 5 : Effects of increasing availability of (a) biological-essential and (b) non-biological-essential trace metals on the organism performance (i.e. yield, growth, survival, reproduction) (adapted from Luoma and Rainbow, 2011).

I.2 Overview of Small Pelagic Fish Studied

I.2.1 Definition of Small Pelagic Fish

Small pelagic fish are shoaling epipelagic fish with excellent horizontal and vertical mobility in coastal waters. They are 10–30 cm long as adults, although others define a middle-sized pelagic fish of 20–60 cm (Bas et al., 1995). Small pelagic fish play a crucial role in marine food webs, situated between the planktonic animal and higher predators at an intermediate trophic level.

They are largely planktivorous in nature, consuming microscopic organisms and, in turn, serve as an important food supply for numerous marine predators such as big fish, seabirds, and sea mammals (Blaxter & Hunter, 1982). Their schooling nature is responsible for their high biomass and intra-specific genetic heterogeneity, which makes them more robust to environmental changes (Ryman et al., 1995).

These species play a very significant role in upwelling systems, which have high species diversity in both the lower and upper trophic levels yet only a few species dominate the middle level (Gibbons et al., 1999). Their ecological function extends to world fisheries, where they represent a high proportion of catches of marine fish. Some of these such as anchoveta, herring, and pilchards form nearly half of the entire world pelagic fishery catch (FAO, 1997), showing their ecological and economic significance.

I.2.2 Presentation of the Studied Species

The Algerian waters are home to a diverse assemblage of small pelagic fish species, many of which hold significant commercial value. Among the most economically and ecologically important species are the European sardine (*Sardina pilchardus*), the round sardinella (*Sardinella aurita*), the bogue (*Boops boops*), the European anchovy (*Engraulis encrasicolus*), the Atlantic horse mackerel (*Trachurus trachurus*), and the Mediterranean horse mackerel (*Trachurus mediterraneus*).

I.2.2.1 Boops boops (Linnaeus, 1758)

I.2.2.1.1 Taxonomy and Classification

- Phylum: Chordata
- Class: Actinopterygii

- Order: Spariformes
- Family: Sparidae
- Genus: *Boops*
- Species: *Boops boops* (Linnaeus, 1758)

The bogue (*Boops boops*) is a teleost fish belonging to the Sparidae family (sea breams). Its name originates from the Greek words *bous* (ox) and *ops* (appearance) (Romero, 2002).

I.2.2.1.2 Morphology and Identification

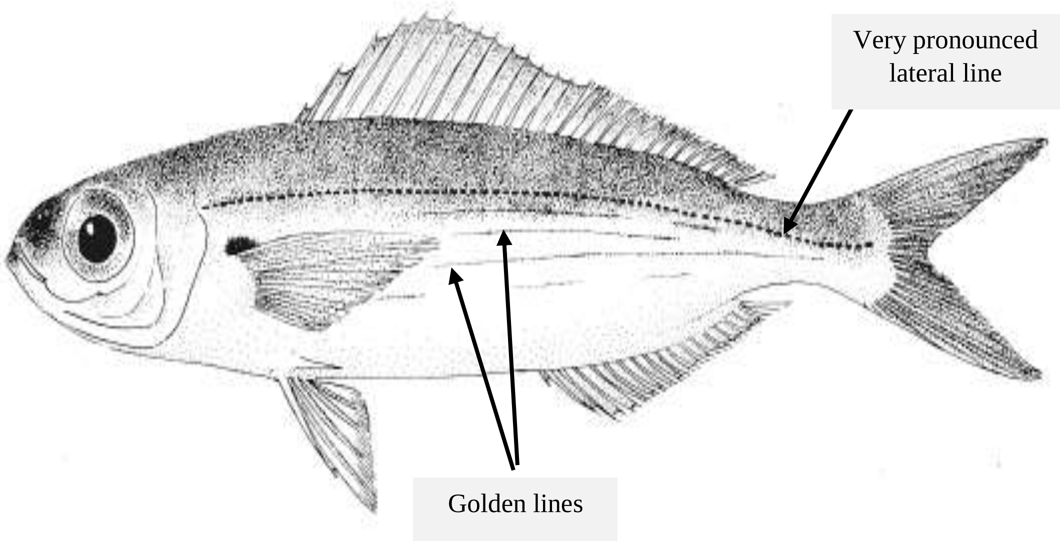


Figure 6 : Morphological Illustration of Boops boops (Linnaeus, 1758)
Source: https://fish-commercial-names.ec.europa.eu/fish-names/species/boops-boops_fr

The bogue has a slender body with 3 to 5 weak golden longitudinal stripes and a black spot at the base of the pectoral fin (Muus & Nielsen, 1999). Its fin structure includes:

- Dorsal fin: 13–15 spines, 12–16 soft rays ;
- Anal fin: 3 spines, 14–16 soft rays (Froese & Pauly, 2024).

I.2.2.1.3 Size and Longevity

- Length at first maturity: 13.6 cm (Froese & Pauly, 2024) ;
- Maximum length: 40 cm TL (Crec'hriou, Neveu, & Lenfant, 2013) ;
- Common length: 20 cm TL (Bauchot, 1987) ;
- Maximum weight: 455 g (Crec'hriou, Neveu, & Lenfant, 2013) ;

- Maximum age: 11 years (Monteiro et al., 2006).

I.2.2.1.4 Biology and Ecology

The bogue is omnivorous, feeding primarily on crustaceans and plankton. It is hermaphroditic, generally protogynous, although some reports suggest a gonochoristic reproductive strategy (Zei & Zupanovio, 1961; Buxton & Garratt, 1990; Sadovy de Mitcheson & Liu, 2008). It is commonly caught in pelagic trawls (Frimodt, 1995)

I.2.2.1.5 Habitat and Distribution

This gregarious semipelagic species inhabits the Eastern Atlantic, from Norway to Angola, including the Canary Islands, Cape Verde, and São Tomé and Príncipe, as well as the Mediterranean and Black Seas (Froese & Pauly, 2024; Bauchot & Hureau, 1986). It is commonly found at depths of 0 to 300 m, though it is more frequent above 150 m, exhibiting diel vertical migration, moving closer to the surface at night (Bauchot & Hureau, 1986).

I.2.2.1.6 Economic Importance

The bogue is commercially exploited, consumed fresh or frozen, and prepared pan-fried, broiled, or baked (Frimodt, 1995).

I.2.2.2 Trachurus trachurus (Linnaeus, 1758)

I.2.2.2.1 Taxonomy and Classification

- Phylum: Chordata
- Class: Actinopterygii
- Order: Carangiformes
- Family: Carangidae
- Subfamily: Caranginae
- Genus: *Trachurus*
- Species: *Trachurus trachurus* (Linnaeus, 1758)

The Atlantic horse mackerel (*Trachurus trachurus*) belongs to the Carangidae family (jacks and pompanos). The genus name *Trachurus* comes from the Greek words *trachys* (rough) and *oura* (tail) due to its characteristic rough tail scutes (Romero, 2002).

I.2.2.2.2 Morphology and Identification

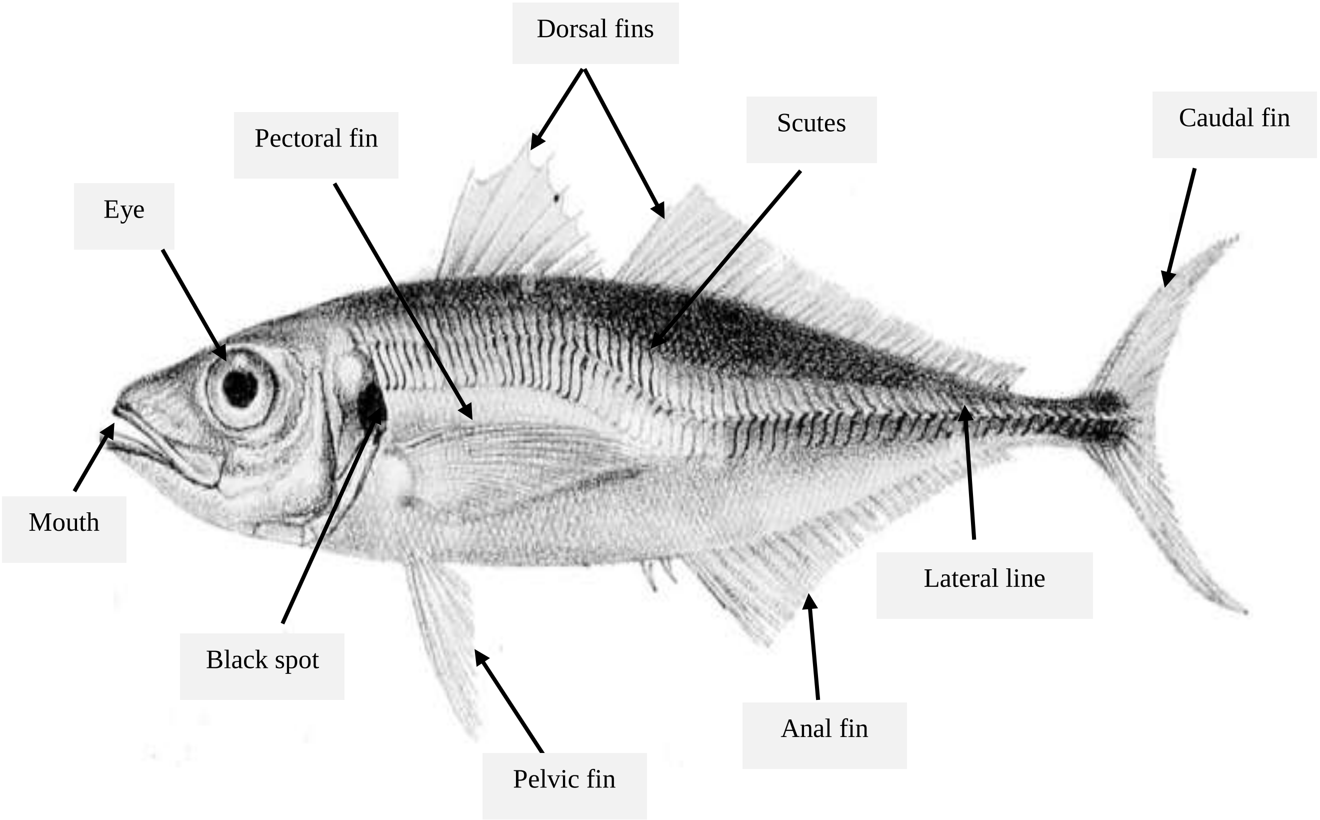


Figure 7 : Morphological Illustration of Trachurus trachurus (Linnaeus, 1758)
Source : https://www.alamy.com/stock-photo/trachurus-trachurus.html?cutout=1&sortBy=relevant

The Atlantic horse mackerel has an elongated, compressed body with a relatively large head. It features tall, keeled lateral scales, and a distinct black spot on the operculum. The species' coloration varies from bluish-green, grey, or black dorsally to silvery-white ventrally (Smith-Vaniz, 1986). Its fin structure includes:

- Dorsal fin: 9 spines, 30–36 soft rays ;
- Anal fin: 3 spines, 24–32 soft rays (Froese & Pauly, 2024) ;
- First dorsal fin: Tall and well-developed (Muus & Nielsen, 1999).

I.2.2.2.3 Size and Longevity

- Length at first maturity: 22.9 cm (range: 21–30 cm) (Froese & Pauly, 2024) ;
- Maximum length: 70 cm TL (Smith-Vaniz, 1986) ;
- Common length: 22 cm FL (Bauchot, 1987) ;
- Maximum published weight**:** 2 kg (Ly, Diop, & Girardin, 1996).

I.2.2.2.4 Biology and Ecology

The Atlantic horse mackerel is a highly migratory schooling species, commonly found in coastal areas with sandy substrates. It primarily feeds on fish, crustaceans, and cephalopods. This species is a batch spawner, with females producing up to 140,000 pelagic eggs, which hatch into 5 mm larvae ((Murua & Saborido-Rey, 2003; Muus & Nielsen, 1999; Smith-Vaniz, 1986).

The population is divided into two main stocks:

- Western stock: Spawns from the Bay of Biscay to Ireland in early spring and migrates northward to southern Norway and the northern North Sea.
- North Sea stock: Spawns in the southern North Sea during summer and migrates to the central North Sea, Skagerrak, and Kattegat (Froese & Pauly, 2024).

I.2.2.2.5 Habitat and Distribution

This oceanodromous species inhabits marine subtropical waters from Norway to South Africa, including the Mediterranean Sea, the Black Sea, and the Central-West Atlantic (Eymarde, 2003). It is found at depths ranging from 0 to 1050 m, but it is most commonly observed between 100 and 200 m (FAO-FIGIS, 2005). Its distribution extends from Madeira, the Straits of Gibraltar, and the Canary and Cape Verde Islands to South Africa, reaching northward along the European Atlantic coast up to Norway (Froese & Pauly, 2024).

I.2.2.2.6 Economic Importance

The Atlantic horse mackerel is commercially exploited and is consumed fresh, smoked, canned, or frozen. It is commonly fried, broiled, or baked (Frimodt, 1995).

I.2.2.3 Trachurus mediterraneus (Steindachhner ,1868)

I.2.2.3.1 Taxonomy and Classification

- Phylum: Chordata
- Class: Actinopterygii
- Order: Carangiformes
- Family: Carangidae
- Subfamily: Caranginae

- Genus: *Trachurus*
- Species: *Trachurus mediterraneus* (Steindachner, 1868)

The name Trachurus derives from the Greek words trachys (rough) and oura (tail), referring to the species' rough-tailed appearance (Romero, 2002).

I.2.2.3.2 Morphology and Identification

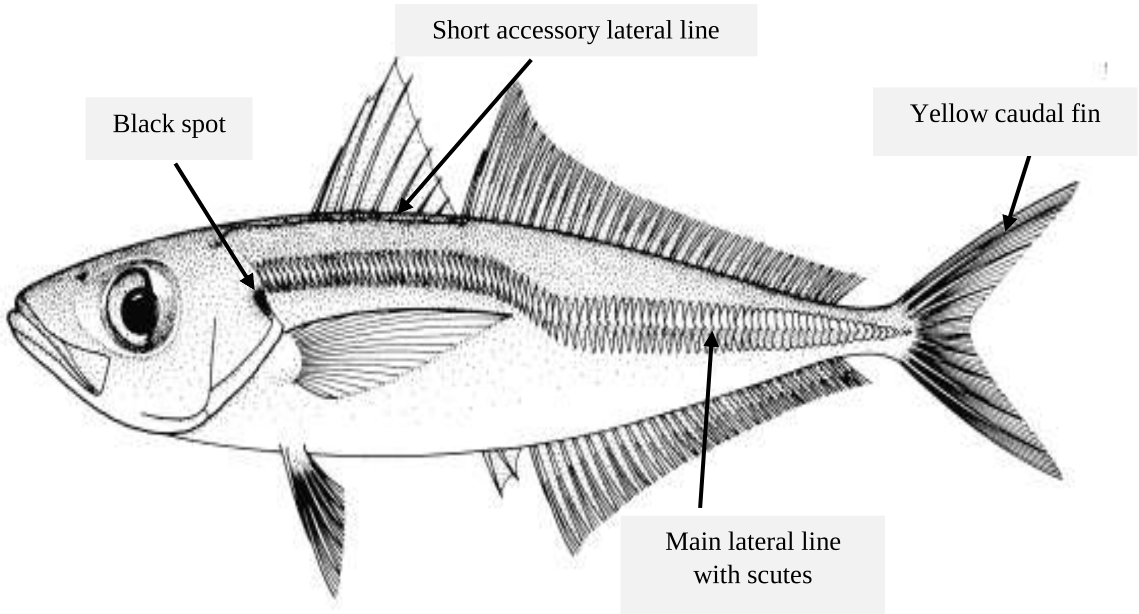


Figure 8 : Morphological Illustration of Trachurus mediterraneus (Steindachner, 1868)
Source : https://fish-commercial-names.ec.europa.eu/fish-names/species/trachurus-mediterraneus_fr

The Mediterranean horse mackerel has an elongated body with a yellowish tail, a characteristic feature that differentiates it from other *Trachurus* species, distinguishing it from other Trachurus species. Its fin structure includes:

- Dorsal fin: Spines and soft rays typical of the Carangidae family.
- Anal fin: Well-developed with characteristic spines aiding in swimming efficiency (Bauchot, 1987).

I.2.2.3.3 Size and Longevity

- Length at first maturity: 20.0 cm (Froese & Pauly, 2024).
- Maximum length: 60.0 cm FL (Bauchot, 1987).
- Common length: 30.0 cm FL (Bauchot, 1987).

I.2.2.3.4 Biology and Ecology

This species is pelagic and migratory, often forming large schools. It is typically found near the seabed but can occasionally occur in surface waters. Its diet primarily consists of small fish such as sardines and anchovies, as well as small crustaceans. *Trachurus mediterraneus* reproduces through pelagic eggs (Smith-Vaniz, 1986).

I.2.2.3.5 Habitat and Distribution

The Mediterranean horse mackerel (*Trachurus mediterraneus*) is a marine and brackish-water species, exhibiting oceanodromous behavior (Riede, 2004). It inhabits depths ranging from 0 to 500 m, though it is more commonly found between 5 and 250 m (FAO-FIGIS, 2005). This subtropical species is distributed between 50°N and 16°N, and 20°W to 43°E (Froese & Pauly, 2024).

It occurs in the Eastern Atlantic, from the Bay of Biscay to Mauritania, including the Mediterranean Sea. A distinct subspecies, *Trachurus mediterraneus ponticus*, is found in the Marmara and Black Seas, as well as in the southern and western parts of the Azov Sea (Froese & Pauly, 2024).

I.2.2.3.6 Economic Importance

The Mediterranean horse mackerel is a commercially significant species, widely targeted in Mediterranean and Atlantic fisheries. It is primarily consumed fresh or frozen and is commonly prepared grilled, pan-fried, or smoked. This species contributes significantly to regional economies, supporting artisanal and industrial fisheries. The economic value of Trachurus mediterraneus is reflected in its high market demand across Europe and North Africa (Ly, Diop, & Girardin, 1996).

I.2.2.4 Sardina pilchardus (Walbaum, 1792)

I.2.2.4.1 Taxonomy and Classification

- Phylum: Chordata

- Class: Actinopterygii
- Order: Clupeiformes
- Family: Clupeidae
- Genus: *Sardina*

- Species: *Sardina pilchardus* (Walbaum, 1792)

The name Sardina originates from the Latin and Greek word sarda, meaning sardine, and is historically linked to the island of Sardinia (Romero, 2002).

I.2.2.4.2 Morphology and Identification

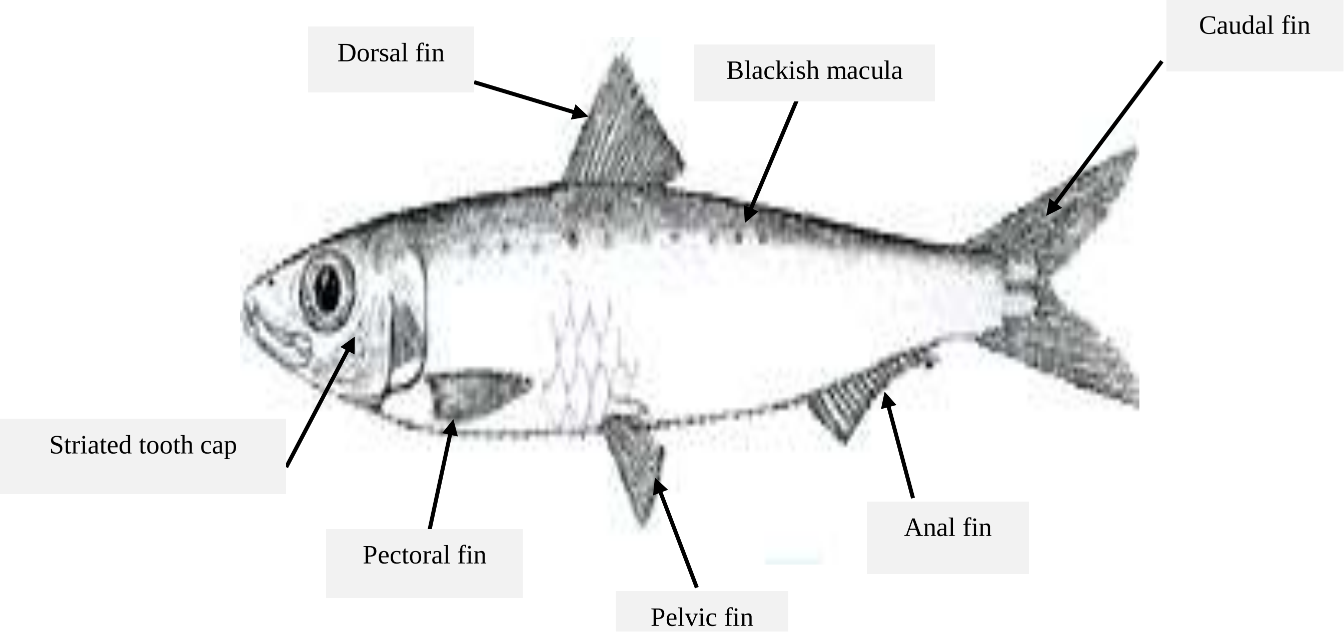


Figure 9 : External morphology of *Sardina pilchardus (Walbaum, 1792)*
Source:https://www.fao.org/fishery/docs/CDrom/ARTFIMED/ArtFiWeb/descript/Species/CLUSAPIL.HTML

The European sardine has an elongated, oval-shaped body with a rounded belly. Distinctive features include:

- 3 to 5 radiating striae on the lower part of the operculum;
- Gill opening with a smoothly rounded hind margin, without fleshy outgrowths;
- Dorsal fin origin slightly ahead of the midpoint of the body;
- Last two anal fin rays distinctly longer than the others;
- Coloration: Greenish or olive back, golden flanks, and silver-white ventral side, often with one to three rows of dark spots along the upper flanks (Fischer et al., 1987).

I.2.2.4.3 Size and Longevity

- Length at first maturity: 14.8 cm (Froese & Pauly, 2024).
- Maximum length: 27.5 cm SL (Macer, 1974).

- Common length: 20 cm SL (Whitehead, 1985).
- Maximum reported age: 15 years (Muus & Nielsen, 1999).

I.2.2.4.4 Biology and Ecology

This species forms large schools and undergoes daily vertical migrations, staying at depths of 25 to 55 m during the day and rising to 10 to 35 m at night (Brito, 1991). It primarily feeds on planktonic crustaceans and larger planktonic organisms (Fischer et al., 1987).

Reproduction varies by region:

- Mediterranean: Spawning occurs from September to June;
- Black Sea: Spawning occurs from June to August;
- Eggs: Pelagic, with females producing between 5,300 and 38,500 eggs per spawning event (Muus & Nielsen, 1999).

I.2.2.4.5 Habitat and Distribution

The European sardine (*Sardina pilchardus*) is a coastal pelagic species found in marine, brackish, and occasionally freshwater environments, exhibiting oceanodromous behavior (Riede, 2004). It inhabits depths ranging from 10 to 100 m, with a preferred range of 25 to 100 m. This subtropical species is distributed between 68°N and 14°N, and 32°W to 43°E (FAO-FIGIS, 2005).

It occurs in the Northeast Atlantic, from Iceland (rare) and the North Sea southward to Gorée Bay, Senegal. In the Mediterranean, it is more common in the western basin and the Adriatic Sea, while it is rarer in the eastern part. The species is also found in the Sea of Marmara and the Black Sea (Froese & Pauly, 2024).

I.2.2.4.6 Economic Importance

The European sardine is one of the most commercially important small pelagic fish, widely exploited in European, North African, and Atlantic fisheries. It is sold fresh, frozen, or canned, and is also processed as dried, salted, or smoked fish (Frimodt, 1995). Its high nutritional value and widespread availability make it a staple in seafood markets (FAO-FIGIS, 2005).

I.2.2.5 *Sardinella aurita* (Valenciennes, 1847)

I.2.2.5.1 Taxonomy and Classification

- Phylum: Chordata
- Class: Actinopterygii
- Order: Clupeiformes
- Family: Clupeidae
- Genus: *Sardinella*
- Species: *Sardinella aurita* (Valenciennes, 1847)

The name Sardinella originates from the Latin and Greek sarda, meaning sardine, and is historically linked to the island of Sardinia (Romero, 2002).

I.2.2.5.2 Morphology and Identification

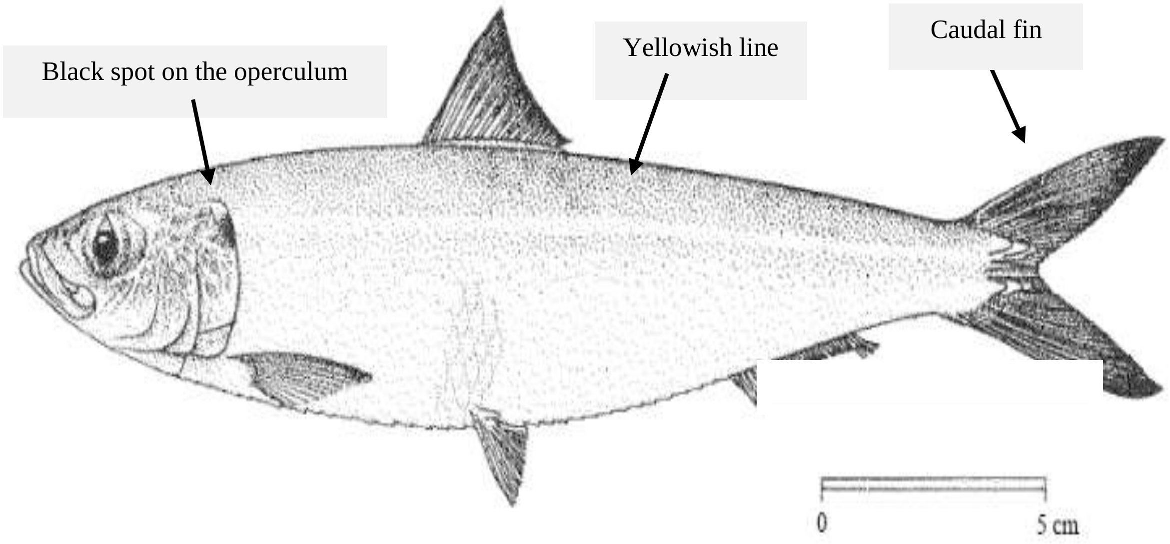


Figure 10 : Morphological Illustration of Sardinella aurita (Valenciennes, 1847)
Source : https://fish-commercial-names.ec.europa.eu/fish-names/species/sardinella-aurita_fr

This species has an elongated, subcylindrical body, sometimes slightly compressed. Key morphological features include:

- A rounded belly with a weakly developed keel of scutes;

- More than 80 fine lower gill rakers, with anterior gill rakers lying flat (Whitehead, 1985; Whitehead, 1981; Paugy, Lévêque, & Teugels, 2003; Teugels, 2007);
- A distinct black spot at the hind border of the gill cover;
- Silvery flanks with a faint golden mid-lateral line, preceded by a golden spot behind the gill opening;
- Fleshy outgrowths along the outer margin of the gill opening, differentiating it from *Clupea* species;
- Pelvic fin ray count: 1 unbranched and 8 branched rays, distinguishing it from other *Sardinella* species (Whitehead, 1985).

I.2.2.5.3 Size and Longevity

- Length at first maturity (Lm): 18.8 cm (range: 13 - 25 cm) (Froese & Pauly, 2024) ;
- Maximum length: 41.0 cm SL (Pham & Szypula, 1975) ;
- Common length: 20.5 cm SL (Whitehead, 1985) ;
- Maximum published weight: 420 g (Poll, 1953) ;
- Maximum reported age: 7 years (Beverton, 1963).

I.2.2.5.4 Biology and Ecology

The round sardinella is a gregarious, highly migratory species, often forming large schools. It prefers clear saline waters and is usually found near the surface above the continental shelf (Bianchi et al., 1999). The species displays seasonal migrations based on temperature and plankton abundance, moving closer to the surface at night and retreating below the thermocline (200-300 m) during warmer periods (Whitehead, 1981; Whitehead et al., 1986).

- Diet: Primarily feeds on zooplankton, particularly copepods and mysid larvae, with juveniles also consuming phytoplankton (Whitehead, 1985; Bianchi et al., 1999; Poll, 1953).
- Reproduction: Occurs year-round, though with two main spawning peaks in some regions associated with West African upwelling regimes (Whitehead, 1985). No spawning occurs in the Black Sea (Whitehead et al., 1986).
- Juveniles remain in nursery areas until maturity, at which point they join the adult offshore stocks (Whitehead, 1985).

I.2.2.5.5 Habitat and Distribution

The round sardinella (*Sardinella aurita*) is a coastal pelagic species found in marine and brackish environments, exhibiting oceanodromous behavior (Riede, 2004). It inhabits depths ranging from 0 to 350 m, with a temperature preference of 18°C - 25°C (Whitehead, 1985; FAO-FIGIS, 2005).

This species is widely distributed in the Atlantic Ocean, particularly along the West African coast, from Gibraltar to Saldanha Bay, South Africa (Whitehead, 1985; Paugy, Lévêque, & Teugels, 2003; Teugels, 2007). It is commonly found in the three West African upwelling zones:

- Mauritania to Guinea
- Côte d'Ivoire to Ghana
- Gabon to Angola (Cury & Fontana, 1998).

  Additionally, *Sardinella aurita* is present in the Mediterranean Sea and the Black Sea, as well as in the Western Atlantic, ranging from Cape Cod (USA) to Argentina, including the Bahamas, Antilles, Gulf of Mexico, and the Caribbean coast (Whitehead, 1985; Quéro et al., 1990; Smith, 1997).

I.2.2.5.6 Economic Importance

The round sardinella is commercially significant in West Africa, the Mediterranean, and the Western Atlantic. It is commonly caught in artisanal and industrial fisheries and marketed fresh, frozen, smoked, dried, or canned. The species plays an important role in local food security and regional economies, particularly in West African upwelling zones where it is a key target species (FAO-FIGIS, 2005; Paugy, Lévêque, & Teugels, 2003).

I.2.2.6 Engraulis encrasicolus (Linnaeus, 1758)

I.2.2.6.1 Taxonomy and Classification

- Phylum: Chordata
- Class: Actinopterygii
- Order: Clupeiformes
- Family: Engraulidae
- Genus: *Engraulis*

- Species**:** *Engraulis encrasicolus* (Linnaeus, 1758)

The name *Engraulis* is derived from the Greek word *eggraulis*, meaning anchovy (Romero, 2002).

I.2.2.6.2 Morphology and Identification

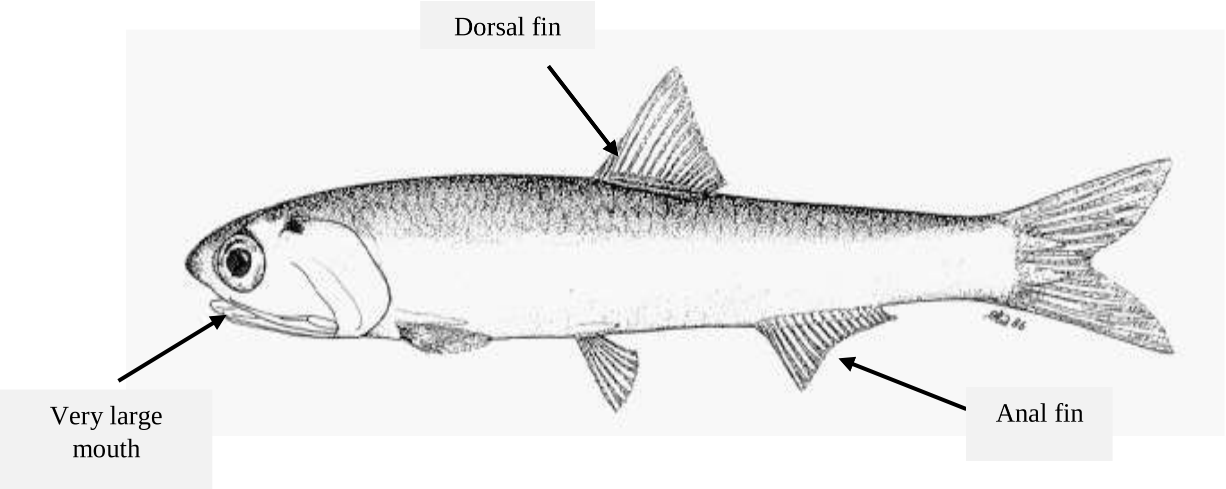


Figure 11 : Morphological Illustration of *Engraulis encrasicolus (Linnaeus, 1758)*
Source: https://animalia.bio/fr/european-anchovy

The European anchovy is a small, elongated fish, typically reaching up to 20 cm in length (Whitehead, Nelson, & Wongratana, 1988). Key morphological features include:

- A pointed snout, with a long upper jaw extending beyond the eye.
- Large, inferior mouth, characteristic of plankton feeders.
- Short maxilla with a blunt tip, almost reaching the front border of the pre-operculum.
- Silver stripe along the flank, which fades with age.
- Dorsal fin located near the mid-body, with 16-18 soft rays.
- Anal fin positioned behind the dorsal fin base, with 13-15 soft rays.
- Forked caudal fin, aiding in rapid swimming and schooling behavior (Basilone et al., 2004).

I.2.2.6.3 Size and Longevity

- Length at first maturity (Lm): 10.1 cm (range: 9 - 14 cm) (Froese & Pauly, 2024) ;
- Maximum length: 20.0 cm SL ;

- Common length: 13.5 cm SL (Whitehead, Nelson, & Wongratana, 1988) ;
- Maximum reported age: 5 years (ICES, 2010).

I.2.2.6.4 Biology and Ecology

The European anchovy is an oceanic, schooling species, often forming large aggregations (Frimodt, 1995). It exhibits seasonal migrations, moving northward and into surface waters during summer, then retreating to deeper waters in winter.

- Salinity Tolerance: Can tolerate salinities between 5-41 ppt, often entering estuaries, lagoons, and lakes, particularly during spawning (Frimodt, 1995).
- Diet: Feeds on planktonic organisms, primarily copepods and other zooplankton.
- Reproduction: Spawns from April to November, peaking in warmer months. Spawning is pelagic, with multiple spawning events throughout the season.
- Eggs: Ellipsoidal to oval, floating in the upper 50 m of the water column. Hatching occurs within 24-65 hours.
- Sex Ratio: Approximately 45% of individuals are female (Koranteng, 1993).

I.2.2.6.5 Habitat and Distribution

The European anchovy (*Engraulis encrasicolus*) is a marine and brackish species, known for its oceanodromous behavior (Riede, 2004). It inhabits depths ranging from 0 to 400 m (Schneider, 1990) and is found in subtropical waters between 62°N and 37°S, 18°W and 42°E (FAO-FIGIS, 2001).

This species is distributed along the Eastern Atlantic, from Bergen, Norway, to East London, South Africa, possibly extending to Durban (Quéro et al., 1990). It is also present in the Mediterranean, Black, and Azov Seas, with some stray individuals recorded in the Suez Canal and Gulf of Suez. Additionally, *E. encrasicolus* has been reported around St. Helena and Estonia (Whitehead, Nelson, & Wongratana, 1988; Anonymous, 1999).

I.2.2.6.6 Economic Importance

The European anchovy is a highly valued commercial species, caught primarily in small-scale and industrial fisheries. It is marketed fresh, dried, smoked, canned, and frozen, and is also used in fish meal production. The species plays a crucial role in local and international fisheries, particularly in the Mediterranean and Eastern Atlantic regions (Frimodt, 1995).

Chapter II

Study Area

CHAPTER II: Study Area

II.1 Geographical Location

The Algerian Basin is situated in the southern part of the western basin of the Mediterranean Sea, and extends roughly between the latitudes of 35° and 40°N and longitudes 2°W to 7°45'E. It is located east of the Alboran Sea, to the south located by Algeria, on its northwest side the Balearic Islands and with Sardinia as its northeastern side (Benzohra & Millot, 1995).

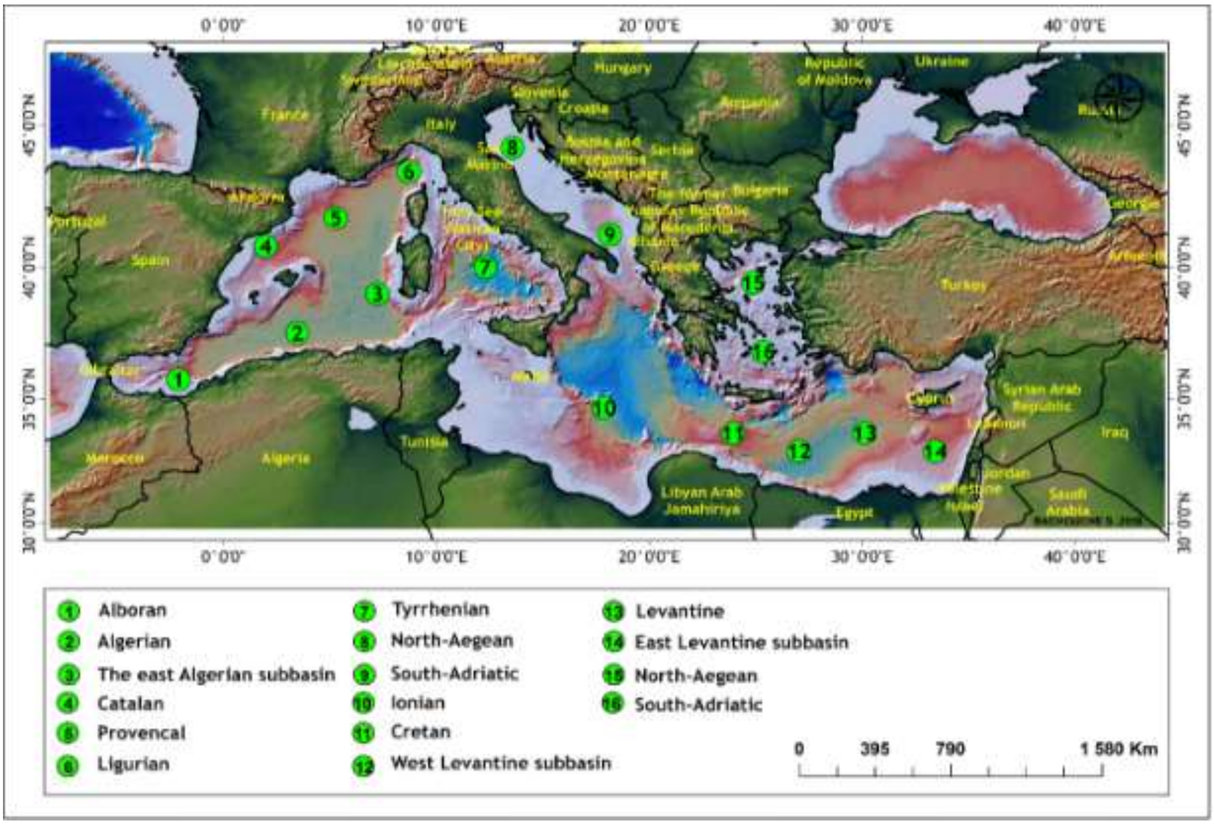


Figure 12: Geographical setting of Algerian basin (Adapted from Inal, 2020)

The Algerian coastline stretches from Aïn B'Har (Tunisian frontier) to Oued Kiss (Moroccan frontier), 1,100 km in the straight line and 1,283 km in the natural sinuosities of the coast. According to Refes (2011), this minor difference amounts to a very straight and weakly indented shoreline in Algeria. On the other hand, data quoted by some references such as Benzohra and Millot (1995) provided that the overall length of Algeria's maritime façade is 1,622 km, taking into account all the topographic characteristics and minor unregularities along the Mediterranean coastline.

From the Oued Kiss to Ras Ténès, the coastline generally follows the southwest–northeast direction, from Ras Ténès to the borders of Tunisia, it is almost rectilinear (east–west direction). The majority of the Algerian coastline is lined with steep cliffs made up of different geological layers, and contains a succession of north-facing recesses resulting in the following bays and gulfs, from east to west: Gulf of Annaba, Gulf of Skikda, Bay of Jijel, Gulf of Béjaïa, Bay of Zemmouri, Bay of Algiers, Bay of Bou-Ismaïl, Gulf of Arzew, Gulf of Oran, Bay of Béni Saf, and Gulf of Ghazaouet (Refes, 2011) (Figure 13).

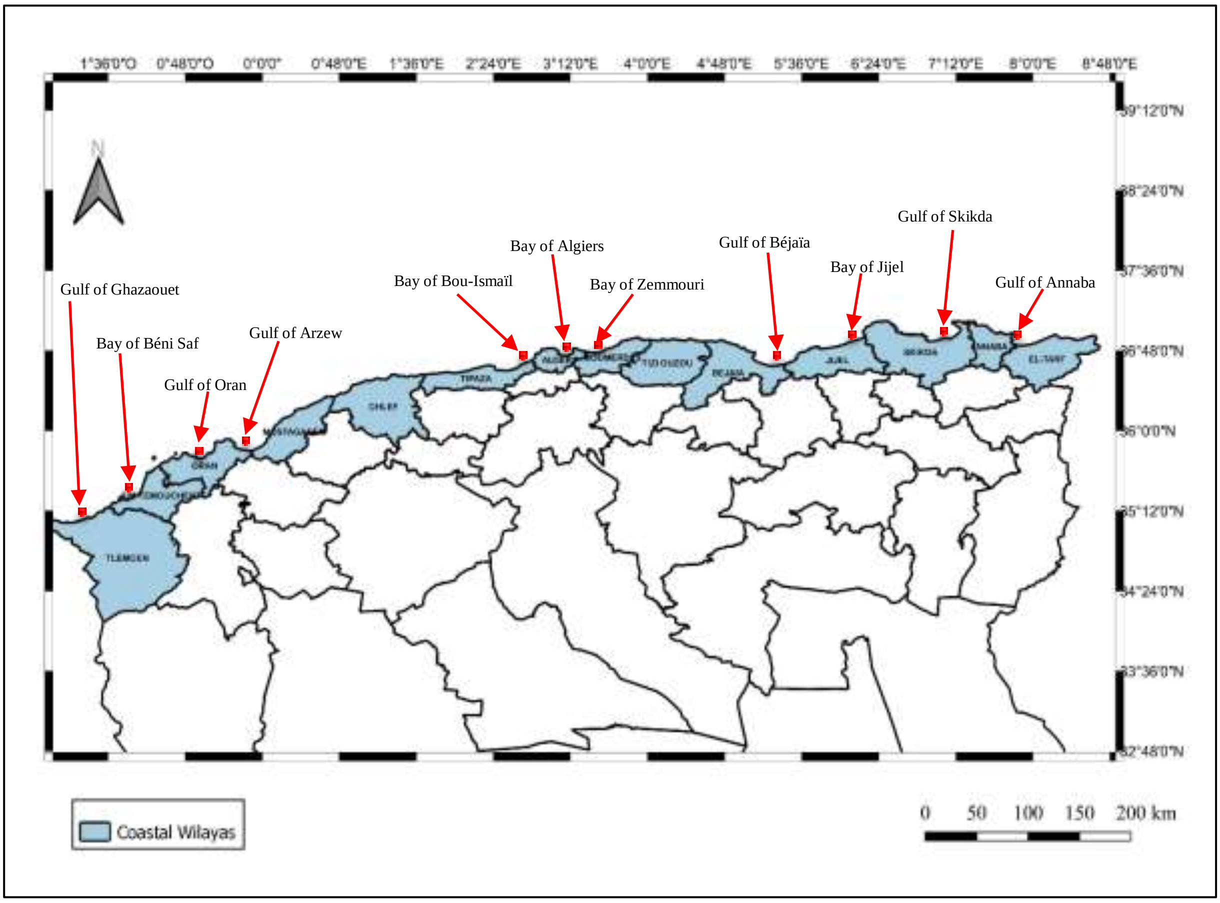


Figure 13 : Geographic Location of Algeria's Coastal Wilayas with Main Bays and Gulfs

This region serves as a crucial transitory zone between the interior Mediterranean waters and the Atlantic influx, contributing significantly to basin-scale circulation patterns and giving Algeria a strategic and ecological edge in the Mediterranean.

II.2 Geomorphological and Ecological Features of the Algerian Coast

The Algerian coast is recognized as a Mediterranean biodiversity hotspot, with an exceptional richness of marine flora, invertebrates, and fish. Although comprehensive systematic lists of marine and coastal fauna and flora have yet to be compiled, data compiled up to 2011 reveals the presence of some 6,488 marine species, a total well beyond the 3,793 species previously estimated by UNDP-Algeria (2005) (Refes, 2011).

Apart from biological richness, the Algerian coastline is ecologically diverse, comprising sandy beaches, rocky shores, and coastal wetlands, all of which are reflected in high levels of marine and terrestrial biodiversity and high biological productivity. Its continental shelf is generally quite narrow, except for El Kala (El Tarf) in the far east and Ghazaouet (Tlemcen) in the far west (Benzohra & Millot, 1995). The narrowness is the cause of a steep bathymetric profile that favors hydrodynamic exchanges and has a determining effect on the modeling of marine habitats (Refes, 2011).

The west coast is more protected than the east side due to north- or northeast-facing headlands and rocky promontories that naturally shelter prevailing westerly and northwesterly winds. It is due to this natural protection that most Algerian port complexes are located in the lee of these landforms (Refes, 2011).

In the resource management point of view, Algeria is controlling a 10-million-hectare maritime zone, exploited essentially for fishing, whereas the continental shelf is the most exploited zone by the national fishing fleet due to accessibility and productivity (Lalami, 1979).

II.3 Climatic Conditions of the Algerian Coastal Region

The Atlantic Water (AW) which enters from the Strait of Gibraltar reaches Algeria's coast just offshore of Oran, roughly around 0° longitude, and is responsible for the prevailing domination of the Atlantic current along Oranese coastal waters (Millot, 1985). Further north, along the margin of North Africa, this energetic flow comes to be called the Algerian Current, due to its normal direction of flow toward the east on the continental slope (Millot, 1985).

Having entered the Alboran Sea, the Atlantic Water then undergoes sequential modification of its initial physical characteristics to form Modified Atlantic Water (MAW) (Benzohra, 1993). After the same author, this body of water extends into the Algerian Basin where it may be identified in a surface layer of approximately 150 meters, whose surface temperature varies between 15°C and 23°C and whose subsurface temperature varies between 13.5°C and 14°C and whose salinities range from 36.5 to 38‰.

II.3.1 General Precipitation

Rainfall on the northern Algerian coast is predominantly associated with the arrival of north-northwest depressions, which are of Atlantic origin. Rainfall distribution is a function of altitude and orientation of mountain ranges, and the maximum rainfall occurs on the northern and northeastern slopes, decreasing from east to west (Seltzer, 1946). The eastern coast of Algeria is characterized by a Mediterranean sub-humid climate with approximately 900 mm of mean annual rainfall

Two wide seasons are distinguished: an unfavorable dry season between May and September (including 25% of annual rainfall, occurring at its minimum in July) and a favorable wet season between October and April (including 75% of annual rainfall with a maximum in December) (Refes, 2011).

II.3.2 Atmospheric temperatures

The average temperature in north Algeria (excluding Sahara) is below the yearly mean (17.57°C) between November and April (9.5°C) and above it between May and October (29.5°C), based on Seltzer (1946). Negative temperatures are absent along the coast, as thermal extremes are moderated by the sea and humidity augmented. Maximum temperatures, usually achieved in July or August, are likely to be linked with the Sirocco winds (de Belair, 1990).

The year can be divided into two thermal periods:

Cold period: October to April,

Warm period: May to September.

National Meteorology Office statistics (1960–1990) indicate an average annual temperature of 18.32°C, with inter-annual variability ranging from 16.33°C in 1980 to 19.38°C in 1990. A 2000–2005 study confirms a thermal amplitude ranging from 12.6°C in January to 25.6°C in August, as reported by Seltzer earlier (Refes, 2011).

II.3.3 Wind Regime

Meteorological data of El Kala, Annaba, Skikda, Jijel, and Béjaïa (2000–2005) indicate the dominance of northwesterly winds, particularly in winter. In spring and summer, a decrease in northwesterly winds is compensated by an increase in northeasterly winds (Refes, 2011).

These results are consistent with Seltzer (1946), who noted that:

West-northwest winds cause rain during the cold season (autumn-winter),

North-northeast winds are connected with periods of high atmospheric pressure and good weather.

Wind speed data collected by Refes (2011) indicate:

39.9% of the winds are < 4 m/s in speed,

32.8% of the winds are between 5 and 9 m/s,

4.5% of the winds are between 10 and 14 m/s,

and 0.3% of the winds are > 15 m/s.

Over 85% of the powerful winds (>16 m/s) are from the northwest, predominately in autumn and winter.

II.4 Hydrodynamic and Oceanographic Features

II.4.1 Current circulation

II.4.1.1 General surface circulation

The general circulation along the Algerian coast is mostly controlled by the entrance of Atlantic Water (AW), which breaks from the anticyclonic gyre of the eastern Alboran Sea and reaches the Algerian coast east of Arzew, near 0° longitude. This structured flow is named Algerian Current (Taupier-Letage, 1988; Arnone et al., 1990).

Between 1°E and 2°E (off Ténès), this current becomes dynamically unstable, generating coastal meanders and eddies, both cyclonic and anticyclonic, which propagate eastward. These eddies promote upwelling by divergence and also cause onshore transport of offshore waters by eddy interactions (Millot, 1987; Taupier-Letage, 1988; Millot, 1994). Eddies regulate chlorophyll distribution: anticyclonic eddies have subsurface chlorophyll maxima (1–3 µg/L), while cyclonic eddies have increased levels (up to 8 µg/L) near the nitracline (Raimbault et al., 1993).

Surface currents reach speeds of 50 cm/s within 10 km of the coast, and 25 cm/s at 100 m depth, 25 km offshore (Taupier-Letage, 1988).

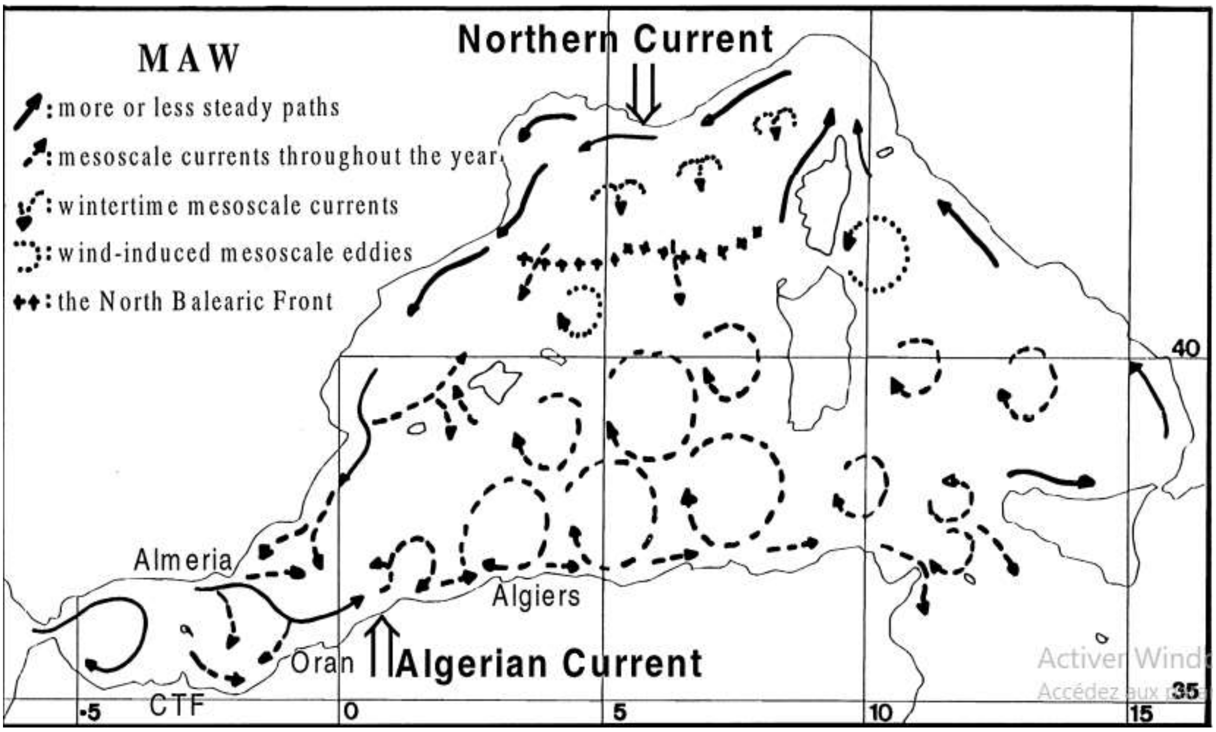


Figure 14: Surface circulation of Atlantic-origin waters in the western Mediterranean, highlighting the Algerian Current and mesoscale eddies along the Algerian coast (adapted from Millot, 1987a). CTF: Cape Tres Forcas.

II.4.1.2 Intermediate and Deep-Water Circulation

- **The Levantine Intermediate Water (LIW)** follows the Algerian slope after circulating in the western Mediterranean. LIW fragments are also cut off by dying offshore eddies and move along the Algerian coast as subsurface lenses (Millot, 1987; Benzohra & Millot, 1995).
- **The deep-water circulation** is less well described but is thought to be dominated by mesoscale features. The waters form in winter convection in the northern Western Mediterranean and sink down the continental slope (Millot, 1987).

II.4.1.3 Coastal Current Dynamics

In the absence of direct current measurements, analysis of wave data indicates a seasonal pattern: westerly swells dominate during winter and easterly swells during summer (USNWC, 1970; Braïk, 1989). These create:

Offshore return currents, dispersing sediments, Longshore drift, causing erosion or sedimentation depending on coastline orientation.

II.4.2 Hydrological Characteristics

The coastal surface waters of Algeria drift eastward under the influence of the Algerian Current, and their vertical range extends from 100 to 200 meters. They gradually lose their Atlantic features as they drift eastward due to evaporation and mixing (Refes, 2011).

Based on summer and winter profiles, Guibout (1987) observed a progressive increase of surface temperature and salinity from west to east. Surface temperatures range from 14.05°C to 14.77°C in winter and from 23.21°C to 25.79°C in summer (Figure 15), while salinity ranges from 36.55 to 36.83 PSU in winter and from 36.32 to 37.27 PSU in summer (Figure 16). These gradual changes indicate modification of Atlantic Water to Modified Atlantic Water (MAW) along the Algerian coast. This surface flow visualization is superimposed on a denser, saltier body of water, located below 200–300 meters to the bottom of the sea (Refes, 2011).

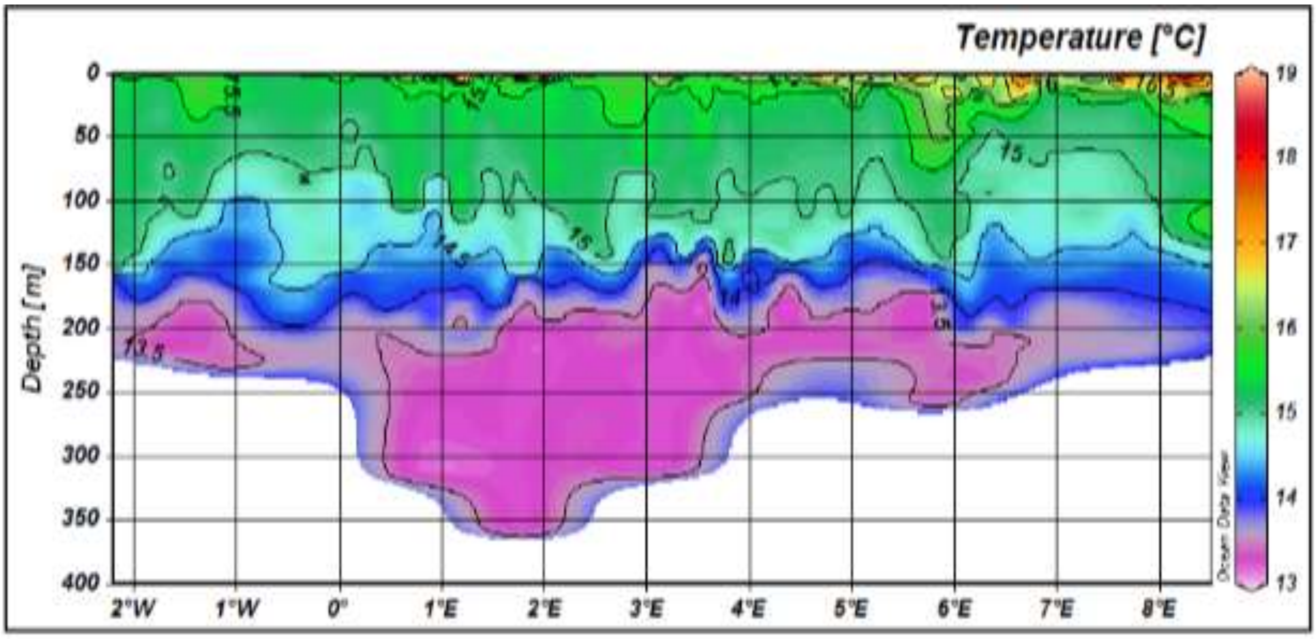


Figure 15: Longitudinal section [2°W–8.5°E] of sea surface temperature along the Algerian coast (adapted from Inal, 2020).

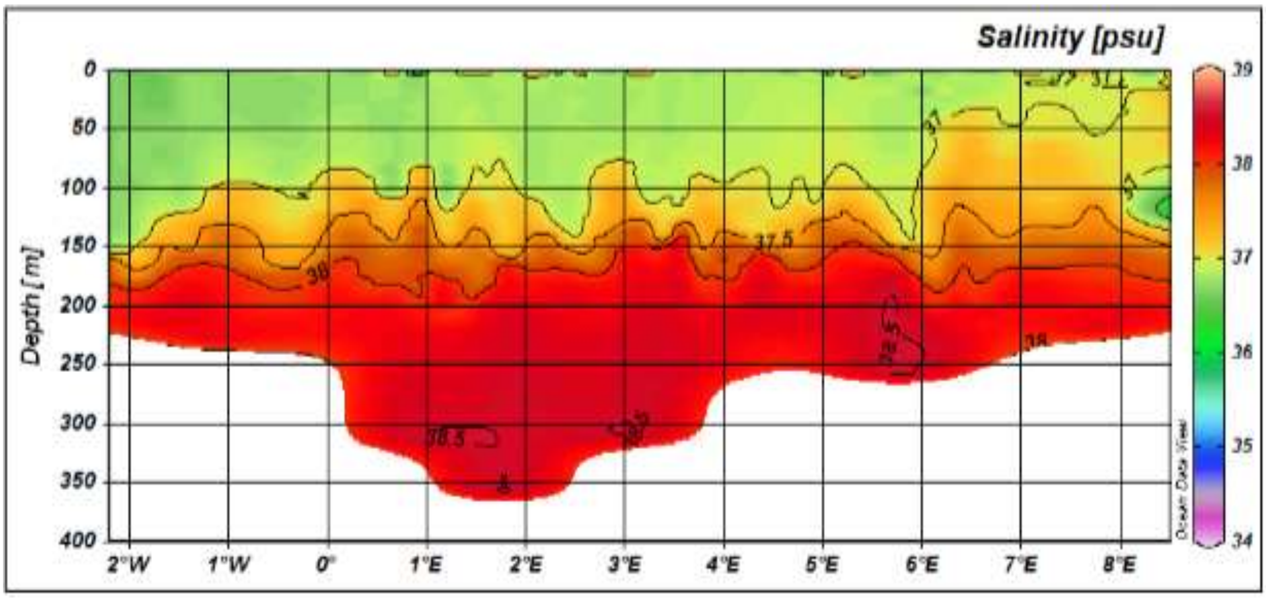


Figure 16: Longitudinal section [2°W–8.5°E] of sea surface salinity along the Algerian coast (adapted from Inal, 2020).

A particularly notable feature is the evident hydrological distinction observed between gulfs and bays along the Algerian coast, brought about by:

Anthropogenic processes along the shore,

Coastal orientation relative to average seasonal swells.

The quantity and significance of wadis (river discharges) that enter the sea.

All these account for local water structure and dynamics differences.

II.5 Fisheries Exploitation and Anthropogenic Pressure along the Algerian Coast

II.5.1 Fisheries Production in Algeria

According to the National Office of Statistics (ONS, 2020), Algeria's total fisheries production was 120,354 tonnes in 2018, representing a rise of 11% from 108,300 tonnes in 2017. Overall growth is principally attributed to increases in catches of pelagic fish, rising by 18.8%, or from 77,776 tonnes in 2017 to 92,392 tonnes in 2018. Pelagic fish alone contributed about 77% of national output.

In addition, mollusk production increased by 25.7%, standing at 1,593 tonnes in 2018, up from 1,267 tonnes in the previous year (Grine & Aouad, 2020).

II.5.2 Trends and Limitations in Algerian Fisheries Catches

Algerian fisheries production has shown fluctuating trends over the last few decades. National catches, according to FAO statistics (2016), have had an upward and downward trend with a record figure of more than 147,000 tonnes in the year 2007. This record was followed by the acquisition of new fishing equipment and small boats (WWF, 2013). But, over the period 1980-2014, output remained generally under 145,000 tonnes despite the availability of 9.5 million hectares of potentially exploitable marine space, with only 2.2 million hectares (23%) actually being used (Yahiaoui & Mouhoubi, 2016).

And, if all the area under the jurisdiction of the Ministry of Fisheries and Fishery Resources (MPRH) were being used, potential output would be over 620,000 tonnes annually. However, real output has been low because of an excess number of idle vessels with 43% of the fleet on average inoperative between the years 2000 and 2014, varying from a low of 36.01% in the year 2012 to 57.26% in 2014 (WWF, 2013). Factors include unavailability of spare parts, financial impediments, and restricted access to bank credit, resulting in disrepair of idle vessels and diminished productivity.

II.5.3 Dominant Species in National Fisheries Catches

Algerian fisheries are dominated by small pelagic fishes, i.e., anchovies, sardines, and mackerels. Pelagic fish made up 85% of landings in 2013, followed by demersal fish (10%), and mollusks and crustaceans (4%) (Sennai Cheniti, 2003). The composition was largely consistent for the period 2009–2012. In the period 2004–2009, pelagic and demersal species were roughly 40% each, while mollusks and crustaceans were 15% (ONS, 2015).

Averaged over the 2000-2013 period, catches comprised 74% small pelagics, 17% demersals, 4% crustaceans, 3% large pelagics (tunas, sharks, swordfish), and 2% mollusks, based on MPRH statistics (2003).

II.5.4 Anthropogenic Pressure

Like most Mediterranean regions, the Algerian littoral is subject to intense human pressures due to the concentration of economic and demographic activities along the coastline (Le Tixerant, 2004; Cuttelod et al., 2008; Plan Bleu, 2015). The coastal zone, which represents no more than 1.9% of the Algerian national territory, contains approximately 37% of the national population, generating high pressure on marine and coastal ecosystems (MREE et al., 2015; Khelil et al., 2019).

This aggregation of the population is associated with intensified coastal artificialization, rapid urban development, and highly intensive economic activities, notably artisanal fisheries and tourism. All these happenings disrupt ecological balances and endanger environmental quality supporting human activity sustainable development (Puente-Rodríguez et al., 2015; Thébault et al., 2011).

Despite relatively auspicious geomorphological conditions e.g., rocky coast and proper exposure to wind and wave forces, favorable to natural dispersion of contaminants parts of the coastline are moderately polluted. This is largely due to household and industrial effluents, often not properly treated due to ineffective wastewater management systems (CNL, 2016, as cited in Silhadi et al., 2020). These issues exemplify a governance deficit, despite a regulatory framework (Law No. 02-02) existing aimed at protecting and enhancing the coastline.

While the degree of anthropogenic pressure is locally heterogeneous, it is generally high along the majority of the coast, and especially in and around large urban agglomerations. Urbanization, lack of facilities for wastewater treatment, poor solid waste collection systems, and uncontrolled development of transport and port infrastructures are a few of the drivers with highest potential influence (Silhadi et al., 2020).

Thus, large parts of the Algerian coastal zone display medium to high sensitivity to the environment. Should such pressures be not addressed, combined effects can degrade long-term resilience of the marine ecosystem as well as life quality of residents of the coasts (Plan Bleu, 2015; Cuttelod et al., 2008).

Table 1 : Main Sources of Industrial Pollution in Algerian Coastal Wilayas (D: Domestic, I: Industrial) (Adapted from Grimes, 2010)

Coastal Wilayas	Sources of Pollution
Tlemcen	ALZINC (D–I)
Béni Saf	Cement, Ferphos, Sablière Terga (D)
Oran	Petrochemicals, ENGI, Alzofér, EMB, Fertalg (D)
Tipaza	SMEs, Alufer, Alumetal, Paper, Glass (D)
Algiers	Fats and oils, Agri-food industry, Paper, Cosmetics, Power plant, Tannery, Hydrocarbons (I–D)
Boumerdès	Dairy, Agri-food, Aluminium, Pharmaceuticals, Power plant (D–I)
Béjaïa	Agri-food, Fats and oils, Packaging, Hydrocarbons, Naphtha (I–D)
Jijel	Canning industry, Agri-food, Glass, Power plant, Tannery (D)
Skikda	Petrochemicals, Power plant, Industrial gases (I–D)
Annaba	Agri-food, Ferphos, ArcelorMittal Steel, Power plant, Nitrogen and phosphate fertilizers (I–D)
El Kala	Canning industry, Agri-food, Galvautube, Steel plant, Wastewater treatment center (D)

Chapter III

Materials

And Methods

CHAPTER III: Material and method

III.1 Sample collection

Fish samples were collected during the oceanographic survey of the research vessel "Grine Belkacem" (Figure 17) in summer 2024 from 25 fishing hauls along the Algerian coast.

Figure 17: Belkacem Grine vessel
Source : https://www.cnrdpa.dz/navire-de-recherche-belkacem-grine/

The geographical location of the hauls is illustrated across four regional maps (Figure 18), showing the location and distribution of fishing operations. Each haul is identified by a unique number corresponding to the metadata detailed in (Table III.1, Appendix III), including the date, region, geographic coordinates (latitude and longitude), and sampling depth.

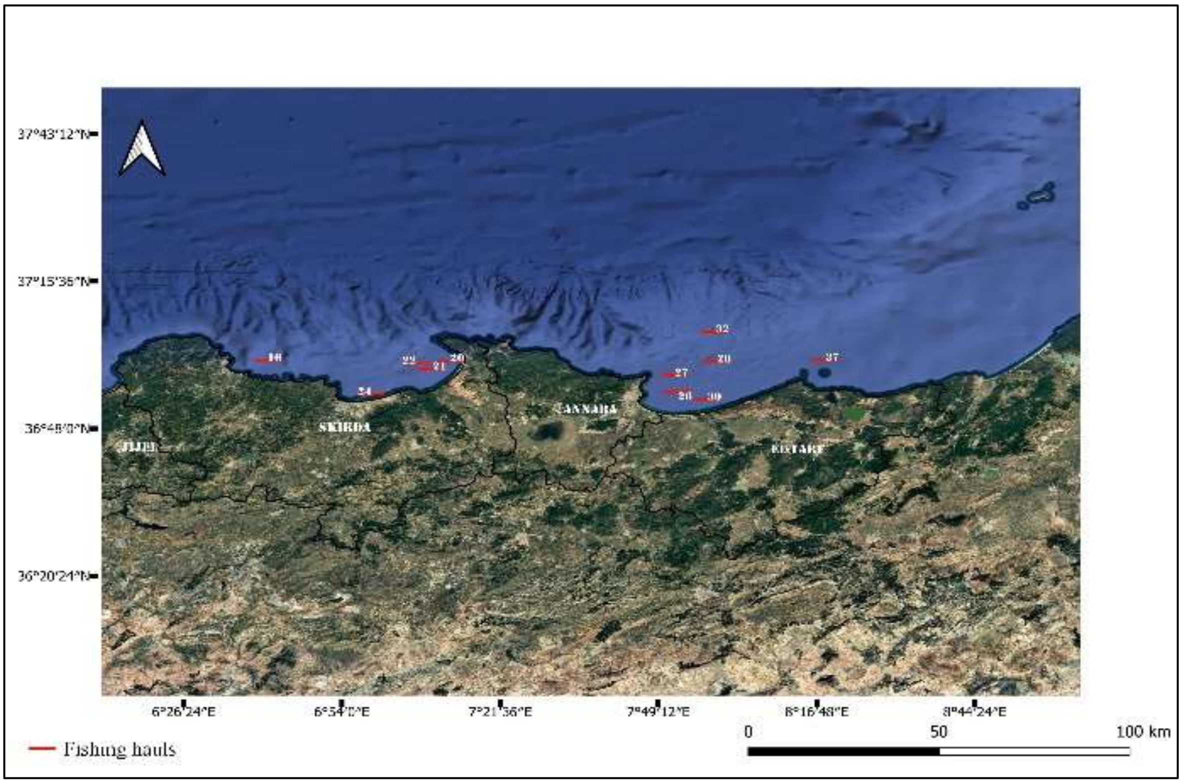


Figure 18.A

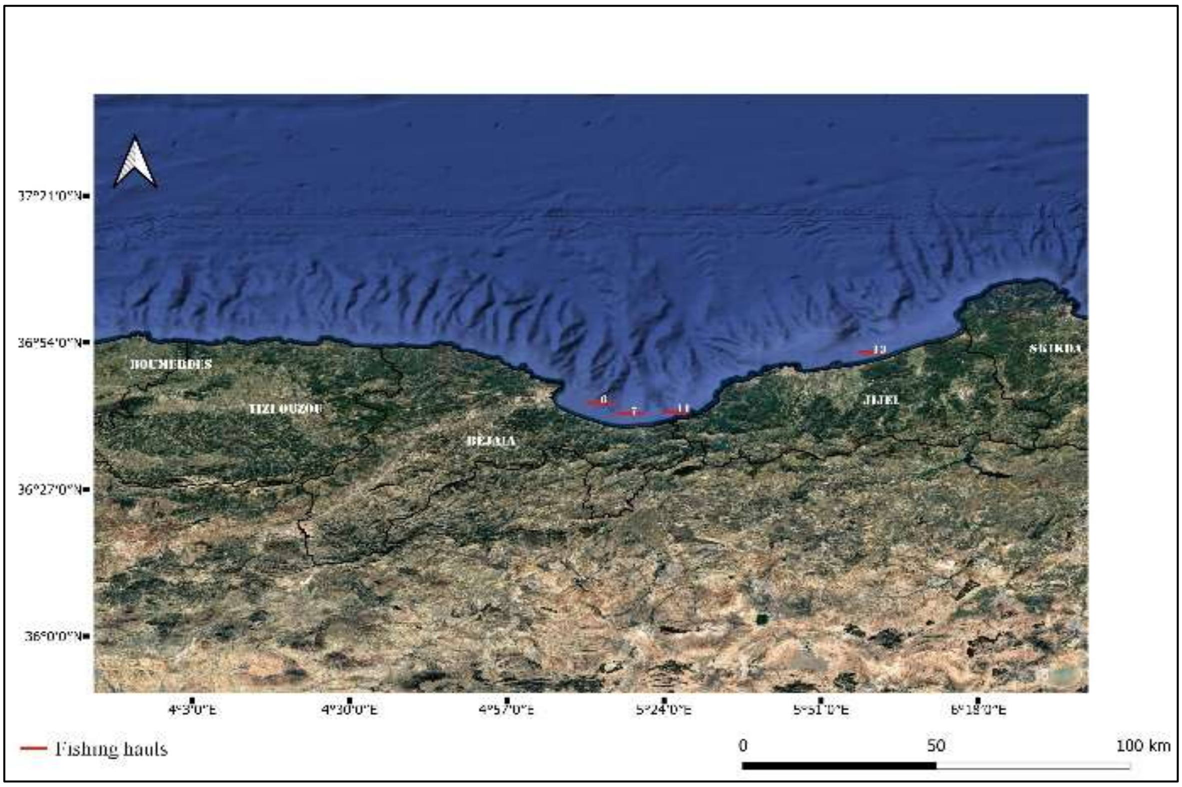


Figure 18.B

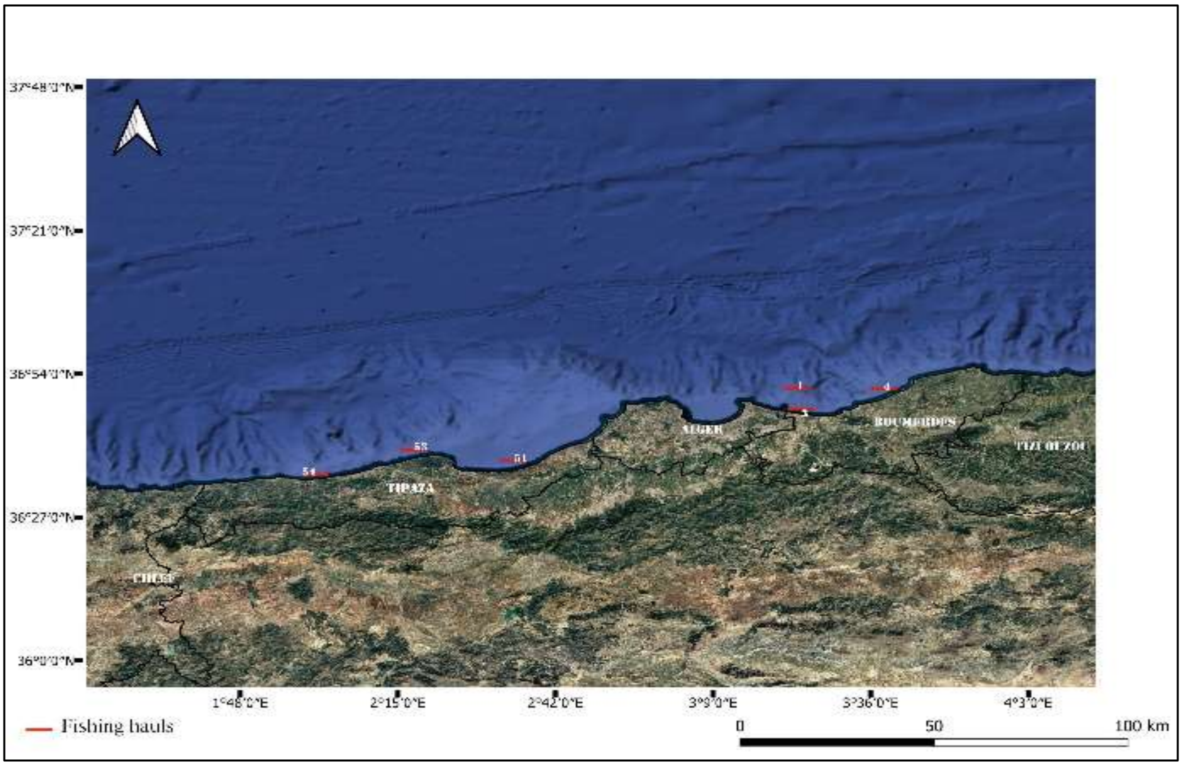


Figure 18.C

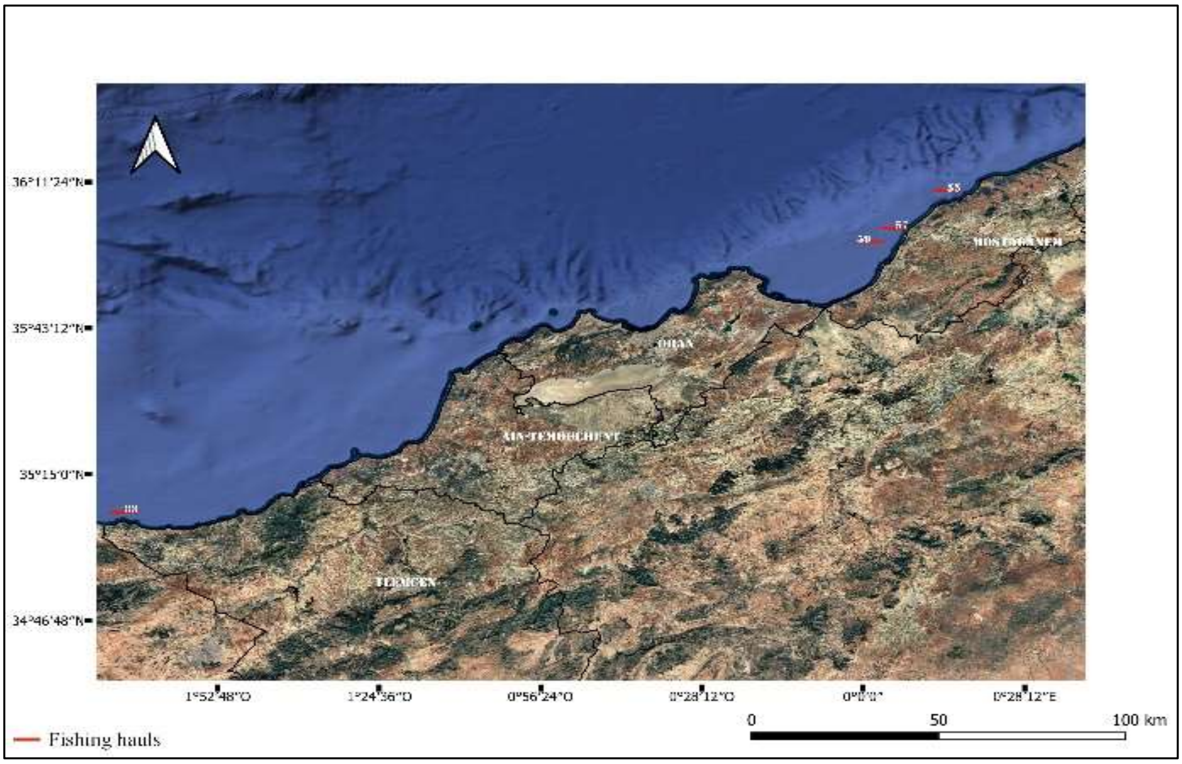


Figure 18.D

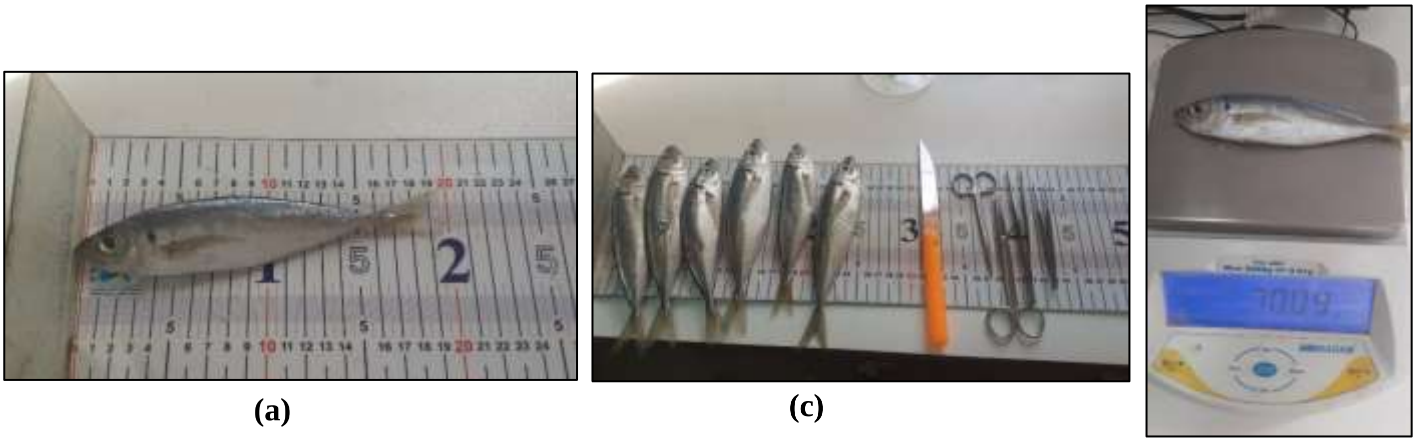
Figure 18 : Spatial distribution of fishing hauls along the Algerian coast: (A–B) eastern sector, (C) central sector, and (D) western sector.

The 6 specimens of the target species were taken per sample per fishing haul in total. They were trawled bottom (using normal net GOC 73) following the MEDITS standardized protocol.

This research fishing cruise offered several methodological advantages, including precise georeferencing of sample stations, and controlled environmental conditions. As a result, the collected specimens were characterized by high quality, freshness and integrity making the biological material suitable for legitimate scientific investigation

III.2 Sample preparation

The samples were dissected to remove muscle and gills. The total length and body weight of every sample were taken prior to preservation and the sex of some was determined. The entire samples were placed in glass pillboxes previously rinsed with nitric acid, diluted several times with distilled water, and frozen at -18 °C on board.



(a) **(c)** **(b)**

Figure 19: Sample preparation procedures: (a) biometric measurement; (b) mass recording; (c) organ dissection.

III.2.1 Freeze-drying

Freeze-drying or lyophilization is a dehydration process that aims to remove water by sublimation under low pressure and temperature conditions after the material has been frozen intensively. This process allows conservation of chemical and structural integrity of delicate molecules. Lyophilization was used in our study as part of a one-week internship in the CNRDPA annex in Beni Saf with a 1-2 LSCbasic freeze-dryer from Christ Alpha. The process consisted of a controlled heat step for 20 minutes, followed by the first desiccation for 24 hours, with the aim of efficient removal of moisture and stabilization of the samples.

Figure 23: Lyophilization process using the Christ Alpha 1–2 LSCbasic freeze-dryer

III.2.2 Grinding

The freeze-dried samples were carefully ground using automatic stainless-steel grinders to obtain a fine, homogeneous powder, facilitating subsequent handling. The powder obtained was transferred to plastic sample vials and stored in a dry place away from moisture.

(c)

(a)

(b)

Figure 24: Grinding and storage of freeze-dried samples: (a, b) mixers used for sample grinding; (c) powdered samples stored in vials.

III.2.3 Homogenization

To ensure uniform distribution of the materials within the dry fish samples, and the representativeness of the aliquots taken for future analysis, manual homogenization was performed.

III.3 Metal Analysis

Trace metal concentrations (Cd, Pb, Cu, and Zn) in fish tissues were determined using Atomic Absorption Spectrometry (AAS)**.** Gill samples were analyzed at the ENSSMAL technical platform using a PinAAcle™ 900H Atomic Absorption Spectrometer (PerkinElmer, USA) while muscle tissues were processed at the CRAPC using SAA240FS/240ZAA-Agilent.

The analytical methodology and principles applied for the quantification of metals by AAS are described below

III.3.1 Atomic Absorption Spectrometry (AAS)

Presentation of the method

Atomic Absorption Spectrometry (AAS) is an analytical technique used for the measurement of trace metal concentrations in a sample by absorption of light by free gaseous atoms. The method involves converting the metallic constituents of the sample into an atomic form, followed by the measurement of the absorption of electromagnetic radiation at the pre-selected wavelengths by the atoms. The damount of light absorbed is proportional to the concentration of the element within the sample, as outlined by Beer-Lambert's law, allowing for precise quantification.

The atomization of metals can be achieved through different techniques depending on the element and its expected concentration:

- Flame Atomization: Here, the sample is vaporized and atomized within a flame. It is used most frequently for elements such as Cr, Cu, Fe, Mn, Ni, and Zn, which are typically present at relatively higher concentrations in the biological matrices.
- Graphite Furnace Atomization (electrothermal atomization): The technique uses pyrolysis and atomization in a graphite furnace and is suitable for elements like Cd and Pb, which are usually found at low concentration. It provides improved sensitivity and lower detection limits than flame atomization.

- Cold Vapor Technique: This special apparatus is used exclusively to mercury, and it enables the trace determination by producing elemental mercury vapor that is directly analyzed.

III.3.2 Sample mineralization

- **Principal of mineralization**

Biological samples are treated with concentrated nitric acid under controlled thermal conditions in order to decompose the samples and solubilize all metals.

- **Blank mineralization**

To assess potential contamination with reagents and materials, a blank mineralization was prepared similarly to the samples, yet without addition of biological material.

- 5 mL of pure concentrated nitric acid (HNO_3, 69%) was added to clean Teflon digestion vessels.
- The vessels were hermetically sealed and heated on a heating plate at 90 °C for 3 hours.
- After heating, the vessels were placed under room temperature and fume hood for cooling.
- The acid was then poured slowly into a designated waste container under the hood.
- Vessels were slowly rinsed with Milli-Q water to remove residual acid.
- Finally, the vessels were oven dried at 70 °C before reuse

Figure 25 : Blank mineralization process with Teflon containers and acid treatment

- **Operating Procedure**

The mineralization of gill tissues was performed following the digestion protocol established by the International Atomic Energy Agency (IAEA, 2001)

- Shake samples bottles for about 2 min. for homogenization.
- Wait a few minutes before opening the bottles.
- Weigh accurately 0.3 g of dry sample in labeled Teflon tubes (FEP, 50 ml, Nalgene)
- Add 5 ml of concentrated Nitric acid HNO3 (69%).
- A procedural blank (control tube with no sample) was prepared following the same steps using only 5 mL of HNO_3.
- Leave samples and the blank at room temperature for at least 1 hour.
- Close the tubes and place them in an aluminum block on a hot plate at 90°C for 3h.
- Allow vessels to cool to room temperature then open the tubes carefully.
- Transfer digests in labeled 50 ml polypropylene graduated tubes. Rinse the Teflon tubes with Milli-Q water 3 times.
- Dilute to the mark (50ml) with Milli-Q water and shake

Figure 26 : Sequential steps of sample mineralization from sample weighing to final solutions before and after dilution.

III.3.3 Metal Quantification by AAS

Analyses were conducted according to IAEA experimental guidelines on:

- **PerkinElmer PinAAcle™ 900H atomic absorption spectrophotometer**: The instrument is part of an advanced series designed to handle complex matrices with high accuracy and efficiency. It supports three atomization modes (flame, graphite furnace, and cold vapor, previously described) and features Zeeman-effect background correction, in accordance with the technical specifications of the manufacturer (Figure 24).

Figure 27 : Atomic Absorption Spectrometer (PerkinElmer PinAAcle™ 900H) used for trace metal analysis.

III.3.4 Expression of Results

The concentration of each metal was determined from the equation of the calibration curve, which was derived from linear regression. Based on the optical density of each metal (automatically calculated by the software), an equivalent concentration in the sample was determined (see calibration tables and corresponding graphs in Appendix III)..

Metal concentrations in the organism were expressed in micrograms per gram of dry weight (µg/g D.W), as follows (AISSO, 1982):

$$\boxed{Cps = \mathbf{Cc*V/Ps}}$$

Where:

Cps: Metal concentration in dry weight (µg/g)

Cc: Metal concentration in the analyzed solution (µg/mL)

Ps: Corrected dry weight of the digested sample (g)

V: Final volume of the digest after mineralization (mL), typically 50 mL

III.4 Biochemical Analysis

A total of 15 muscle tissue samples of different species and fishing hauls were analyzed for their biochemical composition. Carbohydrate analysis were performed at the ENSSMAL, while proteins and lipids analysis were carried out at the CNRDPA.

III.4.1 Cabohydrate measurement

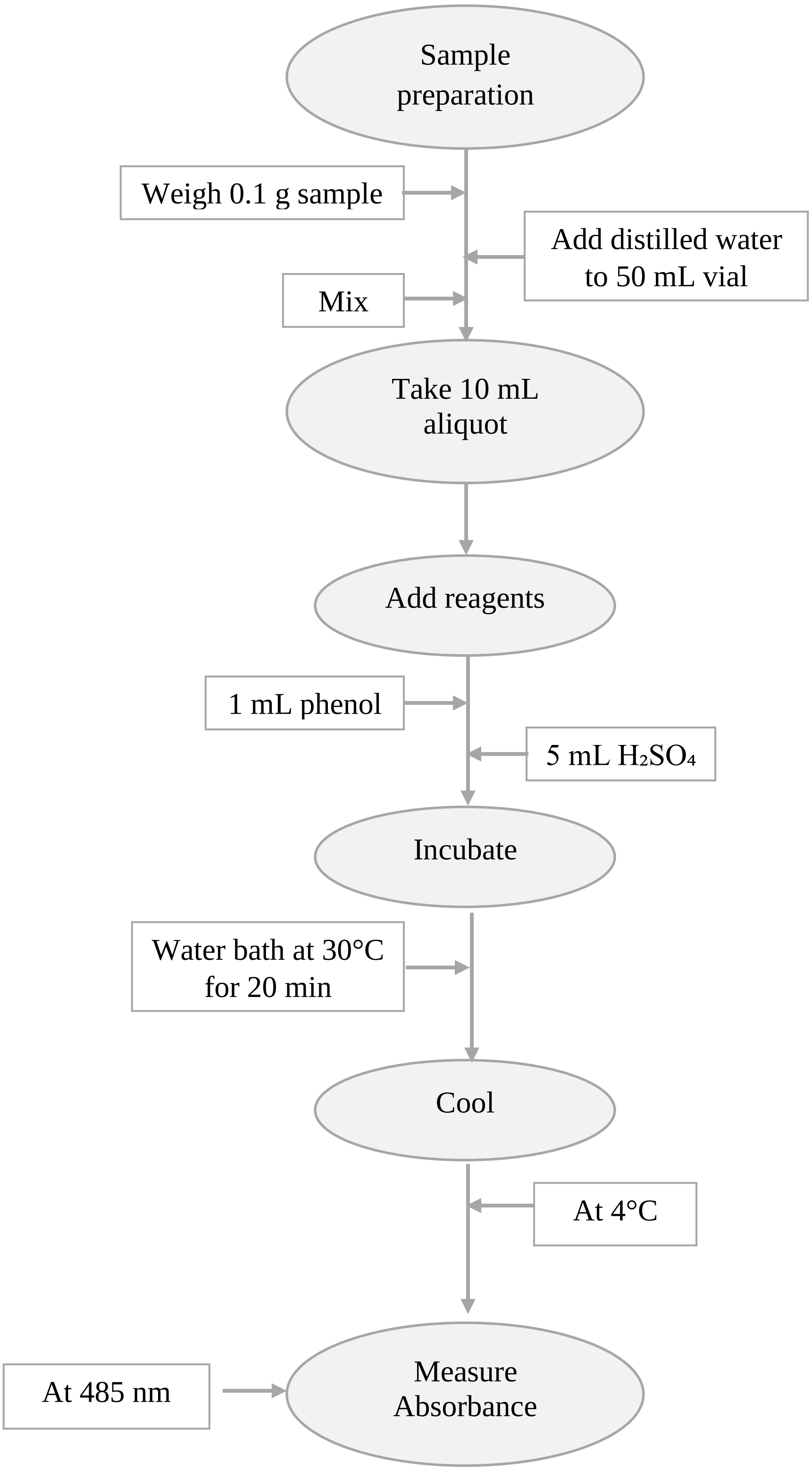
Total soluble sugars are measured using the phenol-sulfuric acid method developed by Dubois et al. (1956).

III.4.1.1 Presentation of the method

The Dubois et al. (1956) method allows oses to be measured using phenol and concentrated sulfuric acid. In the presence of these two reagents, oses produce a yellow-orange color whose intensity is proportional to the concentration of carbohydrates. The optical density is determined between 450 and 550 nm (Nielsen, 1997).

A calibration curve is produced using a glucose solution.

III.4.1.2 Operating procedure



- **The calibration curve**

Add 875mg of glucose to 500ml of distilled water and prepare a 5% phenol solution. Fill 5 test tubes with the glucose solution (0 ml, 2.5 ml, 5 ml, 7.5 ml, 10 ml) and then top up with distilled water to 10ml. Add 1ml of the phenol solution + 5ml of H_2SO_4. The tubes are placed in a water bath at 30°C for 20 minutes, and then cooled under tap water to 20°C. The absorbance is measured at 485nm and the calibration curve is plotted.

- **Sample preparation**

- Weigh 0.1g of each sample into 50ml vials and fill with distilled water.
- Take 10ml of each solution, place in test tubes.
- Add 1ml of phenol and 5ml of sulfuric acid H_2SO_4.
- The tubes are placed in a water bath at 30°C for 20 minutes, then cooled in the refrigerator.
- After cooling, the optical density (absorbance) of the samples is measured at 485nm against the blank of the standard series by spectrophotometry.
- The carbohydrate concentration (mg/mL) in each sample is obtained from the equation derived from the carbohydrate calibration curve (Figure 5, Appendix III).

Figure 28 : Carbohydrate determination by the Dubois colorimetric method

III.4.2 Protein dosage

III.4.2.1 Presentation of the method

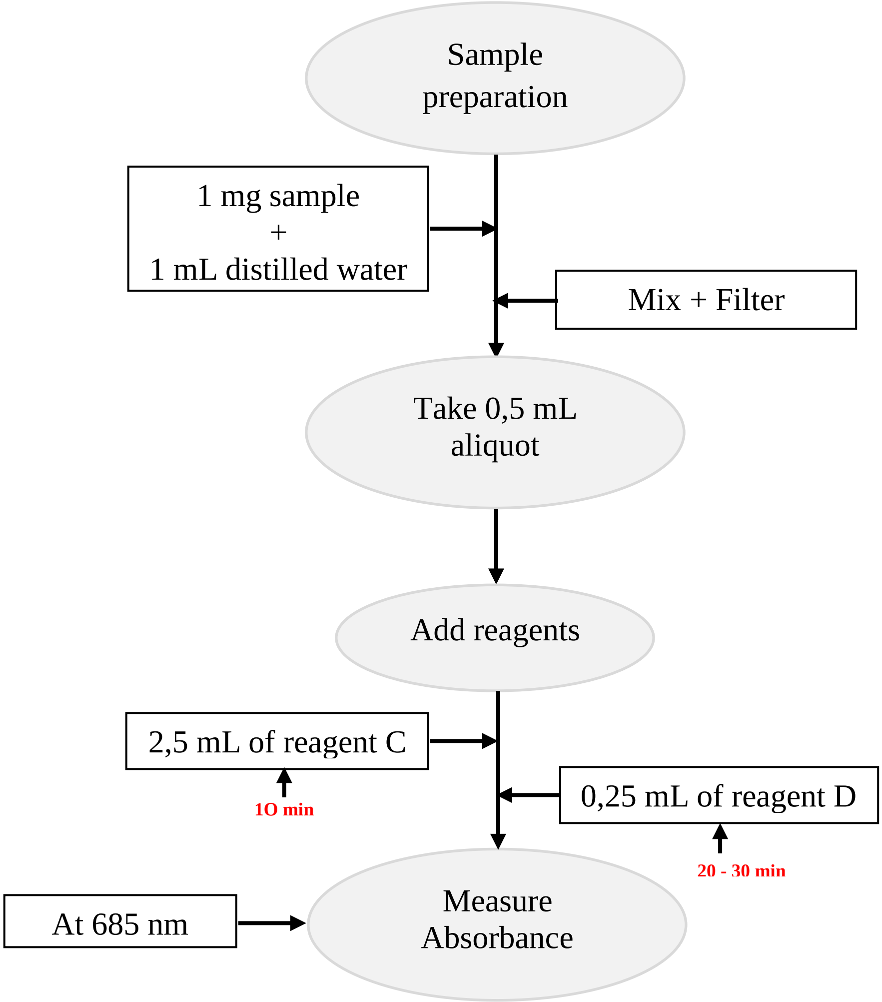
The recommended method is that described by Lowry et al. (1951), in which a copper salt in an alkaline medium forms a colored complex with peptides. The addition of the Folin-Ciocalteu reagent (phosphotungstic and molybdic acid) produces a dark blue color due to both the reaction of copper on the peptide bonds and the reduction of phosphotungstomolybdic acid by tyrosine, tryptophan, and cysteine.

III.4.2.2 Preparation of Reagents

- Reagent A: dissolve 0.5g of ($CuSO_4. 5H_2O$) and 1 g of sodium citrate in 100ml of water. This solution is stable indefinitely (unlike the mixture of copper sulfate and tartrate used in the original method) (RA).
- Reagent B: dissolve 20g of Na_2CO_3 and 4 g of NaOH in 1L of water. (RB)
- Reagent C: add 1ml of reagent A to 50ml of reagent B.
- Reagent D: dilute 1 volume of Folin-Ciocalteu reagent with 1 volume of water.

Figure 29 : Chemical reagents prepared for protein analysis

III.4.2.3 Operating procedure



- Dissolve 1 mg of fish powder in 1ml of distilled water, filter, then take 0.5ml of the solution to be measured (containing a maximum of 0.5mg of protein).
- Add 2.5ml of reagent C, mix and leave for 10 min.
- Add 0.25ml of reagent D, mix well, allow the color to develop for 20 to 30 minutes in the dark.
- Read the absorbance at 685 nm
- The protein concentration (Cp) in mg/L is calculated using the following equation:

$$\boxed{Cp = DO685\ nm\ 0{,}23(mg.\ l\ -1)}$$

The equation was determined based on the calibration curve.

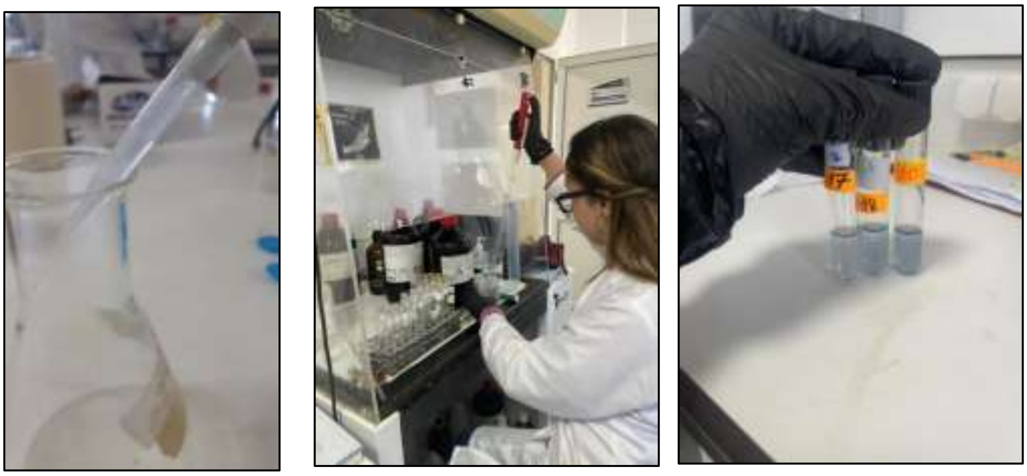


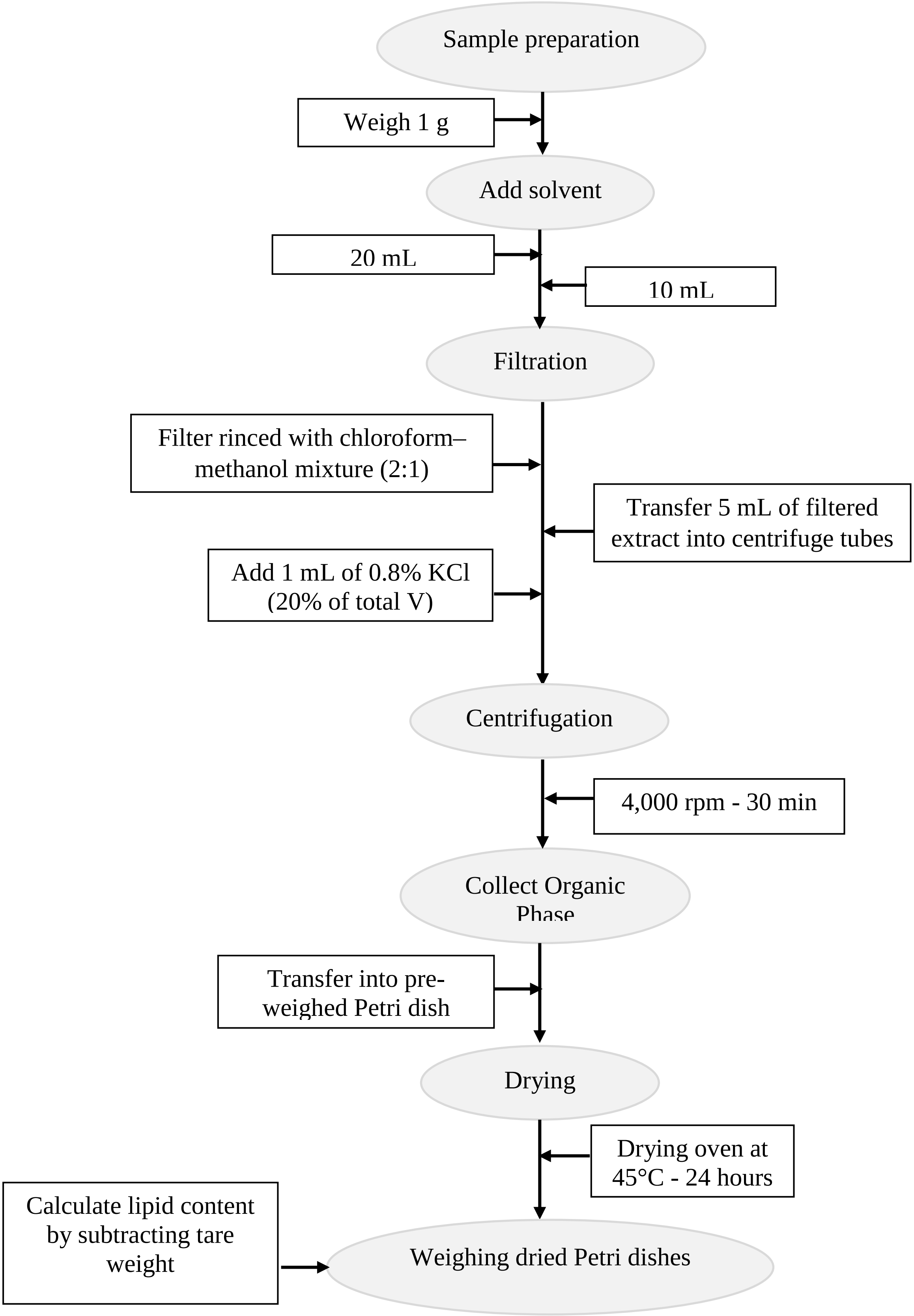
Figure 30: Colorimetric reaction for protein quantification

III.4.3 Lipid measurement

III.4.3.1 Presentation of the method

Lipid measurement is performed according to the method of Folch et al. (1957) modified by Christie (1989). The method relies on solubilization of the lipids in a chloroform-methanol solvent mixture (2:1, v/v), and phase separation is accomplished using a solution of saline. The lipids are cleaned from the organic phase and determined gravimetrically following solvent evaporation.

III.4.3.2 Operating procedure



- Weigh 1 g of freeze-dried sample into a clean Erlenmeyer flask.
- Add 20 ml of chloroform and 10 ml of methanol (2:1, v/v), and agitate the mixture for 1 hour.
- The solution was filtered through grease-free filter paper. The residue was rinsed with the same chloroform–methanol mixture (2:1) to recover any remaining lipids.
- 5 ml of the filtered extract was transferred into centrifuge tubes.
- Add 1 ml of 0.8% KCl solution (20% of the total volume).
- Tubes were centrifuged at 4,000 rpm for 30 minutes.
- The upper (organic) phase was carefully collected using a pipette and transferred into a pre-weighed Petri dish.
- The dishes were placed in a drying oven at 45 °C for 24 hours to allow complete solvent evaporation.
- After drying, the dishes were weighed, and lipid content was determined by subtracting the tare weight.

Figure 31: Extraction and quantification of lipids

III.5 Statistical analysis

III.5.1 Bivariate Correlation Analysis

To investigate the relationships between trace metal accumulation and the biochemical composition of the studied fish species, a bivariate correlation analysis was performed. Pearson's correlation coefficients (r) were calculated to quantify the strength and direction of associations between concentrations of trace metals (Zn, Cu) and biochemical parameters (proteins, lipids, carbohydrates) in muscle tissues.

The statistical tool simple correlation is used to find out the degree of association or relationship between two variables (X, Y) when the relationship is linear or near to linear. The degree of relationship can be quantified by a "correlation coefficient" which is denoted by "r". The correlation coefficient "r" is a number without any unit, which the values lies between -1 and 1.When r is equal or close to 1 and -1, it indicates that there exists a linear relationship, if r is equal or close to 0, it indicates either no relationship or with relationship but not linear. The detailed correlation matrix is provided in Table 4 of the Results section

III.6 Health Risk Assessment Indices

To assess both ecological and human health risks related to trace metal exposure, several indices were calculated based on measured concentrations in fish tissues.

III.6.1 Transfer Factor (TF)

The Transfer Factor, also referred to as the Bioaccumulation Factor, was calculated for gill tissues as an indicator of metal uptake from the aquatic environment. It is defined as the ratio between the metal concentration in the organism (C_biota) and that in the surrounding water (C_water), according to Inal et al. (2025) and Vrhovnik et al. (2013). In this study, metal concentrations in water were obtained from the RESANAL monitoring network.

$$\boxed{TF = \frac{C\_biota}{C\_water}}$$

III.6.2 Human Health Risk Assessment

To evaluate potential risks to human consumers, analyses were performed on muscle tissue, following established international guidelines (EPA, 1992, 2016). The following indices were calculated:

III.6.2.1 Estimated Daily Intake (EDI):

Estimates the daily metal intake (µg/kg/day) via fish consumption using the formula:

$$\boxed{EDI = \frac{IR \times C}{BW}}$$

- C: concentration of the metal (µg/g w.w)
- IR: Ingestion rate (0.01 kg/day)
- BW: body weight (70 kg for adults, 28 kg for children).

III.6.2.2 Target Hazard Quotient (THQ):

Assesses non-carcinogenic health risks based on long-term exposure. A THQ < 1 indicates negligible risk. THQ is calculated as:

$$\boxed{THQ = \frac{EF \times ED \times IR \times C}{RfD \times BW \times AT} \times 10^{-3}}$$

- RfD: the oral reference dose (Cu: 0.04 µg/g/day, Zn: 0.3 µg/g/day),
- EF: exposure frequency,
- ED: exposure duration,
- AT: averaging time.

III.6.2.3 Hazard Index (HI):

Summarizes the cumulative risk from multiple metals by summing individual THQ values:

$$\boxed{HI = \sum THQ_i}$$

An HI < 1 indicates no significant combined risk.

III.6.2.4 Consumption Rate Limit (CRL):

Defines the maximum safe daily fish intake (kg/day), estimated using:

$$\boxed{CRL = \frac{RfD \times BW}{C}}$$

All indices were interpreted based on literature thresholds (Liu et al., 2018; Guendouzi et al., 2020; Rajan & Ishak, 2017) to contextualize the contamination levels and guide public health recommendations.

Chapter IV
Results and Discussion

CHAPTER IV: Results and Discussion

This chapter presents and interprets the analytical results obtained from gill and muscle tissues of six small pelagic fish species sampled from various coastal regions in Algeria. The trace metal concentrations are analyzed by species, organ and geographical zone, and are evaluated in light of international safety standards and relevant scientific literature. Particular attention is given to metals of toxicological concern such as cadmium and lead, whose accumulation patterns reveal both interspecific and spatial variability.

In addition to metal quantification, muscle tissues from the same specimens were subjected to biochemical composition analysis, including the determination of total carbohydrates, proteins, and lipids, in order to assess the nutritional quality of these commercially important fish species. Furthermore, the results were used to estimate key human health risk assessment indices, such as the Estimated Daily Intake (EDI), Target Hazard Quotient (THQ), and Hazard Index (HI), with the aim of evaluating potential exposure risks for Algerian consumers.

The table below summarizes, for each sample, the species, analyzed tissue, sampling region, and measured metal concentrations. These values form the basis of the comparative and interpretative analysis that follows.

Table 2 : Summary of trace metal concentrations (Cd, Pb, Cu, Zn) in gill and muscle tissues of six small pelagic species

ORGAN	Sample Code	Species	Region	**Cd**		**Pb**		**Zn**		**Cu**	
				ɥg/g **D.W**	mg/kg **W.W**	ɥg/g **D.W**	mg/kg **W.W**	mg/kg **D.W**	mg/kg **W.W**	mg/kg **D.W**	mg/kg **W.W**
Gill	**P53/BB/B**	*Boops boops*	Bouismail	0,06	0,02	1,74	0,43	28,76	7,10	0,34	0,08
	P24/SA/B	*Sardinella aurita*	Skikda	0,47	0,11	6,56	1,47	65,91	14,83	0,46	0,10
	P83/TM/B	*Trachurus mediterraneus*	Ghazaouet	0,10	0,03	2,73	0,80	24,08	7,02	0,32	0,09
	P59/A/B	*Engraulis encrasicolus*	Arzew	0,22	0,06	0,67	0,17	34,91	9,05	0,32	0,08
	P32/TT/B	*Trachurus trachurus*	Annaba	0,09	0,03	0,50	0,15	28,81	8,42	0,41	0,12
	P37/SP/B	*Sardina pilchardus*	Annaba	0,21	0,05	0,78	0,20	33,67	8,53	0,36	0,09
Muscle	**P03/TM/M**	*Trachurus mediterraneus*	Zemmouri					31,48	9,61	2,56	0,78
	P55/BB/M	*Boops boops*	Mostaganem					66,42	25,81	6,14	2,39
	P06/TT/M	*Trachurus trachurus*	Bejaia					32,78	9,73	2,48	0,74
	P37/SP/M	*Sardina pilchardus*	Annaba					57,13	27,02	6,12	2,89
	P13/TT/M	*Trachurus trachurus*	Jijel					28,49	9,13	2,47	0,79
	P22/SP/M	*Sardina pilchardus*	Skikda					50,98	15,30	4,56	1,37
	P21/TT/M	*Trachurus trachurus*	Skikda					32,42	20,82	2,66	1,71
	P30/TM/M	*Trachurus mediterraneus*	Annaba					34,33	11,17	2,80	0,91
	P26/TM/M	*Trachurus mediterraneus*	Annaba					30,54	2,37	2,46	0,19
	P57/TM/M	*Trachurus mediterraneus*	Mostaganem					73,05	19,73	8,80	2,38
	P11/TM/M	*Trachurus mediterraneus*	Jijel					29,42	11,21	5,23	1,99
	P28/TT/M	*Trachurus trachurus*	Annaba					26,78	9,94	2,14	0,80
	P83/TM/M	*Trachurus mediterraneus*	Ghazaouet					75,03	18,82	3,32	0,83
	P01/TT/M	*Trachurus trachurus*	Zemmouri					36,02	11,48	3,59	1,143

IV.1 Trace Metal Concentrations

IV.1.1 In gill tissues

Trace metal analyses (Cd, Pb, Cu, Zn) were performed on gill tissues of our species sampled from five distinct coastal zones along the Algerian shoreline: Skikda, Annaba, Tipaza (Bouismail) , Oran (Arzew) and Tlemcen (Ghazaouet).

IV.1.1.1 Cadmium (Cd)

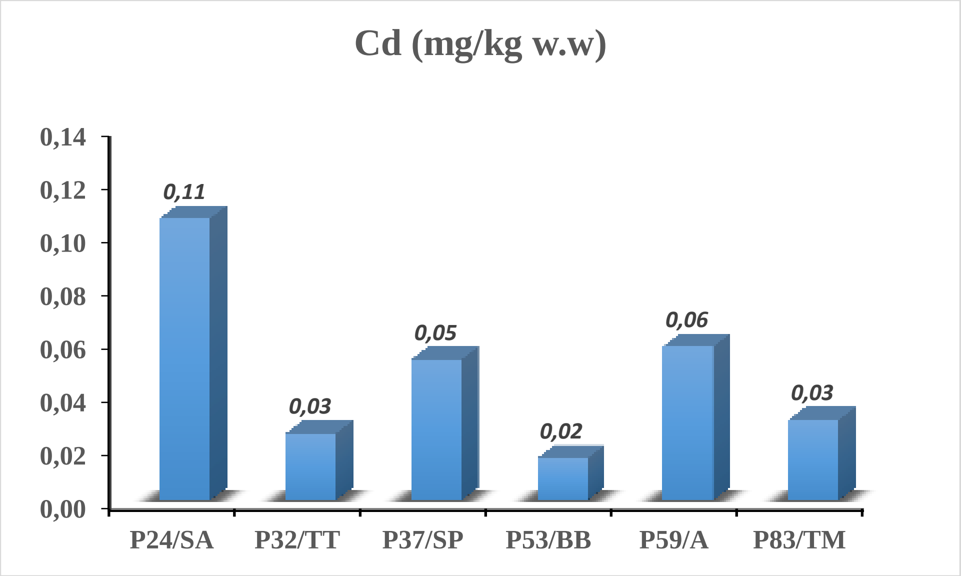


Figure 29: Cadmium concentrations in gill tissues of the small pelagic species

Cadmium concentrations in the analyzed gill tissues ranged from 0.02 to 0.11 mg/kg w.w with two fish samples exceeding the WHO safety limit of 0.05 mg/kg w.w. The highest Cd level was recorded in *Sardinella aurita* from Skikda (P24/SA) at 0.11 mg/kg w.w, followed by *Engraulis encrasicolus* from Arzew (P59/A) at 0.06 mg/kg w.w. Both locations are characterized by intense industrial activity, including petrochemical complexes and steel manufacturing plants (Refes, 2011; Grimes, 2010).

Sardina pilchardus from Annaba (P37/SP) registered exactly at the WHO threshold of 0.05 mg/kg w.w, while (P32/TT) from the same region, (P53/BB) from Bouismail, and (P83/TM) from ghazaouet showed lower concentrations of 0.03, 0.02, and 0.03 mg/kg w.w, respectively, reflecting comparatively reduced cadmium exposure in these areas.

This elevated contamination observed in Arzew and Skikda aligns with documented point-source pollution from fertilizer factories, phosphate processing, and metallurgical industries

(Grimes, 2010; Silhadi et al., 2020). These industrial activities discharge cadmium into the marine environment, where it bioaccumulates particularly in filter-feeding or nearshore species.

Compared to cadmium levels reported in *Oreochromis niloticus* by Nakweti et al. (2021) (0.208 ± 0.095 mg/kg w.w.), all measured values along the Algerian coast remain lower.

Similar bioaccumulation trends have been documented in *Sardinella aurita* from the Bay of Marsa Ben M'hidi, where cadmium concentrations in gill tissues ranged from 0.019 to 0.062 mg/kg dry weight, with a mean of 0.033 mg/kg (Djouzi, 2015). Although these values do not exceed the IAEA limit, they confirm *Sardinella aurita*'s capacity to accumulate cadmium in branchial tissues, likely due to its ecological behavior and filter-feeding tendencies

IV.1.1.2 Lead (Pb)

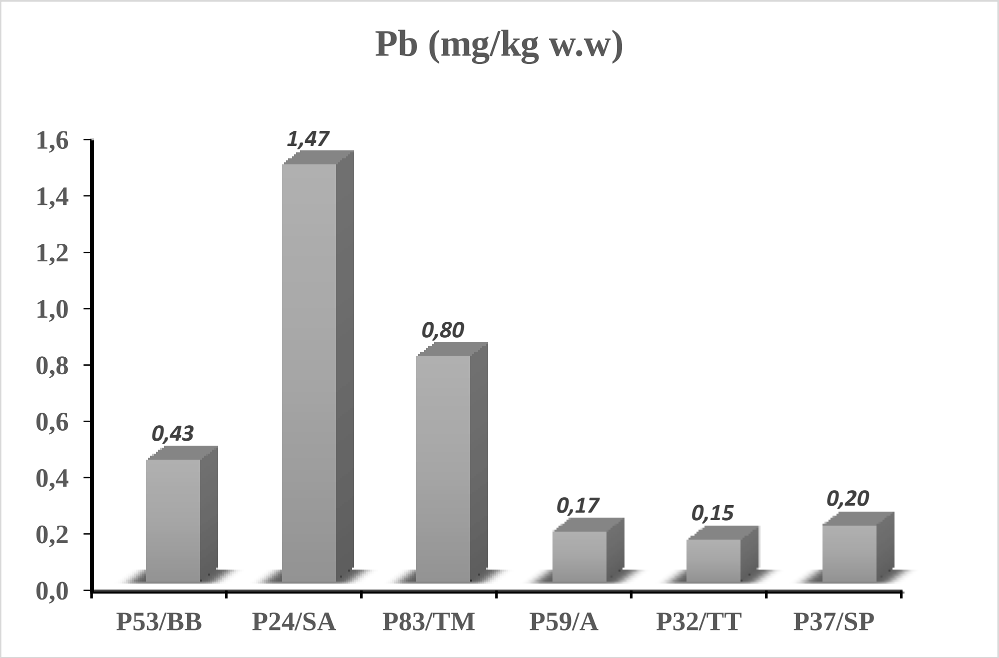


Figure 30: Lead concentrations in gill tissues of the six small pelagic species

Lead concentrations in gill tissues exhibited a broader range, varying from 0.15 to 1.47 mg/kg w.w, with three out of six samples surpassing the WHO safety limit of 0.2 mg/kg w.w. The highest Pb concentration was found in *Sardinella aurita* from Skikda (P24/SA) at 1.47 mg/kg w.w, exceeding the WHO limit by more than sevenfold. This corresponds to the high industrial density of the Skikda region, which hosts petrochemical plants, power stations, and industrial gas production facilities (Grimes, 2010).

Trachurus mediterraneus from Ghazaouet (P83/TM) and *Boops boops* from Bouismail (P53/BB) also exhibited concerning Pb levels of 0.8 mg/kg w.w and 0.43 mg/kg w.w, respectively. Both sites are influenced by metallurgical and agro-industrial activities, such as the ALZINC complex in Tlemcen.

Sardina pilchardus (P37/SP) and *Engraulis encrasicolus* (P59/A) showed Pb concentrations at the WHO threshold of 0.2 mg/kg w.w , while *Trachurus trachurus* from Annaba (P32/TT) recorded the lowest value of 0.15 mg/kg w.w.

When compared to Pb concentrations reported for *O. niloticus* by Nakweti et al. (2021) (0.263 ± 0.055 mg/kg w.w.), most values from Algerian coastal fish, particularly those from Skikda, Bouismail and Ghazaouet, are considerably elevated, underscoring significant ecological and public health concerns.

Comparable findings have been reported in *Sardinella aurita* from Marsa Ben M’hidi by Djouzi (2015), where the mean lead concentration in gill tissues reached 0.366 mg/kg dry weight (corresponding approximately to >0.2 mg/kg w.w), with all individuals exceeding IAEA guideline values (IAEA, 2003)

These consistently elevated levels in *Sardinella aurita*, across different Algerian coastal zones, underscore its known tendency to accumulate lead, particularly in the gills, as confirmed by previous studies.

IV.1.1.3 Zinc (Zn)

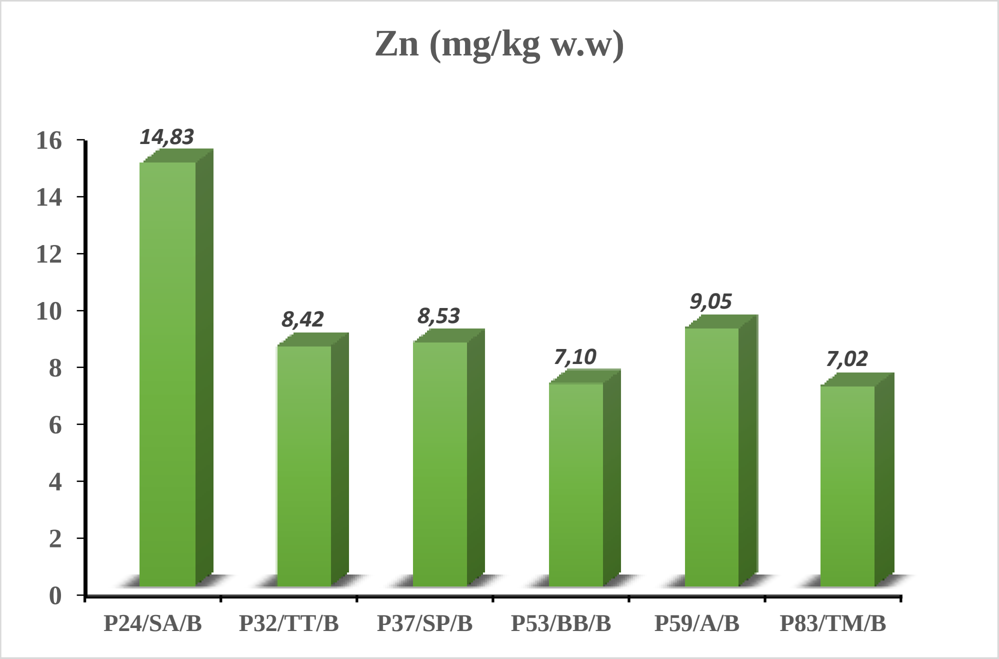


Figure 32 : Zinc concentrations in gill tissues of the six small pelagic species

Zinc concentrations measured in the gill tissues of the six fish species ranged from 7.02 to 14.83 mg/kg w.w, with the highest level detected in *Sardinella aurita* from Skikda (P24/SA) at 14.83 mg/kg w.w. This elevated concentration may reflect a strong environmental exposure to zinc in the Skikda region, known for its dense industrial activity, including chemical plants and port operations (Refes, 2011; Grimes, 2010).

Moderate concentrations were recorded in *Engraulis encrasicolus* from Arzew (P59/A) and *Sardina pilchardus* from Annaba (P37/SP), with values of 9.05 and 8.53 mg/kg w.w, respectively, suggesting variable but persistent zinc inputs along the central and eastern Algerian coast. Lower concentrations were found in *Boops boops* from Bou Ismaïl (P53/BB) and *Trachurus mediterraneus* from Ghazaouet (P83/TM), measuring 7.10 and 7.02 mg/kg w.w, respectively.

These findings are consistent with those reported by Djouzi (2015), who found zinc concentrations in *Sardinella aurita* gills from Marsa Ben M'hidi ranging from 1.06 to 3.60 mg/kg D.W, with a mean of 2.41 mg/kg, which converts approximately to lower wet weight values. Notably, zinc accumulation in *Sardinella aurita* was previously shown to be organ-specific, with higher concentrations often detected in metabolically active tissues such as the gills.

IV.1.1.4 Copper

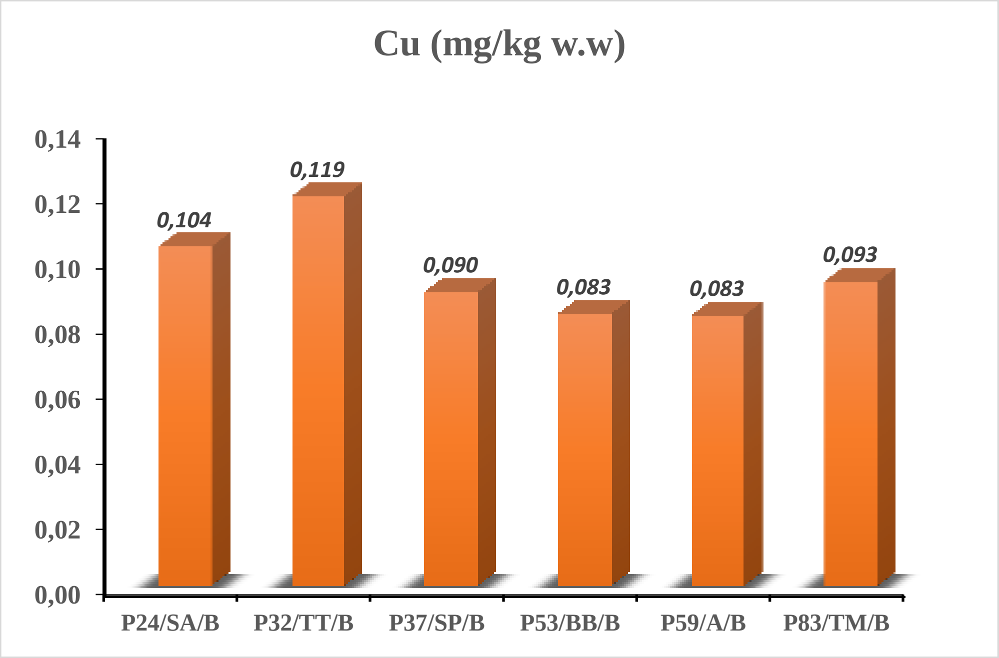


Figure 33 : Copper concentrations in gill tissues of the six small pelagic species

Copper concentrations in the gill tissues of the six pelagic species ranged from 0.083 to 0.119 mg/kg w.w. The highest concentration was found in *Trachurus trachurus* from Annaba (P32/TT) at 0.119 mg/kg w.w, closely followed by *Sardinella aurita* from Skikda (P24/SA) at 0.104 mg/kg w.w. The lowest Cu levels were recorded in *Boops boops* and *Engraulis encrasicolus* from Bou Ismail and Arzew respectively (P53/BB and P59/A), both at 0.083 mg/kg w.w.

These values are well below the guideline concentration established by the IAEA, which is 3.28 mg/kg for marine organisms (IAEA, 1985, cited in Casas, 2005). The overall low Cu levels observed in all gill samples may reflect either limited copper pollution in these coastal zones or efficient regulation and excretion mechanisms in these fish species, particularly in the gill tissues.

Notably, our finding of low Cu accumulation in the gills of *Sardinella aurita* (0.104 mg/kg w.w) is consistent with previous studies on this species, such us the one conducted in the Marsa Ben M'hidi region, *Sardinella aurita* exhibited similarly minimal gill copper levels, with an average of 0.03 mg/kg w.w. This consistent trend suggests that *Sardinella aurita* may possess physiological or ecological traits that limit copper bioaccumulation in its gill tissues.

IV.1.2 In muscle

Trace metal analyses (Zn and Cu) were carried out on muscle tissues of the same six pelagic species, sampled across seven coastal sites along the Algerian coastline: Skikda, Annaba, Jijel, Béjaïa, Zemmouri (Boumerdes), Mostaganem, and Ghazaouet (Tlemcen).

IV.1.2.1 Zinc (Zn)

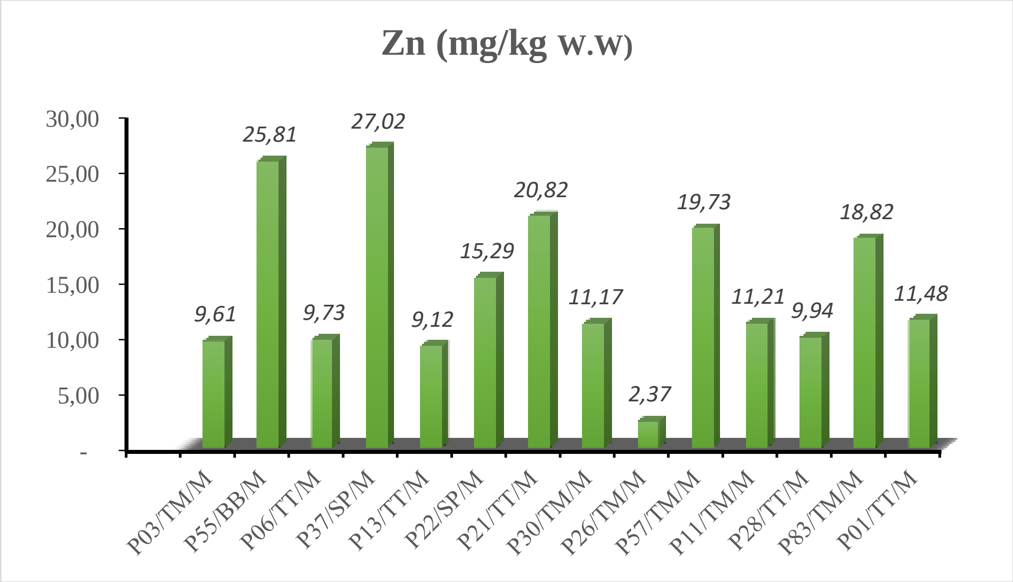


Figure 34 : Zinc concentrations in muscle tissues of *T. trachurus, T. mediterraneus, Sardina pilchardus* and *Boops boops*

Zinc concentrations in muscle tissue ranged from 9.12 to 27.02 mg/kg wet weight. The highest Zn level was observed in *Sardina pilchardus* from Annaba (27.02 mg/kg w.w.), followed closely by *Boops boops* from Mostaganem (25.81 mg/kg w.w.) and *Trachurus trachurus* from Skikda (20.82 mg/kg w.w.). Conversely, the lowest Zn concentrations were recorded in *Trachurus trachurus* from Jijel (9.13 mg/kg w.w.), *Trachurus mediterraneus* from Zemmouri (9.61 mg/kg w.w), and T. trachurus from Béjaïa (9.73 mg/kg w.w).

These values remain within the typical biological range for marine teleosts, although concentrations above 20 mg/kg w.w. are often considered elevated and may indicate chronic environmental exposure to Zn-enriched effluents. The eastern (Annaba, Skikda) and western (Mostaganem, Ghazaouet) coastal sectors showed the highest concentrations, aligning with regions known for intense anthropogenic activities such as port traffic, industrial discharges, and untreated urban effluents (Refes, 2011).

Although the WHO has not established a maximum limit for Zn in fish muscle, other references (FAO/WHO Joint Expert Committee) suggest that values exceeding 30–40 mg/kg W.W. may require attention. In this context, all recorded values remain below such thresholds, suggesting no acute risk to consumers, though the observed regional disparities merit environmental monitoring.

IV.1.2.2 Copper (Cu)

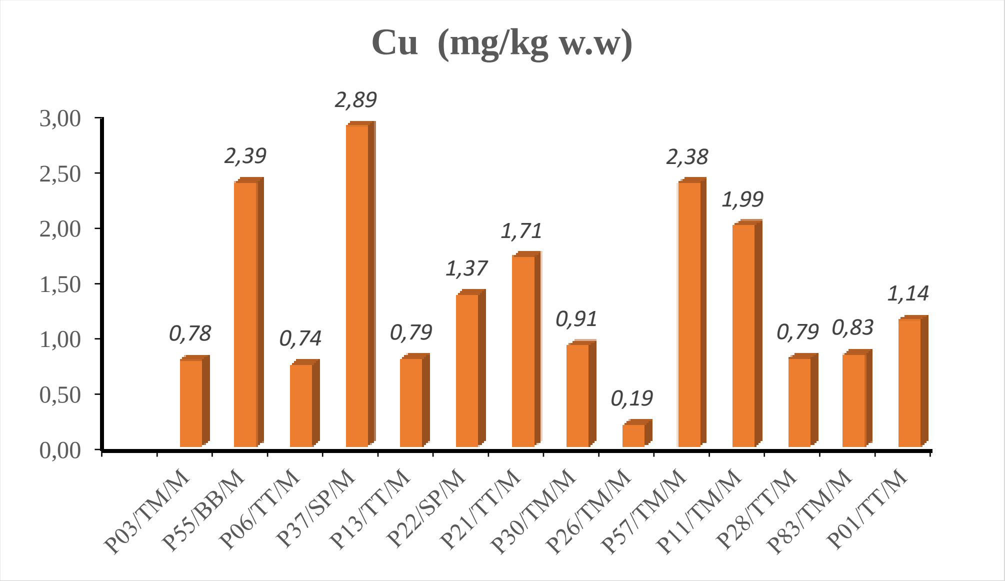


Figure 35 : Copper concentrations in muscle tissues of *T. trachurus, T. mediterraneus, Sardina pilchardus and Boops boops*

Copper concentrations ranged from 0.19 to 2.89 mg/kg W.W., with the highest levels found in *Sardina pilchardus* from Annaba (2.89 mg/kg W.W.), *Boops boops* from Mostaganem (2.39 mg/kg), and *Trachurus mediterraneus* from Mostaganem (2.38 mg/kg). The lowest Cu concentration was measured in *Trachurus mediterraneus* from Annaba (0.19 mg/kg W.W.).

Copper is essential for numerous enzymatic and metabolic functions, but excessive exposure can induce oxidative stress and cytotoxicity. According to WHO and European Commission guidance, the maximum allowable concentration of copper in fish muscle for human consumption is approximately 10 mg/kg W.W. Thus, all measured concentrations are well below this limit, indicating no immediate toxicological concern for human health.

IV.2 Biochemical composition

In addition to trace metal quantification, the biochemical composition of the muscle tissues previously analyzed for Cu and Zn was also assessed.. This included the determination of total carbohydrates, proteins, and lipids, providing valuable insight into the nutritional status and metabolic variability among the studied species. The data are presented in the table below and discussed in terms of interspecies differences. Both interspecific and spatial variations were evaluated to better understand the influence of species identity and geographic origin on biochemical composition.

Table 3 : Biochemical composition (carbohydrates, proteins, lipids) of muscle tissues

Sample	Carbohydrates (%)	Proteins (%)	Lipids (%)
P03/TM/M	13,80	2,74	2,88
P30/TM/M	5,41	2,48	3,32
P26/TM/M	13,60	6,51	2,97
P57/TM/M	16,67	9,32	2,32
P11/TM/M	8,07	8,37	3,02
P83/TM/M	10,32	16,93	2,34
P06/TT/M	10,53	7,25	4,18
P13/TT/M	14,01	7,84	2,55
P21/TT/M	7,66	11,22	2,50
P28/TT/M	4,59	5,50	3,82
P01/TT/M	8,27	1,15	2,12
P37/SP/M	16,47	4,51	2,44
P22/SP/M	7,05	9,38	2,92
P55/BB/M	7,66	2,99	1,33

IV.2.1 Carbohydrates

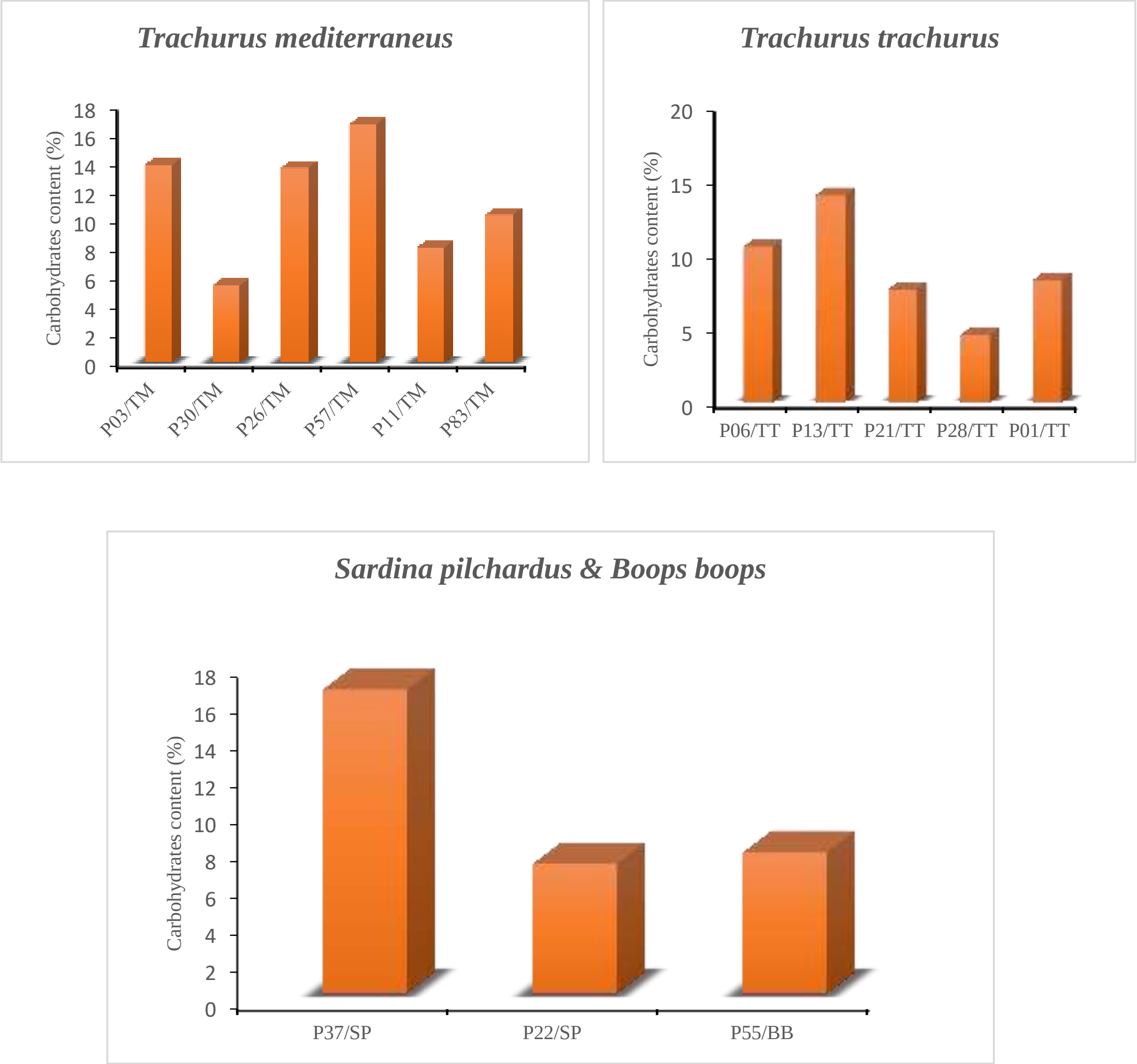
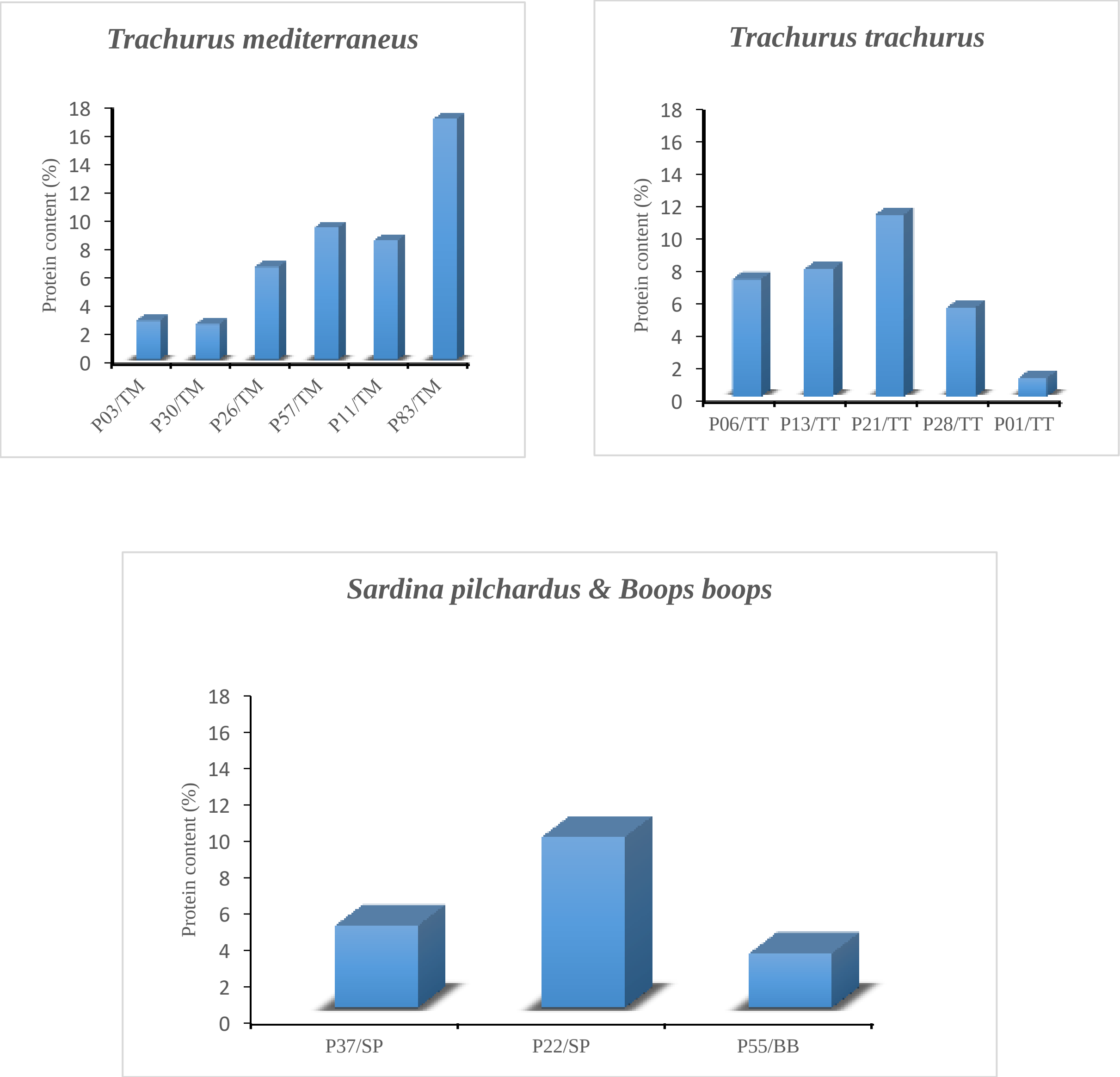


Figure 36 : Carbohydrates content in muscle tissues of *T. trachurus*, *T. mediterraneus*, *S. pilchardus* & *B. boops*

The carbohydrate content observed in *Trachurus mediterraneus* varied markedly by region, ranging from low levels in Annaba (5.41%) to elevated levels in Mostaganem (16.67%) and Zemmouri (13.80%), indicating that environmental productivity and local feeding opportunities significantly influence muscle glycogen reserves. *Trachurus trachurus* similarly showed spatial variability, with the highest content in Jijel (14.01%) and the lowest in Annaba (4.59%), suggesting regional differences in energy storage associated with varying trophic conditions. *Sardina pilchardus* exhibited high carbohydrates in Annaba (16.47%), contrasting with moderate levels in Skikda (7.05%), while *Boops boops*, sampled only in Mostaganem, displayed a mid-range carbohydrate content (7.66%). These values are comparable to those reported for Indian sardines and mackerels by Sumi et al. (2016), where carbohydrate contents fell within similar ranges.

IV.2.2 Protein



Trachurus mediterraneus

Trachurus trachurus

Sardina pilchardus & Boops boops

Figure 37 : Proteins content in muscle tissues of *T. trachurus, T. mediterraneus, S. pilchardus & B. boops*

Protein content in *Trachurus mediterraneus* exhibited strong regional variation, from low values in Zemmouri (2.48%) to very high levels in Ghazaouet (16.93%), reflecting enhanced muscle accretion likely linked to favorable ecological conditions or reproductive readiness. In *Trachurus trachurus*, protein content ranged from minimal (1.15% in Zemmouri) to substantial (11.22% in Skikda), indicating local feeding conditions or fish maturity as key drivers. *Sardina pilchardus* showed moderate protein variation between Annaba (4.51%) and Skikda (9.38%), while *Boops boops* consistently displayed low protein (2.99%), aligning with its lower trophic niche and expected muscle composition. When compared to the Indian study, which reported 17–28% protein in sardines and mackerels (Sumi et al., 2016), the protein levels in *Trachurus mediterraneus*, particularly the Ghazaouet sample, are comparable but generally at the lower end, demonstrating that Algerian small pelagics have substantial protein content without consistently reaching the higher tropical benchmarks.

IV.2.3 Lipid

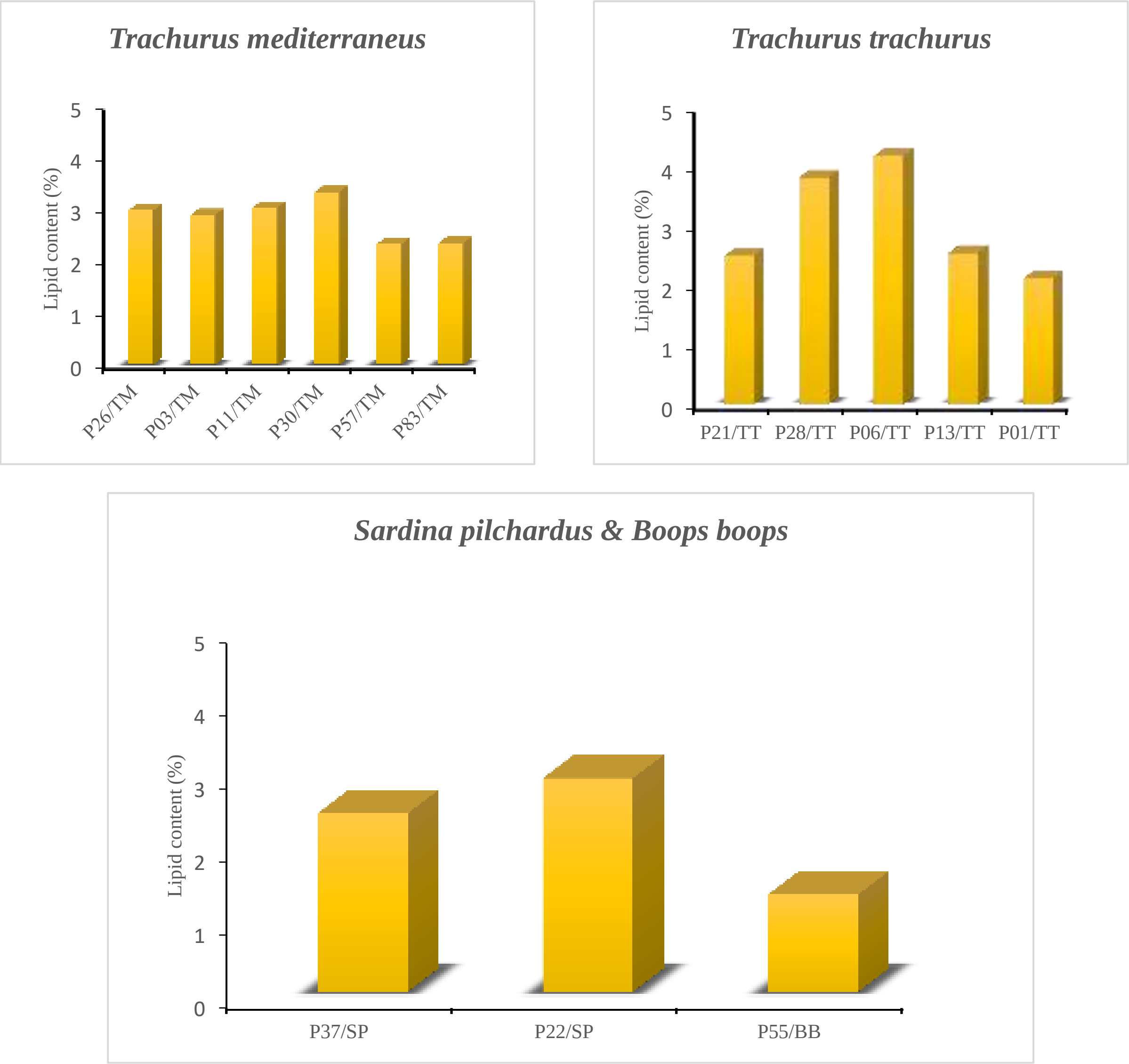


Figure 38 : Lipids content in muscle tissues of *T. trachurus*, *T. mediterraneus*, *S. pilchardus & B. boops*

Lipid concentrations across sampled regions reflected notable species-level differences. *Trachurus trachurus* demonstrated the highest lipid percentages (4.18% in Béjaïa and 3.82% in Annaba), pointing to strong energy reserve deposition in these areas. *Trachurus mediterraneus* maintained moderate lipid levels (2.3–3.3%) across all regions sampled, indicating stable energy storage irrespective of location. *Sardina pilchardus* displayed a balanced lipid composition (2.44–2.92%), suggesting consistent metabolic strategies. In contrast, *Boops boops* exhibited the lowest lipid content (1.33%), aligning with its ecological feeding pattern. These results fall below the higher lipid ranges (6–10%) reported in Indian pelagics (Sumi et al., 2016) but remain within expected values for temperate and sub-tropical marine fish, confirming moderate energy storage across Algerian species.

IV.3 Correlation Between Trace Metals and Biochemical Composition

Table 4 : Correlation matrix between biochemical composition and trace metal concentrations in muscle tissues (Significant correlations are highlighted in red)

	% Carbohydrates	**% Proteins**	**% Lipids**	**Zn (mg/kg)**	**Cu (mg/kg)**
% Carbohydrates	1,00	0,08	- 0,22	0,29	0,37
% Proteins		1,00	0,00	0,38	0,03
% Lipids			1,00	**- 0,59**	**- 0,52**
Zn (mg/kg)				1,00	**0,71**
Cu (mg/kg)					1,00

To better understand the physiological and environmental factors influencing trace metal bioaccumulation, a correlation analysis was performed between the biochemical composition (carbohydrates, proteins, and lipids) and the concentrations of zinc (Zn) and copper (Cu) in muscle tissues.

The results showed that lipid content exhibited a strong negative correlation with both Zn (r = -0.59) and Cu (r = -0.52)**.** This inverse relationship suggests that fish with lower lipid reserves tend to accumulate higher levels of these metals. This could be attributed to the higher metabolic activity and membrane permeability associated with leaner tissues, which may favor metal uptake and retention.

Additionally, Zn and Cu concentrations were positively correlated (r = 0.71)**,** indicating a potential shared regulatory or environmental uptake pathway. This concordance may reflect similar sources of exposure likely linked to anthropogenic inputs and parallel absorption mechanisms at the muscle level. Such a relationship is consistent with findings in the literature, where essential trace metals often follow related homeostatic controls (Burger et al., 2002; Liu et al., 2018).

IV.4 Health Risk Assessment

To evaluate the potential human health risks associated with the consumption of small pelagic fish, a set of standardized risk indices was calculated based on the concentrations of zinc and copper in muscle tissues of 14 specimens. These indices included**)**, Estimated Daily Intake (EDI)**,** Target Hazard Quotient (THQ)**,** Hazard Index (HI)**,** and Consumption Rate Limit (CRL)**,** following international protocols, while the Transfer Factor (TF) was calculated on gill tissues (EPA, 1992; Guendouzi et al., 2020).

IV.4.1 Transfer Factor (TF)

Table 5 : Transfer Factors of Trace Metals (Cd, Pb, Cu, Zn) in Gill Tissues

Sample Code	TF Cd	TF Pb	TF Cu	TF Zn
P53/BB/B	0,10	0,55	2,49	0,25
P24/SA/B	0,70	2,09	1,43	0,35
P83/TM/B	0,15	0,87	2,09	0,24
P59/A/B	0,33	0,21	3,03	0,24
P32/TT/B	0,13	0,16	2,50	0,31
P37/SP/B	0,31	0,25	2,92	0,27
Mean	0,29	0,69	2,41	0,28
Standard Deviation	0,22	0,74	0,59	0,04
Min	0,10	0,16	1,43	0,24
Max	0,70	2,09	3,03	0,35

IV.4.1.1 Cadmium (Cd)

TF values for Cd ranged from 0.1 in *Boops boops* (P53/BB/B) to 0.7 in *Sardinella aurita* (P24/SA/B). Although all values remain below 1, the elevated TF in *S. aurita* suggests a stronger ability to accumulate Cd from the water, potentially due to species-specific physiological traits or regional pollution pressures in Skikda.

IV.4.1.2 Lead (Pb)

Pb showed a broader variation, with TF values from 0.16 (*T. trachurus*) to 2.09 (*S. aurita*). Notably, two samples (*S. aurita* and *T. mediterraneus*) exceeded TF = 1, indicating significant

Pb bioaccumulation. These results are consistent with previous studies associating Pb uptake with industrial contamination and high metal affinity for gill tissues (Lafabrie et al., 2007).

IV.4.1.3 Copper (Cu)

Cu TFs were generally high across all samples, ranging from 1.43 to 3.03, confirming a marked bioaccumulation capacity. The highest TF was observed in *Engraulis encrasicolus*, potentially reflecting increased exposure or efficient uptake mechanisms, as Cu is both essential and actively regulated in fish.

IV.4.1.4 Zinc (Zn)

TF values for Zn remained below 0.35 in all samples, with the highest value recorded in *S. aurita*. Although Zn is essential, its bioaccumulation appears to be more tightly regulated, likely due to homeostatic mechanisms.

IV.4.2 Estimated Daily Intake (EDI)

Table 6 : Summary Statistics of Estimated Daily Intake (EDI) of Zn and Cu in Fish Muscle

	EDI Zn Child	**EDI Cu Child**	**EDI Zn Adult**	**EDI CU Adult**
Mean	5,16E-03	4,82E-04	2,06E-03	1,93E-04
Standard Deviation	2,52E-03	2,84E-04	1,01E-03	1,14E-04
Min	8,47E-04	6,81E-05	3,39E-04	2,72E-05
Max	9,65E-03	1,03E-03	3,86E-03	4,13E-04

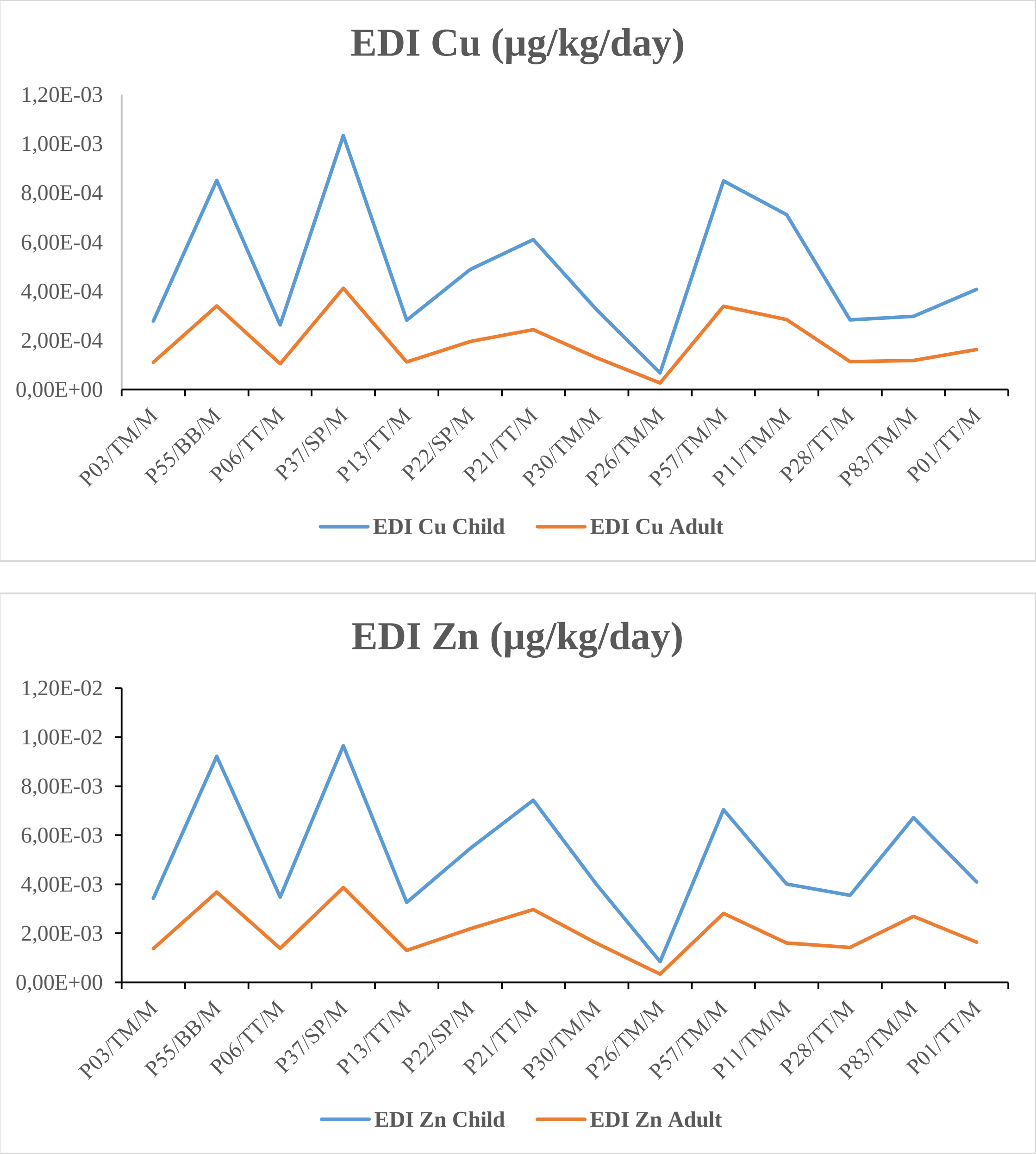


Figure 39 : Estimated Daily Intake (EDI) of Zn and Cu for each muscle sample

The average EDI for zinc was 0.00206 µg/kg/day for adults and 0.00516 µg/kg/day for children. For copper, the average EDI was 0.00019 µg/kg/day for adults and 0.00048 µg/kg/day for children. These values are below the recommended tolerable daily intake levels suggested by the WHO and EPA, suggesting a generally low risk from Zn and Cu exposure through fish consumption.

IV.4.3 Target Hazard Quotient (THQ)

Table 7 : Summary Statistics of Target Hazard Quotient (THQ) for Zn and Cu

	THQ Zn Ch	THQ Cu Ch	THQ Zn Ad	THQ Cu Ad
MOY	6,27	4,40	2,51	1,76
Standard Deviation	3,06	2,59	1,22	1,04
MIN	1,03	0,62	0,41	0,25
MAX	11,74	9,43	4,70	3,77

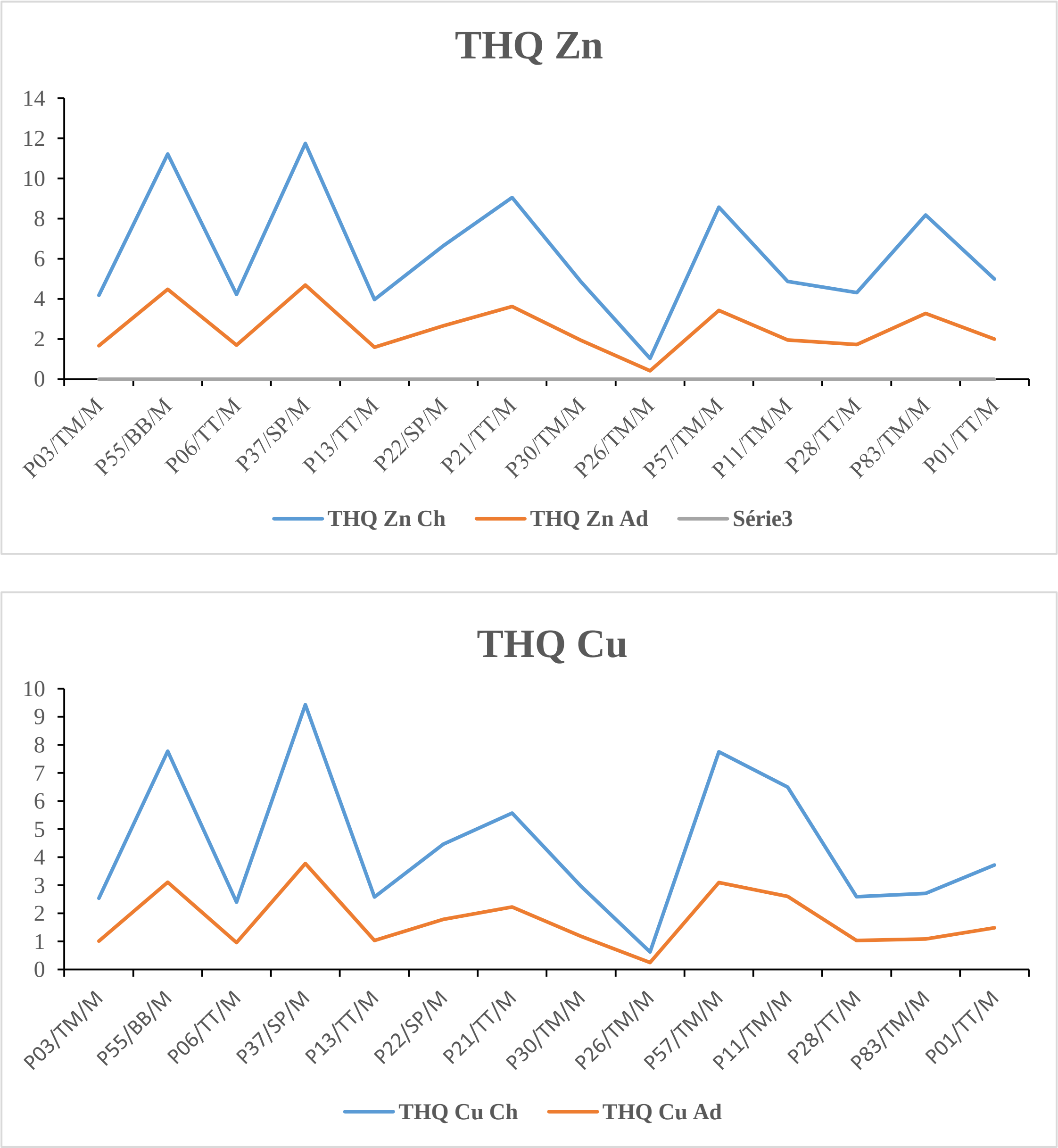


Figure 40 : Target Hazard Quotient (THQ) of Zn and Cu by Sample

According to the established THQ classification grid (THQ < 1: no significant risk; THQ ≥ 1: potential health risk), the results for both adults and children are of particular concern. For adults, most THQ values for zinc ranged from 1.59 to 4.70 and for copper from 1.02 to 3.77, with only rare exceptions falling below 1. In children, the situation is even more alarming: all THQ values for both Zn and Cu were substantially above the safety threshold, with Zn values ranging from 3.96 to 11.74 and Cu from 2.40 to 9.43.

These findings indicate that, under current exposure scenarios, the regular consumption of these fish species poses a significant non-carcinogenic health risk for children, who are especially vulnerable to chronic metal exposure. The highest THQ values for both metals were recorded in samples from the eastern coastal regions (especially Annaba), with maximum values reaching 11.74 for Zn and 9.43 for Cu.

IV.4.4 Hazard Index (HI)

Table 8 : Summary Statistics of Hazard Index (HI) Resulting from Zn and Cu Exposure

	HI Ch	**HI Ad**
Mean	10,67	2,21
Standard Deviation	5,44	1,87
Min	1,65	0,41
Max	21,17	4,70

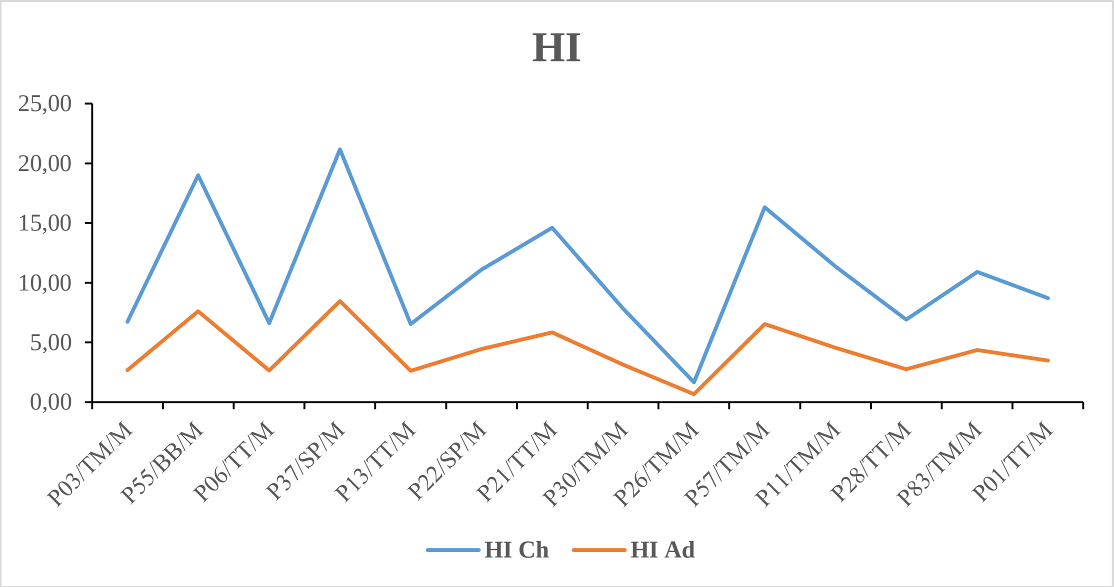


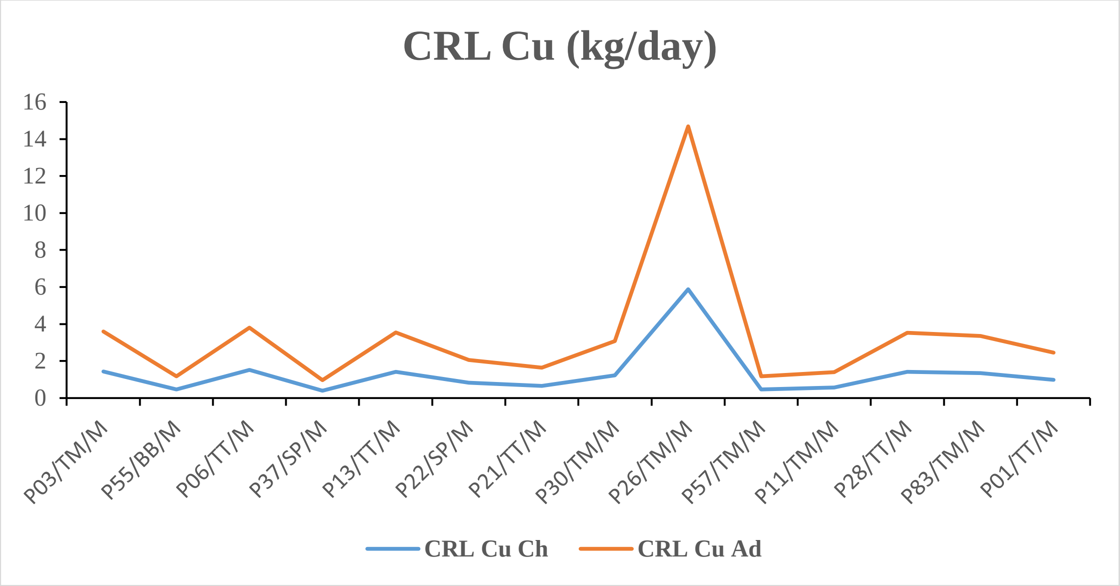
Figure 41 : Hazard Index (HI) Values Across Samples

The HI, representing cumulative risk from both Zn and Cu, averaged 4.27 in adults and 10.67 in children. The maximum HI reached 8.47 in adults and 21.17 in children, further emphasizing the vulnerability of younger populations to metal exposure from fish consumption. Values above 1 in most cases highlight significant combined health risks.

IV.4.5 Consumption Rate Limit (CRL)

Table 9 : Summary Statistics of Consumption Rate Limits (CRL) for Zn and Cu in Fish Muscle

	CRL Zn Ch	CRL Cu Ch	CRL Zn Ad	CRL Cu Ad
Mean	0,84	1,33	2,10	3,32
Standard Deviation	0,81	1,37	2,02	3,43
Min	0,31	0,39	0,78	0,97
Max	3,54	5,87	8,86	14,69



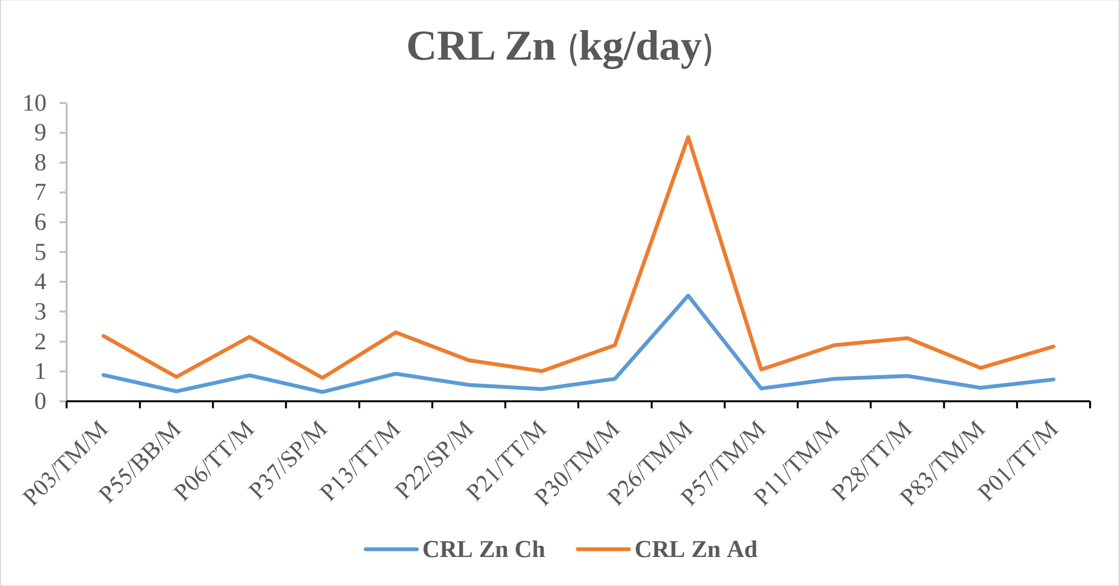


Figure 42 : Maximum Safe Consumption Rate (CRL) for Zn and Cu per Sample

The CRL indicates the maximum safe daily intake of fish. The average CRL for Zn was 2.10 kg/day for adults and 0.84 kg/day for children, while for Cu it was 3.32 kg/day for adults and 1.33 kg/day for children. The lowest CRLs were recorded in the most contaminated samples, underlining the need to monitor and manage seafood intake, especially for children.

Conclusion

Conclusion

This study provides a comprehensive assessment of trace metal bioaccumulation (Cd, Pb, Cu, Zn) in six small pelagic fish species: *Sardina pilchardus*, *Sardinella aurita*, *Boops boops*, *Engraulis encrasicolus*, *Trachurus trachurus*, and *Trachurus. Mediterraneus*, collected from multiple fishing zones along the Algerian coast. The results reveal significant spatial and interspecific variability in metal concentrations, with gills exhibiting consistently higher levels than muscles. Notably, *Sardinella aurita* from Skikda showed the highest cadmium (0.11 mg/kg w.w.) and lead (1.47 mg/kg w.w.) concentrations in gills, both exceeding WHO safety thresholds. In muscle tissue, zinc reached up to 27.02 mg/kg w.w. in *Sardina pilchardus* from Annaba, while copper peaked at 2.89 mg/kg w.w. in the same species and location. However, all muscle copper concentrations remained below international toxicity limits.

Biochemical analyses confirmed species-specific differences in macromolecular content, with *Trachurus mediterraneus* displaying the highest protein (16.93%) and carbohydrate (16.67%) levels, while *Boops boops* had the lowest reserves. Statistically significant negative correlations were observed between lipid content and both Zn ($r = –0.59$) and Cu ($r = –0.52$) concentrations, whereas Zn and Cu were strongly positively correlated ($r = 0.71$).

Health risk indicators such as Estimated Daily Intake (EDI), Target Hazard Quotients (THQ), and Hazard Index (HI) suggest that, while mean EDI values for Cu and Zn remained below international limits, the THQ values in many samples substantially exceeded the safety threshold, especially for children (THQ up to 11.74 for Zn and 9.43 for Cu; HI mean for children: 10.67). Even in adults, THQ reached up to 4.70 for Zn and 3.77 for Cu. These findings highlight a real risk of chronic exposure in sensitive populations, particularly children and frequent fish consumers.

Overall, these findings reinforce the need for regular monitoring programs and stricter pollution control policies, particularly in coastal zones under increasing anthropogenic pressure. This research also validates the use of small pelagic fish as bioindicators for marine pollution, providing valuable insights into both ecological impacts and food safety issues. Future work should consider expanding the study to include seasonal variations, liver tissue analysis, and additional toxic metals such as mercury (Hg) and arsenic (As), as well as molecular biomarkers of oxidative stress and genotoxicity. Strengthening regulatory frameworks and public awareness will be crucial in ensuring sustainable seafood consumption and marine ecosystem health.

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Appendix

Table III.1 : Metadata of fishing hauls

Haul number	Date	Region	Longitude	Latitude	Depth (m)
1	14/08/2024	Zemmouri	36°51'19"N	3°23'21"E	318
3	14/08/2024	Zemmouri	36°47'27"N	3°24'05"E	42
4	14/08/2024	Zemmouri	36°51'09"N	3°38'11"E	40
6	15/08/2024	Béjaia	36°42'58"N	5°13'03"E	74
7	15/08/2024	Béjaia	36°40'53"N	5°18'16"E	79
11	15/08/2024	Ziama	36°41'16"N	5°26'10"E	52
13	16/08/2024	Jijel	36°52'12"N	5°59'47"E	65
16	17/08/2024	Skikda	37°00'45"N	6°41'01"E	173
20	18/08/2024	Skikda	37°00'40"N	7°12'53"E	36
21	18/08/2024	Skikda	36°59'10"N	7°09'48"E	73
22	18/08/2024	Skikda	37°00'13"N	7°06'58"E	113
24	18/08/2024	Skikda	36°54'28"N	6°59'10"E	54
26	19/08/2024	Annaba	36°54'56"N	7°52'37"E	38
27	1908/2024	Annaba	36°57'57"N	7°52'02"E	65
28	19/08/2024	Annaba	37°00'35"N	7°59'25"E	99
30	23/08/2024	Annaba	36°53'26"N	7°57'43"E	37
32	23/08/2024	Annaba	37°06'07"N	7°59'09"E	339
37	24/08/2024	Annaba	37°00'50"N	8°18'17"E	75
51	03/09/2024	Bouismail	36°37'40"N	2°34'52"E	85
53	03/09/2024	Bouismail	36°39'46"N	2°17'39"E	88
54	03/09/2024	Gouraya	36°35'03"N	2°00'55"E	39
55	04/09/2024	Mostaganem	36°09'43"N	0°14'36"E	47
57	04/09/2024	Mostaganem	36°02'31"N	0°05'30"E	28
59	04/09/2024	Arzew	35°59'50"N	0°01'19"E	71
83	09/09/2024	Ghazaouet	35°07'45"N	2°09'09"W	39

Table III.2: Calibration standards used for Cd quantification by AAS

Cd	C (µg/l)	Abs
Calibration Blank	0	0
Calibration std 1	1	0,1057
Calibration std 2	2	0,2123
Calibration std 3	3	0,3082
Calibration std 4	4	0,3991

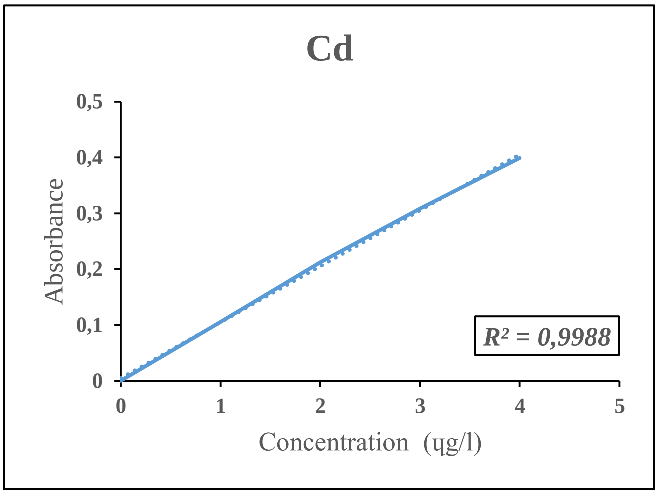

Figure III.1: Calibration curve for Cd

Table III.3: Calibration standards used for Pb quantification by AAS

Pb	C (µg/l)	Abs
Calibration Blank	0	0
Calibration std 1	20	0,1315
Calibration std 2	40	0,2703
Calibration std 3	80	0,5349
Calibration std 4	100	0,6451

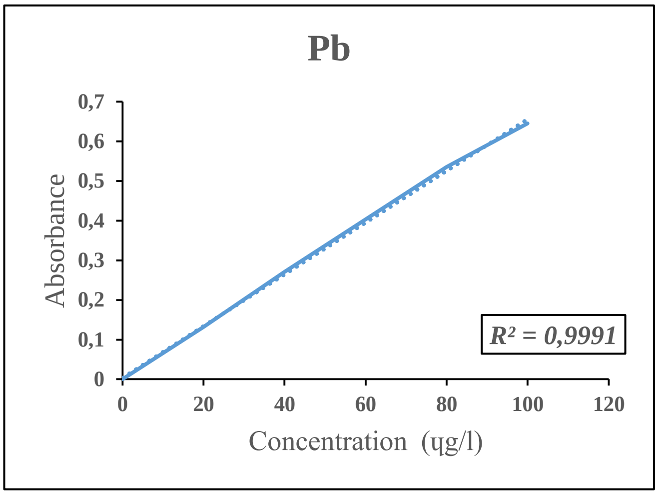

Figure III.2: Calibration curve for Pb

Table III.4: Calibration standards used for Zn quantification by AAS

Zn	C (mg/l)	Abs
Calibration Blank	0	0
Calibration std 1	0,2	0,058
Calibration std 2	0,4	0,1125
Calibration std 3	0,6	0,1817
Calibration std 4	0,8	0,2373

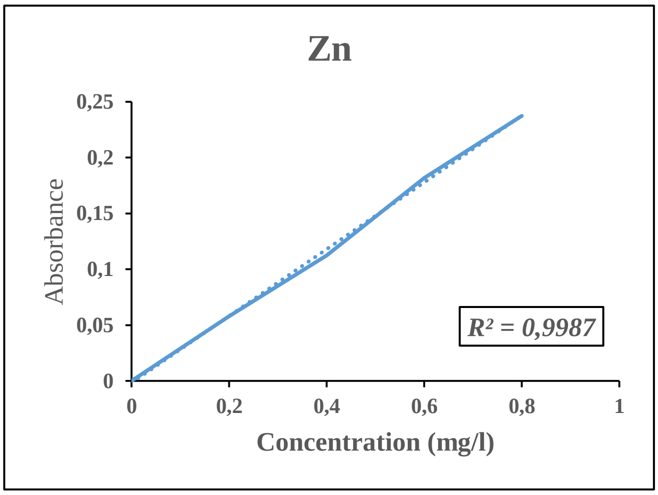

Figure III.3: Calibration curve for Zn

Table III.5: Calibration standards used for Cu quantification by AAS

Cu	C (mg/l)	Abs
Calibration Blank	0	0
Calibration std 1	0,2	0,0172
Calibration std 2	0,4	0,0345
Calibration std 3	0,6	0,0508
Calibration std 4	0,8	0,0671

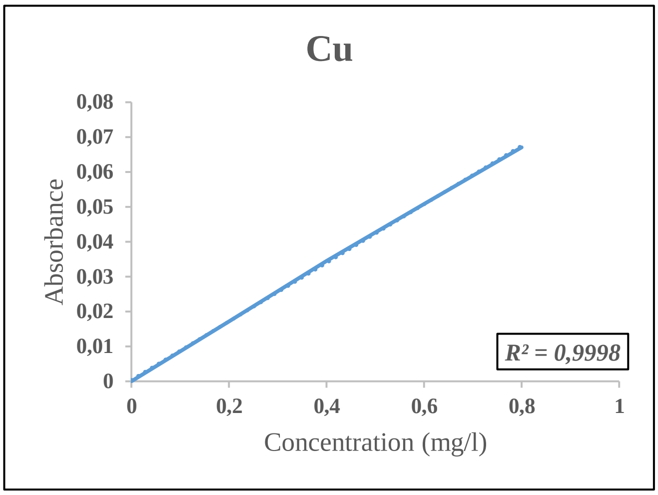

Table III.6: Glucose standards used for carbohydrate quantification by the Dubois method

Concentration (mmol/l)	Abs
0	0
0,607	0,024
1,214	0,058
1,821	0,075
2,428	0,108

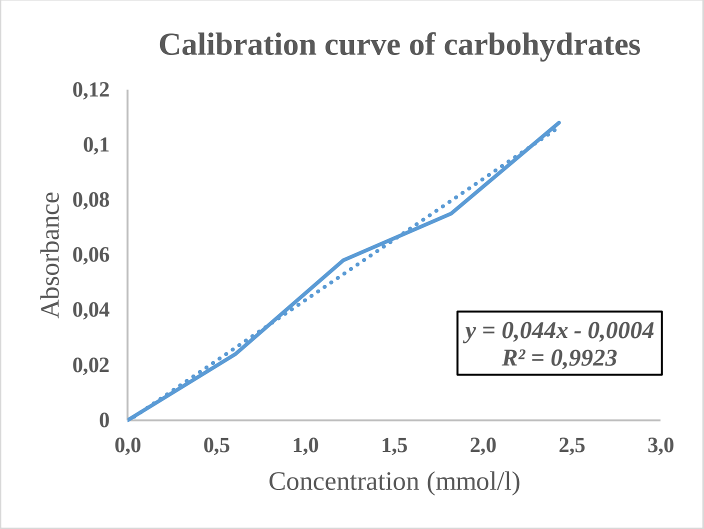

Figure III.4: Calibration curve for glucose

Abstract

The bioaccumulation of trace metals in marine organisms poses a growing concern due to their persistence, toxicity, and ability to biomagnify along food chains.This research investigates the bioaccumulation of trace metals (Cd, Pb, Zn, Cu) in six economically and ecologically important small pelagic fish species (*Sardina pilchardus, Sardinella aurita, Boops boops, Engraulis encrasicolus, Trachurus trachurus, and T. mediterraneus*) along the Algerian coastline. Using Atomic Absorption Spectrometry (AAS), 20 gill and muscle samples were analyzed to determine interspecific, biochemical, and spatial patterns of contamination.

The findings show substantial variability in trace metal accumulation across species and sampling sites. *Sardinella aurita* exhibited the highest gill concentrations, while *Boops boops* and *Sardina pilchardus* showed generally lower levels. Elevated cadmium and lead values were particularly noted in samples from Skikda and Arzew, exceeding WHO safety thresholds. Zinc concentrations were moderately elevated in eastern coastal samples, suggesting chronic exposure, while copper remained within safe and regulated ranges.

Biochemical analysis highlighted *T. mediterraneus* for its high protein and carbohydrate content, confirming its nutritional value. *T. trachurus* displayed high lipid content, notably in Béjaïa and Annaba, while *Boops boops* showed the lowest reserves. These patterns reflect species-specific physiology and regional ecosystem dynamics.

Risk indices, including Target Hazard Quotient (THQ), Hazard Index (HI), and Consumption Rate Limits (CRL), indicate potential chronic exposure to zinc and copper, especially among vulnerable populations such as children. Although average levels remain within acceptable limits for adults, localized contamination poses a long-term health concern.

The study emphasizes the ecological value of small pelagic fish as bioindicators of marine pollution and underscores the urgent need for continuous environmental monitoring. Enhanced regulatory frameworks are essential to ensure food safety and protect coastal communities from toxic metal exposure.

Keywords: Bioaccumulation, trace metals, THQ, HI, marine pollution, small pelagic fish.

Résumé

L'accumulation de métaux traces dans les organismes marins suscite une inquiétude croissante en raison de leur persistance, de leur toxicité et de leur capacité à se biomagnifier dans les réseaux trophiques. Cette étude évalue la bioaccumulation de métaux traces (Cd, Pb, Zn, Cu) chez six espèces de poissons pélagiques de petite taille, importantes sur les plans économique et écologique, le long du littoral algérien. À l'aide de la spectrométrie d'absorption atomique (AAS), 20 échantillons de muscles et de branchies ont été analysés pour déterminer les variations interspécifiques et spatiales de contamination.

Les résultats révèlent une variabilité marquée selon les espèces et les sites d'échantillonnage. *Sardinella aurita* présente les plus fortes concentrations en métaux au niveau des branchies, tandis que *Boops boops* et *Sardina pilchardus* affichent des niveaux généralement plus faibles. Les teneurs en cadmium et en plomb ont dépassé les seuils de sécurité de l'OMS à Skikda et Arzew. Le zinc était modérément élevé à l'Est, tandis que le cuivre est resté globalement faible, suggérant une régulation biologique efficace.

L'analyse biochimique met en évidence la valeur nutritionnelle de *T. mediterraneus* (protéines et glucides élevés) et la richesse lipidique de *T. trachurus*, notamment à Annaba et Béjaïa. *Boops boops* présente les réserves les plus faibles.

Les indices de risque (THQ, HI, CRL) révèlent des risques modérés mais réels, notamment pour les enfants. L'étude souligne la pertinence des petits pélagiques comme bioindicateurs de la pollution marine et appelle à un renforcement des politiques de contrôle environnemental et sanitaire.

Mots-clés : Bioaccumulation, métaux traces, THQ, HI, pollution marine, poissons pélagiques,

التلخيص

تمثل تراكمات المعادن الثقيلة في الكائنات البحرية مصدر قلق متزايد بسبب ثباتها الكيميائي وسميتها وقدرتها على التراكم الحيوي عبر السلسلة الغذائية. هدف هذه الدراسة إلى تقييم التراكم الحيوي للمعادن الثقيلة (الكادميوم، الرصاص، الزنك، النحاس) في ستة أنواع من الأسماك السطحية الصغيرة ذات الأهمية الاقتصادية والبيئية على طول الساحل الجزائري. تم تحليل20 عينة من العضلات والخياشيم باستخدام تقنية الامتصاص الذري (AAS) لتحديد الفروقات بين الأنواع والمناطق.

أظهرت النتائج فروقات واضحة حسب النوع والمنطقة. سجلت *Sardinella aurita* أعلى تركيزات معدنية في الخياشيم، بينما أظهرت *Boops boops* و *Sardina pilchardus*مستويات أقل. تجاوزت مستويات الكادميوم والرصاص معايير السلامة في مناطق مثل سكيكدة وأرزيو. كانت تركيزات الزنك مرتفعة نسبيًا في المناطق الشرقية، بينما بقي النحاس ضمن الحدود المسموح بها.

أظهرت التحاليل الحيوكيميائية أن *T. mediterraneus* يتمتع بأعلى قيمة غذائية (بروتينات وكربوهيدرات)، بينما تميز *T. trachurus* بمحتوى دهني مرتفع، لا سيما في عنابة وبجاية. سجلت *Boops boops* أقل احتياطات غذائية.

تشير مؤشرات الخطرTHQ ، HI، CRL إلى وجود مخاطر محتملة مزمنة خاصة للأطفال. تؤكد الدراسة أهمية هذه الأنواع كمؤشرات حيوية للتلوث البحري وتوصي بتكثيف المراقبة البيئية وتعزيز سياسات سلامة الغذاء.

الكلمات المفتاحية: التراكم الحيوي، المعادن الثقيلة،THQ، HI ، التلوث البحري، الأسماك السطحية،