

The Seasonal Assessment of Heavy Metals Pollution in the Waters of the Mediterranean and Atlantic Seas of Morocco

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[Doi:10.19044/esj.2025.v21n30p47](https://doi.org/10.19044/esj.2025.v21n30p47)

Submitted: 02 April 2025

Accepted: 05 October 2025

Published: 31 October 2025

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Cite As:

Karim, S., Aouniti, A. & Belbachir, C.(2025). *The Seasonal Assessment of Heavy Metals Pollution in the Waters of the Mediterranean and Atlantic Seas of Morocco*. European Scientific Journal, ESJ, 21 (30), 47. <https://doi.org/10.19044/esj.2025.v21n30p47>

Abstract

Heavy metal pollution in marine environments poses a major risk to ecosystems and human health due to the persistence, bioaccumulation, and toxicity of metals. The current study aimed to analyze the seasonal patterns of cadmium (Cd), lead (Pb), zinc (Zn), iron (Fe), copper (Cu), chromium (Cr), and nickel (Ni) in seawater samples from two Moroccan coastal regions, Mediterranean Coast (Nador) and Atlantic Coast (Casablanca), during autumn and spring of the 2023-2024 season. A total of 36 water samples were collected from each coast and were analyzed using ICP-AES following the WHO and USEPA guidelines. The data showed that during both coastal regions, Cd concentrations were 0.002 mg/L to 0.020 mg/L, which is above the WHO limit of 0.003 mg/L. Pb concentrations were also higher than the WHO guideline of 0.01 mg/L and reached 0.036-0.120 mg/L, particularly in Casablanca. On the other hand, Fe and Zn concentrations of 0.010-0.255 mg/L and 0.061-0.255 mg/L, respectively, were within safe limits. Seasonal changes showed greater Cd and Pb concentrations in autumn, most likely due to industrial discharges and agricultural runoff. The study raises alarm on the high levels of Cd and Pb contamination in the Mediterranean region and the need to develop policies to properly manage wastewater, regulate industries, and conduct biomonitoring of marine species.

Keywords: Heavy metals; Contamination; Seawater; Pollution; Moroccan coasts; Seasonal variations

Introduction

Marine pollution has emerged as one of the most pressing environmental challenges worldwide, largely driven by the release of contaminants such as industrial effluents, agricultural runoff, domestic wastewater, and heavy metals into aquatic systems (Duce et al., 2009; Wang et al., 2022). Heavy metals are of particular concern because of their persistence in the environment, tendency to bioaccumulate in the food chain, and toxicity, even at very low concentrations (Ali & Khan, 2019; Luo et al., 2014). Once introduced into marine ecosystems, these elements can accumulate in sediments and aquatic organisms, posing significant threats to both ecosystem health and human well-being (El Nemr, 2020; Rahman et al., 2021).

The Moroccan coastal zone, located at the junction of the Mediterranean and Atlantic basins, is of exceptional ecological and economic value. It supports rich marine biodiversity and sustains key sectors such as fisheries, aquaculture, tourism, and maritime trade (Bounoua et al., 1999; El Morhit et al., 2012). However, the rapid pace of industrial growth, urban development, and agricultural expansion has heightened concerns over heavy metal contamination, with potential consequences for marine life and public health (El Moumni et al., 2015; Salghi et al., 2023).

Sources of heavy metals in the marine environment may be anthropogenic - including industrial discharges, mining operations, shipping activities (such as antifouling paints, fuel combustion, and ballast water discharge), or natural, such as rock weathering, volcanic activity, and atmospheric deposition (Pacyna et al., 2006; Amiard et al., 2021). Metals such as cadmium (Cd), lead (Pb), zinc (Zn), iron (Fe), copper (Cu), chromium (Cr), and nickel (Ni) are widely recognized for their hazardous effects on aquatic ecosystems and human health, particularly through seafood consumption (USEPA, 2017; Ahmed et al., 2021). Elevated levels of these metals have been linked to neurotoxicity, carcinogenicity, and organ damage (Jaishankar et al., 2014; WHO, 2018).

Studies conducted in various regions worldwide have consistently reported high concentrations of heavy metals in heavily industrialized and urbanized coastal areas (Agah et al., 2009; Ganjavi et al., 2010; Malafaia et al., 2022). In the Mediterranean Sea, significant lead and cadmium contamination has been documented, primarily due to untreated wastewater discharges and industrial effluents (Bessa et al., 2020; El Baz et al., 2022). Similarly, Atlantic coasts have been increasingly affected by urban

wastewater, oil spills, and port activities (Anweting et al., 2024; Pereira et al., 2021). Despite these global trends, research on heavy metal pollution in Moroccan marine waters remains scarce (Fahssi & Chafi, 2015; Baghdadi Mazini, 2012).

To address this knowledge gap, the present study investigates seasonal variations in heavy metal concentrations in seawater from two Moroccan coastal regions: the Mediterranean coast (Nador) and the Atlantic coast (Casablanca). These sites were selected due to their high socio-economic importance and significant environmental pressures (El Morhit et al., 2012; Salghi et al., 2023).

Conducted over a two-year period (2023–2024) during the autumn and spring seasons, the study aims to:

- Quantify the concentrations of Cd, Pb, Zn, Fe, Cu, Cr, and Ni in seawater from both sites;
- Compare these values to World Health Organization (WHO) standards to assess potential ecological and human health risks;
- Examine seasonal trends to identify influencing factors;
- Compare findings with previous studies from Morocco and other regions to place results in a broader context.

The outcomes will provide valuable baseline information for Moroccan coastal waters, supporting evidence-based management strategies aimed at mitigating heavy metal contamination.

Methodology

Study Area and sampling

The study was conducted in two Moroccan coastal regions. A total of 12 sampling sites were selected along the Mediterranean coast (Nador) (figure 1), and along the Atlantic coast (Casablanca) (Figure 2): Six sites at Nador were selected along the bay and adjacent areas exposed to port activity, industrial discharges, and agricultural runoff, and six sites at Casablanca were chosen near urban discharge points, industrial zones, and shipping lanes.

The Mediterranean coast (Nador)



Figure 1: Location of the six sampling sites along the Nador (Mediterranean) coasts. Sites are labeled S1–S6.

The Atlantic coast (Casablanca)



Figure 2: Location of the six sampling sites along the Casablanca (Atlantic coast). Sites are labeled S1–S6.

To ensure consistency and comparability across seasons, the same sites were sampled during both campaigns (autumn 2023 and spring 2024). These areas were chosen for their economic significance and environmental

vulnerability. Nador is influenced by industrial effluents, port operations, and agricultural runoff, whereas Casablanca is exposed to urban wastewater, industrial emissions, and intense maritime traffic (El Morhit et al., 2012; Baghdadi Mazini, 2012; Salghi et al., 2023). Both are considered high-risk zones for heavy metal pollution (Fahssi & Chafi, 2015; Anweting et al., 2024). -Water samples were collected during two seasonal campaigns (autumn 2023 and spring 2024) to capture seasonal variations. At each of the 12 sites, three replicate samples were taken, yielding 36 samples per campaign and a total of 72 samples for the study.

This sampling density follows APHA (2017) and ISO 5667-9 :2017 recommendations for marine water monitoring, ensuring statistical representativeness and reproducibility.

Sampling Protocol :

1. Sterilized glass bottles pre-cleaned with acid and distilled water were used to prevent contamination (Rodier et al., 2009).
2. Samples were collected at a depth of 50 cm to minimize surface contamination (El Baz et al., 2022).
3. Filtration was carried out using 0.45 μm Millipore membranes to remove suspended particles (Rahman et al., 2021).
4. Samples were acidified with ultra-pure nitric acid (5 mL/L) and stored at 4°C in polypropylene bottles until analysis (Amiard et al., 2021).

Heavy Metal Analysis

Seven metals; Cd, Pb, Zn, Fe, Cu, Cr, and Ni were quantified using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES), a sensitive and precise method for trace metal detection (El Nemr, 2020; Bessa et al., 2020).

Analytical details :

- Instrument: Thermo Fisher iCAP 6000 Series ICP-AES.
- Calibration: Standard solutions prepared from National Institute of Standards and Technology (NIST) certified reference materials (NIST, 2022).
- Detection limits: Established following USEPA (2017) protocols.

Quality assurance :

- Internal quality control samples analyzed every 10 measurements.
- Matrix effect checks using spiked certified reference materials.
- Triplicate analyses with results expressed as **mean $\pm$ standard deviation**.

Statistical Analysis

Data processing was performed with **SPSS 17.0**.

- Descriptive statistics (mean, standard deviation) were calculated.
- **One-way ANOVA** was used to evaluate seasonal variations.

Data Quality Control

- Blanks and duplicates were included to check for contamination and reproducibility.
- Recovery rates of 92–105% were achieved from spiked sample tests.
- Results were compared with previous Moroccan and international studies for validation (Baghdadi Mazini, 2012; El Moumni et al., 2015; Anweting et al., 2024).

Compliance with International Standards

Measured concentrations were evaluated against:

- WHO water quality standards (2018)
- USEPA guidelines (2017)
- European Union Water Framework Directive (2021)

Results:

Mediterranean Coast (Nador)

Seasonal Variations in Heavy Metal Concentrations in the Mediterranean Coast (Nador)

The concentrations of cadmium (Cd), lead (Pb), zinc (Zn), iron (Fe), copper (Cu), chromium (Cr), and nickel (Ni) in seawater samples collected from the Nador coastline (Mediterranean Sea) during four seasonal campaigns (autumn and spring, 2023–2024) are presented in **Table 1** and illustrated in **Figure 3**. Results are expressed as mean $\pm$ standard deviation (mg/L). Each value represents the mean of triplicate samples collected at six sites, resulting in 18 measurements per season ($n = 18$).

Table 1: Seasonal variations in heavy metal concentrations (mg/L) in seawater from the Mediterranean coast (Nador).

Metal	S1 Autumn	S2 Spring	S3 Autumn	S4 Spring	WHO standard (mg/L)
Cd	0.0047 $\pm$ 0.001	0.004 $\pm$ 0.002	0.005 $\pm$ 0.002	0.014 $\pm$ 0.010	0.003
Pb	0.080 $\pm$ 0.005	0.060 $\pm$ 0.040	0.080 $\pm$ 0.010	0.036 $\pm$ 0.040	0.010
Zn	0.255 $\pm$ 0.090	0.179 $\pm$ 0.080	0.238 $\pm$ 0.100	0.176 $\pm$ 0.080	3.000
Fe	0.010 $\pm$ 0.001	0.060 $\pm$ 0.080	0.013 $\pm$ 0.001	0.045 $\pm$ 0.040	0.300
Cu	0.006 $\pm$ 0.0005	0.034 $\pm$ 0.040	0.006 $\pm$ 0.0005	0.007 $\pm$ 0.001	2.000
Cr	0.002 $\pm$ 0.003	0.019 $\pm$ 0.020	0.001 $\pm$ 0.002	0.006 $\pm$ 0.005	0.050
Ni	0.015 $\pm$ 0.001	0.036 $\pm$ 0.020	0.015 $\pm$ 0.001	0.025 $\pm$ 0.010	0.070

*The highlighted values show that these levels exceed the standard set by the WHO standard

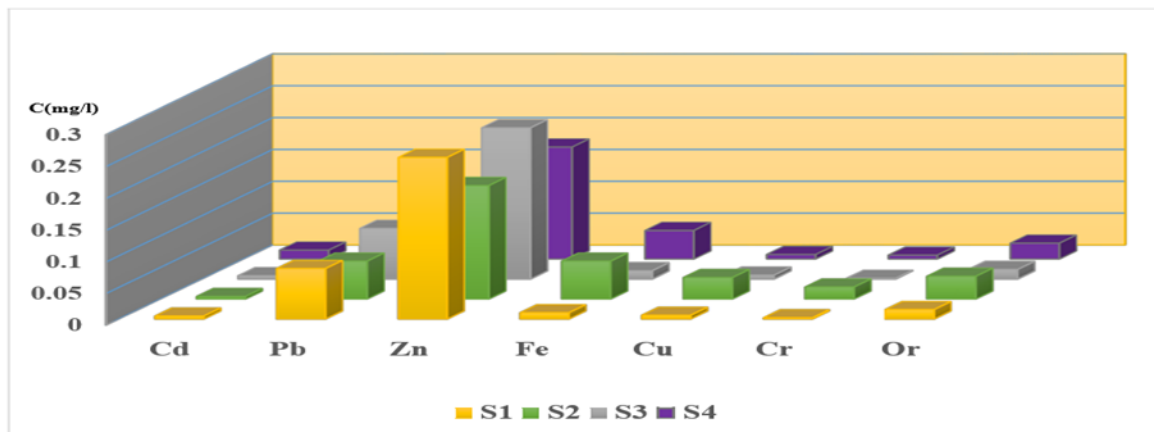


Figure 3: Seasonal variations in metal levels in seawater samples

Analysis of heavy metals in seawater samples shows that the highest concentrations are zinc, which ranges from a minimum of 0.176 mg/L obtained during in the fourth spring season, and a maximum level of 0.255 mg/L recorded during the first autumn season, these values do not exceed the WHO standard of 3 mg/L. For lead, a maximum level of 0.08 mg/L was recorded during the two fall seasons studied, and the lowest level was obtained during the fourth spring season at a value of 0.036 mg/L, the results found during all the seasons studied exceed the WHO standard of 0.01 mg/L for lead. Similarly, for cadmium, the WHO standard is 0.003 mg/L, while the concentrations obtained during the first three seasons exceed this standard, with the highest value being in the order of 0.005 mg/L. Iron concentrations range from 0.06 mg/L, which is the highest concentration, to 0.01 mg/L, which is the lowest concentration obtained during the first fall season. Nickel has non-negligible levels such that the highest level is 0,036 mg/L, and the lowest value is of the order of 0,015 mg/L. For copper and chromium, the concentrations are low such that the highest concentrations are respectively (0.034 mg/L, 0.019 mg/L). The ranking of metal accumulation across the four sampling seasons is summarized in **Table 2**.

Table 2: The order of accumulation of heavy metals during the four seasons

Metal	Seasonal ranking (highest to lowest)
Cd	S4 > S3 > S1 > S2
Pb	S3 > S1 > S2 > S4
Zn	S1 > S3 > S2 > S4
Fe, Cu, Cr, Ni	S2 > S4 > S3 > S1

Thus, we can establish an order of enrichment for the different metal elements during the four seasons studied and we obtain the result presented in the **table 3** below:

Table 3: Heavy metal enrichment order for the four seasons:

Season	Enrichment order
S1 Autumn	Zn> Pb > Ni > Fe > Cu > Cd > Cr
S2 Spring	Zn > Pb > Fe > Ni > Cu > Cr > Cd
S3 Autumn	Zn> Pb > Ni > Fe > Cu > Cd > Cr
S4 Spring	Zn > Fe > Pb > Ni > Cd > Cu > Cr

Atlantic Coast (Casablanca)

Seasonal Variations in Heavy Metal Concentrations in the Atlantic Coast (Casablanca)

The concentrations of cadmium (Cd), lead (Pb), zinc (Zn), iron (Fe), copper (Cu), chromium (Cr), and nickel (Ni) in seawater samples collected from the Casablanca coastline (Atlantic Ocean) during four seasonal campaigns (autumn and spring, 2023–2024) are summarized in **Table 4** and illustrated in **Figure 4**. Results are expressed as mean $\pm$ standard deviation (mg/L). Each value represents the mean of triplicate samples collected at six sites, yielding 18 measurements per season (n = 18).

Table 4: Seasonal variations in heavy metal concentrations (mg/L) in seawater from the Atlantic coast (Casablanca)

Metal	S1 Autumn	S2 Spring	S3 Autumn	S4 Spring	WHO standard (mg/L)
Cd	0.002 $\pm$ 0.0007	0.014 $\pm$ 0.020	0.020 $\pm$ 0.0009	0.016 $\pm$ 0.060	0.003
Pb	0.110 $\pm$ 0.010	0.120 $\pm$ 0.009	0.111 $\pm$ 0.010	0.080 $\pm$ 0.060	0.010
Zn	0.070 $\pm$ 0.010	0.080 $\pm$ 0.005	0.063 $\pm$ 0.020	0.061 $\pm$ 0.030	3.000
Fe	0.139 $\pm$ 0.040	0.140 $\pm$ 0.040	0.112 $\pm$ 0.010	0.145 $\pm$ 0.030	0.300
Cu	0.116 $\pm$ 0.070	0.131 $\pm$ 0.050	0.087 $\pm$ 0.090	0.098 $\pm$ 0.0001	2.000
Cr	0.050 $\pm$ 0.020	0.068 $\pm$ 0.020	0.049 $\pm$ 0.030	0.042 $\pm$ 0.030	0.050
Ni	0.060 $\pm$ 0.010	0.069 $\pm$ 0.010	0.066 $\pm$ 0.0009	0.047 $\pm$ 0.030	0.070

*The highlighted values show that these levels exceed the standard set by the WHO standard

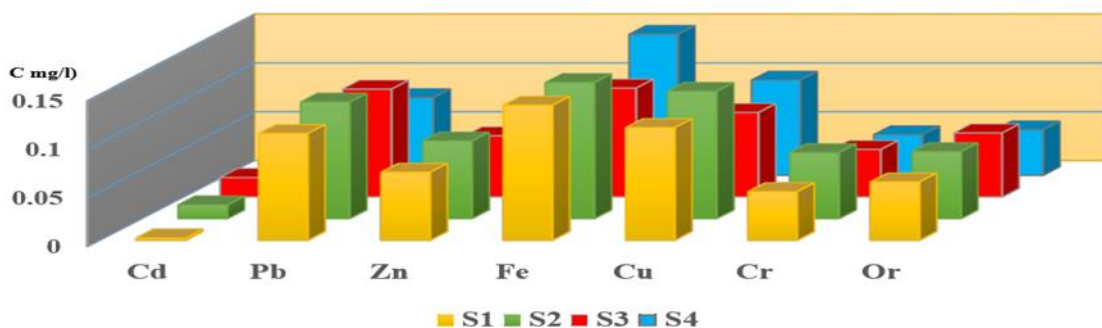


Figure 4: Seasonal variations in metal levels in seawater samples

The results of the analysis of heavy metals in the sea water samples of the Atlantic coast of Casablanca, show that all metal concentrations are high, and that there is not a very significant difference between the concentrations found, such that the iron contents are the highest and they vary between a

minimum of 0.112 mg/L obtained during the third autumn season, and a maximum content of 0.145 mg/L recorded during the fourth spring season, moreover these values do not exceed the WHO standard of 0.3 mg/L. For lead, a maximum level of 0.120 mg/L was recorded during the second spring season, and the lowest level was obtained during the fourth spring season at a value of 0.08 mg/L, the results found during all the seasons studied far exceed the WHO standard of 0.01 mg/L for lead. Similarly, for cadmium, the standard is 0.003 mg/L, while concentrations over three seasons exceed this standard, with the highest value being in the order of 0.02 mg/L. Copper concentrations range from 0.131 mg/L, which is the highest concentration, to 0.087 mg/L, which is the lowest concentration in the third fall season. Zinc has non-negligible levels such that the highest level is 0,08 mg/L and the lowest value is in the order of 0,061 mg/L. For chromium, and nickel, concentrations are low relative to other levels found, such that the highest levels are respectively (0.068 mg/L, 0.069 mg/L). The ranking of metal accumulation across the four sampling seasons is summarized in **Table 5**.

Table 5: Seasonal ranking of heavy metal concentrations in Casablanca seawater

Metal	Seasonal ranking (highest to lowest)
Cd	S3 > S4 > S2 > S1
Pb, Ni	S2 > S3 > S1 > S4
Zn, Cr	S2 > S1 > S3 > S4
Fe	S4 > S2 > S1 > S3
Cu	S2 > S1 > S4 > S3

The overall enrichment order of metals during the four seasons is presented in **Table 6**.

Table 6: Overall enrichment order of heavy metals in Casablanca seawater

Season	Enrichment order
S1 Autumn	Fe > Cu > Pb > Zn > Ni > Cr > Cd
S2 Spring	Fe > Cu > Pb > Zn > Ni > Cr > Cd
S3 Autumn	Fe > Pb > Cu > Ni > Zn > Cr > Cd
S4 Spring	Fe > Cu > Pb > Zn > Ni > Cr > Cd

Discussion

Mediterranean Coast (Nador)

The results from Nador reveal distinct seasonal patterns in heavy metal concentrations. Among the metals analyzed, zinc (Zn) displayed the highest levels across all seasons, ranging from 0.176 to 0.255 mg/L. Although Zn levels were relatively elevated, they remained well below the WHO permissible limit of 3 mg/L.

In contrast, lead (Pb) concentrations were consistently above the WHO guideline of 0.01 mg/L, with values between 0.036 and 0.080 mg/L. Similarly, cadmium (Cd) exceeded its WHO threshold of 0.003 mg/L in three out of four

seasons, reaching up to 0.005 mg/L, and showing a marked increase in spring 2024 (0.014 mg/L). These findings indicate significant contamination risks from Pb and Cd in the study area.

Other metals, including Fe, Cu, Cr, and Ni, were detected at lower levels. Iron (Fe) concentrations ranged from 0.010 to 0.060 mg/L, always remaining below the WHO limit of 0.3 mg/L. Nickel (Ni) levels varied between 0.015 and 0.036 mg/L, also below the WHO permissible value of 0.07 mg/L. Copper (Cu) and chromium (Cr) displayed the lowest concentrations, never approaching international standards.

The elevated levels of Cd and Pb in Nador may be attributed to industrial activities (including metallurgy and phosphate-based industries) and agricultural practices involving fertilizers and pesticides. Phosphate fertilizers are known to contain Cd residues, while Pb contamination is often linked to industrial discharges and shipping activities. Seasonal rainfall likely plays a key role by enhancing surface runoff, which mobilizes these contaminants into coastal waters. The higher autumn values support this explanation, as rainfall and stormwater discharges are more pronounced during this period.

These observations are consistent with studies conducted in other parts of the Mediterranean. For example, research in Turkey (Şimşek et al., 2021) and Italy (Bessa et al., 2020) also reported elevated Cd and Pb levels near industrial and port areas. Conversely, Spanish Mediterranean waters have generally shown lower concentrations (Pereira et al., 2021), reflecting the impact of stricter environmental regulations and wastewater management.

Overall, the results suggest that anthropogenic activities, combined with seasonal hydrological factors, strongly influence the variability of heavy metal pollution in Nador. Continuous monitoring and stricter control of effluents are therefore essential to reduce contamination in this vulnerable coastal ecosystem.

Atlantic Coast (Casablanca)

The results from Casablanca indicate consistently elevated levels of several heavy metals, with iron (Fe) showing the highest concentrations across all seasons. Values ranged between 0.112 and 0.145 mg/L, which are below the WHO permissible limit of 0.3 mg/L but remain relatively high compared to other metals analyzed.

Lead (Pb) and cadmium (Cd) displayed particularly concerning patterns. Pb concentrations varied between 0.080 and 0.120 mg/L, exceeding the WHO guideline of 0.01 mg/L in all seasons. Similarly, Cd levels ranged from 0.002 to 0.020 mg/L, surpassing the WHO standard of 0.003 mg/L during three out of four seasons. These findings highlight significant contamination in the Casablanca coastal waters, particularly from Pb and Cd, which are recognized for their toxicity and persistence.

Copper (Cu) and nickel (Ni) were also present at noteworthy levels. Cu concentrations ranged from 0.087 to 0.131 mg/L, remaining below the WHO limit of 2 mg/L but suggesting local enrichment possibly linked to port activities and antifouling paints. Ni concentrations varied between 0.047 and 0.069 mg/L, approaching but not exceeding the WHO threshold of 0.07 mg/L. Chromium (Cr) levels (0.042–0.068 mg/L) also remained close to the international limit of 0.05 mg/L, which raises concern given their potential ecological and health impacts.

When compared to global studies, the elevated Pb and Cd concentrations in Casablanca are consistent with findings from other industrialized Atlantic coasts. For instance, Brazilian coastal waters showed Pb concentrations of 0.11 mg/L (Malafaia et al., 2022), similar to our maximum of 0.12 mg/L. Likewise, Cd levels above WHO limits have been reported in Nigerian coastal waters (Anweting et al., 2024), where port activities contribute significantly to metal enrichment. In contrast, studies from European Atlantic coasts, such as France, reported Pb concentrations below 0.05 mg/L, largely due to stricter wastewater treatment and environmental policies (Pereira et al., 2021). The markedly higher Pb levels in Casablanca suggest insufficient pollution control and ongoing discharges from industrial and maritime activities.

The most plausible sources of heavy metal contamination in Casablanca include heavy industrialization (notably in the automotive, chemical, and petroleum sectors), untreated wastewater discharges, and intense port activity. Industrial effluents and urban runoff contribute Cd and Pb, while shipping emissions and antifouling coatings are well-documented sources of Cu and Pb in coastal waters (Bouthir et al., 2006; Salghi et al., 2023). Seasonal differences, with higher levels often observed in autumn, are likely linked to rainfall-induced runoff that mobilizes contaminants from terrestrial sources.

Overall, the findings confirm that Casablanca waters are under considerable anthropogenic pressure. The persistence of Pb and Cd contamination, coupled with near-threshold concentrations of Cr and Ni, underscores the urgent need for improved wastewater management, stricter regulatory enforcement, and continuous monitoring programs in this highly industrialized coastal region.

Seasonal Trends and Environmental Implications

Influence of Seasonal Changes

A clear seasonal trend was observed in both study areas, with higher metal concentrations generally recorded during autumn compared to spring. This pattern can be explained by increased rainfall and surface runoff in autumn, which transport contaminants from industrial zones, agricultural

lands, and urban discharge points into the marine environment. Similar findings have been reported in other coastal regions, where stormwater runoff significantly contributes to seasonal metal enrichment (Dupont et al., 2022). In contrast, the lower concentrations observed in spring may result from greater dilution due to enhanced water circulation and, potentially, reduced industrial activity during this season. These seasonal dynamics highlight the strong influence of hydrological conditions on metal mobility and accumulation in coastal waters.

Environmental and Health Risks

The consistent exceedance of WHO standards for Pb and Cd is of particular concern, as both metals are highly toxic and bioaccumulative. Chronic exposure to these contaminants has been associated with severe health effects, including neurological, renal, and cardiovascular disorders (Jaishankar et al., 2014). From an ecological perspective, elevated Pb and Cd levels may impair marine biodiversity by affecting reproduction, growth, and survival of aquatic organisms. Furthermore, the bioaccumulation of these metals in fish and shellfish poses direct risks to seafood safety, particularly for local populations that rely heavily on fisheries for their diet (Ahmed et al., 2021).

In contrast, Fe and Zn concentrations remained within internationally accepted limits, suggesting lower immediate risks from these metals. Nevertheless, continuous monitoring is warranted, as long-term accumulation could still exert ecological pressure. Ni and Cr, although detected below or close to permissible thresholds, should also be carefully monitored given their potential toxicity and the proximity of some values to WHO standards.

Overall, the seasonal variations observed in this study emphasize the combined influence of anthropogenic pressures and natural hydrological cycles. The exceedance of critical thresholds for Pb and Cd demonstrates that Moroccan coastal waters, particularly near urban and industrial hubs, remain vulnerable to heavy metal contamination with direct implications for environmental health and human food safety.

Comparison with Previous Moroccan Studies

The results obtained in this study were compared with previously published data on heavy metal contamination in Moroccan coastal waters (Table 7).

Table 7: Comparison of heavy metal concentrations (mg/L) between this study and previous Moroccan studies

Study Location	Pb (mg/L)	Cd (mg/L)	Zn (mg/L)	Fe (mg/L)	Reference
Casablanca (this study)	0.080–0.120	0.002–0.020	0.070–0.080	0.112–0.145	Current work
Loukkos Estuary	0.060	0.004	0.110	0.090	El Morhit et al., 2012
Saïdia Coast	0.040	0.002	0.090	0.070	Fahssi & Chafi, 2015
Moroccan Atlantic (general)	0.050	0.003	0.080	0.100	Baghdadi Mazini, 2012

When compared with earlier findings, our results reveal a concerning trend, particularly for Pb and Cd. Concentrations of these two metals in Casablanca during 2023–2024 are substantially higher than those reported in previous Moroccan studies. For example, Pb concentrations in Casablanca (0.080–0.120 mg/L) exceed those recorded in Saïdia (0.040 mg/L) and in the Loukkos estuary (0.060 mg/L). Similarly, Cd concentrations in this study reached 0.020 mg/L, far above the values reported in earlier surveys, which rarely exceeded 0.004 mg/L.

The data suggest a worsening trend in Pb and Cd contamination over the last decade, reflecting increased anthropogenic pressures such as industrial discharges, untreated wastewater, and port activities along the Casablanca coastline. Interestingly, earlier research conducted between 2012 and 2015 had indicated a slight improvement in water quality, as Cd and Pb levels were lower in Saïdia compared to the Loukkos estuary. However, the present study demonstrates a reversal of this trend, with renewed increases in toxic metal concentrations.

This comparison highlights the urgent need for tighter environmental regulations and effective wastewater treatment infrastructure in Moroccan coastal cities. Without immediate intervention, Pb and Cd contamination may continue to rise, posing growing risks to marine biodiversity, fisheries, and public health.

Conclusion

This study provides a comprehensive assessment of seasonal variations in heavy metal concentrations in Moroccan coastal waters, focusing on the Mediterranean coast (Nador) and the Atlantic coast (Casablanca) during 2023–2024. The results revealed critical exceedances of lead (Pb) and cadmium (Cd) relative to WHO standards. In Nador, Pb ranged from 0.036 to 0.080 mg/L and Cd from 0.004 to 0.014 mg/L, both surpassing the respective limits of 0.01 mg/L and 0.003 mg/L. In Casablanca, Pb concentrations were even higher (0.080–0.120 mg/L) and Cd reached up to 0.020 mg/L, confirming persistent contamination in both regions.

Other metals, including zinc (Zn: 0.061–0.255 mg/L), iron (Fe: 0.010–0.145 mg/L), copper (Cu: 0.006–0.131 mg/L), chromium (Cr: 0.001–0.068 mg/L), and nickel (Ni: 0.015–0.069 mg/L), remained below international thresholds. However, the proximity of Cr and Ni concentrations to their guideline values suggests that continuous monitoring is necessary.

The observed seasonal differences, with higher concentrations generally recorded in autumn, highlight the influence of rainfall and runoff in mobilizing pollutants from industrial, agricultural, and urban sources. These

findings are consistent with international studies and reinforce the role of both anthropogenic and hydrological factors in shaping coastal water quality.

The implications of these results are significant. Exceedances of Pb and Cd pose risks not only to marine biodiversity but also to human health, particularly through the bioaccumulation of toxic metals in seafood consumed by local populations. Without effective intervention, the contamination trend observed in Casablanca may worsen, as suggested by the comparison with earlier Moroccan studies.

Recommendations

- **Strengthen environmental regulations** to limit heavy metal discharges from industrial and port activities.
- **Implement advanced wastewater treatment plants** to reduce urban and industrial effluents entering coastal waters.
- **Establish continuous biomonitoring programs** for seawater, sediments, and marine organisms to track long-term contamination trends.
- **Promote public awareness and community engagement** regarding the risks of heavy metal pollution and the importance of sustainable coastal management.

In conclusion, Moroccan coastal waters, particularly near Casablanca, are facing increasing heavy metal contamination that requires urgent regulatory and scientific attention. Proactive measures are essential to safeguard both ecosystem health and food safety for coastal communities.

Conflict of Interest: The authors reported no conflict of interest.

Data Availability: All data are included in the content of the paper.

Funding Statement: The authors did not obtain any funding for this research.

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