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Trends in the study and impacts of brine discharge on benthic communities

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ABSTRACT

The increasing global demand for potable water has led to a growing reliance on desalination technologies. However, these processes produce hypersaline brine as a byproduct, which is typically discharged into the marine environment. The ecological consequences of such discharges have become an important area of research, particularly with regard to the protection of sensitive coastal habitats. Among the most affected are benthic communities—organisms living on or near the seabed—which serve as reliable bioindicators due to their sensitivity to environmental change. Despite rising interest in this topic, empirical data on benthic responses to brine exposure remain limited, especially in regions with extensive desalination infrastructure but insufficient ecological monitoring. Benthic fauna are commonly categorized into macrofauna and meiofauna based on size, yet research has predominantly focused on macrofaunal communities. This review synthesizes findings from 100 peer-reviewed scientific articles to assess the effects of brine discharge on benthic abundance, species richness, and diversity. The analysis reveals that while both macrofauna and meiofauna generally exhibit reduced abundance in response to brine exposure, their species richness and diversity often increase, possibly due to shifts in community composition favouring more tolerant taxa. Furthermore, the spatial extent of these ecological impacts correlates with the concentration of discharged brine. To substantiate these patterns and address existing knowledge gaps, particularly concerning meiofauna, further site-specific studies and enhanced long-term monitoring are essential. These efforts will be critical for improving our understanding of brine-induced stress on marine ecosystems and for guiding the development of more sustainable desalination practices.

1. Introduction

Coastal environments have played a crucial role in human development but are now experiencing the consequences of rapid expansion (Lazarus et al., 2016). Human-induced stressors, including ocean warming, acidification, and resource exploitation, pose significant threats to these ecosystems (Küpper and Kamenos, 2018). Among the exploited resources, seawater is now a key target, and the infrastructure associated with its use endangers coastal biodiversity and ecosystem functioning (Halpern et al., 2015; Suebsombut et al., 2017).

Desalination has become an increasingly important method for providing clean water to over 1 billion people who lack safe access (Jones et al., 2019), particularly in arid and water-scarce regions. However, its sustainability remains contested due to significant environmental concerns, including brine discharge impacts on marine ecosystems—as highlighted in this review—as well as the high energy demands and associated carbon footprint of many desalination technologies (Elimelech and Phillip, 2011; Shemer and Semiat, 2017). With a global production of 95 million m^3/day (Eke et al., 2020), desalination is projected to expand further, particularly in water-stressed regions, such as the southern countries of the Northern Hemisphere (Allam et al., 2003; Al-Agha and Mortaja, 2005). However, despite its benefits, desalination has the potential to negatively impact coastal ecosystems, mainly through waste discharge (Miri and Chouikhi, 2005; Mauguin and Corsin, 2005; Panagopoulos and Haralambous, 2020; Xevgenos et al., 2021). During desalination, hypersaline brine is produced and released into the marine environment. This brine is a concentrated salt solution (primarily NaCl) with high salinity levels ranging from 70 to 90 PSU (Younos, 2005; Del-Pilar-Ruso et al., 2007; Roberts et al., 2010). Additionally, it contains various chemicals, including coagulants, antiscalants, and heavy metals introduced during the desalination process (Fritzmann et al., 2007; Roberts et al., 2010). To enhance dilution before discharge, brine is often mixed with heated cooling water from nearby power plants. This process can substantially increase the temperature of the combined effluent—sometimes by more than 5 to 7 °C above ambient seawater—thereby intensifying thermal stress on marine

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ecosystems (Missimer et al., 2015; Petersen et al., 2018). As brine is denser than seawater, it tends to sink and spread along the seabed, following bathymetric contours over long distances unless properly dispersed using diffuser systems (Einav et al., 2002; Fernández-Torquemada and Sánchez-Lizaso, 2005; Bleninger and Jirka, 2008; Voutchkov, 2011). This persistent accumulation of brine can significantly reduce the abundance, species richness, and overall diversity of benthic macrofauna and meiofauna, disrupting sediment communities and altering ecological balance in affected areas (del Pilar-Ruso et al., 2008; Riera et al., 2013).

The abrupt changes in temperature, salinity, dissolved oxygen, and the presence of heavy metals, hydrocarbons, and industrial chemicals can severely impact marine organisms near desalination plant outfalls (Crockett, 1997; Saeed et al., 1999; Miri and Chouikhi, 2005; Roberts et al., 2010). The severity of these effects often depends on outfall distance and plant production capacity (Bianchelli et al., 2022). Benthic habitats, which host high biodiversity across multiple trophic levels (Lubinevsky et al., 2017), are particularly vulnerable to brine exposure. Studies near desalination outfalls report significant declines in benthic macrofaunal abundance and biodiversity, indicating the sensitivity of these communities (Riera et al., 2012; Naser, 2013). Sensitive taxa, such as some Amphipoda and Polychaeta families, often decline, while more tolerant groups, such as Nematoda and Oligochaeta, become dominant (Del-Pilar-Ruso et al., 2007, 2015). Brine discharge can also alter primary productivity in sediments, affecting the availability and biochemical composition of organic matter for benthic organisms (Belkin et al., 2018; Bianchelli et al., 2022). Meiofauna is similarly impacted (Riera et al., 2011; Bianchelli et al., 2022), with studies showing substantial reductions in meiofaunal abundance and biodiversity (Nabavi et al., 2013; Chang, 2015; Frank et al., 2019). However, in certain cases, brine exposure has been linked to increased species richness and diversity, likely due to the creation of novel environmental niches and reduced competition following the decline of sensitive species (del Pilar-Ruso et al., 2008). These conditions can facilitate opportunistic colonization by a wider array of stress-tolerant taxa, temporarily boosting diversity metrics despite overall ecological degradation. Higher brine concentrations are generally associated with more severe biological effects and greater spatial impact, often extending tens to hundreds of meters from the outfall source (Fernández-Torquemada et al., 2009). Conversely, lower concentration plumes tend to result in more localized effects, with a steeper decline in impact intensity with distance, particularly when effective diffuser systems are in place (Roberts et al., 2010; Bianchelli et al., 2022).

To better understand the ecological consequences of brine discharge, this paper presents a comprehensive literature review on its effects on benthic communities. Our primary aim is to assess how brine exposure influences benthic macrofauna and meiofauna, identifying key research trends and knowledge gaps in the field. We analyze organismal responses to varying brine concentrations, focusing on changes in abundance, biodiversity, and species composition. Additionally, we examine physicochemical parameters as comparative tools to contextualize these biological impacts, providing a more integrated understanding of brine-induced environmental stress. Macrofauna and meiofauna often exhibit distinct responses to brine exposure, with macrofauna typically showing more immediate and pronounced declines in abundance and diversity due to their larger size and lower tolerance to salinity and contaminant fluctuations. In contrast, meiofauna—though also negatively affected—tend to display more subtle, long-term shifts in community structure, often with an increase in dominance by opportunistic and highly tolerant taxa. These differences underscore the importance of using both groups as complementary indicators of environmental stress in coastal and marine ecosystems.

2. Material and methods

To achieve the research objectives, a desk-based approach was employed, resulting in the selection of 100 relevant scientific articles. These articles focus on the ecological impacts of brine discharge on benthic macrofauna and meiofauna, published between 2004 and 2024, and employ rigorous methodologies such as field studies or laboratory experiments. Older studies were also included to establish a historical timeline of oceanographic research on desalination's environmental impacts, enabling a comparison between earlier methodologies and more recent advancements. Only peer-reviewed articles of seawater desalination were considered to ensure academic credibility. Among the reviewed literature, *in situ* field sampling combined with spatial and temporal gradient analysis has proven particularly effective for detecting changes in community composition, abundance, and diversity across impact zones. Mesocosm experiments and controlled laboratory assays have also been instrumental in isolating the specific physiological and behavioral responses of benthic organisms to hypersaline and chemically enriched brine conditions. Studies employing multivariate statistical tools and geospatial mapping were especially useful in correlating physicochemical parameters with observed biological responses, thereby enhancing the ecological validity of findings.

The collected articles were categorized into four major groups, based on the primary focus of each study. The first two groups include benthic macrofauna (5 cm–5 μm) and meiofauna (500 μm–40 μm) (Fenchel, 1978), as these organism groups are commonly examined in studies assessing the ecological effects of brine discharge. The remaining two groups focus on other biological and physicochemical parameters, providing a comparative framework to better understand brine-induced environmental changes.

Most literature was accessed through Google Scholar, ScienceDirect, ResearchGate, and Web of Science. Key search terms included: *benthic community* (OR *macrobenthos* OR *meiobenthos* OR *meiofauna* OR *fish* OR *juvenile fish* OR *water parameters*) AND *desalination plants* (OR *desalination processes* OR *desalination infrastructure*) AND *coastal environments*.

3. Results

The literature review revealed that macrofauna (39 %, 53 articles) is the most studied group in the context of desalination impacts, accounting for the largest share of research. Meiofauna, while also investigated, received significantly less attention (26 %, 36 articles). Together, studies on benthic organisms dominated the literature (65 %), highlighting their importance as bioindicators of brine discharge effects. Research on physicochemical parameters was also substantial (24 %, 32 articles), whereas pelagic fish received minimal focus (11 %, 15 articles). These findings emphasize a clear research bias toward benthic communities, underscoring the need for broader investigations into other marine organisms affected by desalination practices (Fig. 1).

The scientific literature reviewed was divided into two groups based on research approach: field studies and desk-based research. Field studies analyze specific sites to assess the effects of desalination, while desk-based research relies on secondary data (Heaton, 2008). Field studies dominate the literature, with twice as many publications as desk-based research (90 *vs.* 46). This trend is most evident in benthic fauna studies, where macrofauna research relies heavily on field data (40 field studies *vs.* 13 desk-based). Meiofauna follows a similar pattern (24 *vs.* 12). In contrast, studies on pelagic fish and physicochemical parameters show a more balanced distribution between field and desk-based research.

Although benthic organisms are widely recognized as bioindicators in coastal environments (Adesakin et al., 2023; Costa et al., 2024; Jombodin et al., 2022), their study in the context of desalination impacts is relatively recent. Modern desalination plants have operated since 1928 (Brewster and Buros, 1985; Lattemann et al., 2010), but early studies rarely focused on benthic communities (Chesher, 1975; Mandelli, 1975). A timeline of research (Fig. 2) shows that from 1975 to 1999, only seven studies addressed these impacts. Interest grew in the 2000s, with 27 articles published between 2000 and 2009. The first peak

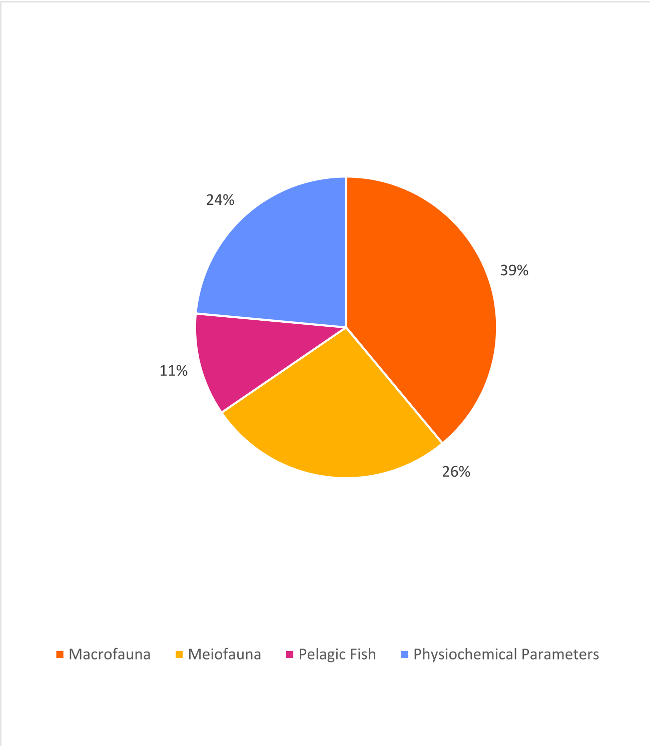

Fig. 1. Percentage of scientific articles by the focused interest group.

occurred in 2005 and 2007, each with eight studies, though some years (2001, 2004) had no publications. The 2010s marked a turning point, with at least three articles published annually and peaks in 2011, 2017, and 2019 (10–12 articles). The current decade continues this trend, with nine studies already published by mid-2024.

Publication trends vary by focus group. Pelagic fish studies remain scarce, with most articles addressing them only as part of broader investigations. Physicochemical parameter studies show steady growth, with 10 publications per decade since 2000, but increasing interest in the 2020s. Benthic macrofauna research dates back to 1975 (Chesher, 1975; Mandelli, 1975), indicating early recognition of their bioindicator role (Navarro-Barranco et al., 2020; Bassey et al., 2022). However, only four studies followed in the next 25 years. Since 2010, at least one macrofauna study has been published annually, reflecting a 300 % increase from the 2000s to the 2010s (7–28 studies). Meiofauna research emerged later, with the first study in 2000 (Yaroslavtseva and Sergeeva, 2000). While its popularity has grown, it remains overshadowed by macrofauna, with only 17 studies in the 2010s compared to 28 for macrofauna.

Desalination has become a vital source of freshwater in water-scarce regions (Williams, 2022). Despite its growing application, comprehensive studies on its environmental impacts remain limited (Moossa et al., 2022). A geographical analysis (Fig. 3) reveals that desalination plants are predominantly located in arid regions, particularly the Persian Gulf, the Levantine Sea, and the Red Sea. This distribution is mirrored in the available research, with 14 studies conducted in the Persian Gulf and 10 in the Levantine Sea (Fig. 4). The Red Sea, despite intensive desalination activity, is represented by only four studies. Similarly, the Alborán Sea and southern Mediterranean are relatively well-studied, with 10 and 4 studies respectively, while the western Mediterranean, though hosting numerous desalination plants, remains underrepresented, with study numbers comparable to less active regions like the Gulf of Mexico. In contrast, Australia shows a distinct pattern—although it has fewer desalination plants, the facilities are high-capacity and have attracted a proportionally higher level of research interest. The Yellow Sea, despite China's considerable desalination capacity (Jones et al., 2019), is the subject of only one study. Notably, no environmental impact studies related to desalination were found for the Indian subcontinent or Southeast Asia.

Brine discharge is the most significant environmental stressor associated with desalination (Almasoudi and Bassam, 2024). To evaluate its ecological effects, this review examined changes in the abundance, species richness, and diversity of benthic organisms in relation to desalination plant capacity (Table 1). Macrofaunal abundance showed a clear negative correlation with increasing plant size, decreasing by 10 % at medium-sized plants (25,000–100,000 m^3/day) and by 79 % at large plants (>100,000 m^3/day). In contrast, meiofaunal abundance did not exhibit a consistent trend, largely due to limited data availability. Interestingly, macrofaunal species richness increased with plant size—by 47 % at medium-sized plants and 36 % at large plants—suggesting a potential shift in community composition. Meiofaunal richness data were lacking for small facilities, but an increase was observed in studies of larger plants. Diversity, as measured by the Shannon–Wiener Index, increased modestly for macrofauna at large-scale facilities, indicating greater ecological complexity in communities exposed to brine discharge. However, due to sparse data, no definitive patterns could be identified for meiofaunal diversity.

The spatial extent of desalination impacts remains understudied. Fig. 5 illustrates the maximum impact range detected across 41 studies. Most impacts on benthic organisms were observed within 1000 m of desalination outfalls, though three cases showed effects beyond 2000 m. Macrofauna impacts were generally confined to 500 m, with some extending beyond 1000 m at medium and large desalination plants.

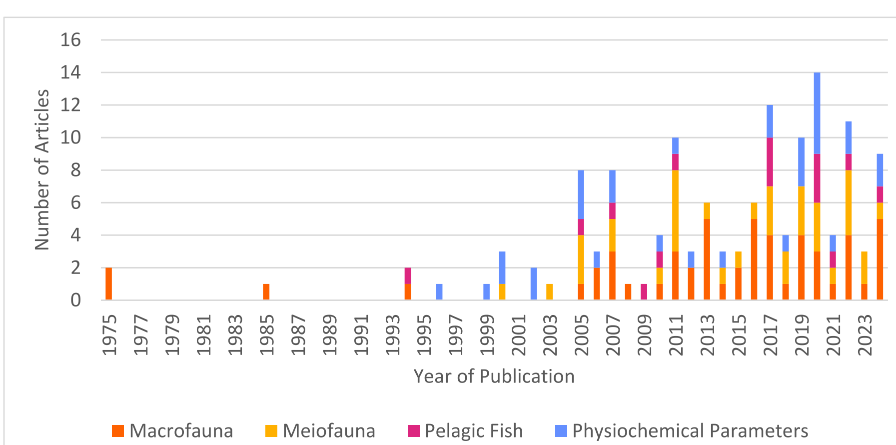

Fig. 2. Timeline of published scientific articles on the effects of desalination practices, categorized by the focused interest group of each scientific article.

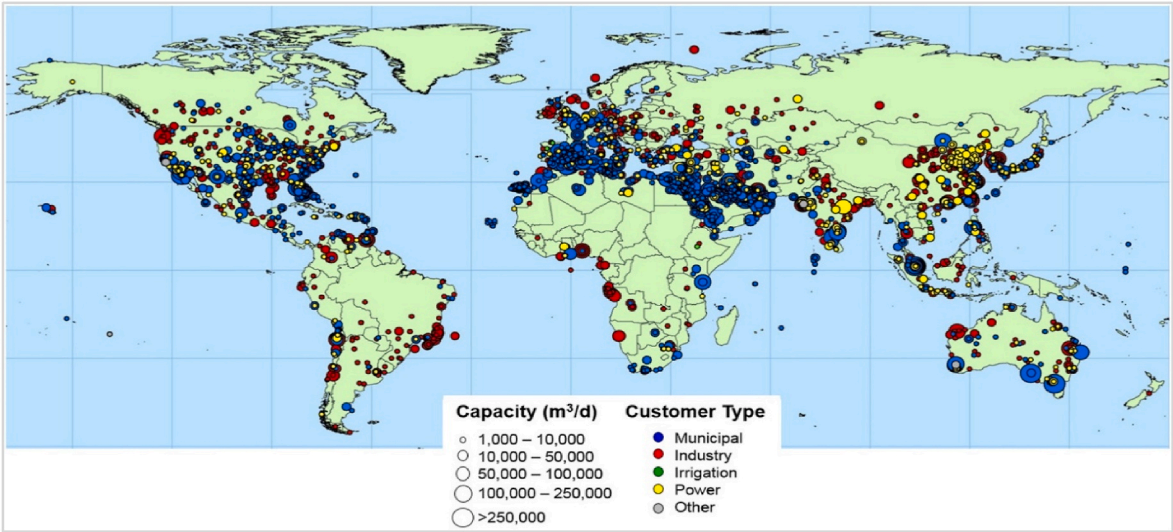

Fig. 3. Map of desalination plant location, capacity, and use (Curto et al., 2021).

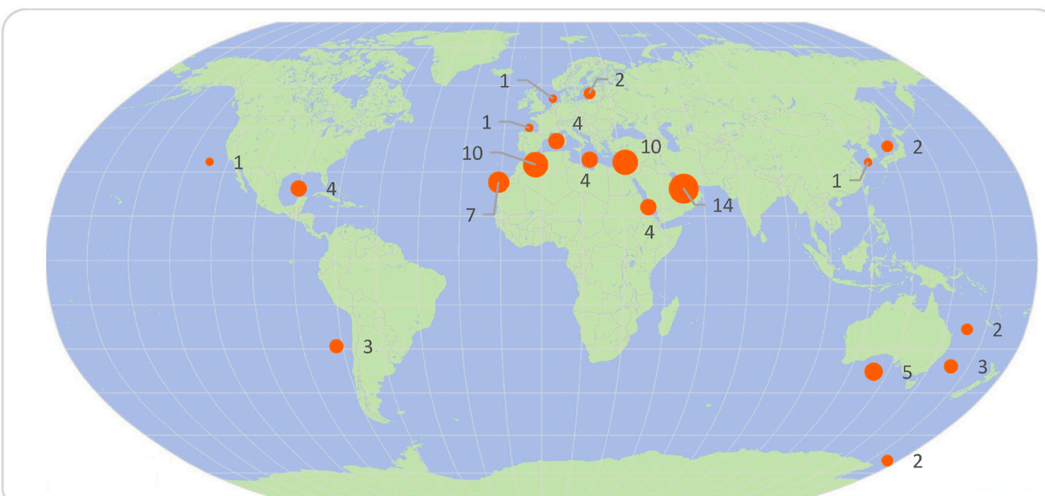

Fig. 4. Map of the locations of published research carried out on the effects of desalination practices on benthic macrofauna and meiofauna, physiochemical parameters and pelagic fish.

Table 1
Mean abundance, species richness and diversity for macrofauna and meiofauna in areas affected by discharges from desalination plants.

		Desalination Plant Capacity (m3/day)		
		1000–25,000	25,000–100,000	>100,000
Abundance (individual/ m2)	Macrofauna	211	190	39
	Meiofauna	1,030[a]	12,000[a]	1888
Species Richness	Macrofauna	7.33	10.75	14.67
	Meiofauna	7[a]	4[a]	11.23
Shannon-Wiener Diversity Index (H′)	Macrofauna	1.17[a]	1.71	1.81
	Meiofauna	–	–	1.87

[a] Low amount of available data may provide inaccurate results.

Meiofauna data were more limited, but impacts followed a similar pattern. Overall, the ecological footprint of desalination outfalls remains uncertain, particularly regarding its long-term and large-scale effects.

There are 15 data points for meiofauna. The impact range for benthic meiofauna follows a pattern similar to macrofauna. In areas with small desalination plants, no impacts are observed beyond 100 m from the outfall. In regions with medium and large desalination plants, meiofauna impacts remain within 800 m, closely aligning with macrofauna trends. Data is more concentrated for desalination plants with capacities exceeding 100,000 m^3/day, with all values remaining near the trendline. Physicochemical parameters show a distinct pattern, with a greater increase in impact range as desalination plant capacity rises. In areas with small desalination plants, no impacts extend beyond 250 m from the outfall. However, in regions with medium-sized plants, impacted waters are detected beyond 1.2 km. This trend continues for larger plants, where impacts reach up to 2 km from the brine outfall. Outliers are present at both extremes, with some studies reporting impacts up to 3.2 km, while others record effects within 100 m.

4. Discussion

The current findings reveal a growing interest in the study of benthic organisms affected by desalination plants and their by-products, while also identifying significant research gaps. Notably, there is a marked

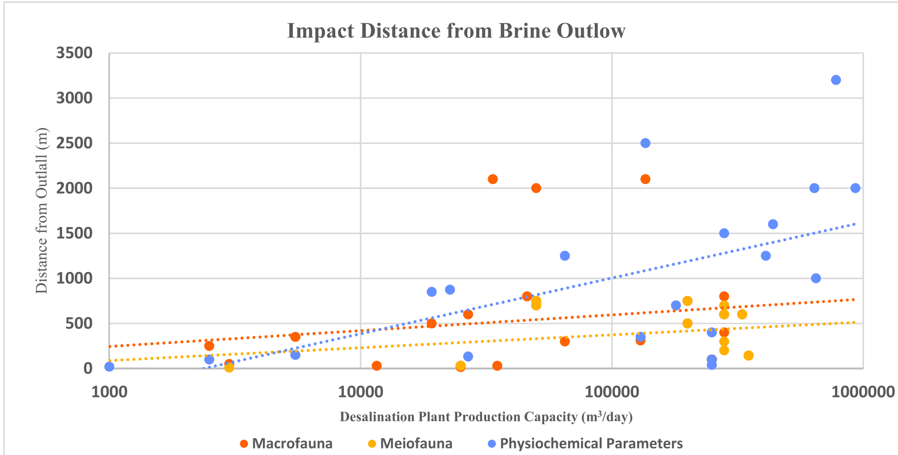

Fig. 5. Impact range of desalination plants on benthic macrofauna, benthic meiofauna and physicochemical parameters.

disparity in the number of studies focusing on benthic macrofauna compared to meiofauna. Of the 53 studies reviewed on macrofauna and 36 on meiofauna, the imbalance highlights a clear area of unmet scientific inquiry. This disproportionate focus on macrofauna is likely due to the relative ease of observing and identifying larger, more conspicuous organisms, in contrast to the smaller and more cryptic meiofauna (Schratzberger and Ingels, 2018). Consequently, macrofauna are often the preferred target of ecological assessments, despite the essential roles meiofauna play in sediment dynamics, trophic interactions, and broader ecosystem functioning. The underrepresentation of meiofaunal studies may obscure the true extent of desalination impacts, potentially leaving sensitive taxa undetected even when macrofaunal responses appear minimal.

There is also a clear distinction between field studies examining the effects of desalination under natural, site-specific conditions and the much smaller number of studies that group results to establish broader standards. This bias towards field studies is understandable, as such research generally provides higher accuracy due to the specific local conditions. However, this focus on localized studies limits the ability to draw generalized conclusions across different geographic regions. Desalination plants tend to be sited in similar locations—outside environmentally sensitive zones, near clean seawater sources, and with suitable brine discharge areas—yet local environmental variables, such as bathymetry, hydrological processes (e.g., currents and waves), sediment composition, and physicochemical parameters, can vary significantly between regions (Tsiourtis, 2008). This geographical variability complicates comparisons of results, as conditions in regions like the Red Sea may not be directly comparable to those in the Yellow Sea or North-Eastern Atlantic Ocean. In this context, studies that rely on desk-based research or meta-analyses are valuable. These studies allow for a broader understanding of how desalination practices impact benthic fauna in diverse environmental settings, providing insights that are more useful for managing specific desalination plants and promoting sustainability.

The study of benthic organisms in the context of desalination has increased in recent decades, though this increase has not been evenly distributed worldwide. Desalination plants are predominantly located along the coasts of developed countries, particularly in arid regions (Curto et al., 2021). The highest concentration of these plants is found around the Arabian Peninsula, the Mediterranean Sea, and East Asia (Curto et al., 2021). While these areas see a significant number of studies on benthic organisms, certain regions remain underrepresented. For instance, despite having 20 operational desalination plants along the Saudi Arabian coast as of 2022, with plans for nine more, only four studies have been conducted in the Red Sea (Ayaz et al., 2022). Similarly, the Yellow Sea also lacks sufficient data on benthic communities in these heavily utilized waters. Establishing a network of studies, particularly in the same regions, is critical for effectively protecting benthic organisms and ensuring the health of the entire water column. Benthic organisms are vital bioindicators of environmental health (Frontalini and Coccioni, 2011; Belal, 2019), and monitoring their status is beneficial for both the ecosystems and the desalination plants, as it promotes more sustainable operations.

Benthic macrofauna and meiofauna, although vastly diverse, often exhibit similar responses to environmental changes. These two groups share the same habitat and can thus be compared in terms of their responses to environmental inputs, including the effects of brine discharge. While brine impacts the population dynamics of these communities, the effects are not always negative. As seen in Table 1, some parameters show positive outcomes, with increases in species richness and diversity observed in both groups as brine levels rise. However, the abundance of macrofauna tends to decrease with direct brine exposure. This increase in diversity could be explained by the colonization of resistant species as more sensitive organisms lose their suitable habitats (Fernández-Torquemada et al., 2019). The increase in diversity in areas with significant desalination activity may also be attributed to the effective implementation of brine diffusion methods. Increasing the diffusion speed of brine as it enters the environment reduces the impacts, such as temperature and salinity changes, by dispersing the brine more efficiently (Ahmed and Anwar, 2012). Desalination plants with larger production capacities prioritize sustainable brine treatment due to the greater volume of brine produced, which would otherwise have more pronounced environmental impacts if released without mitigation (Jones et al., 2019). Plants with lower production capacities, however, may prioritize diffusion less. These factors, among others, help explain the contrasting trends in the effects of brine on diversity and abundance, but more research is necessary to clarify these patterns in benthic populations.

Although research has focused on the response of benthic organisms to brine discharge, the extent of these effects remains poorly described. Of the studies reviewed, 41 % did not report on the spatial range of brine’s impacts. Many studies provide data only from a single location, typically near the brine outfall, which limits the ability to understand how brine impacts extend over larger areas. By comparing these data to control sites, researchers can identify the effects near brine outfalls, but the distance over which these impacts remain significant is still unclear.

The similar sensitivity of benthic macrofauna and meiofauna to brine discharge is evident in the trends observed in the data. The slight difference between the two groups may be attributed to a few outliers in the macrofauna data. Since these two groups inhabit the same environments, it is reasonable to expect similar responses to changes in environmental conditions. The distinction between the organisms’ responses and the physicochemical parameters of the environment is also notable. For example, brine tends to travel greater distances at lower depths, suggesting that hydrological processes and topography play significant roles in its distribution. The production capacity of a desalination plant and the amount of brine discharged are important factors in determining the extent of environmental impacts, but other variables, such as the effectiveness of brine diffusers and the physical conditions of the discharge site, also heavily influence how brine disperses (Bianchelli et al., 2022).

Recent research has increasingly applied molecular tools to better understand the ecological impacts of brine discharge from desalination plants. Grammatiki et al. (2025a) employed eDNA metabarcoding in a seasonal monitoring survey at the Larnaca and Dhekelia SWRO outfalls in Cyprus, revealing elevated benthic diversity near discharge sites, particularly among disturbance-tolerant taxa such as Capitellidae and Cirratulidae. A complementary study (Grammatiki et al., 2025b) focused on diatom communities, showing significant spatial and temporal variation linked to organic enrichment and altered sediment conditions. The combined use of microscopy and metabarcoding provided a more comprehensive assessment, revealing fine-scale spatial patterns and seasonal shifts in diversity, while also demonstrating the value of genetic approaches in detecting subtle community changes often missed by conventional monitoring. Complementing this, Tsioli et al. (2022) and Malandrakis et al. (2017) investigated gene expression changes in *Posidonia oceanica* exposed to hypersaline effluents, uncovering physiological stress responses that provide early warning signs of ecosystem disturbance. These molecular insights enrich our understanding of brine impacts by linking biodiversity changes to underlying biological mechanisms. Additional recent studies have further documented new invertebrate species and records associated with Mediterranean desalination outfalls, highlighting the need for continued biodiversity monitoring in these environments (Stępień et al., 2024; Garcia Gomez et al., 2024; Rousou et al., 2023; Hasan et al., 2023).

Despite recent advances in molecular monitoring and increased documentation of biodiversity near desalination outfalls, the current knowledge based on benthic organisms' responses to brine discharge remains uneven. In particular, data on meiofaunal diversity and species richness are still limited, making it challenging to detect consistent trends or draw robust comparisons between the responses of macrofauna and meiofauna. Given the important role of meiofauna as sensitive bioindicators of environmental change, this knowledge gap underscores the need for targeted studies that address their ecological responses more systematically (see Belal, 2019; Riera et al., 2011). A more comprehensive understanding of their population dynamics and how they are affected by brine is crucial. Further research is needed to explore the spatial extent of these effects and to assess how mitigation technologies can alleviate brine-related impacts, ultimately providing a more accurate picture of the environmental and ecological consequences of desalination practices.

5. Conclusions

The study impacts of desalination on the benthic environment has seen a positive trend, with increased interest since the early 21st century, peaking in 2022. While macrofauna remains the most studied group, meiofauna has recently garnered more attention, though both groups still lack sufficient research. The spatial distribution of studies largely mirrors the locations of desalination plants, but some high-density areas remain underexplored, leaving benthic and marine ecosystems vulnerable to brine impacts. Both macrofauna and meiofauna show similar responses to brine, with a decrease in abundance but an increase in diversity and species richness as brine input rises. This could be due to the settlement of resistant species and the use of diffusion techniques. However, knowledge gaps persist, especially concerning the relationship between brine production capacity and its area of impact. More research and investment are needed to address these gaps and establish a clearer understanding of the effects of desalination.

CRediT authorship contribution statement

Juan F. Hernández-Bentancor: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rodrigo Riera:** Writing – review & editing, Supervision, Resources, Project administration, Investigation, Conceptualization.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2025.107281.

Data availability

Data will be made available on request.

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