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Original article

Assessment of harbor sediment contamination for a path to valorize dredged material

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ABSTRACT

Annually, over one billion m^3 of sediment are dredged worldwide to ensure safe access for ships to harbors. Dredged sediment from harbors, considered as waste, presents an interesting opportunity for sustainable development projects by valorizing it as construction material. Characterizing dredged material is a crucial step to confirm the feasibility of reusing marine sediment and identifying potential valorization pathways. However, previous studies have primarily focused on investigating dredged sediment properties at a physical, geotechnical, and mineralogical level, with limited analysis of the presence of chemical contaminants, despite their impact on assessing sediment quality as a substitute for construction aggregate. The aim of this paper is to evaluate the contamination of marine sediment dredged from Safi harbor, located in central Morocco in an urbanized and industrialized area. Determining the contaminant content in the sediment is a prerequisite for the valorization process. To achieve this objective, the chemical characteristics of sediment collected from six different sampling points are studied. On one hand, the concentrations of the following trace metals are measured: Cadmium (Cd), Arsenic (As), Chromium (Cr), Nickel (Ni), Lead (Pb), Copper (Cu) and Zinc (Zn). On the other hand, Total Petroleum Hydrocarbons (TPH) and Total Organic Carbon (TOC) are analyzed. The results show that the reference values for the studied contaminants are not exceeded at the sampling points located in the port access channel. These findings indicate the potential for valorizing dredged sediment as an alternative source of construction materials.

1. Introduction

Harbor dredging is a fundamental activity that involves the excavation of sediment from the bottom of basins (Slimanou et al., 2019). Its main objective is to deepen or maintain the depths of port channels and basins in order to ensure optimal operating conditions for ships (Bian et al., 2022). It can also be carried out as part of projects to build new port infrastructure or develop existing infrastructure (de Lillis et al., 2020).

Dredging operations worldwide generate over one billion cubic meters of sediment annually (Bose and Dhar, 2022), resulting from both natural and anthropogenic activities (Cox, 2021). The management of these large quantities of sediment obtained through dredging, which holds a legal classification as waste (Bortali et al., Jun. 2022), poses challenges for port authorities (Bel Hadj Ali et al., 2015). Despite some efforts by developed countries to reuse dredged material in land reclamation projects, infrastructure and agriculture-related activities (Rakshith and Singh, 2017), dumping at offshore disposal sites near the port of origin remains the easiest and most cost-effective option for port managers, and thus the most common practice globally (Aoual-Benslafa et al., 2015). Nonetheless, employing this management method can lead to detrimental impacts on the marine environment due to port activities, as well as urban and industrial discharges at port sites (Lim et al., 2020). Increasing environmental regulations related to sediment management (Li et al., 2022), at an international level, require port managers to implement new systems for managing dredged material, within the framework of adopting a circular economy approach.

Urban development has also led to a growing demand for construction materials for building and infrastructure projects (Xue

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et al., 2022). The production of materials used in the construction industry exceeds 50 billion tons per year (Achour et al., 2014). Considering population growth forecasts, construction projects are expected to accelerate at a faster pace (Hatefi and Tamošaitiene, 2018). However, the extensive use of construction aggregates presents risks associated with the scarcity of non-renewable resources on one hand (Hossain et al., 2020), and the negative environmental impacts resulting from the massive exploitation of natural aggregates extracted mainly from natural deposits, riverbeds, and quarries on the other hand (Said et al., 2015). These impacts, which occur during the extraction process, as well as handling and transport to construction sites, can be summarized as the disturbance of natural sites and increased vulnerability of groundwater in the long term (Çevikbilen et al., 2020). This alarming situation has put pressure on the construction sector to consider the adoption of sustainable alternatives based on waste valorization and the utilization of recycled by-products (Shooshtarian et al., 2020).

In light of the foregoing, the valorization of dredged sediment in construction projects represents a potential alternative to natural aggregates. It provides an efficient and sustainable solution to address two issues: the scarcity of non-renewable resources utilized in the construction industry and the adverse effects of dredging operations on the aquatic environment. As a result, numerous research studies have explored the potential for reusing dredged material in civil engineering applications (Zelleg et al., 2018); such as roads (Balkaya et al., 2019), concrete (Beddaa et al., 2022), cement (Amar et al., 2021), mortar (El Moueden et al., 2022), and pavement production (Limeira et al., 2011). Despite the encouraging findings of experimental studies, the utilization of marine sediment in the construction sector is not yet widespread on an industrial scale (Peruzzi et al., 2020). Two main barriers to this approach emerge: first, the contamination of dredged material by chemical components such as heavy metals and organic pollutants, which require costly treatment and chemical analysis (Staniszewska and Boniecka, 2017). Second, the need for thorough characterization on a case-by-case basis to assess the properties of sediment dredged from a specific port and identify the most suitable approaches for its valorization (Rehman et al., 2019; Manap and Voulvoulis, 2015).

However, few case studies have explored the contamination of dredged sediment, particularly in research conducted in developing countries, during the characterization step. For example, research conducted by Loudini et al. (Loudini et al., 2020) and Hassoune et al. (Hassoune et al., 2020) in the Moroccan ports of Safi and Agadir, respectively, focused on conducting physical, geotechnical, and mineralogical characterizations of the sediment. To fill this gap, the objective of the current paper is to evaluate the contamination of sediment dredged from the port of Safi in Morocco, in order to confirm the feasibility of its beneficial use in the construction sector. To achieve this objective, the chemical characteristics of the sediment are studied. On one hand, the concentrations of trace metals including Cadmium (Cd), Arsenic (As), Chromium (Cr), Nickel (Ni), Lead (Pb), Copper (Cu) and Zinc (Zn) are measured. Additionally, Total Petroleum Hydrocarbons (TPH) and total organic carbon (TOC) are investigated. The results are then analyzed and interpreted, and conclusions focusing on the environmental impacts of potential valorization routes are drawn.

The rest of this manuscript is divided as follows: the second section presents background information. Section 3 is dedicated to the description of materials and methods used to perform this research work. Section 4 showcases and examines the results that were obtained during the study. Section 5 discusses the findings, with a focus on further research directions. Section 6 of the paper presents the conclusions drawn from the study.

2. Background

This section is divided into two subsections. First, an overview on the contamination of dredged sediment is presented. Second, the applicable regulations are provided.

2.1. Contamination of harbor dredged sediment

Existing literature confirms that marine sediment commonly host industrial, domestic and harbor wastes from a variety of sources; it is therefore often contaminated by metals and persistent substances with a high level of bioaccumulation and toxicity (Torres, 2009). Dredged sediment is composed of chemical elements that frequently include (Couvidat et al., 2018):

- Traces of heavy metals including chromium, cadmium, copper, mercury, nickel, lead, selenium and arsenic
- Nutrients from urban waste, agricultural, and industrial effluents that depend on the activity of the port of origin, such as phosphorus and nitrogenous compounds
- Organic pollutants, mainly polycyclic aromatic hydrocarbons, pesticides, chlorinated solvents and polychlorinated biphenyls.

These components are considered toxic when they exceed certain thresholds (Bel Hadj Ali et al., 2015). Marine sediment is therefore recognized as the final destination of many contaminants considered hazardous to the environment and human health (Moreira, 2020).

Furthermore, before deciding whether dredged sediment can be discharged into the sea or reclaimed, either in its inert state or after treatment, it is imperative to study its chemical characteristics to assess its level of contamination (Miraoui et al., 2012).

2.2. Applicable regulations

The International Maritime Organization has implemented several texts and conventions that regulate aspects related to the environment and the prevention of pollution in the marine environment, particularly in relation to dredging operations and the disposal of dredged sediment at sea (Staniszewska and Boniecka, 2017). These texts include:

- Barcelona Convention for the Protection of the Mediterranean Sea against Pollution (IMO, 2007)
- Protocol of the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (IMO, 1972);
- Helsinki Convention on the Protection of the Marine Environment of the Baltic Sea (IMO, 1992);
- Oslo-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic (IMO, 2007).

These texts specify the legal basis regarding the criteria that must be met in order to authorize the dumping of dredged sediment at sea, the substances that pose risks to the marine environment, the level of impact of these substances and chemicals in the marine environment, and the reference thresholds of contamination at which the environmental impact of dredging activities must be assessed (Warford, 2022).

At the national level, the conventions of Barcelona and London have been ratified by Morocco.. However, the application of these conventions to port dredging activities requires the implementation of texts that establish, among other things, the thresholds of pollutants that are acceptable (Bortali et al., 2022).

Given these regulations, current environmental requirements, and the increased sensitivity of people around the world to issues related to this topic, dredged material management practices need to be adapted (Ulibarri, 2020).

3. Materials and methods

3.1. Study area

The sediment utilized in this study was obtained from the port of Safi, Morocco. Safi is an industrial and mineral port located in the center of the town of Safi on the Atlantic coast, with coordinates of 32.312642, −9.252548. The main services handled by Safi harbor include phosphate, fertilizer, ore, sulfur, phosphoric acid, and grain traffic, as well as fishing and ship repair. It also receives cruise ships and pleasure sailing ships, with a total number of ships transiting annually close to 500. The study site is known for its high level of silting, which requires recurrent dredging operations generating more than 250,000 m^3 of sediment per year (Charrouf, 1991). The most significant quantities of dredged sediment are extracted from the port access channel (Minoubi et al., 2018). Fig. 1 shows the study area location.

3.2. Data collection

3.2.1. Sampling collection

The sediment studied was collected on two separate occasions by a diver; in July 2022 and February 2023. A sampling plan has been established to ensure that the collected sediment samples accurately accurately depict the actual characteristics of the dredged sediment and provide informative value. Therefore, six sampling points from the different basins of Safi port were chosen. The aforementioned plan includes three locations in the inner basins of the port; P1, P2 and P3 from the commercial basin, the phosphate quay and the ore basin respectively. The three other locations P4, P5 and P6 represent the ends and middle of the harbor access channel. Fig. 2 displays the positions and the coordinates of the six sampling points cited above.

3.2.2. Sampling storage

Sampled sediments were immediately put in 20 L cooler bags (two bags per sample) under a layer of sea water in a dark cold room maintained at 4 °C from time of sampling until analysis and measurement. The conditions adhered to for the conservation of the sediments make it possible to avoid any reactivity of the sediments and to preserve their chemical properties (Couvidat et al., 2018).

3.3. Experimental program

3.3.1. Preliminary studies

Previous study on characterizing sediment dredged from the port Safi for beneficial use in the construction sector (Bortali et al., 2023), has investigated physical, chemical, geotechnical, environmental and mineralogical properties of dredged material, collected on the basis of the same sampling plan as the present study. The findings of the preliminary research identify the sediment excavated from Safi port as sand of category B, that can be utilized in concrete works requiring a resistance of 25 MPa. A pre-treatment, consisting of sediment washing and dehydrating, is necessary to reduce the water and chloride contents.

3.3.2. Characterization methods

Chemical parameters make it possible to detect the presence of pollutants and heavy metals in the sediments studied and to assess their level of contamination. The selection of laboratory tests was guided by the standard tests commonly employed to characterize dredged sediment and evaluate its pollution, with consideration given to the available resources in developing countries. Table 1 summarizes tests carried out to determine the chemical contamination of sediment dredged from Safi port, as well as the followed standards and protocols.

It should be noted that:

- The same tests were conducted during both summer 2022 and winter 2023 to verify the temporal variation of sediment contamination and determine if the deposition of pollutants and accumulation of metals are influenced by seasonal factors
- The tests presented in this section were conducted with a minimum of three repetitions to validate the findings. The subsequent sections will report the averaged values obtained from these three measurements for each test, providing a consolidated and comprehensive analysis of the results.

3.3.3. Reference values

In the absence of a national baseline, on the content of metallic trace elements and organic contaminants in dredged sediment, the concentration values obtained were compared to the reference values of the French regulation (Decrees of June 14, 2000 (French Government, 2000), August 9, 2006 (French Government, 2006), and June 30, 2020 (French Government, 2020). Table 2 summarizes the reference values applicable to marine sediments.

Fig. 1. Study area location.

Code	P1	P2	P3	P4	P5	P6
Latitude	9°24′76.9′′W	9°25′03.7′′W	9°24′97.1′′W	9°25′28.9′′W	9°25′36.4′′W	9°25′54.2′′W
Longitude	32°30′75.8′′N	32°30′94.4′′N	32°31′12.0′′N	32°31′20.7′′N	32°31′32.0′′N	32°31′37.1′′N

Fig. 2. Location of sampling points.

Table 1
Summary of tests carried out.

Analysis type	Parameter	Standard	Equipment/Method	Protocol
Mineral	Heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb and Zn)	ISO 11,466 (International Organization for Standardization, 1995)	Inductively Coupled Plasma – Mass Spectroscopy (ICP-MS)	The ICP plasma torch is utilized to generate positively charged monovalent ions, which are subsequently directed through an interface to a quadruple mass spectrometer. The primary function of the spectrometer is to separate ions based on their atomic mass-to-charge ratio.
Organic	Total Petroleum Hydrocarbons (TPH)	ISO 16,703 (International Organization for Standardization, 2011)	Gas Phase Chromatography (GPC)	The sample is extracted using mechanical stirring with acetone/n-heptane. The organic phase is separated, washed with water, and treated with Florisil to remove polar compounds. Analyzing by capillary column gas chromatography with flame ionization detection enables to quantify hydrocarbons in the sample.
	Total Organic Carbon (TOC)	ISO 14,235 (International Organization for Standardization, 1998)	Infrared detection	The sediment is subjected to high temperatures to facilitate the breakdown of organic matter into carbon dioxide. The latter is then directed to an infrared detector, enabling an automated system to calculate and display the Total Organic Carbon (TOC) content.

Table 2
Reference values applicable to marine sediments (French Government, 2000; French Government, 2006; French Government, 2020).

Parameter	Unit	Level N1	Level N2
As	mg/kg	25	50
Cd		1.2	2.4
Cr		90	180
Cu		45	90
Hg		0.4	0.8
Ni		37	74
Pb		100	200
Zn		276	552
TPH		100	
TOC	%	2.3	5.8

The outcomes of the comparison with the reference values are interpreted as follows:

- Below N1: the levels are considered normal or comparable to the environmental background noise;
- Between N1 and N2: an additional investigation may prove necessary depending on the project in consideration and the degree to which level N1 is exceeded;
- Above N2: the contents are considered non-compliant. Need for further investigation.

4. Results

4.1. Mineral contamination

Mineral analysis has involved investigating the presence of heavy metals commonly found in port dredged material. In this case, the measurement of Cadmium (Cd), Arsenic (As), Chromium (Cr), Nickel (Ni), Lead (Pb), Copper (Cu) and Zinc (Zn) contents has been conducted. These metals are typically found in trace amounts, but they are toxic, abundant, non-biodegradable, persistent, and cumulative in nature (Ferrans et al., 2021). Tests were carried out on sediment samples collected in summer 2022 (*S*) and winter 2023 (*W*). Table 3 summarizes the results of heavy metals tests performed on sediment excavated from Safi harbor.

In order to evaluate the metallic contamination of dredged material, the results obtained were compared with the reference values related to each heavy metal. Fig. 3 shows the comparison results for the eight studied mineral contaminants.

The findings highlight a difference between the levels of contamination found for each substance studied.

- *Arsenic*. The average results obtained were 11.8 mg/kg for the summer season and 10.6 mg/kg for the winter season. Maximum concentrations were observed at the harbor entrance during the summer season and at the ore basin during the winter season. However, none of the six locations studied recorded an exceedance of the reference values of 25 mg/kg and 50 mg/kg, as set by the applicable regulations, meaning that the concentration levels of Arsenic are considered normal or comparable to the environmental background noise.
- *Cadmium*. The average results obtained were 1.24 mg/kg for the summer season and 0.94 mg/kg for the winter season. Maximum concentrations were observed at the commercial basin during the summer season and at the phosphate quay during the winter season. The reference value N2 of 2.4 mg/kg was exceeded at the commercial basin during the summer season, indicating a strong contamination by Cadmium. Additionally, an exceedance of the reference value N1 of 1.2 mg/kg was recorded at the phosphate quay during both seasons, as well as at the commercial basin during the winter season and at the ore basin during the summer season, suggesting that further recommendations are needed for these cases. On the other hand, none of the three sampling points located at the access channel recorded an exceedance of the reference values set by the applicable regulations, indicating that the concentration levels of Cadmium are considered normal or comparable to the environmental background noise at the port access channel.
- *Chromium*. The average results obtained were 24.45 mg/kg for the summer season and 21.49 mg/kg for the winter season. Maximum concentrations were observed at the phosphate quay during the summer season and at the commercial basin during the winter season. However, none of the six locations studied recorded an exceedance of the reference values of 90 mg/kg and 180 mg/kg, as set by the applicable regulations, meaning that the concentration levels of Chromium are considered normal or comparable to the environmental background noise.
- *Copper*. The average results obtained were 56.2 mg/kg for the summer season and 37.9 mg/kg for the winter season. Maximum concentrations were observed at the commercial basin during the summer season and at the phosphate quay during the winter season. The reference value N2 of 90 mg/kg was exceeded at the commercial basin and the phosphate quay during both seasons, indicating a strong contamination by Copper. On the other hand, none of the four other sampling points located at the ore basin and the access channel recorded an exceedance of the reference value N1 of 45 mg/kg set by the applicable regulations, indicating that the concentration levels of Copper are considered normal or comparable to the environmental background noise for these cases.
- *Mercury*. The average results obtained were 0.056 mg/kg for the summer season and 0.046 mg/kg for the winter season. Maximum concentrations were observed at the commercial basin during both seasons. However, none of the six locations studied recorded an exceedance of the reference values of 0.4 mg/kg and 0.8 mg/kg, as set by the applicable regulations, meaning that the concentration levels of Mercury are considered normal or comparable to the environmental background noise.
- *Nickel*. The average results obtained were 6.1 mg/kg for the summer season and 5.1 mg/kg for the winter season. Maximum concentrations were observed at the commercial basin during summer season and at the phosphate quay during winter season. However, none of the six locations studied recorded an exceedance of the reference values of 37 mg/kg and 74 mg/kg, as set by the applicable regulations, meaning that the concentration levels of Nickel are considered normal or comparable to the environmental background noise.
- *Lead*. The average results obtained were 47 mg/kg for the summer season and 48 mg/kg for the winter season. Maximum concentrations were observed at the commercial basin during both seasons. The reference value N1 of 100 mg/kg was exceeded at the commercial basin during both seasons, suggesting that further recommendations are needed for these cases. On the other hand, none of the five other sampling points located at the phosphate quay, the ore basin and the access channel recorded an exceedance of the reference values set by the applicable regulations, indicating that the concentration levels of Lead are considered normal or comparable to the environmental background noise for these cases.
- *Zinc*. The average results obtained were 210.5 mg/kg for the summer season and 138 mg/kg for the winter season. Maximum concentrations were observed at the commercial basin for both seasons. The reference value N2 of 552 mg/kg was exceeded at the commercial basin during the summer season, indicating a strong contamination by Zinc. Additionally, an

Table 3
Concentrations of metallic trace elements.

Sample	Concentration of heavy metals (mg kg^{-1}) in dry materials															
	As		Cd		Cr		Cu		Hg		Ni		Pb		Zn	
	S	*W*	*S*	*W*	*S*	*W*	*S*	*W*	*S*	*W*	*S*	*W*	*S*	*W*	*S*	*W*
P1	13.2	11.8	2.84	1.78	39.6	41.8	183	97	0.1	0.089	11.8	9.7	170	192	749	474
P2	12.4	11.6	2.14	1.82	48.3	36.0	116	102	0.1	0.075	11.1	9.8	83	72	406	230
P3	10.2	12.9	1.36	0.98	28.4	32.2	21.5	13.6	0.058	0.052	5.3	3.4	14	9	67	99
P4	14.3	10.3	0.57	0.41	16.3	10.5	6.9	<5	0.039	0.041	3.5	<2.5	6	<5	23	12
P5	12.6	9.2	0.32	0.35	7.15	4.33	<5	<5	0.024	0.013	<2.5	<2.5	<5	<5	10	6
P6	8.3	7.7	0.23	0.28	6.93	4.12	<5	<5	0.016	0.008	<2.5	<2.5	<5	<5	8	6
Min	8.3	7.7	0.23	0.28	6.93	4.12	<5	<5	0.016	0.008	<2.5	<2.5	<5	<5	8	6
Max	14.3	12.9	2.84	1.82	48.3	41.80	183	102	0.1	0.089	11.8	9.8	170	192	749	474
Mean	11.8	10.6	1.24	0.94	24.45	21.49	56.2	37.9	0.056	0.046	6.1	5.1	47	48	210.5	138
Median	12.5	11.0	0.97	0.70	22.35	21.35	14.2	9.3	0.049	0.047	4.4	3.0	10	7	45	56

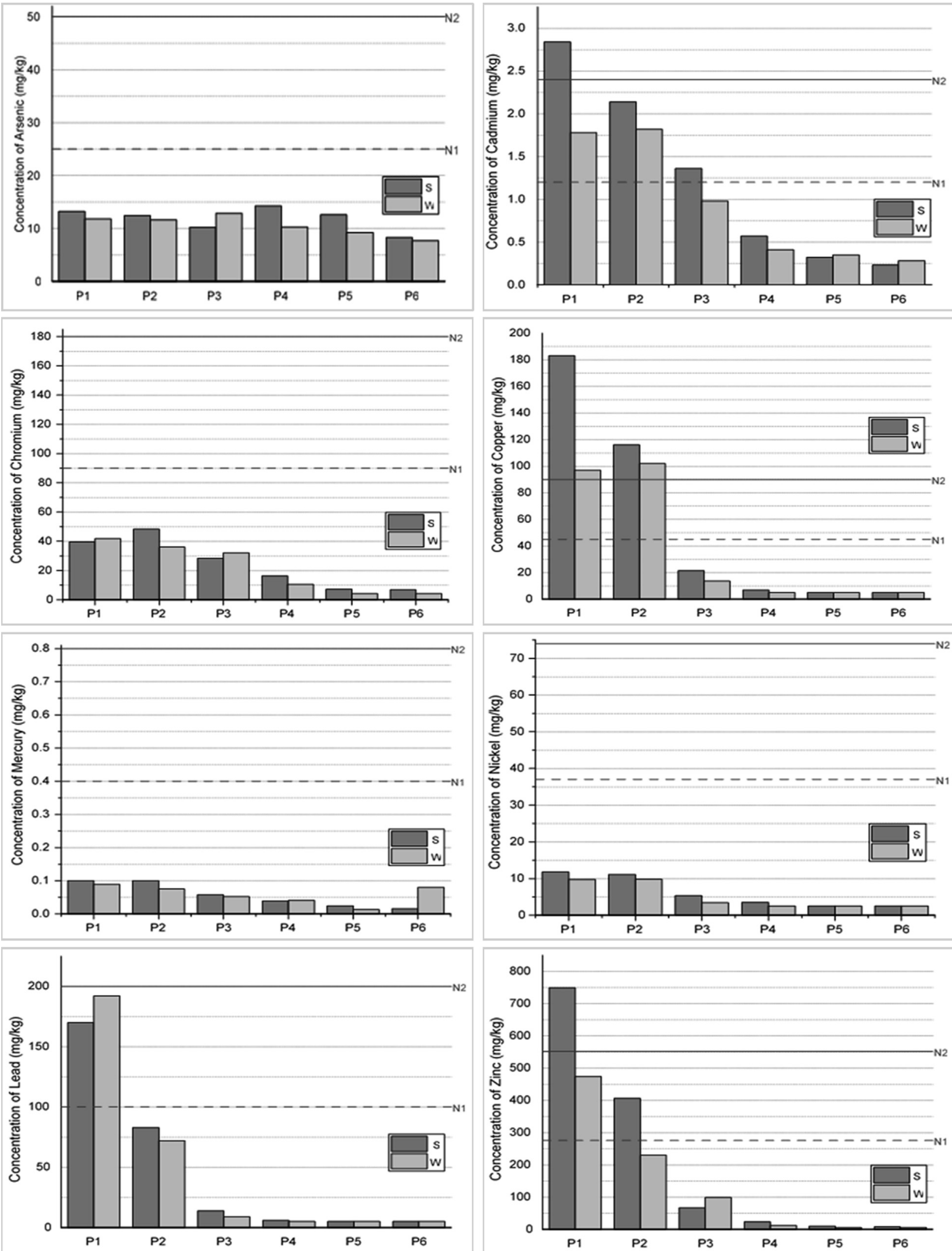

Fig. 3. Assessment of mineral contamination.

exceedance of the reference value N1 of 276 mg/kg was recorded at the phosphate quay during summer season, as well as at the commercial basin during the winter season, suggesting that further recommendations are needed for these cases. On the other hand, none of the four sampling points located at the ore basin and the access channel recorded an exceedance of the reference values set by the applicable regulations, indicating that the concentration levels of Zinc are considered normal or comparable to the environmental background noise at these locations.

4.2. Organic contamination

Organic analysis has involved investigating the presence of organic contaminants commonly found in port dredged material. In this case, the measurement of Total Petroleum Hydrocarbons (TPH) and Total Organic Carbon (TOC) contents has been conducted. TPH represents of all the hydrocarbon ranges between C10 and C40, including substances derived from crude oil and refined petroleum products (Mora et al., 2022). TOC is commonly used as a parameter to assess sediment quality, as it impacts numerous biogeochemical processes, encompassing nutrient cycling, biological availability, chemical transport and interactions (Torres, 2009). The significance of this index lies in its ability to identify potential pathways for valorization by addressing the presence of organic elements in construction materials, which are generally considered undesirable (Loudini et al., 2020). Tests were carried out on sediment samples collected in summer 2022 (S) and winter 2023 (W). Table 4 summarizes the results of organic analysis tests conducted on sediment excavated from Safi harbor.

In order to evaluate the organic contamination of dredged material, the results obtained were compared with the reference values related to each pollutant. Fig. 4 shows the comparison results for the two studied organic contaminants.

The findings highlight a difference between the levels of contamination found for each substance studied.

- *Total Petroleum Hydrocarbons*. The average results obtained were 179.3 mg/kg for the summer season and 158.3 mg/kg for the winter season. Maximum concentrations were observed at the commercial basin during the summer season and at the phosphate quay during the winter season. The reference value N of 100 mg/kg was exceeded at the commercial basin, the phosphate quay and the ore basin during both seasons, which indicates a contamination by Total Petroleum Hydrocarbons. On the other hand, none of the three sampling points located at the access channel recorded an exceedance of the reference values set by the applicable regulations, indicating that the concentration levels of Total Petroleum Hydrocarbons are considered normal or comparable to the environmental background noise at the port access channel.
- *Total Organic Carbon*. The average results obtained were 1.17 mg/kg for the summer season and 0.85 mg/kg for the winter season. Maximum concentrations were observed at the commercial basin during the summer season and at the phosphate quay during the winter season. However, none of the six locations studied recorded an exceedance of the reference values of 2.3 mg/kg and 5.8 mg/kg, as set by the applicable regulations, meaning that the concentration levels of Total Organic Carbon are considered normal or comparable to the environmental background noise.

Table 4
Concentrations of hydrocarbons and organic matter.

Sample	Concentration of organic contaminants			
	TPH (mg kg^{-1})		TOC (%)	
	S	*W*	*S*	*W*
P1	481	376	2.13	1.72
P2	392	388	1.86	1.79
P3	119	126	1.15	0.93
P4	44	<20	1.02	0.39
P5	<20	<20	0.54	0.13
P6	<20	<20	0.33	0.17
Min	<20	<20	0.33	0.13
Max	481	388	2.13	1.79
Mean	179.3	158.3	1.17	0.85
Median	81.5	73	1.09	0.66

5. Discussion

5.1. Assessment of dredged sediment contamination

Compared with existing literature, this study investigated the contamination of dredged sediment with regard to mineral and organic pollutants. This investigation aimed to assess the viability of repurposing dredged sediment as construction aggregate, for widespread use in civil engineering. We selected the port of Safi as our study area due to its substantial accumulation of dredged material caused by high levels of silting, which presents a potential opportunity for valorization (Bortali et al., 2023). Six sampling points from the different basins of Safi port were chosen, within a sampling plan established to accurately depict the actual charac-

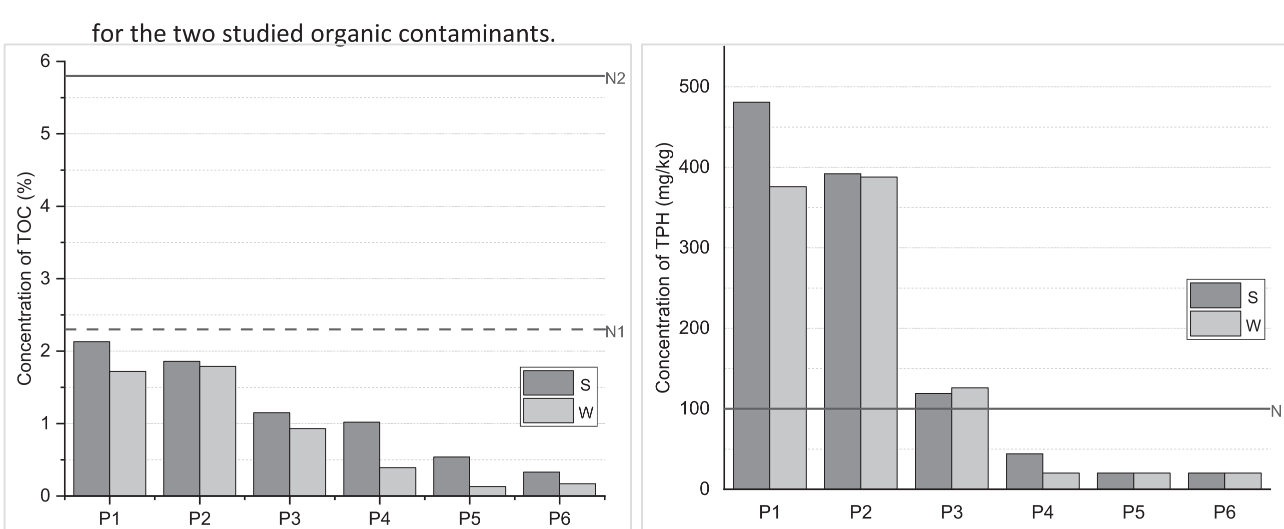

Fig. 4. Assessment of organic contamination.

teristics of the dredged sediment and provide informative value. In the continuity of the preliminary research work consisting of the characterization of the dredged sediment from a geotechnical, physical, chemical, environmental and mineralogical perspective (Bortali et al., 2023), an experimental program was conducted, involving two main steps. First, mineral analysis were performed to explore the presence of heavy metals commonly found in port dredged material. In this case, the measurement of Cadmium (Cd), Arsenic (As), Chromium (Cr), Nickel (Ni), Lead (Pb), Copper (Cu) and Zinc (Zn) contents has been conducted. Second, concentrations of Total Petroleum Hydrocarbons (TPH) and Total Organic Carbon (TOC) were measured, as part of the organic analysis. Laboratory tests were conducted during both summer and winter seasons to verify the temporal variation of sediment contamination. Results obtained were then compared to the reference values set by applicable regulations.

On the basis of the comparison results, the three sampling points located at the port access channel present favourable results of mineral and organic contaminants. We can therefore confirm that the sediment excavated from the access channel of Safi port indicates normal levels of contamination that are comparable to the environmental background noise. On the other hand, findings highlight strong contaminations by the following pollutants: Cadmium and Zinc at the commercial basin during summer season, Copper at the commercial basin and the phosphate quay during both seasons, as well as Total Petroleum Hydrocarbons at the commercial basin, the phosphate quay and the ore basins during both seasons. Further investigations are recommended for some contaminants that represent moderate contamination, such as Cadmium (at the commercial basin during the winter season, at the phosphate quay during both seasons, and at the at the ore basin during the summer season), Lead (at the commercial basin during both seasons), and Zinc (at the commercial basin during the winter season, and at the phosphate quay during summer season). In a general way, the contamination of the majority of sampling points located in the port interior basins is attributed to the industrial and mineral activities of the port. Table 5 summarizes the main sources of contaminants found in our case study (Mora et al., 2022; He et al., 2013).

On a whole, the findings of the present research work indicate that sediment excavated from the access channel of Safi port, representing the most significant quantities generated by dredging operations, is not contaminated by mineral and organic pollutants studied. Therefore, it can be reused as an alternative to natural aggregates used in the construction industry, with no adverse impacts. Hence, from an environmental perspective, the feasibility of valorizing sediment dredged in civil engineering is confirmed.

Table 5
Potential sources of contaminants (Mora et al., 2022; He et al., 2013).

Contaminant	Potential sources
Cadmium	Used in the manufacture of batteries, cadmium is used in the surface treatment of steel, in the stabilization of plastics and in the composition of non-ferrous alloys.
Zinc	Natural global emissions from soil erosion, volcanism and vegetation are small compared to anthropogenic contributions, mainly attributed to metallurgy and wood and coal burning.
Copper	Used in the composition of antifouling paints to replace stannic compounds.
Lead	Mainly found in carbonated form and has a strong affinity for particulate matter.
Total Petroleum Hydrocarbons	Crude oil and refined petroleum products used for vessels navigation.

5.2. Spatiotemporal variation

This study aimed to assess the distribution of 10 chemical contaminants in six sampling points within the port of Safi during both summer and winter seasons, using French sediment quality guidelines as a reference. The results revealed exceedances of Cadmium, Zinc, Copper, Lead, and Total Petroleum Hydrocarbons, indicating sediment contamination. However, the contamination levels of dredged material exhibited spatial and temporal variability.

The concentrations of contaminants showed considerable variation among the sampling points, with a noticeable improvement observed from the interior basins of the port to its access channel. The sediment quality in the exploitation areas appeared to be adversely affected by the industrial and urban activities within the port, as evidenced by all the parameters studied.

Temporal variation was also observed, with higher contaminant levels measured during the summer season compared to the winter season. Despite this variation, the overall assessment of contamination levels based on applicable guidelines remained relatively consistent.

In summary, this study found that the distribution of chemical contaminants in the port of Safi exhibited spatial and temporal variability, with exceedances of sediment quality guidelines indicating contamination of some zones. The findings also highlighted the impact of industrial and urban activities on sediment quality and the influence of seasonal factors on contaminant deposition.

5.3. Potential pathways

The port of Safi generates substantial quantities of marine sediment through regular dredging activities. Given its favorable characteristics, beneficial reuse of dredged material has the potential to serve as a viable alternative to conventional sand in the construction sector (Bortali et al., 2023). However, the management of dredged sediment is subject to international regulatory frameworks that outline various approaches based on the level of contamination detected (French Government, 2000; French Government, 2006; French Government, 2020). Fig. 5 summarizes the possible destinations identified by applicable regulations.

Based on applicable regulations, the possible destinations for sediment dredged from Safi port vary depending on the dredging zone. Marine sediment excavated from the port access channel, characterized by normal levels of chemical contaminants, can be utilized in civil engineering without preliminary treatment, as part of a sustainable development approach. However, material dredged from the interior basins, which is highly contaminated by mineral and organic pollutants, can either be stored on land or treated before being reused as construction material. Treatment of contaminated sediment involves physical and chemical processes to inhibit the mobility of the detected pollutants (Couvidat et al., 2018).

5.4. Comparison with literature values

As reference values for the study area were not available, the findings of the current study were compared with values previously reported in the literature. Previous studies have consistently shown that port dredged material is polluted to varying degrees (Wang, 2018). The present study further confirms the presence of mineral and organic pollutants in the chemical composition of marine sediment, which aligns with previous research findings (Zuliani et al., 2016). Nevertheless, there are variations in the concentrations of different contaminants in dredged sediment reported in different studies. Table 6 provides a summary of the comparison between contamination levels found in the current study (average of the values obtained per season and per sample)

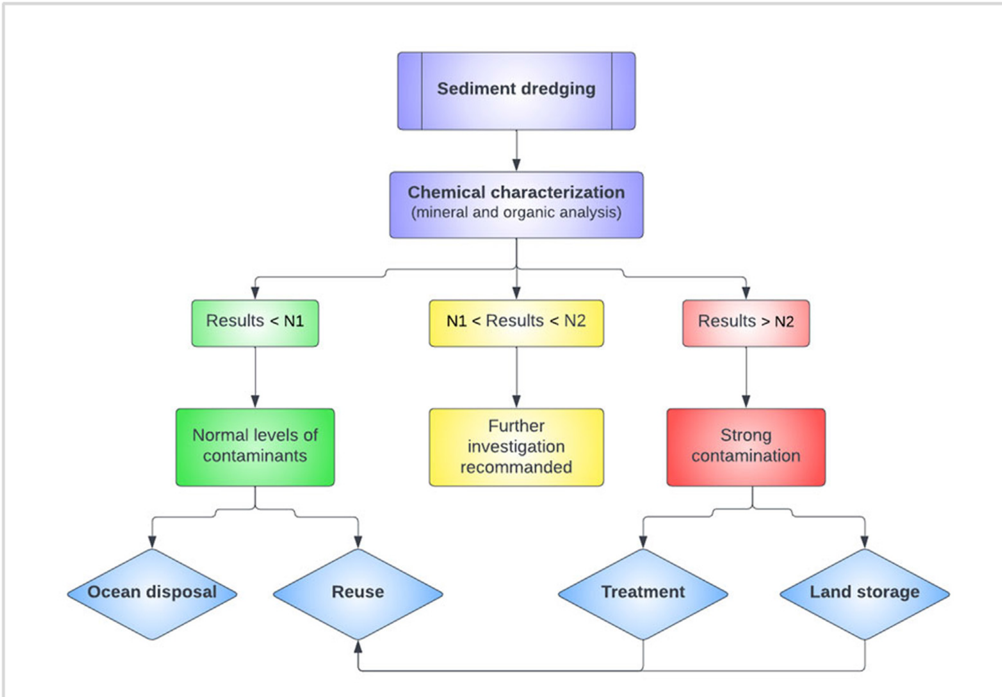

Fig. 5. Approaches to dredged sediment management (French Government, 2000; French Government, 2006; French Government, 2020).

Table 6
Comparison of concrete properties with literature values*.

Site	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	TPH	TOC	Reference
Safi, Morocco	11.2	1.1	23	47.1	0.05	5.6	51.4	174.2	168.8	1	Present study
Nova Scotia, Canada	2.8	0.5	45.6	3	20.3	2.4	3.3	0.6	–	–	Zhang et al. (Zhang et al., 2019)
Lamma, Hong Kong	7.8	1.8	29.7	378.5	–	23.6	101.1	138.5	–	2.5	Zhou et al. (Zhou et al., 2021)
Brussels, Belgium	14.4	2.2	10.6	63	0.3	25.5	99	459.5	15.1	–	Lemière et al. (Lemière, 2022)
Livorno, Italy	–	–	64	123	–	49.1	59.7	240	5447	1.9	Doni et al. (Doni et al., 2018)
Difference** (%)	26	38	63	201	205	350	51	20	1517	122	–

* All values are in (mg/kg) except of TOC that is expressed in (%).
** Difference between the value from the present study and the average of values reported in the literature.

on the one hand, and literature values obtained from previous studies on marine sediment characterization on the other hand.

The comparison of results reveals significant variability in contaminant concentrations across different sites, which could be attributed to the specific activities conducted at each study area. These findings align with previous research, suggesting that sediment dredged from ports can demonstrate varying levels of contamination, spanning from low to moderate to high, contingent upon the extent of port activity.

5.5. Limitations and directions for future research

The chemical properties of sediment dredged from the port of Safi were investigated, and potential sediment management options were identified based on the contamination level. The results indicated that the sediment dredged from the port access channel did not show signs of pollution, as the organic and mineral parameters analyzed were found to be below regulatory thresholds. The chemical characterization of the sediment revealed that it is of good quality, which suggests the possibility of utilizing it as an alternative source of construction materials. The proposed valorization of dredged sediment would help mitigate environmental and ecological issues associated with sea disposal of the material. However, there are limitations to this study. The feasibility of reusing dredged sediment was assessed based on its characterization. Further research should be conducted to assess the quality of construction products (such as concrete, brick, road, etc.) that incorporate dredged sediment as an aggregate. Additionally, it is recommended that future research focus on conducting a comprehensive environmental impact assessment of the proposed valorization approach.

6. Conclusion

Valorizing waste is an environmentally sustainable approach to address the increasing scarcity of non-renewable resources used in the construction industry. Ports worldwide periodically dredge significant amounts of marine sediment to maintain navigation channels. Reusing this harbor dredged sediment as construction aggregate offers a promising solution to tackle both the environmental impacts of dredging and the overexploitation of natural resources, providing a joint benefit.

In this paper, we conducted an assessment of the contamination levels in sediment excavated from the port of Safi, with the aim of studying the feasibility of its valorization in civil engineering applications. The method employed in this study involved the chemical characterization of the dredged material, with a focus on evaluating the concentrations of mineral and organic pollutants commonly investigated. We chose Safi port as our study area due to the significant accumulation of dredged material caused by high levels of silting, which presents a potential opportunity for valorization. We selected six sampling points from different basins within Safi port based on a sampling plan designed with the aim of precisely reflecting the characteristics of the dredged sediment and providing informative data. Following the preliminary research work that involved geotechnical, physical, chemical, environmental, and mineralogical characterization of the dredged sediment, we conducted an experimental program in two main steps. The first step involved mineral analysis to investigate the presence of heavy metals commonly found in port dredged material, including Cadmium (Cd), Arsenic (As), Chromium (Cr), Nickel (Ni), Lead (Pb), Copper (Cu) and Zinc (Zn). The concentrations of these heavy metals were measured. The second step involved measuring the concentrations of Total Petroleum Hydrocarbons (TPH) and Total Organic Carbon (TOC) as part of the organic analysis. Laboratory tests were conducted during both summer and winter seasons to determine any temporal variation of sediment contamination. The results obtained were then compared to the reference values set by applicable regulations.

The findings of our study indicated that the sediment dredged from the access channel of Safi port, which represents the largest quantities generated by dredging operations, was found to be free of contamination from the mineral and organic pollutants that were studied. As a result, it can be potentially utilized as an alternative to natural aggregates in the construction industry, without causing any adverse impacts on the environment. Furthermore, and prior to its valorization, sediment dredged from the interior basins, highly contaminated by cadmium, copper, zinc, and Total Petroleum Hydrocarbons, requires a preliminary treatment to prevent the mobility of pollutants. Regarding spatiotemporal variations, our findings revealed significant differences in contaminant concentrations among the sampling points, with noticeable improvement observed from the interior basins of the port to its access channel. The sediment quality in the exploitation areas appeared to be negatively impacted by industrial and urban activities within the port, as indicated by all the parameters studied. Temporal variation was also observed, with higher contaminant levels measured during the summer season compared to the winter season. However, despite this variation, the overall assessment of contamination levels based on applicable guidelines remained relatively consistent.

The present research has confirmed, from an environmental perspective, that the dredged sediment has good chemical quality, meeting the requirements of the construction sector. This confirms the feasibility of valorizing dredged sediment in civil engineering applications.

This case study significantly enhances our comprehension of the process for evaluating the environmental feasibility of utilizing dredged sediment as construction material, which can be applied in other site areas. A comprehensive study of the chemical properties of dredged material is crucial in identifying potential management approaches, guiding port managers towards suitable valorization routes, and ensuring that the dredged sediment meets the appropriate quality standards as a construction aggregate, in line with sustainable development principles.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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