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Ostracoda (Crustacea) as indicators of anthropogenic impacts – a review

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Abstract

The impact of human activities on aquatic ecosystems has been a growing concern requiring reliable bioindicators for monitoring environmental changes. Ostracods, a group of small crustaceans, have shown great potential in this role due to their sensitivity to various pollutants and environmental conditions. We review all studied responses of Ostracoda to anthropogenic environmental stresses, covering different types of water bodies worldwide. The review is intended to summarize and highlight benefits of ostracods as indicators for potential implementation in water quality and other studies related to human impacts, including palaeo-research. We document the high value of ostracods for indicating anthropogenic pressures on aquatic ecosystems such as nutrients input, pollution by heavy metals, fertilizers, oil spills and even nuclear pollution with steadily increasing publication output since 1969. Most studies focus on eutrophication so far, but results on metalloids, pesticides, and hydrocarbons look very promising for further exploration. We expect future applications in the field of thermal and nuclear pollution as well as microplastic contamination, where almost no information concerning ostracods exists so far. Analytical methods in use involve indicator species approaches, including toxicity tests, association analysis, morphological variability, and shell chemistry with a recent trend of increasing numbers of papers on ecotoxicology.

Key words

Ostracods, aquatic ecology, monitoring, paleoecology, pollution, habitat degradation

1 Introduction

Ostracods are small crustaceans, commonly known as seed or mussel shrimps due to their bivalve calcitic shell, which resembles a clam or mussel. Ostracods are found in various aquatic environments, including freshwater, marine, and brackish water habitats (Griffiths and Holmes, 2000; Boomer and Eisenhauer, 2002; Ikeya et al., 2005). They have a wide distribution and can be found in both shallow and deep-sea environments. The applications of ostracods in scientific research are abundant and diverse (Rodriguez-Lazaro and Ruiz-Muñoz, 2012). They have been used to study many ecological factors such as salinity, temperature, dissolved oxygen, organic matter, and metal concentration (Zhu et al., 2010; Frenzel et al., 2010a, b; Lord et al., 2011; Salel et al., 2016; Schwalb et al., 2018; Pessoa et al., 2020; Barik et al., 2022; Wang et al., 2022a) due to their exceptional preservation and fossilization potential (Matzke-Karasz and Smith, 2022). For palaeo-related studies, specific reconstruction methods were developed, including the Mutual Ostracod Temperature Range (MOTR) developed by Horne (2007), conductivity transfer functions (Mischke et al., 2010, 2014; Alivernini et al., 2018), and stable isotope analysis of ostracod shells (Palacios-Fest, 1994, 1997; Anadón and Gabàs, 2009; Escobar et al., 2010; Horne et al., 2012; Leipe et al., 2014).

The calcitic shell of ostracods is the reason for their high preservation potential, making them excellent proxies in geosciences (Horne et al. 2012). Besides many studies using ostracods as index fossils or proxies through Earth's history there is an especially rich publication record for the Quaternary. This is true for the Holocene as well where several studies have explored the correlation between the periods of historical human impacts as effects of soil erosion, settlement, and other anthropogenic influence in geoarchaeology using ostracods (Deckers and Riehl, 2007; Keatings et al., 2010; Fischer et al., 2011; Rossi et al., 2013; Kulesza, 2024). Furthermore, they can be used for the reconstruction of natural reference conditions as needed for the management and restoration of water bodies.

The high potential for serving as proxies of modern anthropogenic impacts is demonstrated by examples for changes in water quality, pollution levels, and habitat degradation which can be detected through the analysis of ostracod assemblages (Ruiz et al., 2005; Frenzel and Boomer, 2005; Van der Meeren et al., 2010; Ruiz et al., 2013; Quante et al., 2022). Their small size, short life cycle, and ability to produce large numbers of offspring make them particularly suitable for monitoring and assessing anthropogenic impacts. Ostracod shells can serve as tracers of water quality due to their ability to incorporate and retain geochemical elements (Holmes and Chivas, 2002; Frenzel and Boomer, 2005; Ruiz et al., 2013). Changes in the elemental composition of ostracod shells can provide information about variations in water chemistry and pollution levels (Holmes and Chivas, 2002; Boomer et al., 2003; Holmes and De Deckker, 2012; Börner et al., 2013). Freshwater ostracods have been used in ecotoxicological studies to assess the toxicity of water, soil, and sediment (Havel and Talbott, 1995; Faupel et al., 2011; Shokry et al., 2021;

Zawierucha et al., 2022). Their sensitivity to pollutants makes them suitable for monitoring the effects of contaminants on aquatic ecosystems. Morphological changes of ostracod valves, such as noding in *Cyprideis torosa*, can serve as a proxy for salinity, as was proven through field observations and long-term microcosm experiments (van Harten, 2000; Keyser and Aladin, 2004; Frenzel et al. 2012, 2017).

The increasing number of publications on ostracods as indicators of anthropogenic impacts and their high potential in this field are the motivation for the present review paper. It aims to compile the documented responses of ostracods to various anthropogenic impacts, including eutrophication, heavy metals, habitat degradation, hydrological changes, hydrocarbon pollution, fertilizers, and nuclear waste. Based on the available literature we compiled two tables with identified indicator species (sensitive/tolerant), which we hope will help researchers in their future work (see appendix Tab. 1 & 2). We cover a wide range of aquatic environments, spanning from freshwater to deep ocean waters, encompassing lotic and lentic habitats on a global scale. Additionally, we review existing literature on benchmarks, bioassays, and controlled laboratory experiments involving ostracods in numerous studies (electronic appendix Tab. A, B & C).

We hope that our paper will serve as a valuable resource for researchers seeking up-to-date information on ostracods as indicators of anthropogenic pressure, indicating research gaps, as well as contributing to integration of ostracods into water quality management strategies.

2 Materials and methods

We undertook a comprehensive global review of scientific literature concerning ostracods as indicators of human-induced activities, following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines (see Page et al., 2020). This method aims to ensure transparent reporting of the review’s rationale, methodology, and findings. Utilizing Web of Science, Scopus and Google Scholar databases, we conducted a thorough search using specific keywords related to ostracods (including ostracods, ostracod, ostracode, Ostracoda) and various anthropogenic influences on water quality, including: eutrophication, heavy metals, pollution, anthropogenic influence/effect, organic pollution, eutrophication, fertilizer, pesticide, Ostracodtoxkit, ecotoxicology, toxic, toxicity, bioindicator, sentinel, salinization, degradation, alteration, invasive species, pollution, nuclear pollution, hydrocarbon, oil spills, POPs, persistent organic pollutant, farming, agriculture, industrial wastes, waste, sewage or specific ecological methods like experiments and microcosms. The queries were defined for each platform (Web of Science, Scopus, Google Scholar) and in Web of Science and Scopus we could additionally use a combination of Boolean operators (AND, OR, NOT) and wildcards (*) together with key words (such as pollution, contamination and all mentioned above), which aids to find all publications with these terms. Wildcards help to find all versions of the term (e.g., "Ostracoda" vs. "ostracods"). Literature quoted in relevant papers served as reference for further search. Our review is mainly confined to articles published in indexed journals up to April 1, 2024, with newer references incorporated only in response to reviewers' comments.

To refine our focus on ostracods as environmental sentinels, we established criteria to exclude studies that did not directly address anthropogenically induced organic pollution, lacked data on ostracod distribution, used ostracods on group level only among other groups, or omitted crucial abiotic parameters. Ecotoxicology publications with a use of ostracods were considered without any limitations. Through this process, we identified 190 relevant studies (all can be found in the electronic appendix Tab. A, B & C), from which we extracted key information including publication details, study location, associated abiotic parameters, and species composition, not only by discussing main findings, but also by creating tables with tolerant and sensitive species useful for future studies on ostracods in water quality. This approach enables the synthesis of research findings, highlighting evidence and identifying areas requiring further investigation—essential for constructing theoretical frameworks and conceptual models. We also considered five PhD theses (e.g., Tétart, J., 1975; Kantorek, 1992; Külköylüoğlu, O., 1999; Khanal R., 2013; Anttila, 2019) and one Master thesis (e.g., Taylor, 1992). Standardization of species names was carried out in accordance with the World Register of Marine Species (WoRMS), with respective description years and author attributions assigned to each species.

3 Publication patterns and overviews

The research on ostracods as bioindicators has significantly increased over time (Fig. 1) despite the reduced numbers of active ostracodologists over the past decades. Since the 2000s, there has been a shift in focus from using fossil ostracods solely for palaeoenvironmental reconstructions to tracing anthropogenic pressure through time (using cores) and their application in modern environmental monitoring (mostly from surface sediment) (e.g., Boomer et al., 2003; Schornikov and Zenina, 2014; Hong et al., 2017, 2019, 2021). Fields of study are dominated by research about the impact of organic and heavy metal pollution as well as habitat degradation (Fig. 2). Published studies can be found in the Northern Hemisphere mainly and are quantitatively centred to Europe and Japan (Fig. 3).

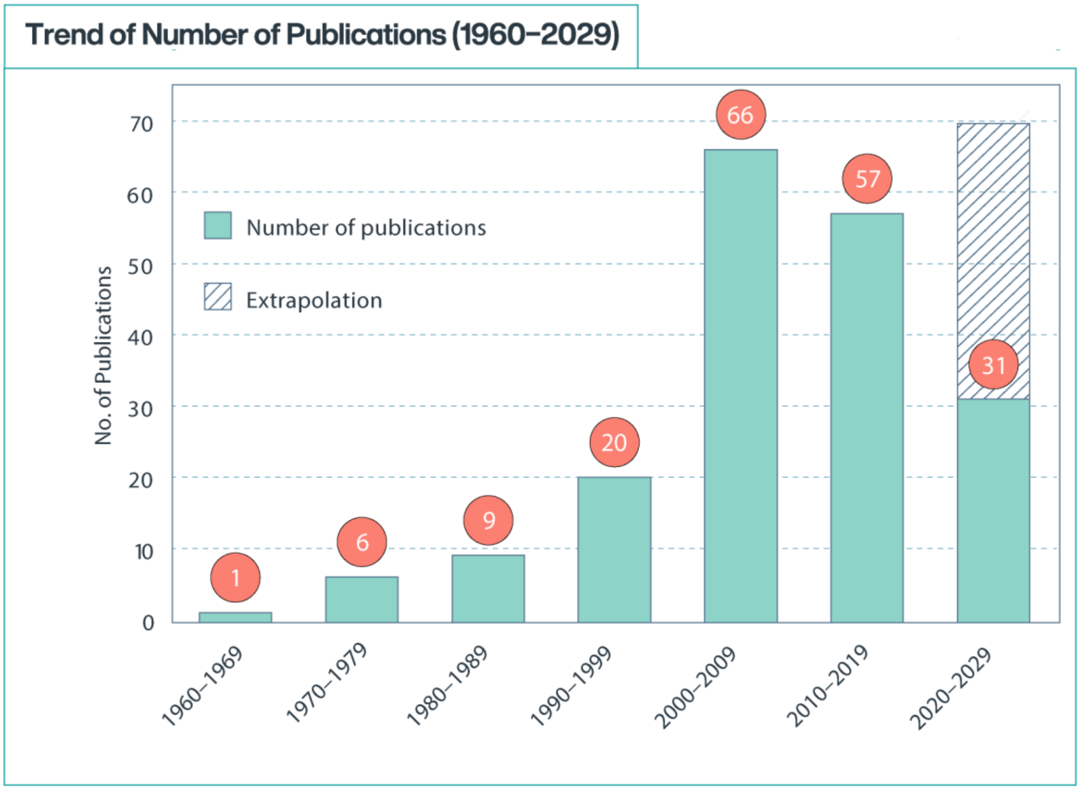

Figure 1: *Overview of studies on ostracods as tracers of anthropogenic impacts over the past decades. Circles show exact number of publications; dashed extrapolation illustrates expected number of publications according to the current trend.*

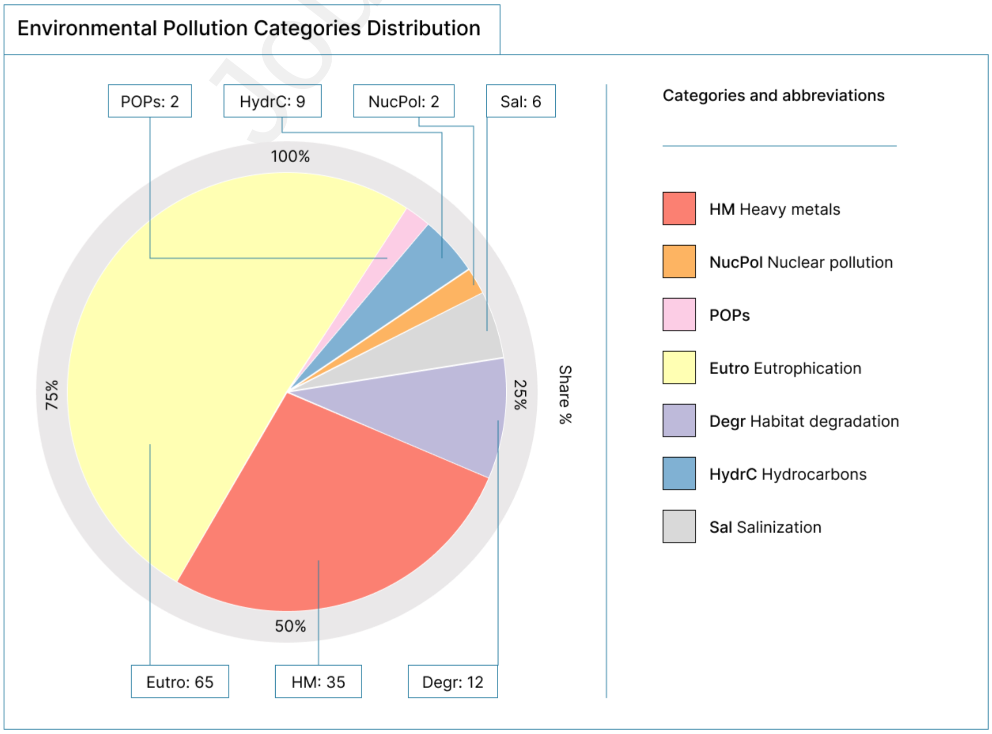

Figure 2: *Papers with different applications of ostracods as bioindicators or tracers of anthropogenic impacts. POPs refer to persistent organic pollutants.*

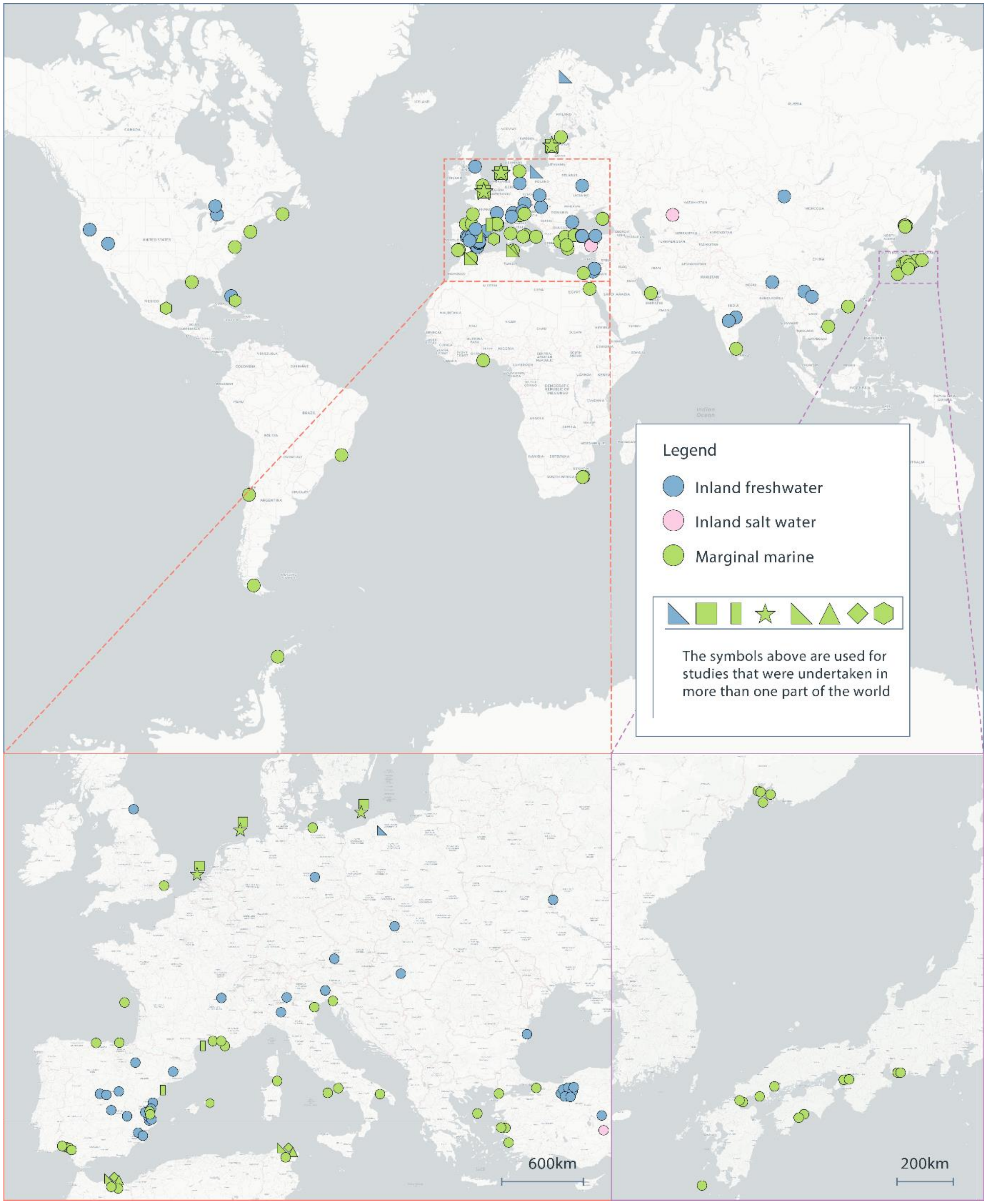

Figure 3: *Geographical overview of studies on ostracods as bioindicators of anthropogenic impacts around the world. Laboratory studies with microcosms and ecotoxicological tests are not included.*

Several review papers across various disciplines have emerged, offering comparisons of meiofaunal responses to pollution across different trophic levels (Dalto and Albuquerque, 2000; Stark et al., 2003; Lenihan et al., 2003). These publications delve into diverse aspects of pollution impacts, shedding light on how meiofauna populations are affected within various ecosystems. Moreover, they serve as crucial resources for understanding the broader implications of anthropogenic disturbances on meiofaunal biodiversity and ecosystem functioning. Typically, such studies examine ostracods as a group, without specifying particular taxa, posing challenges for future implications in water quality research. However, more specific studies consistently demonstrated ostracods' sensitivity to pollution, highlighting their significant potential in water quality monitoring strategies (Alvarez Zarikian et al., 2000; Smith et al., 2003; Külköylüoğlu, 2004; Frenzel and Boomer, 2005; Ruiz et al., 2005; Ruiz et al., 2013).

There are several review papers focusing specifically on pressures, and their impact on ostracods across various environments (Smith et al., 2003, 2018; Frenzel and Boomer, 2005; Ruiz et al., 2005; Yasuhara et al., 2012; Ruiz et al., 2013). However, while researchers have been trying to bring attention to ostracods as environmental sentinels, this field has only begun to grow over the past two decades.

In an earlier study, Smith et al. (2003) discuss ostracods as a tool for environmental assessment, referring as potential “biomonitors” and “sentinels”. Their review is specifically focusing on springs, streams and wetlands, listing indicator species of good quality for all three types of environments.

Another type of overview paper was published by Frenzel and Boomer (2005). They explored the use of ostracods from marginal marine and brackish waters as bioindicators for assessing both modern and Quaternary environmental changes. The paper presents a comprehensive overview of the potential applications of ostracods in ecological monitoring and palaeoenvironmental analyses. It covers topics such as the hydrochemical parameters influencing ostracods, stable isotopes and trace elements in ostracod shells and compares ostracods with other brackish water fossil bioindicators.

The same year, Ruiz et al. (2005) published an overview paper on ostracods as environmental sentinels in marine and brackish-water settings. Their research delved into various aspects, including the benefits of using ostracods, laboratory and field experiments as promising approaches, and their responses to anthropogenic impacts such as oil and heavy metal pollution. Additionally, they explored how ostracods can serve as short-term tracers of industrial, urban, and agricultural waste, and discussed the geochemistry of ostracod carapaces as environmental indicators. The paper provides insights through a few detailed case studies across marine and brackish-water environments. In their subsequent overview paper, Ruiz et al. (2013) explored this time the freshwater realm and the role of freshwater ostracods as bioindicators for assessing water quality and environmental impacts. The paper covers various aspects, such as the influence of physical-chemical properties of water on ostracod development, the impacts of human activities on ostracod diversity and abundances, palaeoenvironmental applications, laboratory experiments including the Ostracodtoxkit^{TM}, and the use of ostracod carapace morphology and geochemistry as indicators of water quality. The main questions addressed are 1) how can ostracods effectively indicate environmental changes, encompassing pollution from urban, industrial, and agricultural origins and 2) how their morphological and geochemical traits can be used to reconstruct historical environmental conditions. The authors also discuss ostracod taxa: which are most sensitive or tolerant to different abiotic factors, such as salinity, temperature, oxygen-dissolved concentrations, pH, water depth, nutrient level and hydraulic conditions.

Yasuhara et al. (2012) overviewed the ecological degradation of marine ecosystems caused by anthropogenic activities around the world, using the reaction of different microfossil groups as a proxy, with focus on benthic Foraminifera and Ostracoda, as well as diatoms and dinoflagellates. Yasuhara et al. (2012) showed that eutrophication and resulting deoxygenation were the main cause of the marine ecological degradation and this typically happened after the industrialization of the affected area. Moreover, the industrialization timing is earlier in "western" countries and later e.g. in Asia. Yasuhara et al. (2012) also see global "acceleration" as well known in Anthropocene studies, also detecting some recovery, but not always.

There are several review papers on the use of nonmarine ostracods (Quante et al., 2022) as well as marine and marginal marine ostracods as proxies in (geo-)archaeology (Mazzini et al., 2022) or in archaeological contexts (Mazzini et al., 2015). All these reviews touch on human influence, for instance on landscape changes by human activity, water use and water works and provenance studies.

Smith et al. (2018) gives an overview on research on ostracods in rice fields, exploring their ecological significance and providing a species checklist. Their comprehensive discussion encompasses various aspects of ostracod ecology in rice fields, including their behavior, feeding habits, predators, and survival strategies. Of particular relevance to our review paper is their examination of the impacts of pesticides and fertilizers on ostracods in rice fields, as well as the discussion on invasive ostracod species in these environments.

As we have seen above, there are already several overview papers on ostracods as indicators of anthropogenic impacts. However, they are either aiming to specific aspects, regions, and settings, or were published more than twenty years ago and thus cannot cover most studies including more recent observations and new approaches as intended by the present review.

4. Impact-specific reaction of Ostracods

We discuss different pollutants and environmental pressures on aquatic systems and Ostracod-specific known responses, covering inland, groundwater, coastal waters and deep sea. We also mention laboratory *ex-situ* experiments, to show known sensitivity of Ostracods, highlighting their absolute potential for future water quality studies.

4.1 Eutrophication

The extensive livestock and fish farming, domestic waste sewage, and use of fertilizers are causing excessive loads of nutrients in water bodies, promoting eutrophication. Sooner or later, it causes oxygen depletion which will change the structure of biocoenoses. Furthermore, eutrophication can cause algal blooms which can trigger red tides with release of toxins accumulating in organisms and causing poisoning. There are only limited studies on effects of organic enrichment on deep-sea ostracods (Yasuhara et al., 2012, 2025). It is still unknown which are the impacts of anthropogenic organic enrichments on deep sea ostracods, while it is proven that eutrophication-induced deoxygenation often causes ostracod defaunation in marginal marine environments (e.g., Yasuhara et al., 2007; Yasuhara and Yamazaki, 2005).

There are three approaches to study the reflection of eutrophication in ostracods, focusing on ostracod associations: changes in species composition of ostracod communities in response to nutrient enrichment, shifts in the abundance and diversity of particular species as a result of altered water quality, and the use of ecotoxicological studies to assess the impacts of eutrophication through mortality rates or developmental disruptions in cultured ostracods.

Across different studies successive effects of organic pollution on ostracods were found: In the first stage, with minimal organic pollution, the whole aquatic ecosystem may benefit and improve its productivity, particularly if natural nutrient concentration was very low. Abundances increase with higher nutrition input resulting in higher productivity of the entire ecosystem (see fig. 4: stage 2) (Yasuhara et al. 2007; Irizuki et al. 2011; Schornikov et al. 2014). If the organic loads increase more, the amount of dissolved oxygen decreases, extinguishing oxygen-sensitive species (see fig. 4: stage 3). In most cases ostracod species richness decreases, with increase of number of individuals of the tolerant species or a monospecific population (Bodergat et al. 1998; Eagar 1998, 1999, 2000; Yasuhara et al. 2003; Ruiz et al. 2006b; Yasuhara et al. 2007; Irizuki et al. 2008, 2015, 2022; Pieri et al., 2009, 2012) or resulting in total lack of ostracods in the worst case (Ruiz et al. 2006b). If the pollution increases even more, the level of dissolved oxygen will dramatically decrease or drop down to zero (see fig. 4: stage 4). In this stage of pollution, the ecosystem will be severely damaged as demonstrated in Osaka Bay (Japan), where Yasuhara and Yamazaki (2005) found an abrupt decline in ostracod abundances after Japan's industrialization at ~1900 and very low abundance during the maximum pollution periods in Japan ~1970s and onward.

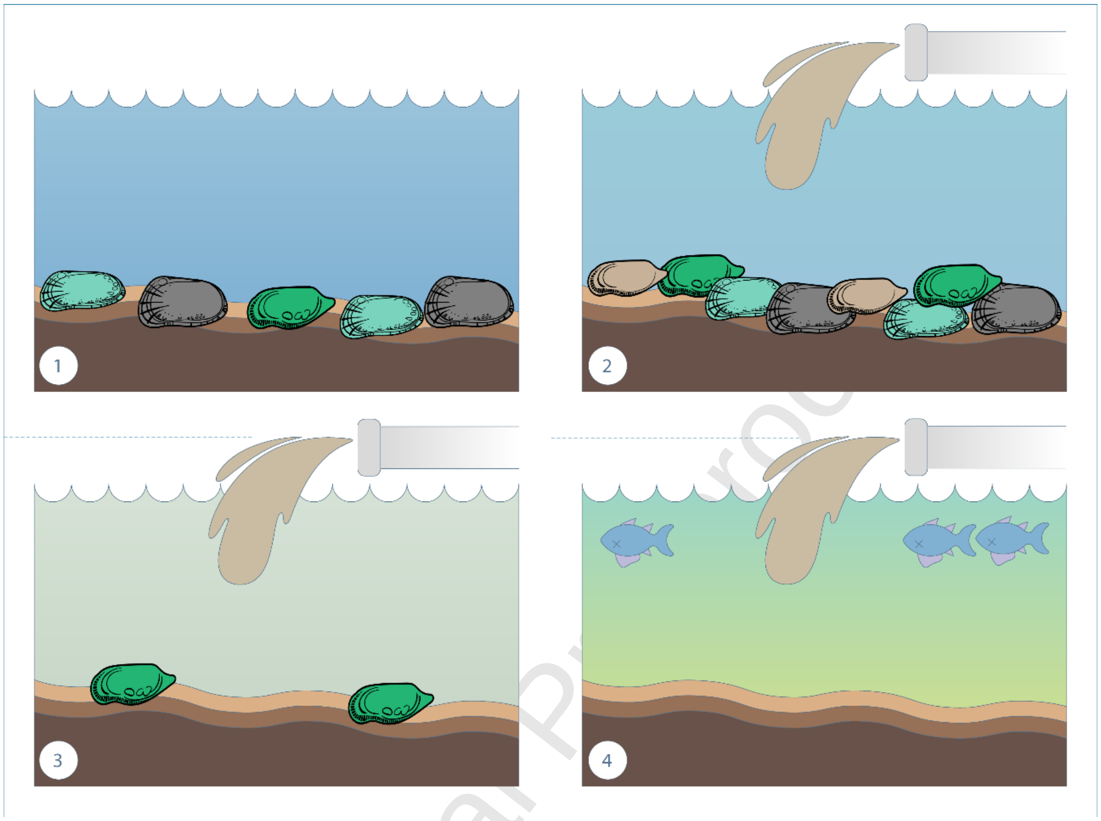

Figure 4: *Stages of pollution levels affecting ostracod associations. 1. Non-affected oligotrophic water body with high diversity and many low tolerance species. 2. Diversity and abundance of ostracods tend to increase with moderate organic input. 3. As eutrophication sets in, there is a subsequent decrease in species richness and only tolerant, opportunistic species survive. 4. Eventually anoxic conditions lead to total mortality and no ostracods or only empty shells can be found (created with BioRender).*

Polluted habitats can create favorable conditions for colonizers with broad tolerance ranges, as ecological changes reduce competition with local species. Many cosmopolitan species exhibit high tolerances to abiotic factors (Külköylüoğlu, 2004, 2005a, b, c; Külköylüoğlu et al., 2007; Dügel et al., 2008; Çapraz et al., 2022), suggesting that increasing pollution levels could benefit them to some extent. Therefore, a proportional relationship between the abundance of opportunistic (often cosmopolitan) species and pollution levels in eutrophicated lakes might be expected, highlighting their potential as indicators of aquatic conditions and as valuable tools for water quality management (Külköylüoğlu et al., 2007; Pokrajac et al., 2024). Külköylüoğlu (2005a) identified the deteriorating condition of a lake in Turkey primarily attributed to organic pollution and eutrophication from two polluted creeks, which disproportionately affect the phenology of native or sensitive species over opportunistic or cosmopolitan ones, contributing to the increased relative abundance of cosmopolitan ostracods and invasive zebra mussels (*Dreissena polymorpha*). The dominance of opportunistic cosmopolitan ostracod species showed resilience to environmental changes in the Yumrukaya reedbeds. Alongside the overall low diversity of ostracods, it suggests diminished water quality (Külköylüoğlu, 2005b).

Agriculture can significantly impact the biodiversity of ostracods. The expansion of agriculture and the intensification of farming practices, such as the use of fertilizers and pesticides, can lead to increased pollution of water and soil. This pollution can alter the quality of water bodies where ostracods live, thereby affecting their survival and diversity. Moreover, agricultural wastes and other by-products can also influence the water quality. Studies on ostracods as indicators of water quality and ecological health reveal several common trends across different regions (see Fig. 5). Among them is a high number of studies from Spain (Mezquita et al. 1999a, b; Poquet et al., 2008; Castillo-Escrivà et al., 2016) where correlation between ostracod communities and organic enrichment was found. Valls et al. (2016) observed similar trends in the Marjal dels Moros wetland, suggesting that agriculture might play a role in shaping spatial variations within the area and could potentially contribute to the differences between the taphocoenoses and biocoenoses observed there.

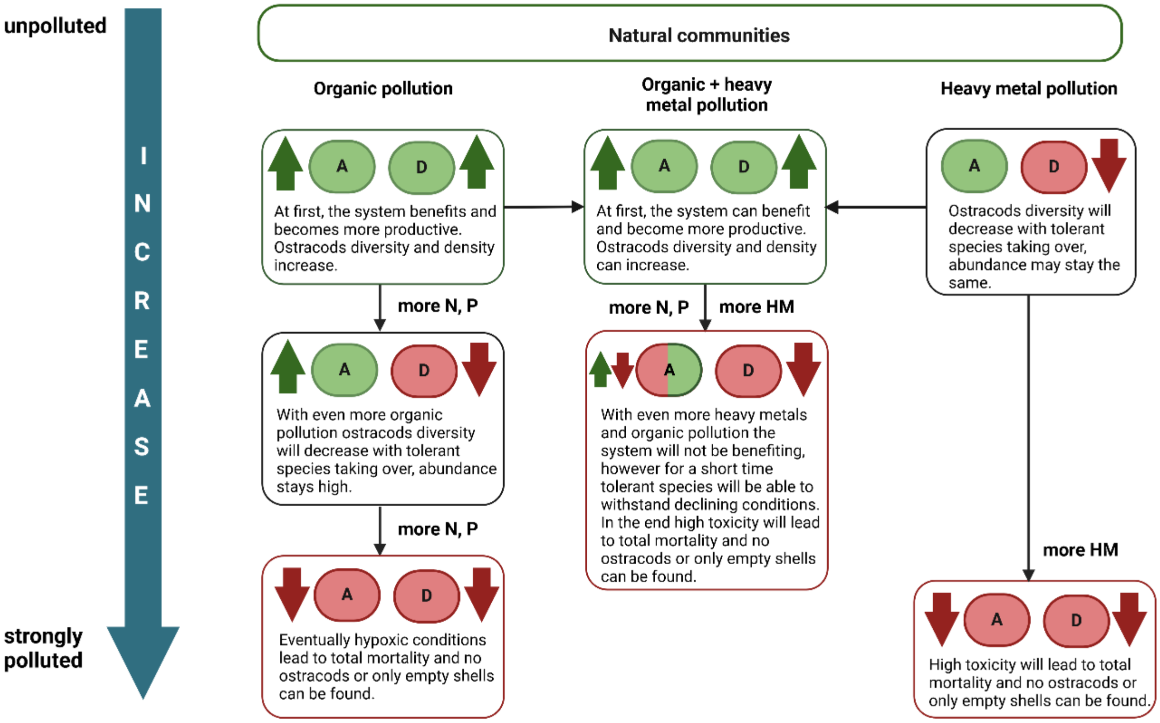

Figure 5: *Schematic response of ostracod associations from marine, brackish and freshwater to organic pollution, heavy metal contamination and their combined effects. Green symbols stand for high, red ones for low values of abundance (A) and diversity (D). Arrows show trends. HM – heavy metals, N – nitrogen, P – phosphorus. Created with BioRender.*

On the other hand, Allen and Dodson (2011) found a lower species richness of ostracods associated with a lower level of agriculture, while a more diverse landscape led to regions with a higher richness of ostracods. The biodiversity of ostracods was not only impacted by the land uses around, but also by the spread of invasive aquatic plants such as *Myriophyllum spicatum* and *Potamogeton crispus*, which can displace native plants and decrease habitat complexity. This way, the regression tree analysis of lake sites from the North American Non-marine ostracod database (NANODe) revealed that row-crop agriculture was the primary determinant of biodiversity. Considering these findings, we can assume that moderate organic pollution from agricultural runoff, may have accidentally provided a favorable environment for ostracods to thrive. The fertilizers used in agriculture, while harmful to many microorganisms, could have selectively favored ostracods, thereby enhancing their prominence in these ecosystems. This phenomenon can be attributed to the concept of competitive release, where the reduction or elimination of competing organisms allows a particular taxon to profit. Consequently, being more resilient to these conditions, ostracods could have benefitted from the reduced competition and expanded their populations (see fig. 4: stage 2) (Allen and Dodson, 2011).

Aquaculture is a special case of eutrophication in marginal marine water bodies, and its related eutrophication negatively impacts ostracod populations, significantly declining them, especially right beneath fish cages (Mazzola et al., 1999; Mazzola et al., 2000).

At the same time, examining historical palaeorecords revealed that organic pollution does not consistently result in a decrease in ostracod diversity; sometimes, their effect is limited to only altering the taxonomic composition of the assemblages. One of the commonly used approaches is to combine Foraminifera and Ostracoda together in brackish-marine waters (e.g., Ruiz et al., 2012; Gildeeva et al., 2021; Schmitz et al., 2024). After years of ostracod studies in two north African lagoons (Ruiz et al., 2006a, b), Ruiz et al. (2012) proposed to use both groups as bioindicators of water quality. They suggested these categories for interpretation (Ruiz et al., 2012): (a) significant heavy metal pollution (tolerant foraminifera and absence of ostracods), (b) eutrophication or hypoxic conditions (coexistence of tolerant foraminifera and ostracods), (c) artificial inlets or dilution by freshwater (resulting in new assemblages), (d) minor oxygen depletion, (e) minimal impact from small agricultural or urban sewage (resulting in low ostracod diversity).

Several publications rely solely on indicator species or species assemblages of ostracods for environmental interpretation, lacking specific data on dissolved oxygen levels (e.g., Altinsaçlı and Griffiths, 2001). These interpretations are based on the known ecology of the species from previous studies, not always from the same regions. However, some species may have different behaviors in other aquatic systems, influenced also by factors such as predation and variable water chemistry. Additionally, tolerance limits for specific ecological factors may shift under other ecological conditions as for instance organic-rich habitats or adaptation to a changing climate (Weiskopf et al., 2020; Spence and Tingley, 2020). Their response should not be generalized and can depend on the composition of the local ostracod community and the type as well as the magnitude of the pollution (Pieri et al., 2012). That is why a more comprehensive understanding could be achieved by measuring additional parameters. The interaction between agricultural practices, organic pollution and biodiversity stresses the complexity of these ecological dynamics. Because of its complexity, it is important to consider not only organic pollution (DO, TOC, etc.), but also look at the POPs/heavy metals concentrations in water or/and in sediments.

4.2 Habitat degradation / disturbances

Habitat degradation and disturbances significantly impact ostracods, as it can alter water quality, forces habitat loss, and changes ecological conditions in the entire system. For instance, construction activities and wetland conversion can disrupt habitats, thus affecting ostracod distribution and diversity. Coastal waters are very complex and dynamic systems. One of the most important factors are inlet dimensions. If the lagoon mouth extends, or the barrier between lagoon and ocean intrudes, then it can significantly affect hydrology, salinity, sedimentology, and ecology of the system. Another important aspect is bottom topography together with natural and man-made channels, which are guiding the tidal circulations in the lagoon. All these environmental factors can be triggered or empowered by anthropogenic activities.

Habitat degradation and disturbances lead to reduced ostracod species diversity and richness, with tolerant or opportunistic species often thriving in disturbed environments. Human activities such as wetland destruction (Külköylüoğlu 2004; Külköylüoğlu and Dügel 2004; Külköylüoğlu et al., 2022), artificial inlets (Ruiz et al., 2006a), and sediment deposition disrupt natural habitats (Stark et al., 2003), causing long-term declines in sensitive species and altering community composition.

In Nador lagoon, Morocco, and El Meleh lagoon, Tunisia, the introduction of artificial inlets led to hydrodynamic changes (Ruiz et al., 2006a). These semi-arid lagoons typically undergo a natural process of closure, transitioning to a sabkha environment (Ruiz et al., 2006a). However, the artificial inlets disrupted this natural evolution, introducing marine sediments and species while causing partial erosion of the nearby bottom areas due to altered tidal currents (Ruiz et al., 2006a). Consequently, these new hydrological conditions adversely affected ostracods, which were only found as transported specimens of marine or brackish species (Ruiz et al., 2006a). Ruiz et al. (2004) described similar effects in Odiel Estuary, Spain.

In another example, the experimental dumpings of sediment in the Mecklenburg Bight, southern Baltic Sea, were compared before and after a sediment deposition event, revealing a potential short-term change in living associations (Frenzel et al., 2009). However, due to significant time intervals between samplings and limited sediment samples shortly after the deposition, they could not definitively prove this change.

Nevertheless, they observed that the taphocoenosis recovered more slowly than the biocoenosis indicating a gradual restoration of composition and abundance (Frenzel et al., 2009). This phenomenon, influenced by the burial and dilution effects of normal sedimentation, preserved allochthonous elements introduced with the redeposited sediment in surface samples for up to two and a half years after the sediment dumping event (Frenzel et al., 2009).

On the other hand, meiofauna can also benefit from hydrological changes since it can decrease an impact from sewages. Exactly that was demonstrated by Bodergat et al. (1998) in Makawa Bay, where inflow of marine water slows down the anthropogenic contamination. Another positive alteration from these anthropogenically induced factors was shown by Irizuki et al. (2008). There, in Uranouchi Bay (Japan), artificial banks were constructed to decrease the inflow of sandy sediments, which actually created preferable conditions for ostracods. It all resulted in an increase of species richness and abundances of ostracods.

Deep sea (ocean deeper than 200 m) is also not immune from disturbances by anthropogenic impacts. Commercial trawling operates as deep as ~1200 m water depth (Glover and Smith, 2003; Cryer et al., 2002; Martín de Nascimento et al., 2014; Clark et al., 2016) and has physically affected deep-sea benthic habitats and communities substantially and unsustainably (Glover and Smith, 2003; Althaus et al., 2009; Pusceddu et al., 2014; Puig et al., 2012). Trawling causes sediment downslope re-distribution, and thus affects much deeper depths beyond their operation via excess sediment and organic matter supply (Puig et al., 2015). Nevertheless, so far, trawling impact study using ostracods is limited to shallow marine environment (Zenina et al., 2022). There are increasing interests and technological maturation for deep-sea mining on the abyssal plain, yet rigorous environmental and ecosystem assessments are warranted since there are serious concerns on their negative impacts on deep-sea ecosystems (Amon et al., 2022; Wedding et al., 2015; Van Dover, 2011; Vanreusel et al., 2016). Similarly, scientists worry that new technologies for ocean-based climate interventions such as carbon dioxide sequestration will affect deep-sea ecosystem negatively if implemented (Levin et al., 2023). However, there are no studies on ostracods on such great depths investigating this kind of disturbances, except a study that discussed potential temperature and iron fertilization impact on deep-sea ostracods in a context of ocean-based climate interventions and marine carbon dioxide removal (Yasuhara et al., 2025).

Hydrographic changes and habitat degradation or disturbance can significantly impact ostracod populations. Alterations in water flow, temperature, and salinity, often associated with hydrographic changes, can disrupt the ecological balance and affect the distribution and diversity of Ostracoda. Additionally, habitat degradation, stemming from factors like pollution (see subsections 4.1 and 4.3) or habitat destruction, poses a threat to ostracod communities, leading to declines in population size and changes in species composition. On the other hand, it can also positively affect ostracods and create better settings, as certain species may adapt to new conditions, and altered habitats can create niches that foster the development of more diverse ostracod communities.

4.3 Heavy metal pollution

During the past decades, heavy metal pollution has become one of the most challenging problems for aquatic ecosystems. Its ubiquity, the curse of past contamination and new technologies continue to pose stress on aquatic life. Heavy metals are not degrading, unlike organic pollution, and stay in the ecosystem for a very long time. They are readily absorbed, tend to accumulate in the sediment, bio-accumulate in organisms and transfer through the food chain. Sources of heavy metal pollution threatening inland and coastal waters are industry, mining, domestic sewage, poor waste-management, anti-fouling on ships, and soil erosion.

There are three approaches to study the reflection of heavy metal pollution in ostracods: Species composition changes of ostracod associations, incorporation of heavy metals into ostracod shells, and ecotoxicological studies or tests using selected ostracod species in cultures for mortality assessment or detecting ontogenetic disturbances.

Association-based analyses of ostracods confirmed their indicative value for heavy metals in aquatic ecosystems. Elevated heavy metal concentrations are known to cause low species richness (Bodergat and Ikeya, 1988; Lee and Correa, 2005; Poquet et al., 2008; El-Kahawy et al., 2021; Tan et al., 2021; Schmitz et al., 2024) but, because heavy metal pollution is often associated with organic pollution in sewage water, higher abundance of ostracods at lower water quality (moderately polluted) are found frequently, while higher water quality produces a lower population density and higher species richness (Padmanabha and Belagali, 2008; Anandakumar and Thajuddin, 2021). Interestingly, Aiello et al. (2021) observed an increased proportion of heavy metal tolerant species without general abundance effects onto the associations within the oligotrophic Gulf of Pozzuoli (Italy). Very high heavy metal concentrations may cause the total absence of living ostracods in critically polluted water bodies (Ruiz et al., 2000a, b, 2004, 2006a; Schmitz et al., 2024). While elevated concentrations have generally a negative impact on ostracod abundance, selected elements show often differing effects onto given species (Yasuhara et al., 2003; Iepure et al., 2014; Irizuki et al., 2015; El-Kahawy et al., 2021; Tan et al., 2021), thus demonstrating the need of more research on indicator species and their potential for recording specific heavy metals.

As, Cr, Cu, Mn, Ni, Pb and Zn in the environment are recorded to have a negative impact on ostracod abundance (Ruiz et al., 2000a, b; Lee and Correa, 2005; Iepure et al., 2014). Fe and Mn in high concentrations are amongst these harmful elements changing the composition of ostracod associations (Hegde et al., 2021). A different result was found by Hong et al. (2022) who investigated ostracod diversity and biogeography in the urbanized seascape of Hong Kong. High concentrations of Zn affected the diversity of abundant and dominant species negatively, but highest diversities of ostracods were observed in sites with elevated Cu levels. Factors such as temperature, salinity, pH, organic matter, and sulphide content may affect metal toxicity, but their influence on Cu concentration and co-dependant ostracod diversity remains uncertain (Hong et al., 2022). Irizuki et al (2015) produced a pioneering paper by using metal toxicity guidelines for marine sediment to interpret palaeo-ostracod data.

The bio-indicative approach of ostracod association analysis is used for palaeo-studies as well, especially for marine sediment cores covering the past Centuries (Ruiz et al., 1997; Yasuhara et al., 2003; Ruiz et al., 2004; Irizuki et al., 2015; Hong et al., 2021). This allows tracing pollution histories and the reconstruction of natural reference values, a great advantage of ostracod analysis compared to non-skeleton-bearing or macrofaunal bioindicators.

Multiple factors influence the chemical composition of ostracod valves, which can, in turn, provide insights into the physico-chemical conditions of their habitat (Carbonel and Tolderer-Farmer, 1988). Ostracods undergo rapid carapace regeneration through moulting, enabling them to record short-lived environmental chemical changes. Ostracod shells, at the time of secretion, are intaking the components of the hosting water, including heavy metals. Exactly that was demonstrated by Bodergat in 1978, where she examined the impact of a sewer in France on *Aurila speyeri*. The results showed the presence of Ce in an *A. speyeri* valves, which not only indicated a significant contribution from wastewater through the moulting stages, but also highlighted the pioneering role of ostracods in monitoring peak chemical pollutions within a biotope. Later, Bodergat et al. (1991, 1998), documented again incorporation of heavy metals (Fe, Ce) in ostracod shells of marginal marine habitats. Bodergat’s studies are among the first ones showing that ostracod shells can be considered as potential archives of heavy metal pollution and can be used for water quality monitoring. Other heavy metals recorded are Fe, Mg, and Mn which can indicate pollution (Rio et al., 1997; Palacios-Fest et al., 2003). The distribution of elements within a given shell, however, shows significant anisotropy (e.g., Rio et al., 1997; Börner et al., 2013).

The mechanisms and modulations of absorbing heavy metals into the shell are not well understood yet. Beside bioavailability of these substances, the biology of ostracod species plays a role in the process. Kantorek (1992) investigated the potential of eurytopic freshwater ostracod species for detecting heavy metal contamination from industry. Surprising differences in metal content were observed among ostracod species from the same locations, but with different lifestyles. Swimming species exhibited lower metal values compared to crawling species. These differences may be attributed to different microhabitats and positions of species in food chains.

Ecotoxicology studies involving ostracods play already an important role in assessing the potential impacts of heavy metals and other contaminants on an entire aquatic ecosystem. Cultivating experiments with ostracods in a controlled laboratory setting allow to examine how different heavy metals affect these organisms under controlled conditions. These experiments provide valuable insights into the toxicity thresholds and sublethal effects on ostracods, helping to establish guidelines for water quality monitoring. Such tests can assess various endpoints, including survival, reproduction (hatching eggs), and behavioural responses, to understand the potential harm caused by contaminants. The integration of ostracods into ecotoxicology gained momentum as the importance of bioindication grew across various fields (see the overall list of publications on ecotoxicology in electronic appendix Tab. B).

Resting eggs are a commonly observed trait among freshwater ostracods, as noted by Tetart (1975), McLay (1978), and Delorme (1991), enabling many species to withstand intermittent freezing and drying in temporary ponds (Tressler, 1959; McLay, 1978). Subsequently, research on the cues triggering hatching of ostracod resting eggs showed good results (Angell and Hancock, 1989), becoming a very useful tool in ecotoxicology, thus providing the base for Ostracodtoxkit^{TM} and other culturing methods. By now, there are numerous studies with Ostracodtoxkit F test showing a great sensitivity of *H. incongruens* to heavy metals and other pollutants (Szmigielska et al., 2018; electronic appendix Tab. C). Species of the cosmopolitan genus *Heterocypris*, typical for small non-permanent water bodies, are often used in this context.

Experiments with ostracod cultures can show specific reactions of selected species in more detail, what is problematic in the field. For instance, such an experiment demonstrated that the toxicity of Cu depends on bioavailability, e.g., pH levels, with low pH increasing toxicity (Khangarot and Rey, 1987). Furthermore, toxicity of heavy metals is shown to be depending on the element, e.g., Khangarot and Das (2009) assessed the toxicity of 36 metals, metalloids, and twelve reference toxicants over 48 hours, measuring the median effective concentration (EC50) of *Cypris granulata*. The results showed osmium (Os) as the most toxic and boron (B) as the least toxic among the substances tested. In addition, Khangarot and Das (2009) found a positive correlation between EC50 values and already well-established test models involving various aquatic organisms. Thus, the authors emphasized the importance of including ostracods in biotests to detect hazardous chemicals in diverse environments: The *C. subglobosa* immobilization assay is highly sensitive, cost-effective, and trustworthy for assessing acute toxicity, suggesting its potential as an alternative bioassay for routine monitoring of polluted water, industrial effluents, and soil and sediment toxicity studies in general.

Despite promising results of ostracod research in the field of heavy metal pollution there is still a strong need of investigations. Heavy metal pollution has been shown to have harmful effects on ostracods, yet there is a notable scarcity of ostracod studies conducting geochemical analyses specifically on heavy metals in both water and/or sediments. While several studies exist for marine and coastal waters, there remains a significant gap in research concerning inland waters. Many studies attribute pollution sources to "sewage", often conflating heavy metal pollution with organic pollutants, yet only providing data on total organic carbon.

Ostracods exhibit a similar response pattern when exposed to high concentrations of heavy metals like with oil spills. Millward et al. (2004), however, found ostracods to be heavier metal-resistant than tolerant against hydrocarbon pollution. If the levels of heavy metals increase above a critical threshold, there is a noticeable decline in ostracod abundance. This phenomenon is accompanied by a reduction in species richness, with only those species possessing a higher tolerance for the metal concentrations persisting and occupying the ecological niche. Over time, this limited diversity of species may become less resilient, with the potential for eventual population decline and mortality among the remaining tolerant species. There are, however, examples (e.g. Gildeeva et al., 2021) of higher diversity under heavy metal pollution. This is partly because of frequent studies of taphocoenoses, i.e. living + dead from surface sediments, thus adding a taphonomic factor with potential time averaging and input of allochthonous material distorting the original diversity signal.

We like to stress that the impact of heavy metals on ostracods regarding bioavailability, toxic effects and other environmental factors influencing the impact, is not well understood yet. For instance, Meriç et al. (2018) examined the influence of submarine thermal springs at Doğanbey Cape in Turkey on ostracods and discovered that, while the chemical and radioactive properties of sediments affected the tests of benthic foraminifers, there was no impact observed on ostracods richness and abundances. This underscores the urgent need for detailed high-quality research on ostracods in this field.

While many studies are focusing on heavy metals in controlled culture/bioassays experiments, there is still a need for more field-based research to understand the implications of heavy metal pollution on ostracods in natural ecosystems. The identification of indicator values of ostracod species pushing environmental research based on ostracods from a qualitative to a quantitative level is especially needed.

4.4 Hydrocarbons and Persistent Organic Pollutants

Oil spills have been seriously affecting marine and coastal ecosystems including deep sea ecosystems (Halanych et al., 2021; Fisher et al., 2016). However, there is a surprising gap in research concerning the impact of hydrocarbons and Persistent Organic Pollutants (POPs) on ostracods in deep sea and inland waters, as studies have primarily focused on coastal and marine environments.-Despite this, investigations into POPs have predominantly been limited to controlled lab experiments (Sánchez-Bayo, 2006; Sánchez-Bayo and Goka, 2006, 2012; Houssou et al., 2021).

Different lab and field-based observations showed that ostracods are sensitive to oil contamination. The effects tend to have a similar pattern of decrease in densities and diversities of ostracods. This was demonstrated in the Persian Gulf, where a complex anthropogenic impact after the 1991 Gulf War was investigated. In the polluted sites almost complete absence of ostracods with soft parts was observed (Mostafawi, 2001). Another example of high mortality rate up to total extermination of ostracods was observed in parts of Amurskii Bay (Russia) contaminated by wastewater and oil hydrocarbons (Zenina 2009). The same result was revealed in Vladivostok Port (Russia), where in the most polluted zones with oil films only some single ostracod valves were found, and no living ones at all (Schornikov, 2000). Another study by Widbom and Oviatt (1994) evaluated the impact of oil exposure to crustaceans during the initial five weeks following a spill. Their research encompassed five stations within Narragansett Bay, Rhode Island, each experiencing varying degrees of oil exposure. The results of their investigation revealed significant distinctions in both ostracod abundance and distribution. These findings provided clear evidence of the high vulnerability of ostracods to the effects of oil pollution. Another study confirmed same trends with ostracods reaction to a nuclear accident and excessive oil pollution in Peter the Great Bay (Russia). As a response, ostracods showed a high mortality rate up to total extinction. It remained unclear if the extermination was a result of a synergistic interaction of pollutants or if the primary toxicant was petroleum (Schornikov and Zenina 2007).

Another interesting aspect was described by Pascual et al. (2008) on the aftermath of the "Prestige" oil spill on the Basque shelf, where among the affected ostracods, many exhibited highly ornamented valves with oil filling the reticulation. Notably, the most affected species included *Loxoconcha guttata*, *Costa edwardsii*, *Carinocythereis quadridentata*, and *Echinocythereis laticarina*.

Nevertheless, Kaesler et al. (1979) determined that 20 months post the incident in the Strait of Magellan, the ostracod community, although impacted by oil spills initially, had fully recovered by the time of sampling. Notably, species richness in the shallow and heavily polluted zones showed no indications of ecosystem imbalance, indicating the full recovery of the biocoenosis (Kaesler et al. 1979).

Ostracods face potential risks from pesticide applications, either through their impact on nitrogen-fixing cyanobacteria or exposure to pesticides targeting other organisms (Sánchez-Bayo, 2006) and can affect them at individual and population levels (Houssou et al., 2021). Sanders (1970) conducted one of the pioneering ecotoxicological studies, using various taxa, including *Cypridopsis vidua*, to test the effects of sixteen herbicides. His findings revealed that both ostracods and cladocerans were highly sensitive to most herbicides. Due to its cosmopolitan distribution, *C. vidua* became a model species in further studies, including community-level microcosm experiments (Taub et al., 1981; Takamura and Yasuno, 1986; Landis et al., 1992). These studies found that while moderate pesticide exposure initially reduced ostracod and algal densities, long-term observations showed an increase in ostracod populations, likely due to the suppression of their competitors and predators. Similar effect was found from a pollutant of Zpt-shampoo, where it decreased predatory pressure in these fields and ostracods could thrive, but in the imidacloprid (insecticide) fields ostracods were present in very low numbers (Sánchez-Bayo and Goka, 2006). Generally, application of insecticides shows a slow recovery of ostracods (Sánchez-Bayo and Goka, 2012) or rapid decline in population size (Sánchez-Bayo, 2006). Smith et al. (2018) reviewed the effects of pesticides on rice field ostracods, highlighting a decline in diversity over several decades due to harmful pesticides, with species like *Notodromas trulla* in Japanese rice fields also being at risk from both pesticides use and habitat loss (Okubo, 2003).

POPs are a very wide category of chemicals and not all of them have a very harmful effect on ostracods. However, there is a limited number of studies directly analysing POPs from sediment/water in the field and comparing them with ostracod distribution (e.g., Smith et al., 2018). The same case is with hydrocarbon pollution, when it is unclear until which point a system cannot or can start recovering. These gaps show the need for further research to better understand the impact of these pollutants on ostracod populations in both freshwater and marine ecosystems to provide valuable insights into environmental health and conservation efforts.

4.5 Thermal pollution

It is increasingly better understood that human-induced climate change causing warming, acidification, and deoxygenation affects marine ecosystem and biodiversity (Yasuhara and Danovaro, 2016; Chaudhary et al., 2021, Yasuhara et al., 2020, Breitburg et al., 2018; Doney et al., 2020). This is very likely true in deep sea as well, yet empirical evidence is still limited (Levin and Le Bris, 2015; Sweetman et al., 2017). In this chapter of our review, however, we are focusing on direct thermal pollution often caused by the discharge of heated water from industrial processes, power plants, or other anthropogenic activities.

Elevated water temperatures resulting from thermal pollution can directly impact meiofauna in several ways. First, increased temperatures can decrease the availability of dissolved oxygen in the water, making it harder to respire and thrive. Second, temperature changes can disrupt the metabolic processes of meiofauna, potentially leading to changes in their abundance and distribution. Moreover, higher temperatures may affect the microbial communities that meiofauna depends on for food and other ecological interactions. While many studies have investigated the impacts of thermal pollution on various aquatic organisms (e.g., Verones et al., 2010; Malik et al., 2020), there are only laboratory experiment studies on ostracods so far (Martens 1985; Mezquita et al.,1999c; Prayudi et al., 2024). Martens (1985) and Mezquita et al. (1999c) looked more into the survival and molting stages, whereas Prayudi et al. (2024) evaluated extreme temperatures with mortality rates.

The controlled experiment with thermal impact on living *Cyprideis* sp. from Murray's Pool initiated their comatose state around 39.4°C, with confirmed mortality occurring at 47.5°C, and full mortality observed at 53.5°C, setting a baseline for understanding the observed kill zone on Murray's Pool mudflat (Prayudi et al., 2024). This is the first experiment of its kind in the Gulf area, highlighting the need for further research on the thermal limits of ostracods, especially given the projected temperature increases. With rising temperatures threatening shallow-marine organisms, additional research on different ostracod species and other benthic organisms is crucial to better understand their thermal limits and ecological implications in the face of climate change.

4.6 Salinization and water chemistry

Many studies have been conducted on the use of Ostracoda for salinity reconstruction. Salinity is known as one of the major drivers and controlling factors of ostracod distribution. Certain species of ostracods indicate preferences for specific salinity levels, but there are also species that are highly tolerant to salinity changes (Taylor, 1992; Ruiz et al. 2013). As the anthropogenically induced salinity will increase, salt-tolerant ostracods will replace less tolerant ones, as it happened in spring systems due to de-icing (Taylor, 1992). *Cyprideis torosa* shows morphological changes in their carapace, including variations in size, sieve pore shapes, and nodes (e.g., Frenzel et al., 2011).

According to Löffler (1983), Traunsee in Austria was previously a holomictic lake until industrial discharges from the alkali works in Ebensee began. The industrial discharges not only induced meromixis, but also caused the deposition of highly alkaline sediment in the southern part of the profundal zone. Through direct comparison of subfossil benthic fauna from cores extracted within and outside the affected area, it was found that the widespread deposition of sediment from the alkali works in the southern profundal zone likely resulted in the extinction of benthic fauna including ostracods, potentially attributed to its highly alkaline nature acting as a limiting factor.

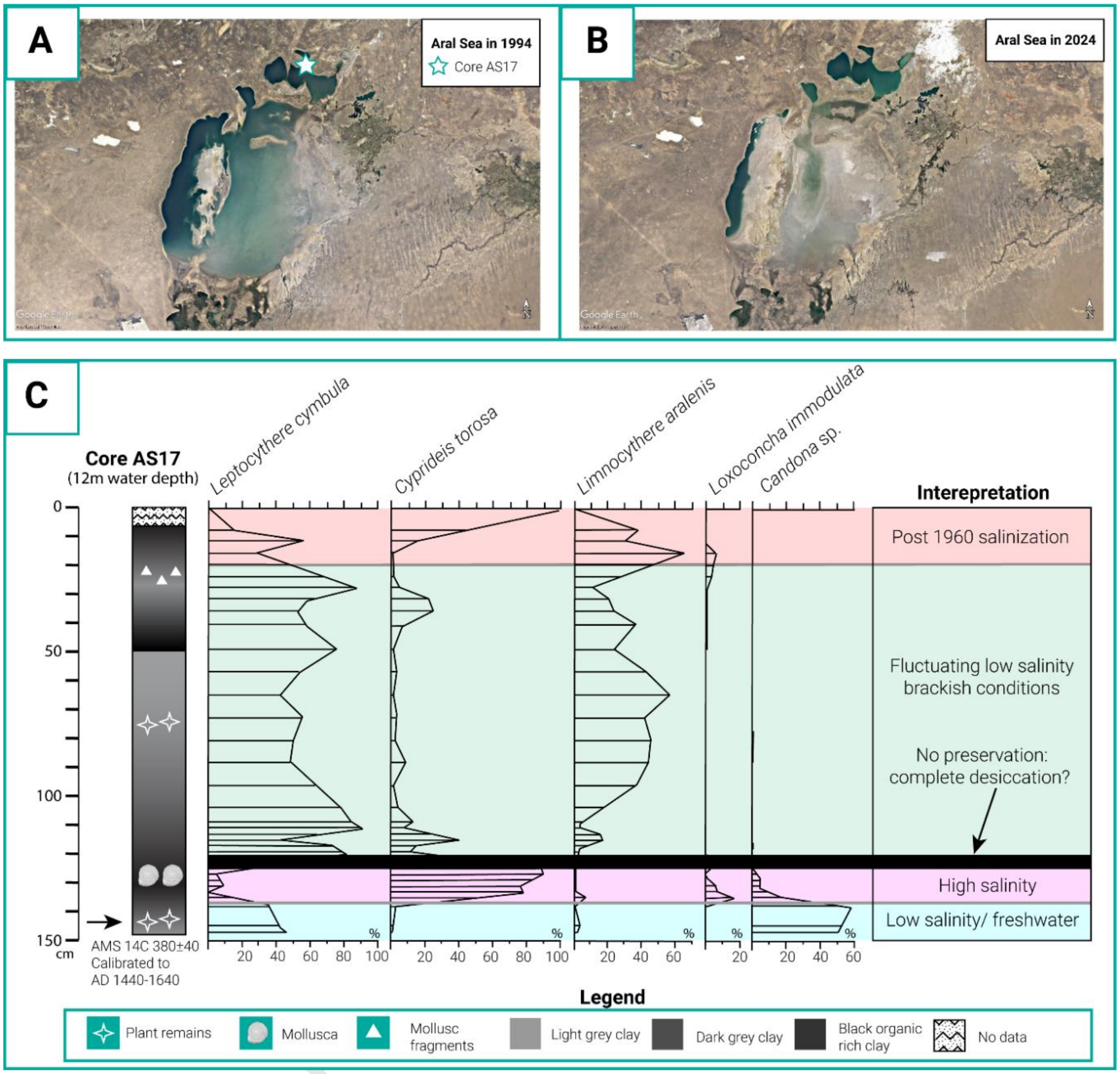

Figure 6: *A. Location of the core AS17 and the aerial view of the Aral Sea in 1994, when it was collected (collected by S. Juggins and B. Davis, University of Newcastle in 1994). B. The aerial view of the present state of Aral Sea in 2024. C. Sedimentology and ostracod associations with salinization stages of the core AS17. Modified from Boomer et al. (2003). A and B are Google Earth satellite images*.

Boomer (1993a, b), Boomer et al. (1996) and Boomer et al. (2003) conducted studies on Ostracoda in the Aral Sea. The study revealed that of the eleven species of Ostracoda known to have been living in the Aral Sea in 1960, only *Cyprideis torosa* survives today due to the anthropogenically induced increase of salinity (fig. 6). The origins of a mixed fresh- and brackish-water ostracod fauna indicate that some of the major faunal elements must have reached the Aral Sea Basin during a past high water level phase when a connection existed with the Caspian Sea. Alternatively, meiofauna can also immigrate via avian transport as other studies suggest (Baltanás et al., 1990; Martens, 1994; Brochet et al., 2010; Mužek et al., 2023).

All mentioned above studies by Boomer and Boomer et al. also found that ostracods reflected salinization and water levels, with dominating *Cyprideis torosa* indicating hypersaline conditions. Altınsaçlı and Mezquita (2008) studied lake Acıgöl and found that its relatively rich ostracod community is primarily supported by small, diverse habitats, notably freshwater springs. However, the prevalence of salt-tolerant species like *Heterocypris salina* and *Cyprideis torosa* raises concerns about the future of lake Acıgöl. Uncontrolled water resource management, especially excessive aquifer exploitation, may lead to a decline in biodiversity, mirroring the fate of lakes such as the Aral Sea.

Ostracods serve as reliable indicators of increased salinity due to human impact, particularly in cases of water overuse, that result in loss of stenohaline freshwater species.

4.7 Nuclear pollution

The menace of nuclear pollution presents a serious concern for aquatic fauna, adversely affecting diverse species through radiation exposure and the contamination of their habitats (Hinton et al., 2007; Strand et al., 2017; Han, 2023). While the broader consequences for aquatic life encompass genetic mutations, reproductive challenges, and decreasing population sizes, the precise ramifications for ostracods dwelling in inland water ecosystems remain uncertain.

Schornikov and Zenina (2007) investigated buried ostracods from a nuclear submarine accident site in Chazhma Cove, Peter the Great Bay, Sea of Japan. The cause of ostracod mortality there remains unknown. On the other hand, there was no evidence that radioactive contamination from the Chernobyl accident affected the diversity of ostracods or other invertebrates in lake communities (Murphy et al., 2011). In fact, even the most contaminated lake, Glubokoye, had the highest richness of aquatic invertebrates, with overall natural environmental factors like lake size and hydrochemistry being the main drivers of species richness (Murphy et al., 2011).

However, the role of the radiation accidents cannot be discounted entirely. The effects of pollution with radioactive materials on ostracods needs more attention.

4.8 (Micro)plastic

Microplastic pollution poses a significant anthropogenic threat to aquatic ecosystems, yet its impact on meiofauna remains not fully understood. While there have been studies investigating the effects of microplastic on various marine organisms, such as foraminifera for instance (Birarda et al., 2021; Joppien et al., 2022; Bouchet et al., 2023), specific research on ostracods is notably lacking. The only study on microplastic known to us is from laboratory experiments on Podocopida (Aguirre-Martínez et al., 2023). Aguirre-Martínez et al. (2023) revealed microplastics ingestion and entrapment in podocopid ostracods, with smaller particles inducing toxic effects despite being non-toxic when pure. Additionally, microplastics act as vectors for hydrophobic organic pollutants like phenanthrene and chlorpyrifos, exacerbating their toxicity with increased exposure time and concentration, which poses threats to survival, reproduction, and development of ostracod.

Microplastics have also been detected from deep-sea sediments (Van Cauwenberghe et al., 2013; Woodall et al., 2014) and organisms (Courtene-Jones et al., 2019). Their ecological impacts have been indicated (Franzellitti et al., 2019; Ma et al., 2020) but are largely unknown in deep sea, especially for ostracods. It shows an urgent need to continue research on various types of microplastics, as well as combining it with different organic pollutants to address microplastics impact on the food chain for instance.

4.9 Invasive species

Invasive species pose significant threats to aquatic ecosystems due to their ability to outcompete native species, disrupt food webs, alter habitats, and spread diseases (Charles and Dukes, 2007; Kernan, 2015). By declining native biodiversity, cascading ecological impacts such as reduced water quality, loss of ecosystem services, and economic losses in fisheries and recreational activities can be triggered (Cambray, 2003; Walsh et al., 2016). In 1986, McKenzie and Moroni reported about *ospiti esteri* ostracods (Italian for “foreign guests”) from Italian ricefields, discussing their possible dispersal mechanisms. Ostracods can become alien species through various pathways, including transportation of cargo, aquaculture activities, non-native fish introductions, bird-mediated dispersal, and human activities related to land management and infrastructures (McKenzie and Moroni, 1986; Escrivà et al., 2012). While birds can migrate long distances and contribute to ostracod dispersal, human-mediated dispersal, particularly through inter-continental shipping, appears to be a major vector for the spread of invasive species (Escrivà et al., 2012). Additionally, activities associated with ricefield management, such as seed and soil transport, have been implicated as potential mechanisms for introducing exotic ostracods into new environments (Escrivà et al., 2012). Despite the potential for bird or human-mediated dispersal, cosmopolitanism is rare in freshwater ostracods, with only a few species exhibiting global distribution, primarily in rice fields (Escrivà et al., 2012).

One more interesting way for new or invasive species to enter new regions of the world is the pet trade (Smith et al, 2024). Pet trade served as a pathway for seven “alien hitchhikers” ostracod species to enter Japan, where they may become invasive (Smith et al, 2024).

Escrivà et al. (2012) expanded the known distribution of the taxon *Fabaeformiscandona subacuta* through literature reviews, specimen examination, and sampling in Spain and Japan. This species was found in 78 aquatic environments across nine countries. They reported its presence in mainland eastern Asia, Australia, and South America, along with reviewing its distribution on the Iberian Peninsula. Despite its global distribution, they hypothesized it to be an invasive species on the Iberian Peninsula due to its absence in other European countries, disjunct global distribution, and preference for artificial human-impacted habitats like reservoirs and rice fields. The study sheds light on the lack of knowledge regarding the ecological impacts and biology of exotic ostracods, leading to their frequent neglect in freshwater research. However, data from the Iberian Peninsula suggest that exotic ostracods, including *F. subacuta*, may create a significant portion of the exotic invertebrate fauna in freshwater environments, particularly in rice fields. Pieri et al. (2007) also found *Chlamydotheca incisa,* known as South American species (Martens and Harrison, 1993; Díaz and Lopretto, 2011), in lowland springs from Lombardy in Italy; the species was already found in Italian ricefields by Rossi et al. (2003). Rossi et al. (2003) also recorded *Chrissia* sp. of African (Hartmann, 1957), Indian and Malaysian origin (Victor and Fernando 1981, 1982), as well as *Hemicypris dentatomarginata* of Indian origin (Victor and Fernando 1981; Martens and Wouters 1985).

In 2014, Escrivà et al. identified *Ilyocypris getica*, *Candonocypris novaezelandiae*, and *Ilyocypris beauchampi* as invasive or exotic species across 24 reservoirs in the Xúquer River basin. *I. getica* is known living in Northern Africa and European Mediterranean countries, although it has also been found in Germany (Meisch et al., 1996). *C. novaezelandiae* was previously found in Eastern Africa, Eastern Asia, Australia and New Zealand, but not in Europe (Valls et al., 2013, Valls et al., 2014) and *I. beauchampi* is likely of African origin (Meisch, 2000). The presence of invasive or exotic species among others was notably higher in the reservoirs, confirming previous observations regarding the facilitation of aquatic invasions by artificial ecosystems (Escrivà et al., 2014). The researchers also argue that ongoing global warming might promote the colonization of northern habitats by non-indigenous species, primarily originating from Africa and possibly transported by migratory birds stopping at the Iberian Peninsula on their migration routes (Escrivà et al., 2014). Warming results also in summer dominance of species tolerant to low oxygen and high temperatures, such as *Darwinula stevensoni* and *Fabaeformiscandona subacuta* (Escrivà et al., 2014). Valls et al. (2014) found high xenodiversity in ten rice fields located in the Albufera Natural Park in Spain: *Fabaeformiscandona subacuta* of Asian origin (Escrivà et al., 2012), *Stenocypris macedonica* was found worldwide in tropical wetlands, usually including rice fields, from Africa, America, Asia and Europe (Martens and Toguebaye 1985), *Hemicypris barbadensis* was previously found in the Barbados and Japanese rice fields (Broodbakker 1983; Okubo 1990) and *C. novaezelandiae* (see above). Moreover, *H. barbadensis* and *C. novaezelandiae* showed high adaptation and preference to low oxygenated environment. The dispersal and colonization paths of exotic ostracods in dynamic and human-altered environments may surpass those observed in more pristine habitats. It is plausible that rice trading facilitated long-distance dispersal of ostracods through the transportation of seeds, soil, and machinery across various regions.

In their study on the ostracod metacommunity spanning 22 endorheic lakes in the Central Iberian Peninsula, Spain, Castillo-Escrivà et al. (2016) identified the presence of the exotic species *C. novaezelandiae*. This discovery echoes a previous finding by Escrivà (2011) (as “Cypridinae sp. 1”) and Valls et al. (2013) in Raco de l’Olla, Spain, suggesting a potential correlation with artificially prolonged hydroperiods in lakes impacted by wastewater inputs, such as Taray and La Veguilla. Similar phenomena have been observed in other Mediterranean systems invaded by this species (Valls et al., 2013; Escrivà et al., 2014; Escrivà et al., 2015). Moreover, this shows similar traits as the invader of Asian origin, *F. subacuta* (Escrivà et al., 2012).

Anthropogenic pressure on water bodies is clearly leading to increasing numbers and densities of cosmopolitan species and to the loss of endemic ostracods (Roca et al., 2000). The significant alteration of agricultural practices in rice fields in Italy, as shown by Rossi et al. (2003) may have primarily impacted interspecies competition by making more beneficial conditions for invasive species, consequently resulting in a reduction in native species abundances. This emphasizes the importance of further research to understand the ecological implications of invasive Ostracoda species, their transport or dispersal mechanisms, their role in freshwater ecosystems and the role of changing climate to it. Currently, documentation of present-day Ostracoda distribution is insufficient, highlighting the necessity for more comprehensive faunistic studies.

5 Perspectives

5.1 Ostracod-based water quality benchmarks

Ostracod-based water quality benchmarks are established through the analysis of large datasets comprising numerous samples collected from aquatic environments. These benchmarks are derived by correlating the abundance and distribution of ostracod species with geochemical compounds present in the water and sediment, or by means of other proxies for water quality such as macroinvertebrates or diatoms. By classifying ostracod indicator species that exhibit tolerance or sensitivity to specific environmental conditions or pollutants, these benchmarks provide valuable insights into water quality and ecosystem health (Külköylüoğlu et al., 2020). Through careful analysis and interpretation of ostracod assemblages, these benchmarks serve as effective tools for monitoring and assessing the impact of anthropogenic activities on aquatic ecosystems. The very first attempt with ostracods as bioindicators in this field was published by Kantorek (1992) from Ostrava in former Czechoslovak territory. Based on the assessment of ostracod relationships with known ecology, physical-chemical data, and water quality, he evaluated ostracods as sentinels and made a list of saprobity indicators: *Neglecandona neglecta*, *Cavernocypris subterranea*, *Cypris ophtalmica*, *Cypridopsis vidua*, and *Dolerocypris fasciata*, *Fabaeformiscandona caudata*, *Cyclocypris serena*, *Psychrodromus olivaceus*, and *Potamocypris zschokkei*.

One of the pioneering studies by Irizuki et al. (2011) was based on a large-scale sampling and revealed fluctuations in bioassociations. The study identified two distinct bioassociations: one vulnerable to human-induced eutrophication/hypoxia and the other tolerant. This study established indicators applicable to broad East Asian coasts. Schornikov and Zenina (2014) long-term work in Peter the Great port (Russia) resulted in the compilation of a base for future monitoring of the surveyed water areas. In the most polluted areas, they found a single juvenile ostracod or total absence of them. Based on ostracod distribution according to the degree of pollution, important steps have been taken to move from accumulation of factual data to creation of a system. That system will help to classify quality of a water body based on the nature of a succession of ostracod associations. Schornikov and Zenina (2014) distinguished opportunistic species with high tolerance to oxygen deficiency: *Spinileberis quadriaculeata*, *Spinileberis?* sp., *Paracytheroma asamushiensis*, *Bicornucythere bisanensis*, *Cytheromorpha acupunctata*, *Howeina camptocytheroidea* and *Howeina* sp. 5. However, the authors did not provide details regarding specific pollutants, merely noting the most contaminated category - the subzone where ostracod remains are covered by successive sediment layers, suggesting prolonged and extensive pollution accumulation over more than a decade. This lack of specific contaminant information complicates the categorization of this study within chapters focusing on pollution sources, as the site, a major port, likely endures multifaceted anthropogenic pollution factors. A very important remark from the authors and for the future water quality ostracod-based studies is that brackish-water ostracods exhibit greater pollution resistance compared to marine species but are less resilient than many freshwater ostracods found in lower river valleys. This observation was made based on many other study sites in Russia, which are also discussed in Schornikov and Zenina (2014).

A first ground-breaking attempt to create an ostracod-based baseline after Irizuki et al. (2011) and Schornikov and Zenina (2014) was done by Hong et al. (2017), where they investigated the impact of reservoir construction on ostracod abundance in Hong Kong. During the construction period (1960–1968), ostracod abundance significantly decreased, but certain species like *Bicornucythere bisanensis* s.l., *Loxoconcha zhejiangensis*, *Xestoleberis* spp., *Loxoconcha japonica*, and *Aurila* spp. persisted. *Bicornucythere bisanensis* s.l. is known to tolerate eutrophication and low-oxygen conditions. In the post-construction period (1968-present), the freshwater environment of Plover Cove Reservoir prevented the presence of marine biota, with no freshwater ostracods found due to anoxic bottom waters. The few ostracods recorded were likely reworked specimens. Hong et al. (2019) continued in this niche of ostracod research and in a couple of years compiled an impressive dataset on an ostracod-based baseline for northwestern Pacific and Indo-Pacific waters. For the first time, they identified indicator species for heavy metals pollution and eutrophication in tropical environments. For example, from the subtropical group, *Sinocytheridea impressa* is withstanding eutrophication and bottom-water hypoxia, while *Neomonoceratina delicata* is tolerant to heavy metal pollution and increased turbidity. Other indicative species are *Stigmatocythere roesmani* and *Hemicytheridea reticulata*, which are sensitive to Pb. The tropical group has different indicative species, which mostly correlate only with natural factors, except one tolerant to low oxygen content taxon, *Loxoconcha malayensis*.

In a recent study, Pokrajac et al. (2024) investigated the freshwater Ostracoda diversity and ecology in Central Serbia, employing hypothesis testing based on the ratio of non-cosmopolitan species, which tend to be pollution-sensitive, what serves as an indicator of anthropogenic pressure and/or habitat degradation. The non-cosmopolitan species (i.e., sensitivity) ratio, calculated as NC/TS (NC = number of non-cosmopolitan species; TS = total number of species), ranges from 0 to 1, with 0 indicating the absence of non-cosmopolitan (i.e., sensitive) species. In their case, this testing did not necessarily adequately represent the observable conditions, but it remains a potentially valuable method for assessing water pollution.

These results demonstrate that ostracods can effectively reflect anthropogenic pressure in a standardized way, making them valuable indicators of water quality. Analyzing ostracod assemblages from sediment cores allows researchers to trace their reactions to environmental changes, providing reference conditions to be compared with modern-day situation. Ostracod-based water quality benchmarks are derived from extensive datasets, correlating ostracod associations, diversity, and abundance with pollution levels. These benchmarks have a huge potential and can help monitor and assess the impact of human activities on aquatic ecosystems in a quantitative way.

5.2 Bioindicators in EU Water Quality Regulations: Assessing Ecological Health and Compliance

The European Union (EU) has established several regulations and directives aimed at monitoring and maintaining water quality (Kallis and Butler, 2001; Allan et al., 2006). In 2000, the Water Framework Directive (WFD; EC, 2000) reshaped the evaluation of surface water quality, prioritizing biological communities such as fish, benthic invertebrates, phytobenthos, and macrophytes over traditional physicochemical parameters. This marked a shift from viewing water solely as a resource to recognizing its role as a crucial component of ecosystems (Pinheiro et al., 2020). The WFD mandates that all water bodies in the European Union should achieve a "Good" ecological status by 2027, with benthic invertebrates, fish, macrophytes, and phytobenthos serving as key assessment components, supported by physicochemical and hydromorphological parameters. The WFD requirement to meet reference conditions for various types of water bodies can be acquired with a use of microfossils. Microfossils can provide baseline data to access historical change helping to set restoration benchmarks (Finnegan et al., 2023), and, certainly, it can be traced with a use of Ostracoda (Hong et al., 2019). Despite regional improvements in water quality, there is no evidence of overall global improvement (UN, 2012). Moreover, research indicates that by 2030, approximately half of the river basins in the European Union are expected to undergo high water scarcity and stress (EC, 2012; UN, 2014; Pinheiro et al., 2020). Currently, there are two distinct strategies for chemical biomonitoring, namely passive and active approaches. Passive methods utilize native organisms (Goldberg, 1975), whereas active methods use transplanted or caged individuals from a reference site (Andral et al., 2004).

Table 1: *Selecting biota species for EQS compliance checks and trend monitoring involves choosing sensitive indicators of environmental conditions and pollutant levels. Modified from Besse et al. (2012).*

WFD Recommendations for the choice of indicator species
1. Accumulation of contaminants
2. The metabolic efficiency
3. Endangered/require special protection
4. Non-native/invasive
5. Widespread and abundant in the study area
6. Large enough to yield sufficient tissue for analysis
7. Seek continuity with pre-existing monitoring programs when designing sampling strategies
8. Harmonized biota sampling with ecological status classification where relevant
9. Select species based on trophic level for which an EQS has been derived
10. Choose species that can satisfy multiple protection goals
11. Adjust biota quality standards if necessary, based on the trophic level of the monitored species

Addressing relevant recommendations (Tab. 1) based on the previous parts of this review, we can clearly say, that ostracods fulfill most criteria, but still need additional research in some fields. They have been shown to accumulate contaminants present in water in their shells, making them effective bioindicators of water quality (1). Through numerous controlled experiments ostracods showed having efficient metabolic processes, allowing them to respond sensitively to changes in environmental conditions, including exposure to pollutants (2). Ostracod species are not listed as endangered so far because their status is not well known (3). More research, however, could deliver information needed for identifying endangered species. Ostracods are rarely classified as invasive because of poor distribution data; nevertheless, there have been research on the potential invasiveness of certain ostracod species (see 4.9) (4). Ostracods are commonly found in all kinds of aquatic environments, including freshwater bodies like recreational pools, making them readily available for monitoring purposes (5). They are very small crustaceans with a soft body weight of some µg only, but they can provide high numbers of individuals for analysis (6). Ostracods can be integrated into existing monitoring programs, ensuring continuity and comparability of data over time (7). They can be sampled alongside other biota to assess ecological status, allowing for a comprehensive understanding of ecosystem health (8). The identification of indicator taxa and adjustment of quality standards based on trophic levels is still lacking for ostracods (9, 11). Ostracods can fulfill multiple protection goals, including assessing water quality, ecological status, potential human health risks associated with pollutant exposure and provide data on reference conditions for renaturalization practices (10).

5.3 Databases

The integration of ostracod data into bio- and geoscience databases has revolutionized research in palaeontology and (palaeo)ecology. By integrating diverse datasets, databases have facilitated comprehensive analyses of ostracod taxonomy, distribution, and palaeoenvironments. Given available data on geochemistry and further metadata, it complements research and helps to compare with "background" statuses of aquatic systems for future integration of ostracods into water management strategies. An extensive review on ostracods in databases is available in the work by Huang et al. (2022).

Databases offer several advantages, including efficient data organization, integration of diverse datasets for comprehensive analyses, promotion of collaboration through data sharing, facilitation of complex data analysis, and, potentially, support for decision-making processes in various sectors. However, possible problems such as data quality, standardizing data formats, and handling large data volumes, do exist. Despite these challenges, databases remain invaluable tools for advancing scientific knowledge and addressing complex geoscientific questions.

5.4 Controversy in identification of indicator species

Sometimes, disagreements about the response of indicator species, such as *Cypridopsis vidua* and *Prionocypris zenkeri*, are evident in the literature. While some studies, like Mezquita et al. (1999a), Külköylüoğlu (2004) and Iglikowska and Namiotko (2012) suggest that *Cypridopsis vidua* is sensitive to organic pollution and prefers highly oxygenated water, others such as Rossi et al. (2003), Külköylüoğlu (2005b) and Martínez-García et al. (2015) argue that it is resistant to pesticides like carbofuran and endosulfan and can tolerate wide range of low and high dissolved oxygen.

Similarly, *Prionocypris zenkeri* is described as both sensitive to discharges and heavy metals in one study (Iepure et al., 2014) and tolerant to pollution in another (Yavuzatmaca et al., 2024). The conflicting findings regarding the sensitivity of indicator species like *Cypridopsis vidua* and *Prionocypris zenkeri* to various pollutants underscore the challenges of relying solely on literature references on ecology of these species. We strongly believe that it is essential to complement literature reviews on ecology of the species with empirical data collection on parameters like total organic carbon and heavy metals to validate findings and draw accurate conclusions regarding environmental assessments. This approach not only enhances the credibility of the study but also provides a comprehensive understanding of the ecosystem under investigation. The controversy surrounding the tolerance levels of the same species in aquatic environments can stem from various factors related to environmental conditions, genetic variability, and methodological differences in research. Individual organisms may show phenotypic plasticity in response to environmental changes. This could potentially be a very valuable study on *Cypridopsis vidua* and/or *Pryonocypris zenkeri* from two different environments for developmental evolutionary biologists. This inconsistency highlights the need for further research and standardization in the identification of indicator species to accurately assess environmental conditions.

6 Further research and conclusions

To grasp the full potential of ostracods, it is imperative to delve into the complexities of their ecological dynamics. Furthermore, their responses and species composition can vary significantly by region, making it challenging to establish universal standards for environmental assessment. Thus, more information about regional faunas is urgently needed. Even though there is a positive tendency in the past decades with more databases, there is still a lack of comprehensive taxonomic atlases because of biogeographical differences among taxa, further complicating their use as bioindicators. Also, ostracod abundance can fluctuate seasonally, potentially affecting their reliability as bioindicators. Implementing a consistent water quality monitoring program with ostracods requires several years of continuous sampling and verification to ensure reliable results. Further research is essential to understand the ecological implications of invasive ostracod species, their transport, and their role in freshwater ecosystems amid changing climates. Insufficient documentation of present-day ostracod distribution hampers the detection of invasive species, what underscores the need for comprehensive faunistic studies as well. Moreover, future efforts could potentially find human-induced impacts on deep-sea ostracods, potentially enabling us to use them as bio- and palaeobio-indicators.

We compiled tables with sensitive and resistant species of ostracods applicable for tracing anthropogenic impacts based on the screened published records (appendix Tab. 1, 2). Additionally, it would be very useful to identify sensitive and tolerant taxa based on the genus level instead of the species level, e.g. *Loxoconcha* seems to be ecologically tolerant and *Callistocythere* sensitive. Such a genus level-based classification would allow the transfer of classification schemes to poorly investigated regions and into the geological past.

First ostracod-based water quality benchmarks studies showed how ostracods effectively reflect anthropogenic pressure, what derived from extensive datasets correlating ostracod associations with pollution levels. However, there is a notable scarcity of geochemical analyses focusing on heavy metals in inland waters, highlighting the need for more field-based research to comprehend their implications on ostracods in natural ecosystems.

Live-dead comparisons of ostracod communities offer a valuable tool for assessing environmental status, identifying local species losses and unravelling recovery dynamics, thus overcoming the limitations of solely relying on present-day observations. This is a great advantage of ostracods compared to bioindicators without mineralised skeletons. The impact of overall organic input on ostracod communities varies with its level, initially boosting species richness and abundance. However, as eutrophication takes hold, species richness declines and only tolerant species endure reaching peak abundance but leading to eventual mortality under hypoxic conditions. Industrial wastes may not consistently decrease ostracod diversity, sometimes only altering the taxonomic composition of assemblages.

Research on oil spill impacts underscores their devastating effect on ostracods, resulting in widespread mortality. The timing of sampling is crucial for assessing recovery extents, with some taxa showing full restoration after prolonged durations. However, long-term ecosystem effects persist, highlighting dependence on hydrological regimes and various influencing factors. Ostracods exhibit similar response patterns to high concentrations of heavy metals, akin to oil spills or nuclear pollution incidents, with increased metal levels causing declines in abundance and species richness. Hydrographic changes and habitat degradation significantly impact ostracod populations, disrupting ecological balance and altering distribution and diversity. However, altered habitats may foster resilient ostracod communities depending on local situations.

Ostracod shell chemistry can serve as a valuable tool for reflecting heavy metal pollution over time, aiding in understanding contemporary impacts and reconstructing historical trends. Promising outcomes from ex-situ experiments emphasize ostracods' potential in water quality monitoring, revolutionizing current practices for more effective water management.

Moreover, as it was shown in many mentioned studies (electronic appendix Tab. A, B & C), ostracods are very sensitive to environmental changes, capable of responding to subtle shifts in water quality, temperature, and sediment characteristics. Their well-preserved shells in sediment provide valuable historical data about past environmental conditions, and they inhabit a wide range of aquatic habitats, spanning freshwater, brackish water, and marine environments. Future research on ostracods holds promise in harnessing them as living tracers for human impacts.

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Appendix: List of indicator species

Appendix. Table 1. *Ostracod species indicating organic and hydrochemical pollution levels of inland waters.*

Species	Study area	Indication	References
Bradleycypris sp.	Italy	Organic pollution tolerant	Pieri et al. (2009)
Candona candida (O.F. Müller, 1776)	Romania, Poland and Finland	Sensitive to organic pollution, discharges and specifically As	Iglikowska and Namiotko (2012), Iepure et al. (2014)
Cavernocypris subterranea (Wolf, 1920)	Czech Republic	Eutrophication and heavy metals tolerant	Kantorek (1992)
Cyclocypris ovum (Jurine, 1820)	England, Italy	Hydrochemical and organic pollution tolerant	Boomer & Attwood (2007), Pieri et al. (2009)
Cyclocypris serena (Koch, 1838)	Czech Republic	Eutrophication and heavy metals tolerant	Kantorek (1992),
Cypria ophtalmica (Jurine, 1820)	Czech Republic, England, Turkey, Italy	Hydrochemically, heavy metal and organic pollution tolerant	Kantorek (1992), Boomer & Attwood (2007), Dügel et al. (2008), Pieri et al. (2009), Külköylüoğlu et al. (2014)
Cyprideis torosa (Jones, 1850)	Turkey	Organic pollution tolerant	Percin-Pacal et al. (2018)
Cypridopsis vidua (Müller, 1776)	Spain, Finland, Poland, Turkey	Sensitive to organic pollution and discharges	Mezquita et al. (1999a), Iglikowska and Namiotko (2012), Külköylüoğlu 2004
	Czech Republic, Italy, Turkey, Spain	Resistant to organic pollution, heavy metals, pesticides such as carbofuran and endosulfan	Kantorek (1992), Rossi et al. (2003), Külköylüoğlu (2005b), Martínez-García et al. (2015)

Cypris bispinosa Lucas, 1849	Spain	Sensitive to discharges	Castillo-Escrivà et al. (2016)
Dolerocypris fasciata (G. W. Müller, 1776)	Czech Republic	Eutrophication and heavy metals tolerant	Kantorek (1992)
Eucypris virens (Jurine, 1820)	Spain, Turkey, Poland, Finland	Organic pollution tolerant	Roca et al. (2000), Külköylüoğlu (2004), Külköylüoğlu (2005b), Iglikowska and Namiotko (2012), Martínez-García et al. (2015)
Fabaeformiscandona caudata (Kaufmann, 1900)	Czech Republic, China	Resistence to high concentrations of Pb and other heavy metals	Kantorek (1992), Wang et al. (2022b)
Herpetocypris brevicaudata Kaufmann, 1900	Spain, Romania	Sensitive to discharges and specifically As	Mezquita et al. (1999a), Iepure et al. (2014)
Herpetocypris chevreuxi (Sars, 1896)	Turkey	Low oxygen tolerant	Dügel et al. (2008)
Heterocypris incongruens (Ramdohr, 1808)	USA, Spain, Israel, Italy, Turkey, China	Organic pollution tolerant, human activities including road constructing and livestock	Külköylüoğlu (1999), Mezquita et al. (1999a, 1999b), Rosental & Ortal (1983), Rosental et al. (2000), Roca et al. (2000), Rossi et al. (2003), Külköylüoğlu (2005b), Castillo-Escrivà et al. (2016), Zhai et al. (2022)
Heterocypris salina (Brady, 1868)	Spain, Israel, Turkey	Organic pollution tolerant	Mezquita et al. (1999a, 1999b), Rosental & Ortal (1983), Rosental et al. (2000), Altinsaçlı (2004) Yavuzatmaca et al. (2024)
Ilyocypris bradyi Sars, 1890	Spain, Israel, England, Romania	sensitive to discharges and specifically Cu, Mn, Ni	Mezquita et al. (1999a), Rosental & Ortal (1983), Rosental et al. (2000), Boomer & Attwood (2007), Iepure et al. (2014)
Ilyocypris echinata Huang, 1979	China	Resistant to high concentrations of Pb	Wang et al. (2022b)
Ilyocypris inermis	Italy	Sensitive to discharges	Pieri et al. (2009)

Kaufmann, 1900			
Limnocythere floridensis Keyser, 1975	Bahamas	Sensitive to discharges	Michelson et al. (2018)
Limnocythere inopinata (Baird, 1843)	China, Spain	Eutrophication tolerant	Wang et al. (2005), Martínez-García et al. (2015)
Neglecandona neglecta (G.O. Sars, 1887)	Czech Republic, Turkey	Eutrophication and heavy metals tolerant	Kantorek (1992), Altinsaçlı (2004), Külköylüoglu (2005), Dügel et al. (2008)
	Israel, Turkey	Sensitive to discharges	Rosental & Ortal (1983), Rosental et al. (2000), Külköylüoğlu et al. (2014)
Notodromas persica (Koch, 1838)	Italy	Hypoxic or anoxic conditions tolerant	Pieri et al. (2009)
Physocypria kraepelini G. W. Müller, 1903	Turkey, China	Resistant to discharges	Külköylüoğlu et al. (2014), Zhai et al. (2022)
Potamocypris variegata (Brady & Norman, 1889)	Italy	Organic pollution tolerant	Pieri et al. (2009)
Potamocypris villosa (Jurine, 1820)	Spain	Eutrophication tolerant, discharges, coal-burning atmospheric pollution	Martínez-García et al. (2015)
Potamocypris zschokkei (Kaufmann, 1900)	Czech Republic	Eutrophication and heavy metals tolerant	Kantorek (1992),
Prionocypris zenkeri (Chyzer & Toth, 1858)	Romania	Sensitive to discharges and specifically As, Cu, Mn, Ni	Iepure et al. (2014)
	Turkey	Tolerant to pollution	Yavuzatmaca et al. (2024)
Pseudocandona compressa	Turkey	Redox potential tolerant	Dügel et al. (2008)
Psychrodromus olivaceus (Brady &	Czech Republic	Eutrophication and heavy metals tolerant	Kantorek (1992)

Norman, 1889)			
Sarscypridopsis aculeata (Costa, 1847)	Israel, Spain,	Sensitive to discharges	Rosental & Ortal (1983), Rosental et al. (2000), Martínez-García et al. (2015)
Sarscypridopsis lanzarotensis (Mallwitz, 1984)	Spain	Sensitive to discharges	Mezquita et al. (1999a)
Stenocypris major (Baird, 1859)	Italy, India	Particularly resistant to pesticides such as carbofuran and endosulfan and heavy metals	Rossi et al. (2003), Hegde et al. (2021)

Appendix Table 2. *Ostracod species indicating organic and hydrochemical pollution levels of coastal waters.*

Species	Distribution	Indication	References
Alocopocythere reticulata (Hartmann, 1964)	Egypt	Pollution tolerant	El-Kahawy et al. (2021)
Aurila sp.	Brazil	Sensitive to discharges	Vilela et al., 2003
Australoloxoconcha favornamentata Hartmann, 1974	South Africa	Sensitive to discharges	Schmitz et al. (2024)
Bicornucythere bisanensis (Okubo, 1975)	Japan, Russia, Hong Kong SAR	Hypoxic or anoxic conditions tolerant	Yasuhara et al. (2003), Schornikov & Zenina (2014), Yasuhara et al. (2007), Irizuki et al. (2015, 2022), Hong et al. (2017)
Bicornucythere sp.	Japan	Hypoxic or anoxic conditions tolerant	Yasuhara et al. (2007)
Callistocythere alata Hanai, 1957	Japan	Sensitive to discharges	Yasuhara et al. (2003), Irizuki et al. (2015), Irizuki et al. (2022)
Callistocythere	Brazil	Sensitive to discharges	Vilela et al., 2003

sigmocostelata Coimbra, Sanguinetti & Bittencourt-Calagno, 1995			
Carinocythereis whitei (Baird, 1850)	Italy	Organic and heavy metal pollution tolerant	Salvi et al. (2020)
Cushmanidea turbida (Müller, 1894)	Italy	Pollution tolerant	Aiello et al. (2020)
Cyprideis sp.	Brazil	Pollution tolerant	Vilela et al. (2003)
Cyprideis torosa (Jones, 1850)	Coast of England, the Netherlands and the southern coasts of the Baltic Sea, Turkey, Italy, Egypt, Morocco, France, Spain	Organic pollution, heavy metals, hydrocarbons tolerant, fecal discharges	Sywula et al. (1995), Samir (2000), Ruiz et al. (2006b), Barut et al. (2015), Yümün et al. (2016), Salel et al. (2016), Ferraro et al., (2017), El-Kahawy et al. (2021),
Cytheridea neapolitana Kollmann, 1960	Italy	Organic and heavy metal pollution tolerant	Salvi et al. (2020)
Cytheroma dimorpha Hartmann, 1964	Egypt	Pollution tolerant	El-Kahawy et al. (2021)
Cytheromorpha acupunctata (Brady, 1880)	Japan, Russia	Hypoxic or anoxic conditions tolerant	Yasuhara et al. (2007), Schornikov & Zenina (2014), Irizuki et al. (2015, 2022)
Cytheromorpha curta Edwards, 1944	USA	Hypoxic or anoxic conditions tolerant	Cronin and Vann (2003)
Ghardaglaia triebeli Hartmann, 1964	Egypt	Pollution tolerant	El-Kahawy et al. (2021)
Hemicytheridea reticulata Kingma, 1948	Hong Kong SAR	Sensitive to Pb	Hong et al. (2019)
Heterocypris salina (Brady, 1868)	Turkey	Pollution tolerant	Yümün et al. (2016)
Howeina	Russia	Hypoxic or anoxic	Schornikov & Zenina

camptocytheroidea Hanai, 1957		conditions tolerant	(2014)
Howeina sp. 5	Russia	Hypoxic or anoxic conditions tolerant	Schornikov & Zenina (2014)
Jugosocythereis borchersi (Hartmann, 1964)	Egypt	Pollution tolerant	El-Kahawy et al. (2021)
Krithe japonica Ishizaki, 1971	Japan	Sensitive to discharges, eutrophication/hypoxia	Irizuki et al. (2011, 2015, 2022)
Leptocythere ramosa (Rome, 1942)	Italy	Organic and heavy metal pollution tolerant	Salvi et al. (2020)
Loxoconcha bispinosa Kajiyama, 1913	Japan	Hypoxic or anoxic conditions tolerant	Irizuki et al. (2015, 2022)
Loxoconcha elliptica Brady, 1868	Spain, Turkey	Organic and fertilizers pollution tolerant	Ruiz Munoz et al. (1997), Ruiz et al., (2004), Martínez-García et al. (2013), Yümün et al. (2016)
Loxoconcha malayensis Zhao & Whatley, 1989	Hong Kong SAR	Hypoxic or anoxic conditions tolerant	Hong et al. (2019)
Loxoconcha parvifoveata Hartmann, 1980	New Zealand	Organic pollution tolerant	Eagar (1999)
Loxoconcha rhomboidea (Fischer, 1855)	Morocco	Organic and heavy metal pollution tolerant	Ruiz et al. (2006b)
Loxoconcha spp.	Greece, USA, Italy, Spain	Pollution tolerant	Alvarez Zarikian et al. (2000), Triantaphyllou et al. (2005), Ruiz et al. (2006a), Salvi et al.

			(2015, 2020), Aiello et al. (2021)
Loxoconcha viva Ishizaki, 1968	Japan	Hypoxic or anoxic conditions tolerant, geochemical pollution	Yasuhara et al. (2007), Irizuki et al. (2015)
Loxocorniculum ghardaquensis (Hartmann, 1964)	Egypt	Pollution tolerant	El-Kahawy et al. (2021)
Moosella striata Hartmann, 1964	Egypt	Pollution tolerant	El-Kahawy et al. (2021)
Neomonoceratina delicata Ishizaki & Kato, 1976	Hong Kong SAR	Heavy metal pollution and increased turbidity tolerant	Hong et al. (2019)
Palmoconcha turbida (Müller, 1894)	Morocco, Japan, Tunisia, Spain	Organic and heavy metal pollution tolerant	Bodergat et al. (1998), Ruiz et al. (2006b), Salel et al. (2016)
Paracypris complanata (Brady & Robertson, 1869)	Spain, Italy	Pollution tolerant	Castillo-Escrivà et al. (2016), Salvi et al. (2015)
Paracypris sp.	Brazil	Sensitive to discharges	Vilela et al. (2003)
Paracytheroma asamushiensis (Ishizaki, 1971)	Russia	Hypoxic or anoxic conditions tolerant	Schornikov & Zenina (2014)
Perissocytheridea estuaria Benson & Maddocks, 1964	South Africa	Sensitive to discharges	Schmitz et al. (2024)
Pterygocythereis jonesii (Baird, 1850)	Italy	Organic and heavy metal pollution tolerant	Salvi et al. (2020)
Semicytherura incongruens (Müller, 1894)	Italy	Organic and heavy metal pollution tolerant	Salvi et al. (2020)
Semicytherura rarecostata Bonaduce, Ciampo & Masoli, 1976	Italy	Hypoxic or anoxic conditions tolerant	Aiello et al. (2021)

Semicytherura sulcata (Müller, 1894)	Italy	Pollution tolerant	Aiello et al. (2020)
Sinocytheridea impressa (Brady, 1869)	Vietnam, Hong Kong SAR	Pollution tolerant	Tan et al. (2021), Hong et al. (2019)
Spinileberis quadriaculeata (Brady, 1880)	Russia	Hypoxic or anoxic conditions tolerant	Schornikov & Zenina (2014)
Spinileberis? sp.	Russia	Hypoxic or anoxic conditions tolerant	Schornikov & Zenina (2014)
Stigmatocythere roesmani (Kingma, 1948)	Hong Kong SAR	Sensitive to Pb	Hong et al. (2019)
Tenedocythere sp.	Republic of Kiribati	Organic pollution tolerant	Eagar (2000)
Touroconcha marcida (Brady, 1890)	Republic of Kiribati	Organic pollution tolerant	Eagar (2000)
Xestoleberis communis Müller, 1894	Greece	Sensitive to discharges	Triantaphyllou et al. (2005)
Xestoleberis rhomboidea Hartmann, 1964	Egypt	Sensitive to discharges	El-Kahawy et al. (2021)
Xestoleberis sp.	Brazil, Italy	Sensitive to discharges	Vilela et al. (2003), Salvi et al. (2015), Aiello et al. (2021)

Declaration of interests

☒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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Highlights

- Human activities impact aquatic ecosystems, requiring reliable bioindicators.

- Ostracods, small crustaceans, are sensitive to pollutants, making them excellent indicators.

- The review covers ostracod responses to anthropogenic stresses globally.

- Ostracods indicate pollution from nutrients, heavy metals, fertilizers, oil spills, and nuclear pollution.