Ben-Haddad *et al. Water Emerg Contam Nanoplastics* 2024;3:10
DOI: 10.20517/wecn.2023.70

Water Emerging Contaminants & Nanoplastics

Perspective

Open Access

Check for updates

Per- and polyfluoroalkyl pollution in marine environments: a viewpoint about Africa

Mohamed Ben-Haddad[1], Gabriel E. De-la-Torre[2], Tadele Assefa Aragaw[3], Bilal Mghili[4], Mohamed Rida Abelouah[1], Sara Hajji[1], Aicha Ait Alla[1]

[1]Department of biology, Laboratory of Aquatic Systems: Marine and Continental Environments (AQUAMAR), Faculty of Sciences, Ibn Zohr University, Agadir 80000, Morocco.
[2]Biodiversity, Environment, and Society Research Group, San Ignacio de Loyola University, Lima 15012, Peru.
[3]Faculty of Chemical and Food Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar 6000, Ethiopia.
[4]LESCB, URL-CNRST N° 18, Abdelmalek Essaadi University, Faculty of Sciences, Tetouan 93000, Morocco.

Correspondence to: Dr. Mohamed Ben-Haddad, Department of biology, Laboratory of Aquatic Systems: Marine and Continental Environments (AQUAMAR), Faculty of Sciences, Ibn Zohr University, Dakhla avenue, Agadir 80000, Morocco. E-mail: mohamed.ben-haddad@edu.uiz.ac.ma

How to cite this article: Ben-Haddad M, De-la-Torre GE, Aragaw TA, Mghili B, Abelouah MR, Hajji S, Ait Alla A. Per- and polyfluoroalkyl pollution in marine environments: a viewpoint about Africa. *Water Emerg Contam Nanoplastics* 2024;3:10. https://dx.doi.org/10.20517/wecn.2023.70

Received: 20 Nov 2023 **First Decision:** 22 Feb 2024 **Revised:** 1 Mar 2024 **Accepted:** 14 Mar 2024 **Published:** 1 Apr 2024

Academic Editor: Marta Otero **Copy Editor:** Dong-Li Li **Production Editor:** Dong-Li Li

Abstract

Per- and poly-fluoroalkyl substances (PFAS) represent an extensive and expanding group of chemicals considered contaminants of emerging concern (CECs). These elements have found widespread usage in diverse industrial and commercial sectors since the 1940s. The advancement of modern analytical methods in developed countries has significantly contributed to the increased research on the environmental behavior and risk assessment of PFAS. However, what about developing countries? Over time, the focus on PFAS has expanded beyond legacy PFAS to encompass novel ones. In this perspective, we focus on analyzing the existing knowledge concerning PFAS in the marine environment, aiming to shed light on the limited research pertaining to per- and polyfluoroalkyl pollution in the marine ecosystems of Africa.

Keywords: Per- and polyfluoroalkyl substances, Africa, marine environment, contaminants of emerging concern, pollution, toxicity

INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) represent a set of anthropogenic organic substances, comprising more than 8,000 distinct acknowledged structures listed in the Toxic Substances Control Act Inventory[1,2]. These compounds are employed in various utilizations in commercial and industrial sectors dating back to the 1940s[2]. Owing to their extensive use in numerous consumer items such as food packaging and water-resistant textiles, coatings, and firefighting foams, these elements are now pervasive throughout the environment[3,4]. Referred to as the “forever chemicals”, PFAS exhibit remarkable persistence in the environment and resist degradation due to the exceptional durability of their carbon-fluorine bonds, making their breakdown particularly challenging. PFAS [e.g., perfluorooctane sulfonate (PFOS) or perfluorooctanoic acid (PFOA)] emissions into the environment originate from multiple sources, including intentional manufacturing, utilization, and disposal processes[5-7]. Furthermore, PFAS can be present as impurities in substances emitted into the environment or can result from the degradation of precursor substances through abiotic or biotic pathways[8].

While the focus on PFAS has primarily revolved around their negative effects on human health, there is an increasing awareness of their bioaccumulation in biota, particularly in marine organisms, owing to the growing number of studies highlighting their presence in these ecosystems[9]. PFAS have demonstrated the capability to disrupt various physiological functions and biochemical routes that are conserved among different phyla, raising concerns regarding their impacts on marine biota[2,9]. To achieve improved risk management objectives concerning PFAS occurrence, bioaccumulation, and biomagnification, it is imperative to further advance our understanding of uptake and elimination kinetics[2]. This necessitates obtaining additional information and data on these crucial processes from several parts of the world, including developing countries.

As of the existing global knowledge concerning PFAS, there is growing concern about their impact on marine environments. PFAS, known for their persistence and bioaccumulative properties, have become a significant environmental issue worldwide[7,10]. Despite extensive research on PFAS pollution, there remains a need to deepen our understanding of their distribution, behavior, and long-term effects on marine ecosystems, particularly in developing countries. In light of the current situation, here we attempted to answer the question: “What is the position of Africa in the current knowledge about PFAS pollution in marine environments?”

CURRENT KNOWLEDGE ABOUT PFAS IN THE MARINE ENVIRONMENT

First, compared with freshwater environments, marine matrices have not attracted significant interest from scientists, especially in Africa[11]. According to a recent review by Khan *et al.*, the majority of worldwide studies concerning PFAS in the marine environment have primarily focused on water and sediment[2]. Limited information is available regarding PFAS bioaccumulation in invertebrates, with most data concentrated on crustaceans and mollusks. In fish, PFAS concentrations are commonly recorded in muscle tissue or fillet, primarily addressing concerns related to seafood safety. However, some studies have also investigated PFAS burdens in whole fish and liver. In the case of seabirds, research on PFAS occurrence and bioaccumulation often involves examining levels in eggs, liver, and blood (or plasma). It is recognized that marine mammals can bioaccumulate these compounds at significant levels, particularly in hepatic and circulatory tissues. Thus, the essential origins of PFAS in the marine environment are land-generated, including pesticides, paints, surfactants, textiles, firefighting foams, and fast food packaging, among several others. These chemicals are transported from land into the marine environment via the water cycle[4]. Then, various ecological phenomena interfere, such as the accumulation in organisms, transfer through food chains, and magnification within ecosystems[12].

Second, the quantification methods of PFAS involved a series of procedures, including preconditioning, extraction, clean-up, and concentration before the analytical instrumentation. Hence, liquid chromatography (LC) coupled with tandem mass spectrometry (MS/MS) is a widely employed technique for PFAS analysis with notable sophistication as well as meticulous calibration and quality control strategies. Indeed, this technique provides high sensitivity, excellent selectivity, and considerable precision even in complex environmental matrices like seawater and sediment. However, this technique may have limitations in detecting all possible PFAS compounds owing to differences in ionization efficiency and fragmentation patterns among various PFAS species[13]. LC-MS/MS methods can be technically complex, expensive, and require expertise for operation and maintenance, which is the main reason for the limited number of studies about PFAS in African and developing countries. Table 1 presents examples of field investigations that unveil the presence of PFAS across diverse marine matrices globally, delineating their geographical distribution, study matrix, identification methodology, and the range of occurrence.

WHAT IS AFRICA'S POSITION IN THE GLOBAL KNOWLEDGE ABOUT PFAS IN THE MARINE ENVIRONMENT?

The studies conducted on PFAS in Africa have predominantly focused on terrestrial aquatic ecosystems, primarily rivers, and lakes. Research efforts have been dedicated to understanding the presence, distribution, and potential ecological impacts of PFAS compounds in sediment and freshwater, mainly in South Africa, Nigeria, and Kenya[31]. Thus, this context forces us to raise relevant questions about the place of marine and coastal environments in the global knowledge of PFAS in Africa. To the best of our knowledge, the two only marine field studies in Africa were carried out in a lagoon area in the north of Tunisia in 2018 and in the Gulf of Guinea in 2022 [Table 1]. The study of Tunisia investigated nine marine species (three fish, two crustaceans, and four mollusks) collected from Bizerte lagoon using (LC-MS/MS) technique, reporting values between 0.20-2.89 ng/g dry weight[29]. The second study utilized the same technique to quantify the amount of PFAS in four fishery products along the Gulf of Guinea, revealing values between 91 and 1,510 pg/g wet weight[30]. In a separate investigation, the assessment of PFAS was conducted on marine shellfish farmed in land-based facilities in South Africa. The PFAS concentrations (expressed in ng/g wet weight) varied between 0.12 and 0.49 in abalone, 4.83-6.43 in mussels, 0.64-0.66 in oysters, and 0.22 ng/g ww in lobsters using UHPLC-MS/MS method[32]. Few other studies included some sampling points in estuaries in global surveys of terrestrial water bodies[11,13,33].

Unfortunately, the lack of studies in Africa is a significant concern. While PFAS pollution has been extensively researched in various parts of the world, there remains a notable gap in our understanding of the presence and impact of these chemicals on this continent. This group of human-made chemicals is widely used in various industrial and consumer products in Africa for their water and grease-resistance properties[34,35]. However, their persistent nature and potential adverse health effects have raised global concerns[36-38] that must not exclude African countries. Despite the growing recognition of PFAS as emerging contaminants, research efforts have predominantly focused on regions such as North America, Europe, and parts of Asia[18].

With its diverse coastal and marine ecosystems and substantial population relying on fisheries, the African continent should not be overlooked in PFAS research. Marine areas in Africa face unique environmental challenges, including industrial activities, burgeoning urbanization, climate change vulnerability, threatened biodiversity hotspots, and increasing plastic waste generation[39-41]. These factors can contribute to the release and accumulation of PFAS in coastal waters, sediments, and organisms, potentially posing risks to both human and ecological health. By expanding studies to include African coasts and marine habitats, researchers can gain valuable insights into the presence, distribution, and potential impacts of PFAS in new

Table 1. Examples of field investigations reporting PFAS are available for various marine matrices worldwide, with only two studies conducted in African marine environments

Country	Location	Matrix	Identification technique	Range (min - max)	Ref.
US	Florida	Seawater Coastal sediment	UHPLC system coupled to mass spectrometer	1.1-113 ng/L (seawater) 0.1-8.4 ng/g (sediment)	[14]
		Coastal waterway	UHPLC-MS/MS	2.47-4.69 ng/L	[15]
Sweden Denmark Germany	Baltic sea	Several marine organisms such as the blue mussel (*Mytilus edulis*), the Atlantic herring (*Clupea harengus*), and the grey seal (*Halichoerus grypus*)	LC-MS/MS	1.1-450 ng/g per wet weight	[16]
Germany	Seaside Büsum village	Coastal atmosphere	GC-MS	8.6-155 pg/m^3	[17]
Antarctica	Ross island	Blood of Weddell seal (*Leptonychotes weddellii*)	UHPLC-MS/MS	0.08-0.23 ng/mL	[18]
	Livingston Island	Seawater Coastal snow Plankton	UFLC-MS/MS coupled to a triple quadrupole mass spectrometer	94-420 pg/L (seawater) 760-3,600 pg/L (snow) 3.1-16 ng/g dry weight (plankton)	[19]
China	Estuaries and Delta of Pearl River region	Coastal water	HPLC-MS/MS	0.003-2.09 items/m^3 of water	[20]
	Bohai sea	Marine mollusks such as *Chlamys farreri*, *Crassostrea talienwhanensis*, *Meretrix meretrix*, and *Mytilus edulis*	Liquid chromatography column equipped with a tandem mass spectrometry system	2.51-1,351 ng/g dry weight	[21]
	South China sea	Seawater Coastal sediment	Ultra-performance liquid chromatograph interfaced with mass spectrometer	38-1,015 pg/L (seawater) 7.5-84.2 pg/g dry weight (sediment)	[22]
Australia	Estuary of Werribee River	Coastal water	HPLC-MS/MS	22-187 ng/L	[23]
France	Bay of Marseille	Coastal water	LC-QTOF-MS	0.11-9 ng/L	[24]
	Several locations in the English channel, the Mediterranean sea, and the Atlantic ocean	Mussel (*Mytilus edulis*, *Mytilus galloprovincialis*) Oyster (*Crassostrea gigas*)	Acquity ultra performance liquid chromatograph coupled to a triple quadrupole mass spectrometer	0.007-0.549 ng/g wet weight	[25]
Chile	Central coast	Coastal litter	HPLC-MS/MS	279-1,211 pg/g	[26]
Saudi Arabia	Red sea	Seawater	QqQ equipped with the AJS-ESI	0-956 ng/L	[27]
Spain	Coastal area of Ebro Delta	Coastal water Coastal sediment	TQ-MS	0-2,775 ng/L (water) 0-22.6 ng/g (sediment)	[28]
Tunisia (Africa)	Bizerte lagoon	Seafood	UPLC system coupled to a LC-MS/MS	0.20-2.89 ng/g dry weight	[29]
Guinea (Africa)	Golf of Guinea	Fishery products	LC-MS/MS	91-1,510 pg/g wet weight	[30]

PFAS: Per- and poly-fluoroalkyl substances; UHPLC: ultra-high performance liquid chromatography; UHPLC-MS/MS: ultra-high-pressure liquid chromatography coupled with tandem mass spectrometry; LC-MS/MS: liquid chromatography and tandem mass spectrometry; GC-MS: gas chromatography coupled with mass spectrometer; UFLC-MS/MS: ultra-fast liquid chromatography-tandem mass spectrometry; HPLC-MS/MS: high-performance liquid chromatography coupled with tandem mass spectrometry; LC-QTOF-MS: liquid chromatography quadrupole time-of-flight mass spectrometry; QqQ: triple quadrupole tandem mass spectrometer; AJS-ESI: jet stream electrospray ionization; TQ-MS: triple quadrupole mass spectrometer; UPLC: ultra-performance liquid chromatography.

environmental conditions. It is essential to evaluate the levels of contamination, identify potential sources, and understand the pathways through which PFAS enter the African marine environment. Moreover, the pervasive presence of PFAS poses a significant risk to marine products intended for export, particularly in the context of food safety. Investigations into the accumulation of PFAS in marine biota are crucial to understanding the potential hazards associated with seafood consumption by human populations. As these substances accumulate in marine life, they can find their way into the food supply chain, posing risks to consumers both domestically and internationally. Therefore, comprehensive studies addressing the bioaccumulation of PFAS in marine species are indispensable for safeguarding the integrity of exported marine products and ensuring global food safety standards.

CONCLUSION

Overall, the existing literature on PFAS in the marine environment, particularly in Africa, reveals a noticeable lack of interest and a limited number of studies conducted in this context. The coasts and marine habitats of Africa remain relatively unexplored and understudied. This knowledge gap calls for urgent attention and increased research efforts to understand the potential presence, distribution, and ecological impacts of PFAS chemicals. Addressing the lack of studies on PFAS in the marine environment of Africa requires collaborative efforts among researchers, environmental agencies, and policymakers. It is imperative to foster more robust international collaborations and partnerships with leading scientists in the field from across the world, such as China, the USA, and Europe. Leveraging the expertise and experience of these prominent researchers can facilitate knowledge transfer, exchange of methodologies, and establishment of standardized protocols for PFAS studies in marine environments. Such initiatives can help generate region-specific data, raise awareness about PFAS pollution, and guide the development of appropriate mitigation and regulatory measures. By shedding light on the presence and potential risks of PFAS in African marine environments, we can work towards safeguarding both the environment and the well-being of the communities relying on these vital ecosystems.

DECLARATIONS

Acknowledgments

The authors would like to thank the editors and reviewers for their efforts in improving the manuscript.

Authors' contributions

Conceptualization, methodology, validation, formal analysis, investigation, and writing - original draft: Ben-Haddad M

Conceptualization, methodology, validation: De-la-Torre GE, Aragaw TA, Mghili B, Abelouah MR, Hajji S, Ait Alla A

Availability of data and materials

Not applicable.

Financial support and sponsorship

None.

Conflicts of interest

All authors declared that there are no conflicts of interest. De-la-Torre GE is an Editorial Board Member of the journal *Water Emerging Contaminants* & *Nanoplastics*.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

REFERENCES

1. Evich MG, Davis MJB, McCord JP, et al. Per- and polyfluoroalkyl substances in the environment. *Science* 2022;375:eabg9065. DOI PubMed PMC
2. Khan B, Burgess RM, Cantwell MG. Occurrence and bioaccumulation patterns of per- and polyfluoroalkyl substances (PFAS) in the marine environment. *ACS ES T Water* 2023;3:1243-59. DOI PubMed PMC
3. Boisvert G, Sonne C, Rigét FF, Dietz R, Letcher RJ. Bioaccumulation and biomagnification of perfluoroalkyl acids and precursors in East Greenland polar bears and their ringed seal prey. *Environ Pollut* 2019;252:1335-43. DOI PubMed
4. Dickman RA, Aga DS. A review of recent studies on toxicity, sequestration, and degradation of per- and polyfluoroalkyl substances (PFAS). *J Hazard Mater* 2022;436:129120. DOI PubMed
5. Buck RC, Franklin J, Berger U, et al. Perfluoroalkyl and polyfluoroalkyl substances in the environment: terminology, classification, and origins. *Integr Environ Assess Manag* 2011;7:513-41. DOI PubMed PMC
6. Kwiatkowski CF, Andrews DQ, Birnbaum LS, et al. Scientific basis for managing PFAS as a chemical class. *Environ Sci Technol Lett* 2020;7:532-43. DOI PubMed PMC
7. Wang Z, Boucher JM, Scheringer M, Cousins IT, Hungerbühler K. Toward a comprehensive global emission inventory of C_4-C_{10} perfluoroalkanesulfonic acids (PFSAs) and related precursors: focus on the life cycle of C_8-based products and ongoing industrial transition. *Environ Sci Technol* 2017;51:4482-93. DOI PubMed
8. Gao K, Chen Y, Xue Q, et al. Trends and perspectives in per-and polyfluorinated alkyl substances (PFASs) determination: faster and broader. *TrAC Trends Anal Chem* 2020;133:116114. DOI
9. Lee JW, Choi K, Park K, Seong C, Yu SD, Kim P. Adverse effects of perfluoroalkyl acids on fish and other aquatic organisms: a review. *Sci Total Environ* 2020;707:135334. DOI
10. Kang P, Zhao Y, Zuo C, et al. The unheeded inherent connections and overlap between microplastics and poly- and perfluoroalkyl substances: a comprehensive review. *Sci Total Environ* 2023;878:163028. DOI
11. Ssebugere P, Sillanpää M, Matovu H, et al. Environmental levels and human body burdens of per- and poly-fluoroalkyl substances in Africa: a critical review. *Sci Total Environ* 2020;739:139913. DOI
12. Du D, Lu Y, Zhou Y, et al. Bioaccumulation, trophic transfer and biomagnification of perfluoroalkyl acids (PFAAs) in the marine food web of the South China Sea. *J Hazard Mater* 2021;405:124681. DOI
13. Mullin L, Katz D, Riddell N, et al. Analysis of hexafluoropropylene oxide-dimer acid (HFPO-DA) by liquid chromatography-mass spectrometry (LC-MS): review of current approaches and environmental levels. *Trends Analyt Chem* 2019;118:828-39. DOI PubMed PMC
14. Griffin EK, Hall LM, Brown MA, et al. PFAS surveillance in abiotic matrices within vital aquatic habitats throughout Florida. *Mar Pollut Bull* 2023;192:115011. DOI
15. Martinez B, Da Silva BF, Aristizabal-Henao JJ, et al. Increased levels of perfluorooctanesulfonic acid (PFOS) during Hurricane Dorian on the east coast of Florida. *Environ Res* 2022;208:112635. DOI
16. de Wit CA, Bossi R, Dietz R, et al. Organohalogen compounds of emerging concern in Baltic Sea biota: levels, biomagnification potential and comparisons with legacy contaminants. *Environ Int* 2020;144:106037. DOI
17. Wang Z, Xie Z, Möller A, Mi W, Wolschke H, Ebinghaus R. Atmospheric concentrations and gas/particle partitioning of neutral poly- and perfluoroalkyl substances in northern German coast. *Atmospheric Environment* 2014;95:207-13. DOI
18. Routti H, Krafft BA, Herzke D, Eisert R, Oftedal O. Perfluoroalkyl substances detected in the world's southernmost marine mammal, the Weddell seal (*Leptonychotes weddellii*). *Environ Pollut* 2015;197:62-7. DOI PubMed
19. Casal P, Zhang Y, Martin JW, Pizarro M, Jiménez B, Dachs J. Role of snow deposition of perfluoroalkylated substances at Coastal Livingston Island (Maritime Antarctica). *Environ Sci Technol* 2017;51:8460-70. DOI PubMed
20. Cheng Y, Mai L, Lu X, et al. Occurrence and abundance of poly- and perfluoroalkyl substances (PFASs) on microplastics (MPs) in Pearl River Estuary (PRE) region: spatial and temporal variations. *Environ Pollut* 2021;281:117025. DOI
21. Meng L, Lu Y, Wang Y, et al. Occurrence, temporal variation (2010-2018), distribution, and source appointment of per- and polyfluoroalkyl substances (PFAS) in mollusks from the Bohai Sea, China. *ACS EST Water* 2022;2:195-205. DOI
22. Wang Q, Tsui MMP, Ruan Y, et al. Occurrence and distribution of per- and polyfluoroalkyl substances (PFASs) in the seawater and sediment of the South China sea coastal region. *Chemosphere* 2019;231:468-77. DOI
23. Allinson M, Yamashita N, Taniyasu S, Yamazaki E, Allinson G. Occurrence of perfluoroalkyl substances in selected Victorian rivers and estuaries: an historical snapshot. *Heliyon* 2019;5:e02472. DOI PubMed PMC
24. Schmidt N, Fauvelle V, Castro-Jiménez J, et al. Occurrence of perfluoroalkyl substances in the Bay of Marseille (NW Mediterranean Sea) and the Rhône River. *Mar Pollut Bull* 2019;149:110491. DOI
25. Catherine M, Nadège B, Charles P, Yann A. Perfluoroalkyl substances (PFASs) in the marine environment: spatial distribution and temporal profile shifts in shellfish from French coasts. *Chemosphere* 2019;228:640-8. DOI PubMed
26. Gómez V, Torres M, Karásková P, Přibylová P, Klánová J, Pozo K. Occurrence of perfluoroalkyl substances (PFASs) in marine plastic litter from coastal areas of Central Chile. *Mar Pollut Bull* 2021;172:112818. DOI PubMed

27. Ali AM, Higgins CP, Alarif WM, Al-Lihaibi SS, Ghandourah M, Kallenborn R. Per- and polyfluoroalkyl substances (PFASs) in contaminated coastal marine waters of the Saudi Arabian Red Sea: a baseline study. *Environ Sci Pollut Res Int* 2021;28:2791-803. DOI PubMed PMC
28. Pignotti E, Casas G, Llorca M, et al. Seasonal variations in the occurrence of perfluoroalkyl substances in water, sediment and fish samples from Ebro Delta (Catalonia, Spain). *Sci Total Environ* 2017;607-8:933-43. DOI
29. Barhoumi B, Sander SG, Driss MR, Tolosa I. Survey of legacy and emerging per- and polyfluorinated alkyl substances in Mediterranean seafood from a North African ecosystem. *Environ Pollut* 2022;292:118398. DOI PubMed
30. Ekperusi AO, Bely N, Pollono C, Mahé K, Munschy C, Aminot Y. Prevalence of per- and polyfluoroalkyl substances (PFASs) in marine seafood from the Gulf of Guinea. *Chemosphere* 2023;335:139110. DOI PubMed
31. Groffen T, Nkuba B, Wepener V, Bervoets L. Risks posed by per- and polyfluoroalkyl substances (PFAS) on the African continent, emphasizing aquatic ecosystems. *Integr Environ Assess Manag* 2021;17:726-32. DOI PubMed
32. Abafe OA, Macheka LR, Abafe OT, Chokwe TB. Concentrations and human exposure assessment of per and polyfluoroalkyl substances in farmed marine shellfish in South Africa. *Chemosphere* 2021;281:130985. DOI PubMed
33. Fauconier G, Groffen T, Wepener V, Bervoets L. Perfluorinated compounds in the aquatic food chains of two subtropical estuaries. *Sci Total Environ* 2020;719:135047. DOI PubMed
34. Nakayama SF, Yoshikane M, Onoda Y, et al. Worldwide trends in tracing poly- and perfluoroalkyl substances (PFAS) in the environment. *TrAC Trends Anal Chem* 2019;121:115410. DOI
35. Xiao F. Emerging poly- and perfluoroalkyl substances in the aquatic environment: a review of current literature. *Water Res* 2017;124:482-95. DOI PubMed
36. Mao W, Li M, Xue X, et al. Bioaccumulation and toxicity of perfluorooctanoic acid and perfluorooctane sulfonate in marine algae Chlorella sp. *Sci Total Environ* 2023;870:161882. DOI
37. Martín J, Hidalgo F, García-Corcoles MT, et al. Bioaccumulation of perfluoroalkyl substances in marine echinoderms: results of laboratory-scale experiments with Holothuria tubulosa Gmelin, 1791. *Chemosphere* 2019;215:261-71. DOI
38. Otero-Sabio C, Giacomello M, Centelleghe C, et al. Cell cycle alterations due to perfluoroalkyl substances PFOS, PFOA, PFBS, PFBA and the new PFAS C6O4 on bottlenose dolphin (*Tursiops truncatus*) skin cell. *Ecotoxicol Environ Saf* 2022;244:113980. DOI PubMed
39. Fayiga AO, Ipinmoroti MO, Chirenje T. Environmental pollution in Africa. *Environ Dev Sustain* 2018;20:41-73. DOI
40. Ouda M, Kadadou D, Swaidan B, et al. Emerging contaminants in the water bodies of the Middle East and North Africa (MENA): a critical review. *Sci Total Environ* 2021;754:142177. DOI
41. Mghili B, Ben-haddad M, Zerrad O, Rangel-buitrago N, Aksissou M. Tackling marine plastic pollution in Morocco: a review of current research, regulatory measures, and future challenges. *Reg Stud Mar Sci* 2024;69:103286. DOI