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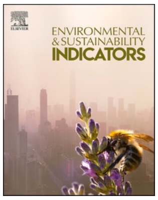

Scanning the horizon: anticipating future changes in Portuguese aquatic ecosystems

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ABSTRACT

We identified 15 emerging and poorly understood topics related to aquatic ecosystems in Portugal (from an initial pool of 43), which were scored and prioritized using a consensus-based Delphi technique. For marine ecosystems, the topics included current and future threats to low-lying sandy coasts, the impacts of the green energy transition, the risks posed by pathogens on floating ocean debris, the strategic importance of algae for a sustainable future, and Portugal's potential contribution to the expansion of Marine Protected Areas. For freshwater ecosystems, the topics included identifying drought refuges for freshwater biodiversity, assessing the potential ecological and social costs of water highways, uncovering the hidden impacts of clean energy (floating solar panels and lithium mining), managing water quality in reservoirs, and understanding the potential impacts of the recent expansion of intensive olive orchards. For cross-cutting topics relevant to both types of ecosystems, the most scored topics included the importance of aquatic super-sites for ecological monitoring, new solutions for detecting and removing emerging pollutants, the application of rewilding, the impact of forest pathogens and emerging zoonoses, and the rise of organic compounds as a multidimensional threat. Prioritizing these topics can support a more proactive approach to conserving, managing, and sustainably exploring aquatic ecosystems in Portugal. This methodology can also be used to prioritize research funding areas identified bottom up (by the scientific community) rather than dictated from the top down (by decision-makers) and serve as a roadmap for conducting similar exercises in other regions of the world.

1. Introduction

Portugal has a deep and longstanding connection with aquatic ecosystems, which has shaped its history, culture, and identity. With an extensive coastline, Portugal's maritime traditions trace back to the early Phoenician and Roman periods (Arruda, 1999–2000). However, it

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was during the Age of Exploration in the 15th and 16th centuries that this relationship with marine ecosystems flourished. Portuguese navigators such as Bartolomeu Dias, Vasco da Gama, Pedro Álvares Cabral, and Fernão de Magalhães, pioneered new sea routes to Africa, Asia, and the Americas, establishing Portugal as a dominant maritime power of the time (Newitt, 2004). Similarly, Portugal has a long and deep-rooted relationship with freshwater and estuarine ecosystems, with the largest cities, Lisboa and Porto, situated near the mouth of large rivers, which functioned as waterways for people and commodities from and to the inner parts of the country. These aquatic ecosystems have influenced not only the Portuguese economy, through fishing and trade, but also its folklore, cuisine, and traditions (Rodrigues, 2018).

In this review, we use the definition by Wetzel (2001) and by Levinton (2017) of aquatic ecosystems as communities of organisms that interact with each other and their physical environment in bodies of water, including freshwater (e.g., rivers, lakes, wetlands) and marine (e.g., oceans, estuaries) systems. These ecosystems are characterized by the presence of water as the dominant environmental factor and support a wide range of life forms adapted to wet conditions, including plants, animals, and microorganisms. Aquatic ecosystems are structured by various environmental factors, including water chemistry, depth, temperature, light availability, among others, as well as biotic interactions such as predation, competition, facilitation, parasitism, and diseases. These ecosystems are among the most dynamic and vital components of our planet, providing essential services such as water purification, food resources, climate regulation, coastal defence, recreational opportunities, and habitats for biodiversity (Dudgeon et al., 2006; Halpern et al., 2008; Barbier, 2017; Biel et al., 2017; Reid et al., 2019; Ranta et al., 2021). In Portugal, these ecosystems include a diverse range of freshwater, brackish, and marine environments—such as rivers, lakes, estuaries, saltmarshes, and coastal and deep waters—each playing a vital role in ecological stability and human well-being (Domingues et al., 2017). Mainland Portugal's long coastline stretches over 900 km. In addition to the mainland shore, there are also the archipelagos of Madeira and the Azores in the Atlantic Ocean. Portugal has one of the largest Exclusive Economic Zones (EEZ) in the world and has shown interest in expanding its area of maritime jurisdiction by submitting a request for Extension of the Continental Shelf to the United Nations (https://en.emepc.pt/missao).

The geographic location of the Portuguese coast, along with its distinct environmental conditions—a cooler northern region influenced by upwelling and a much warmer southern region with a strong Mediterranean influence—creates an environmental and biogeographic gradient that supports high biodiversity (Cardoso et al., 2019). Regarding mainland aquatic ecosystems, Portugal is home to several major hydrological basins, many of which extend into Spain, as well as economically and ecologically important estuaries (Cabral et al., 2007; Vasconcelos et al., 2007; Erzini et al., 2022). For freshwater ecosystems, the unique environmental conditions and the isolation of the Iberian Peninsula due to the Pyrenees have contributed to rich endemic freshwater biodiversity among fish, invertebrates, and other taxonomic groups (e.g., Almaça, 1995; Froufe et al., 2016; Collares-Pereira et al., 2021).

Despite the high biodiversity and high economic importance of fisheries, aquaculture, and tourism, among other activities, the fact is that these ecosystems have been suffering the pressure of many human disturbances such as habitat loss and fragmentation, pollution, overexploitation, the introduction of non-native species, and climate change (Halpern et al., 2008; Vörösmarty et al., 2010; Reid et al., 2019). Despite the limited information available on several threats affecting Portuguese aquatic ecosystems, there is significant spatial variation in some of them (erosion, urbanization and water quality), and many aquatic ecosystems are severely disturbed (Fig. 1). These threats may disrupt several ecosystem services and lead to changes in biodiversity, including species extinctions and a higher occurrence of non-native species, as well as alterations in ecosystem functions (Chainho et al., 2015; Anastácio et al., 2019; Bueno-Pardo et al., 2021; Couto and Ribeiro, 2022).

Given ongoing changes in biodiversity and the European Union's environmental policies and frameworks—such as the Water Framework Directive, the Marine Strategy Framework Directive, the European Biodiversity Strategy for 2030, the EU Nature Restoration Law, and the Green Deal—there is a pressing need for the sustainable management of water resources. In this context, a horizon-scanning exercise focused on Portuguese aquatic ecosystems is both timely and highly relevant. It aligns with these frameworks by facilitating the early detection of compliance issues and supporting the development of innovative

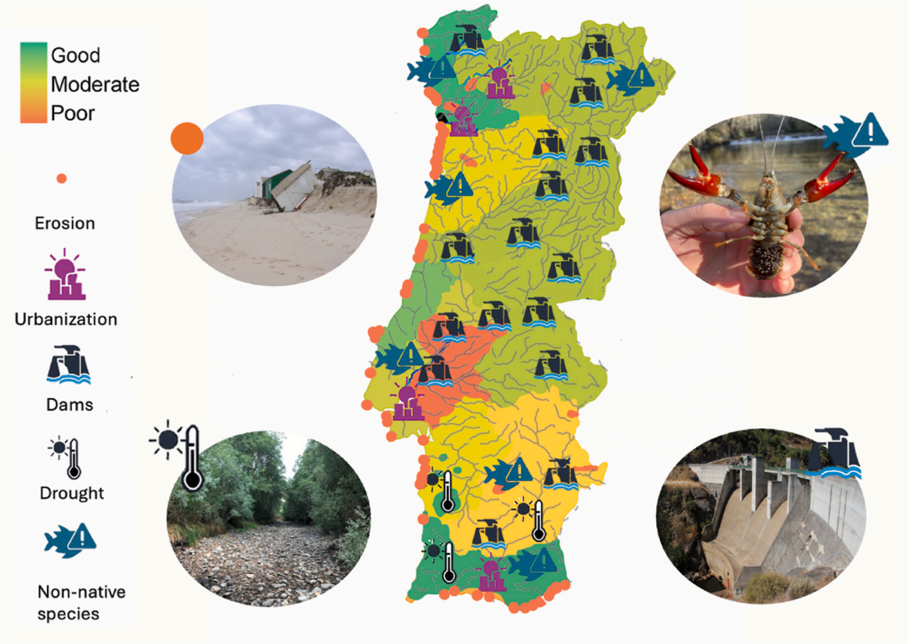

Fig. 1. Some of the major threats affecting Portuguese aquatic ecosystems. Water quality classification (Good, Moderate, Poor) follows the Water Framework Directive assessment. Icons represent coastal erosion (APA, 2025a), urban areas (INE - Instituto Nacional de Estatística, 2021), dams (APA, 2025b), drought (IPMA - Instituto Português do Mar e da Atmosfera, 2025), and aquatic non-native species (GBIF, 2025).

solutions to meet regulatory requirements. In addition, over the past decade, the concept of horizon scanning has gained traction in environmental sciences due to its ability to inform adaptive management strategies (Sutherland et al., 2011; Zieritz et al., 2024).

Traditional environmental monitoring methods often rely on retrospective data analysis, whereas horizon scanning focuses on foresight, enabling the identification of emerging trends, technologies, socio-economic factors, and uncertainties (Sutherland and Woodroof, 2009). This proactive approach can significantly enhance decision-making processes, helping policymakers, researchers, and environmental managers anticipate and mitigate potential risks before irreversible damage occurs. In this context, horizon scanning is a crucial tool for identifying and addressing both threats and opportunities in the management and conservation of aquatic ecosystems. Given the ecological and socio-economic importance of Portuguese aquatic ecosystems—as well as the growing challenges they face—it is essential to conduct an exercise that identifies emerging threats and anticipates risks. Using a consensus-building approach, we identified 15 priority topics that could shape the research and management agenda for aquatic ecosystems in Portugal over the next decade.

2. Methodology for identifying and evaluating horizon scan topics

A team of 18 Portuguese researchers working on aquatic sciences was assembled. These researchers represent a broad geographic distribution, spanning from the north to the south of the country, and work across marine, estuarine, and freshwater ecosystems (Fig. 2; Table S1). Their scientific backgrounds are varied, including physical geographers, oceanographers, geomorphologists, biologists, toxicologists, geneticists, ecologists, and conservationists, with a wide range of experience levels, from PhD students to researchers and professors with over 40 years of academic expertise (Table S1). A balanced sex ratio was achieved with 56 % of the authors being females and 44 % males.

Each member was tasked with writing at least two concise synopses (maximum 250 words) highlighting novel or emerging issues they identified as either “challenges” or “opportunities” for Portuguese aquatic ecosystems over the next decade. To encourage a diversity of

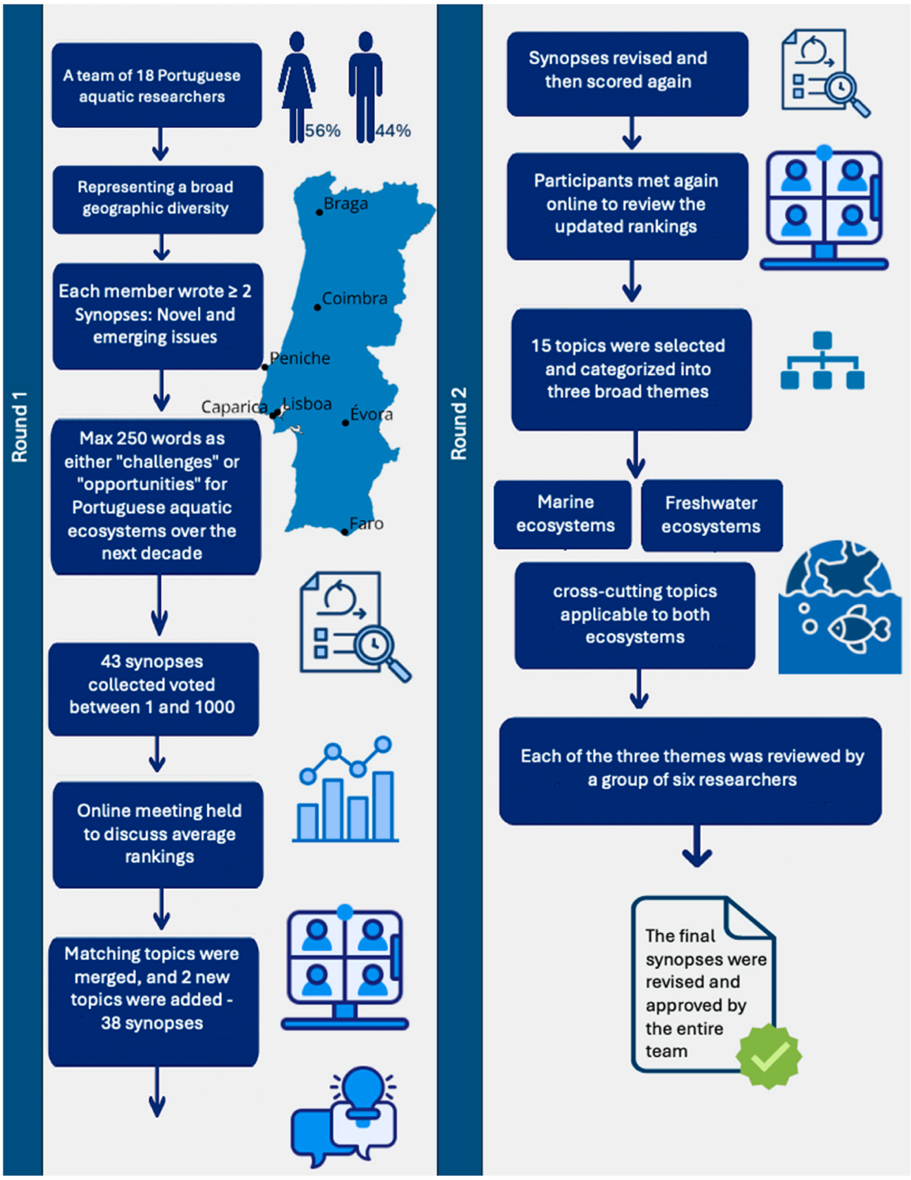

Fig. 2. Graphical overview of the stepwise process used to identify, score and select the 15 horizon topics likely to impact aquatic ecosystems in Portugal during the next decade. Left and right columns show the process for the first and second rounds of scoring, respectively.

ideas, participants were urged to consult their network of researchers and practitioners.

In total, participants submitted 43 synopses. The Delphi technique (Fig. 2) was then applied to identify the most critical topics, following established best practices for anonymity, inclusivity, and iterative voting rounds (details in Sutherland and Burgman, 2015). For this, the received synopses were anonymized, arranged in random order, and distributed to all participants, who scored them between 1 and 1000 based on criteria such as novelty, likelihood of emergence, pervasiveness (scope of influence), and potential impact on Portuguese aquatic ecosystems within the next 10 years. Synopses were then ranked based on their average score (Fig. S1, Table S2). This ranking was shared with participants before the first meeting.

The team convened online in February 2025 to discuss the topics and the average ranking. To prevent bias, discussion guidelines stipulated that the original author of a synopsis should not be among the first two speakers discussing the topic. After this first round of discussion, duplicate topics were merged, and two new topics were added, leading to a revised set of 38 synopses for the second round of voting.

After incorporating new insights from the first meeting, participants re-scored the synopses using the same criteria as described above, and the synopses were again ranked based on their average score (Fig. S1, Table S2). Participants met again online to review the updated rankings in March 2025. Ultimately, 15 topics were selected and grouped into three broad themes encompassing marine ecosystems, freshwater ecosystems, and cross-cutting topics in both ecosystems. A working group with six different researchers was formed for each broad theme to refine and standardize the final selected synopses.

3. Topics identified in marine ecosystems

3.1. *Present and future threats to low-lying sandy coasts*

Low-lying sandy coasts provide vital socioeconomic benefits through ecosystem services such as tourism and recreation (Barbier et al., 2011). However, they are constantly changing due to meteorological, geological, and anthropogenic factors, a trend worsened by climate change (Lansu et al., 2024; Nawarat et al., 2024; Oppenheimer et al., 2019). In Portugal, 45 % of these coasts face long-term erosion (Dias et al., 2024). Projecting the future dynamics of these environments remains one of the most pressing challenges in coastal science (Cooper et al., 2020; Vousdoukas et al., 2020). A key limitation is the lack of a comprehensive understanding of sediment transport processes within and between the lower and upper shoreface (Harley et al., 2022). This uncertainty is further highlighted by the ongoing debate about how beaches will respond to rising sea levels. Bruun (1962) assumes that sea-level rise causes shoreline retreat through sediment transfer from the subaerial beach to the submerged profile. However, this framework has faced significant criticism, with some researchers advocating for onshore sediment transport as an alternative (e.g., Cooper et al., 2020). The knowledge gap in understanding beach profile adaptation can largely be attributed to the scarcity of long-term, high-resolution data covering the entire beach profile, from dunes to the lower shoreface. Furthermore, the absence of integrated seabed mapping that links the evolution of the upper and lower shoreface adds to this challenge. To partially address this challenge, the Portuguese Environmental Agency initiated in 2018 a monitoring program that collects high-resolution data at a few segments of the coast (Pinto et al., 2021). However, the spatial coverage of this program is very limited due to budget constraints. Therefore, high-resolution seabed mapping and satellite-based shoreline monitoring could help bridge these gaps by revealing sediment dynamics across different depths. Achieving this requires a holistic approach that integrates two traditionally separate perspectives: studying the beach profile both from the shoreline and from deeper waters.

3.2. *Impacts of the green energy transition on marine ecosystems*

In the effort to reduce greenhouse gas emissions, transitioning to renewable energy sources has been recognized as a crucial strategy for combating climate change (Xiao, 2025). However, this transition may have severe impacts on marine ecosystems, compromising their conservation and sustainable exploitation (Martínez et al., 2021). Offshore wind energy has emerged as a crucial component of global renewable energy (Díaz and Guedes Soares, 2020). In Portugal, the Council of Ministers Resolution 19/2025, approved the Allocation Plan for Offshore Renewable Energy (PAER) to promote the installation of 2 GW of offshore renewable energy capacity by 2030. National resolutions stress the need to ensure the compatibility of the implementation and exploration of this activity with sustainable marine environments, as well as the assessment of short and long-term environmental impacts (Christiansen et al., 2022; Akhtar et al., 2021). On the other hand, deep-sea mining has been proposed to boost supplies of minerals used to produce clean energy technologies (Vivoda, 2024). The most attractive mineral deposits are on the ocean floor in international waters, regulated by the International Seabed Authority (ISA). Yet, exploitation is conditioned by the approval of rules to regulate deep-sea mining based on scientific evidence, in turn largely limited by the significant scientific gaps regarding deep-sea ecosystems. Portugal made a historic move, becoming the first country to impose a moratorium on deep-sea mining in its waters until at least 2050 (Decreto Lei nr. 36/2025, 31st of March). Therefore, there is a critical need to explore and expand our understanding of this environment (Koschinsky et al., 2018) to better assess the potential impacts of future mining activities in Portugal.

3.3. *Hidden threat of pathogens on floating ocean debris*

The proliferation of floating marine plastic debris raises concerns regarding its role in spreading pathogens (Beloe et al., 2022). This situation fosters the development of the "plastisphere", a microbial community uniquely adapted to colonizing floating plastic (Lacerda et al., 2024). This debris provides surfaces and "shelter" for microbial colonization, becoming hotspots for pathogens and aiding their propagation across ecosystems (Zettler et al., 2013; Amaral-Zettler et al., 2020). Recent studies have identified floating structures as reservoirs for harmful bacteria, viruses, and fungi that can infect marine organisms (e.g., fish, crustaceans; Kutralam-Muniasamy et al., 2024). Investigation focusing on the Mediterranean Sea plastisphere found pathogens such as *Vibrio* species (e.g., *V. campbellii*, *V. alginolyticus*) and viruses like White Spot Syndrome Virus (WSSV), previously linked to devastating economic losses in aquaculture (Lacerda et al., 2024). Human populations dependent on marine resources face heightened exposure risks. Pathogens such as *V. alginolyticus*, linked to seafood contamination, have been identified on microplastic debris collected from European waters, posing direct threats to public health and fisheries sustainability (Keswani et al., 2016). Future research should focus on mapping microbiomes on floating structures in key regions, such as Portugal's coastal waters and the Azores and Madeira archipelagos, to identify high-risk areas and key pathogens. Advanced molecular tools, including environmental DNA (eDNA)-based approaches such as metagenomics and metatranscriptomics, as well as complementary methods like metaproteomics, can provide comprehensive insights into pathogen presence, diversity, activity, and ecological roles. By addressing these challenges, Portugal could lead in safeguarding marine ecosystems while ensuring the sustainability of its marine industries.

3.4. *Algae: A strategic resource for a sustainable future planet*

As primary producers, algae are a virtually limitless resource for addressing global challenges, offering transformative solutions for marine conservation and the development of a sustainable economy (Roy et al., 2022). In addition, kelp forests and calcareous algae habitats can play a significant role in long-term marine carbon storage and climate change mitigation (Filbee-Dexter et al., 2024; Schubert et al., 2024). However, despite this potential, comprehensive habitat mapping and robust carbon assessments are still lacking for temperate regions such as Portugal (Santos et al., 2023). Bridging these gaps is essential for accurately quantifying their role in the global carbon cycle and supporting evidence-based conservation and policy efforts (Filbee-Dexter et al., 2024). With rapid growth rates, high biomass yields, and rich biochemical profiles, algae are increasingly used in biotechnology, sustainable agriculture, and biofuels (Singh and Olsen, 2011; Roy et al., 2022). Algae-derived products—such as biodegradable plastics, biofertilizers, and protein-rich food—contribute to circular economy principles and food security (Araújo et al., 2021; European Union, 2024). Due to the extensive Portuguese EEZ, the ecological and economic potential of algae—restoring marine ecosystems while providing renewable resources—positions them as a strategic asset in meeting global sustainability targets. To ensure these solutions are truly sustainable, commercial applications should prioritize the cultivation of algae rather than wild harvesting of native species, minimizing impacts on natural ecosystems (Duarte et al., 2022). A good example is the work carried out by ALGAplus, which cultivates organic-certified seaweed in land-based facilities as a sustainable alternative to wild harvesting (Buschmann et al., 2017). Therefore, advancing research into their ecological functions and applications is key to unlocking solutions that align economic development with ocean health.

3.5. *Contributing to 30×30 through enhanced size and connectivity of Portugal's Marine Protected Areas*

Marine Protected Areas (MPAs) in Portugal play a vital role in conserving marine biodiversity and supporting fisheries (Abecasis et al., 2017; Timonet and Abecasis, 2020). However, with the global 30×30 conservation target—protecting 30 % of the ocean by 2030—there is an urgent need to assess and enhance the existing network. Until recently, only around 4.5 % of Portugal's EEZ was designated as protected. Recent efforts, including the establishment of the Pedra do Valado Marine Park in 2024 and the approval of a new MPA network in the Azores covering 287,000 km^2 (IUCN, 2024), have significantly expanded this coverage. As of 2024, MPAs now encompass approximately 16.8 % of Portugal's EEZ (World Bank, 2024). Despite this progress, a considerable gap remains to reach the 30 % target by 2030. Achieving this will require not only expanding coverage but also improving the ecological design of MPAs—namely, their size, placement, and connectivity—particularly in the context of the region's dynamic ocean-climate conditions (Abecasis et al., 2017; Timonet and Abecasis, 2020). Both large and small MPAs are critical for marine conservation. Larger MPAs disproportionately contribute to global conservation goals, increase commercial fish density within reserves, and promote spillover benefits to adjacent areas (Claudet et al., 2008; Toonen et al., 2013), while smaller MPAs often support higher overall catch rates and complement the ecological function of larger reserves (Vandeperre et al., 2011). Connectivity between MPAs enhances gene flow, population stability, and ecosystem resilience (Carr et al., 2017), yet many MPA systems currently lack functional connectivity, reducing their overall effectiveness (Assis et al., 2021). In the case of Portugal, creating new MPAs interspersed among existing ones—whether recent (e.g., Pedra do Valado MPA), long-established (e.g., Berlengas MPA), or under other protection status (e.g., Gorringe Bank, Natura2000)—could help address connectivity gaps and enhance ecosystem resilience and biodiversity conservation. This strategy, combined with a comprehensive assessment of the spatial and ecological performance of the MPA network, will be crucial for achieving the 30×30 target and ensuring the long-term sustainability of marine resources within Portugal's dynamic ocean-climate context.

4. Topics identified in freshwater ecosystems

4.1. *Identification of drought refuges for freshwater biodiversity*

Climate change has intensified the frequency and severity of droughts in Portugal, threatening the integrity of freshwater ecosystems and associated biodiversity (Lopes-Lima et al., 2023). In the semi-arid regions of southern Portugal, identifying drought refuges is crucial to ensure the persistence of aquatic species during prolonged hydrological stress (Martelo et al., 2024). These refuges include deep pools, springs, and groundwater-fed river segments that maintain suitable conditions for biodiversity even under extreme drought conditions (Gomes-dos-Santos et al., 2019). By acting as biological reservoirs, these refuges ensure that species have a place to survive and from which to repopulate once favorable conditions return, thus maintaining genetic diversity and supporting ecosystem resilience (Gomes-dos-Santos et al., 2019). The identification and monitoring of these refuges require the integration of ecological and hydrological data, combined with advanced techniques such as remote sensing and spatial modeling (Van Horn et al., 2022), and even citizen science. Recent studies suggest that artificial structures, such as mill dams and small weirs, play a key role in biodiversity conservation by acting as temporary refuges (Deacon et al., 2018; Sousa et al., 2019, 2021). Therefore, there is still uncertainty about the impact of removing these structures, particularly in semi-arid Mediterranean ecosystems. On one hand, they may contribute to habitat fragmentation, but on the other hand, they can help retain water during seasonal droughts. To enhance conservation strategies for drought refuges, it is essential to develop long-term monitoring plans that integrate scientific research, habitat restoration, and water management (Reside et al., 2019). The protection and proper management of these refuges are critical for mitigating biodiversity loss and ensuring the resilience of freshwater ecosystems in Portugal and other regions facing similar challenges.

4.2. *Water highways and their potential ecological and social costs*

Water highways have been proposed as a solution to water scarcity and the uneven distribution of water resources in Portugal (and elsewhere). The idea is not new, but the narrative surrounding the need for a water highway has resurfaced in recent years (Palha et al., 2024). The water highway is being presented as a panacea for the problems caused by recent droughts and water shortages, coupled with the idea that there is excess water in the northern part of the country, while it is scarce in the southern part. This proposal has been primarily supported by the agricultural sector (along with the construction sector), which seeks to expand areas dedicated to irrigated agriculture (Palha et al., 2024). The several variants of the project consist of a transfer system covering the Douro-Tejo-Guadiana river basins up to the Algarve, creating a water highway through the countryside (Palha et al., 2024). This putative system includes a set of pumping stations and canals with a total length of approximately 500 km, which implies a substantial financial investment. Although it is technically ingenious, the implementation of such projects raises significant ecological concerns (Shumilova et al., 2018). For example, the built infrastructures act as barriers for fauna fragmenting terrestrial habitats, while promoting native species translocation and conveying non-native species, parasites, and diseases across basins (Shumilova et al., 2018). The existing water transfer from the Guadiana to the Sado basin has already led to the translocation of the native river blenny (*Salariopsis fluviatilis*) to the Sado basin due to larvae dispersal, which demonstrates an unequivocal risk of ecological impact by these development schemes (Collares-Pereira et al., 2021). In addition, the energy costs associated with pumping and managing these highways can increase greenhouse gas emissions (Shumilova et al., 2018). While water highways can alleviate water scarcity in the south, their implications require careful assessment, not only to understand the minimum amount of water to be retained to maintain ecosystem functioning, but also because the north of the country has been suffering as well the ecological and socio-economic impacts of recent droughts (summers of 2017 and 2022; Sousa et al., 2018; Lopes-Lima et al., 2023) increasing the chances of social and political conflicts.

4.3. *The hidden costs of clean energy: ecological risks of floating solar panels and lithium mining*

Global incentives for the clean energy transition are triggering new research areas and fostering the development of novel technologies for energy production and storage (Hassan et al., 2024). Floating solar photovoltaic systems (FPV) are an innovative technology that integrates solar panels into water bodies, offering several advantages in terms of energy production and land-use efficiency (Kumar et al., 2021). Three FPVs are already in operation in Portuguese reservoirs, and the global installed capacity is expected to grow 22.5 % by 2030 (Greim et al., 2022). Notwithstanding, the ecological impacts on aquatic ecosystems are not yet fully assessed (Benjamins et al., 2024; but see Yang et al., 2024; Oliveira et al., 2024), namely the disruption of aquatic food webs by water shading and the installation of floating and submerged structures that disturb benthic habitats and serve as a colonizable substrate for non-native species (reviewed in Yang et al., 2024). Furthermore, the necessity of storing energy from intermittent sources such as the FPVs has boosted the global demand for lithium (Greim et al., 2020). Portugal holds considerable lithium deposits, and its potential exploration has sparked debate about likely environmental impacts (Blair et al., 2024). These include considerable water abstraction from water bodies and potential chemical runoff, imperiling aquatic life and reducing water quality (Balaram et al., 2024). Therefore, it is urgent to fully understand the impacts of clean energy production and storage on freshwater ecosystems, as careful site selection, environmental monitoring, and adaptive design are crucial to balance the clean energy transition with aquatic ecosystems' health.

4.4. *Managing water quality in reservoirs to prevent extreme biological events*

Reservoirs are increasingly more strategic reserves for water supply, irrigation and food provisioning (Beça et al., 2023). The worldwide number of reservoirs has increased in the last decades as a societal answer to the natural seasonal asymmetry of water availability, further aggravated by extreme drought and heatwave events, which set uncertainties for the future (Rosa and Sangiorgio, 2025). However, these water bodies are subjected to multiple pressures, including runoff from increasing agriculture, ineffective watershed management, and the growing number of species introductions, among others (Anastácio et al., 2019). These pressures have led to more frequent hypertrophy and dystrophy events in reservoirs primarily due to the loss of the buffering capacity to higher nutrient and pollutant inputs from the watersheds (Pinto et al., 2025). Consequently, fish kills or algal blooms may happen, causing a strong societal alarm, particularly in drinking water reservoirs (Brito et al., 2018; Godinho et al., 2019; Feio et al., 2022). Yet, the causes of these extreme die-off events remain poorly understood due to limited knowledge of the underlying biological and chemical processes (Brito et al., 2018). Although much is known about temperate natural lentic systems, this knowledge is not completely transferable to reservoirs due to their different characteristics, such as severe water level fluctuations (Hayes et al., 2017). Therefore, there is an urgent need to understand how reservoirs, as heavily modified water bodies, function from the molecules to the ecosystem, aiming at maintaining a good ecological potential status and the provision of key ecosystem services. To achieve this, investment is needed in automated monitoring systems that provide data to support predictive models focused on extreme biological events. These models will function as early warning systems based on anthropogenic pressures and climatic and geographic conditions. This investment should be expanded to train technical staff and stakeholders to effectively manage reservoirs in a future marked by increasing human water demand and projected water scarcity.

4.5. *The expansion of intensive olive orchards and their potential impacts on freshwater ecosystems*

High global demand for olive oil has been stimulating the expansion of intensive olive (*Olea europaea*) orchards in southern Portugal (Alentejo) over the last 30 years, where they have been replacing mostly rainfed annual crops and traditional rainfed olive orchards, and now cover 85,000 ha (>40 % of total olive orchard area) (Morgado et al., 2022). Management of these intensive orchards (high-density: 401–1500 trees/ha; super-high-density: 1501–2500 trees/ha) includes irrigation, fertilization, pesticide use, and high mechanization levels (Sobreiro et al., 2023). These practices can affect freshwater ecosystems, and research is urgently needed to assess impacts and propose mitigation measures. Impacts may stem from water abstraction for irrigation, which will likely exacerbate water stress in freshwater ecosystems, especially during the dry periods typical of the Mediterranean climate (Godinho et al., 2014; Karaouzas et al., 2018); small streams can, nevertheless, experience increased water availability in summer as a result of irrigation (see Merchán et al., 2013). The massive use of fertilizers and pesticides to sustain high olive production (Sales et al., 2022) may lead to nutrient and chemical runoff, with the potential to increase toxicity and eutrophication, especially in summer when water levels are low and temperature and light incidence are high. Irrigation, limited soil plant cover, and high mechanization facilitate soil erosion (Rodríguez Sousa et al., 2023), which may cause sediment input to nearby freshwaters, particularly if the riparian vegetation has been removed, further degrading water quality and homogenizing benthic habitats (Matono et al., 2013). Nevertheless, recent studies comparing olive orchard types on soil erosion and impacts on freshwater ecosystems have shown that more important than tree density are the management practices (Matono et al., 2013), suggesting that there is room for making intensive olive orchards more environmentally sustainable. These practices may include efficient water use, reduced chemical inputs, mitigation of soil erosion, and maintenance of native riparian vegetation (Sobreiro et al., 2023). Although olive orchards are exempt from environmental requirements (Pe'er et al., 2019), strong public concerns about the impacts of intensive olive orchards make research urgent.

5. Cross-cutting topics for both ecosystems

5.1. *Aquatic super-sites for ecological monitoring in Portugal*

In situ conservation occurs within dynamic social-ecological systems, where conservation actions must respond rapidly to environmental changes to enhance the chances of success (Boult, 2023). This is challenging because gaps in ecological monitoring data and delays between monitoring and management decisions mean that many conservation actions are reactive rather than proactive (Margules and Pressey, 2000). This situation may be particularly challenging for countries such as Portugal, where long-term studies are lacking at appropriate spatial and temporal scales. Focusing on ongoing research efforts at a small number of field sites, termed 'super-sites', following Ewers (2024), might open up the opportunity for understanding the complexity of natural environments. These super-sites would serve as an equivalent to a model organism (e.g., *Drosophila melanogaster* and *Danio rerio*): a site that is well-known and could give insight into systems of higher complexity (Ankeny and Leonelli, 2021). The data collected in these super-sites may fuel models that could, in turn, revolutionize our ability to predict the future state of those systems and provide unparalleled insight into how they might be most effectively managed. The integration of eDNA tools (Duarte et al., 2023; Afonso et al., 2024) and artificial intelligence (Olawade et al., 2024) can significantly enhance biodiversity monitoring and ecosystem analysis by providing high-resolution, cost-effective data and improving model accuracy and predictive power. Some marine and freshwater ecosystems already monitored in Portugal (e.g., Sabor River and Minho, Mondego, Tejo, and Mira estuaries; Castellanos et al., 2021) in the aim of Long Term Ecological Research and Portuguese CoastNet research infrastructure networks can be part of these super-sites. Financial, logistical, and technological support should be committed to these super-sites, and cooperation between universities, research groups, disciplines, and stakeholders should be pursued.

5.2. *Innovative solutions for monitoring and removal of emerging pollutants in aquatic systems*

Recent studies and legislation emphasize the pressing need to address emerging pollutants in aquatic systems, including microplastics (MP), per- and polyfluoroalkyl substances (PFAS), and antibiotics, while also drawing increasing attention to antimicrobial resistance in the environment (Gomes, 2025). In Portugal, despite growing awareness, monitoring and mitigation strategies for these pollutants remain limited, particularly in rural areas and smaller municipalities, where centralized infrastructure is lacking (Silva et al., 2021). Studies in the Minho, Lima, Douro, and Tejo Rivers have revealed the widespread occurrence of persistent and emerging pollutants, highlighting the urgent need for more regionally adapted monitoring strategies (Montes et al., 2023). MP, due to their abundance and prevalence, promote the dispersion of contaminants, posing significant risks to water quality, ecosystems, and public health, thus highlighting the need for innovative solutions for monitoring and removal, particularly in wastewater treatment for reclamation and reuse (Xia et al., 2023). Time-consuming traditional methods for MP monitoring can be replaced by *in situ* sensors (Cocciaro et al., 2023; Abimbola et al., 2024; Penso et al., 2025). A portable, *in situ* sensor employing lab-on-chip technology combined with infrared optoacoustic will enable large-scale deployments for real-time quantification and identification of MP both in water and wastewater (Kuru et al., 2023). On the other hand, advanced treatment technologies, such as cold plasma combined with an AI-driven Decision Support System, seem to be promising approaches to integrate real-time data on both standard and emerging pollutants, to enable precise water quality assessments and guide cost-effective, eco-friendly treatment strategies (Gururani et al., 2021; Velasquez et al., 2024; Gonçalves et al., 2025). The combination of advanced monitoring with transformative treatment technologies, addresses critical gaps in water management in Portugal, offering a comprehensive and scalable pathway to combat antimicrobial resistance, mitigate emerging pollutants, and protect aquatic ecosystems in the context of increasing global water scarcity.

5.3. *Rewilding in Portuguese aquatic ecosystems*

Rewilding is a conservation approach to restore natural processes and biodiversity (Perino et al., 2019). Rewilding focuses on re-establishing ecological functions that have been degraded or lost due to human activities by prioritizing the recovery of keystone species and ecological dynamics (Pereira and Navarro, 2015). However, rewilding has been applied almost exclusively on terrestrial ecosystems, while aquatic realms have been generally ignored (but see Willby et al., 2018). One key strategy for freshwater ecosystems is the removal of physical barriers like dams and levees, which impede natural water flow and disrupt migratory pathways for fish species (Thieme et al., 2023). In Portugal, dam removals and fish passage improvements in the Mondego and Minho Rivers have benefited some native migratory species (Pereira et al., 2017). Wetland rewilding, often achieved through re-flooding drained areas, is another critical focus. This helps sequester carbon, reduce flood risks, and provide habitats for species such as amphibians, waterbirds, and freshwater invertebrates (Mitsch et al., 2013). Reintroducing and promoting recolonization of keystone species, such as beavers, is another hallmark of aquatic rewilding (Willby et al., 2018). These organisms act as ecosystem engineers, and their possible reintroduction can create wetlands through dam-building and increase habitat complexity (Veríssimo and Roseta-Palma, 2023). Similarly, restoring shellfish beds and aquatic vegetation promotes biodiversity and improves water filtration in estuarine and coastal areas (V.H. Oliveira et al., 2024). In the rewilding approach, less charismatic aquatic species—such as fungi, mollusks, crustaceans, and small fish—should not be overlooked, not only for their intrinsic value but also for their broader impact on ecosystems and human society (Corlett, 2016; Mammola et al., 2023). Community involvement and adaptive management are crucial to the success of rewilding projects; by engaging with local stakeholders, sustainable use of aquatic resources, and natural regeneration of aquatic ecosystems could be possible.

5.4. *Cross-ecosystem disease dynamics: The impact of forest pathogens and emerging zoonoses on aquatic ecosystems*

Environmental changes, non-native species, and global trade are driving the spread of diseases across ecosystems, affecting both terrestrial and aquatic environments (Baker et al., 2022). Forest infections and zoonotic diseases in aquatic systems have significant cross-ecosystem effects, impacting biodiversity, ecosystem services, and public health (Okamura and Feist, 2011). Riparian forests regulate stream ecosystems, but the spread of pathogens like *Phytophthora* × *alni*, which causes alder decline, disrupts leaf litter inputs, nutrient cycling, and aquatic food webs (Bjelke et al., 2016; Ferreira et al., 2022). These disturbances can weaken ecosystem resilience and create favorable conditions for opportunistic pathogens (Sokolow et al., 2019). At the same time, emerging zoonotic diseases in aquatic environments pose growing concerns for human health. In Portugal, non-native species such as *Trachemys scripta* (red-eared slider) harbor pathogens like *Salmonella*, while the establishment of *Aedes albopictus* mosquitoes increases the risk of diseases like dengue and Zika (Zé-Zé et al., 2024). In marine systems, bivalve populations are threatened by infectious diseases, affecting biodiversity and fisheries (Pires et al., 2022), including leukemia-like cancers (Metzger et al., 2015, 2016). The convergence of forest pathogens, aquatic zoonoses, and marine disease outbreaks highlights the urgent need for a cross-ecosystem approach to disease ecology (Borremans et al., 2019). Future research should explore how climate change, species introductions, and forest change amplify pathogen dynamics, integrating ecological and epidemiological perspectives (Lafferty, 2009). Addressing these challenges is crucial for conservation and public health. Proactive management strategies can help mitigate risks and strengthen ecosystem resilience against emerging infectious diseases.

5.5. *Emerging organic compounds as a multidimensional threat to aquatic ecosystems in Portugal*

Emerging organic compounds, including pharmaceuticals, pesticides, and illicit drugs, represent a growing challenge for aquatic ecosystems worldwide, and Portugal is no exception (Estévez-Danta et al., 2022; Rodrigues et al., 2024). These compounds, often untreated by conventional wastewater treatment systems, accumulate in rivers, estuaries, and coastal areas, disrupting ecological processes and threatening biodiversity (Petrie et al., 2015; Tran et al., 2018). The Tejo, Douro, and Sado river basins are particularly vulnerable, receiving runoff from urban, industrial, and agricultural sources (Duarte et al., 2023). Pharmaceutical pollutants can alter fish behavior, impair microbial communities, and contribute to antimicrobial resistance (Punginelli et al., 2024). Agricultural chemicals, such as glyphosate, have been linked to reduced soil and water health, harming aquatic organisms by disrupting nutrient cycles (Ahuja et al., 2024). Additionally, illicit drugs have been detected in Portuguese aquatic ecosystems (Duarte et al., 2023). Recent studies in transnational river basins and coastal areas of the north of Portugal and Spain reveal the pervasive presence of 52 contaminants of emerging concern, many of which exhibit persistence and mobility (Montes et al., 2023). Even after secondary wastewater treatments, over 60 % of these compounds remain in aquatic ecosystems, with substances reaching concentrations that raise significant ecological concerns. A coordinated research initiative focused on emerging organic compounds should map their distribution in Portuguese water bodies and assess their ecological impacts. Experimental studies should explore combined pollutant effects on biodiversity, while innovative treatments like ozonation, biochar, and membrane bioreactors offer effective mitigation (Schneider et al., 2020). Complementing technological interventions, public policies that promote sustainable agricultural practices and proper drug disposal systems are vital to reduce pollutant inputs at the source (OECD, 2019). Finally, fostering interdisciplinary collaboration between policymakers, scientists, and local communities is crucial to develop and implement effective mitigation strategies.

6. Brief overview of the topics not selected as higher research priorities

Several topics were not included in the top 15 of our horizon scan, primarily because they were considered either lacking novelty or unlikely to play a particularly significant role in Portuguese aquatic ecosystems over the next decade. However, these topics remain crucial and continue to receive substantial research attention. These include: biodiversity monitoring using DNA-based systems such as eDNA and metabarcoding; using drones to assess aquatic biodiversity and support fisheries management; barrier removal to enhance diadromous (and other) fish populations; citizen science initiatives that leverage mobile applications and digital platforms to monitor biodiversity and coastal erosion; use of functional tools as indicators of stream integrity; the need for more quantitative systematic syntheses to provide evidence-based management strategies; research on natural microflora of aquatic organisms across different habitats and subjected to distinct human disturbances to better understand how microbial composition influences resistance to pollutants; the use of filter-feeding organisms as proxies to estimate environmental concentrations of micro- and nanoplastics; loss of ecological knowledge and its potential impact on the conservation and sustainability of natural aquatic resources; the need of more holistic coastal eco-geomorphology assessments that integrate biological factors and sediment supply; the lack of consensus on international agreements about climate change; non-native species management, including their role in pollutant transfer across trophic levels; the use of non-native fish species for commercial purposes, and the debate over controlling or utilizing these species; the need for water management transformation in Portugal, particularly in the southern region where current agriculture practices are no longer sustainable; geopolitical risks and energy security; the lack of studies on Portuguese tidal freshwater ecosystems; and the need for legislation and measures to protect and restore urban freshwater ecosystems. In addition to these topics, we also identified emerging areas of interest that may gain importance over longer timescales, such as the future colonization of the ocean through underwater cities and the deep sea as the next frontier of marine biotechnology in Portugal.

7. Conclusion

Both freshwater and marine ecosystems provide essential services that support the Portuguese economy and influence its culture, yet they are facing numerous threats. Some of these threats, such as eutrophication, overexploitation, biological invasions, dams, and tourism, have been studied for decades (Anastácio et al., 2019; Alves et al., 2020; Sousa et al., 2020; Rodriguez-Mozaz et al., 2020; Pimentel de Oliveira and Pitarch-Garrido, 2023). Others are more recent and have been identified through this horizon scanning as emerging concerns that require attention in the coming decade (Fig. 3). While some of the challenges and opportunities identified may be shared by many countries, others—such as the impact of intensive olive oil plantations and drought refuges—seem to be of particular importance for Mediterranean countries.

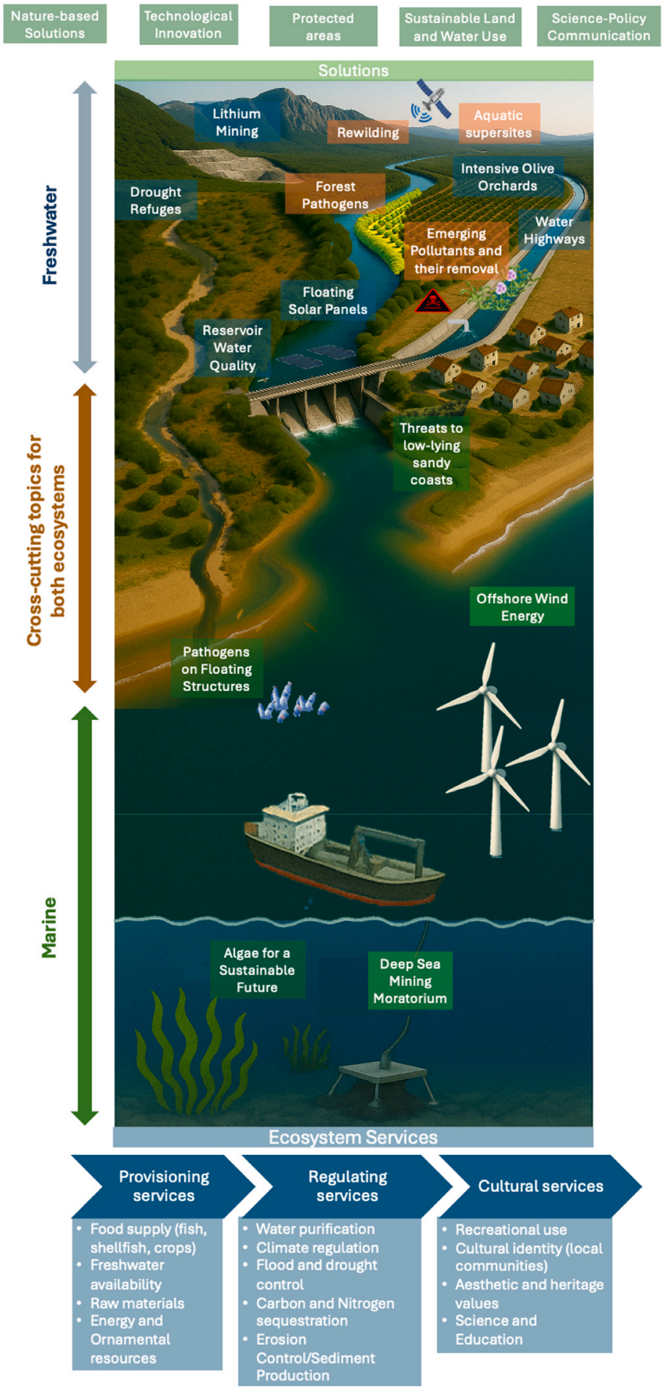

Fig. 3. Schematic overview of emerging challenges and solution pathways categorized by aquatic ecosystems (freshwater, marine, or both) in Portugal and linked to five solution domains: Nature-based Solutions, Technological Innovation, Protected Areas, Sustainable Land and Water Use, and Science-Policy Communication. Ecosystem services are grouped as provisioning, regulating, and cultural services. Note: 'Lithium Mining' and 'Floating Solar Panels' are part of the same topic – 'The hidden costs of clean energy' – though shown in separate locations for clarity.

To address these challenges and opportunities, the country needs to invest significantly more in science and innovation through both public and private funding. Currently, this is not the case. For instance, the Portuguese budget for science has decreased by 10% between 2024 and 2025, and the country is still far from reaching the 3% gross domestic product target outlined, for example, in the recent report of the president of the European Central Bank, Mario Draghi, *The Future of European Competitiveness*. Achieving these investments seems even more challenging in light of the recent calls in Europe for increased spending on defense, which will inevitably have consequences for the overall funding in environmental science and innovation (Sousa et al., 2025).

The 15 topics identified in this horizon scanning provide a roadmap for where Portugal should focus more attention over the next decade, supporting a more proactive rather than reactive approach to management. A marked improvement in the communication of science to the public and stakeholders, making use of citizen science, traditional media, and social media is mandatory. Particularly important is the continuous communication and collaboration among scientists, policymakers, and stakeholders working on aquatic ecosystems, including the important role played by local knowledge that should not be ignored. Because some topics address cross-ecosystem or interdisciplinary issues, close collaboration is needed between professionals working on different ecosystems and disciplines.

Although a few recent horizon scanning exercises have been conducted for aquatic ecosystems (e.g., Herbert-Read et al., 2022), they mainly aimed to cover global problems. While these global exercises are essential, they may lack resolution for specific regions. We advocate for other countries to conduct similar exercises to better understand which challenges and threats are global in nature but require local solutions.

CRediT authorship contribution statement

Ronaldo Sousa: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Verónica Ferreira:** Writing – review & editing, Investigation. **Susana Costas:** Writing – review & editing, Investigation. **Celso Alves:** Writing – review & editing, Investigation. **Pedro Anastácio:** Writing – review & editing, Investigation. **Paula Chaínho:** Writing – review & editing, Investigation. **Pedro A. Costa:** Writing – review & editing, Investigation. **Sofia Duarte:** Writing – review & editing, Investigation. **Maria João Feio:** Writing – review & editing, Investigation. **João N. Franco:** Writing – review & editing, Investigation. **José Gonçalves:** Writing – review & editing, Investigation. **Filipe Ribeiro:** Writing – review & editing, Investigation. **Joana I. Robalo:** Writing – review & editing, Investigation. **Rui Rivaes:** Writing – review & editing, Investigation. **Jacqueline Santos:** Writing – review & editing, Investigation. **Janine Silva:** Writing – review & editing, Investigation. **Paula Sobral:** Writing – review & editing, Investigation. **Janeide Padilha:** Writing – review & editing, Investigation.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2025.100876.

Data availability

No data was used for the research described in the article.

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