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Review

A critical review of pollution active biomonitoring using sentinel fish: Challenges and opportunities☆

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ABSTRACT

Water pollution is a significant threat to aquatic ecosystems. Various methods of monitoring, such as *in situ* approaches, are currently available to assess its impact. In this paper we examine the use of fish in active biomonitoring to study contamination and toxicity of surface waters. We analysed 148 previous studies conducted between 2005 and 2022, including both marine and freshwater environments, focusing on the characteristics of the organisms used as well as the principal goals of these studies. The main conclusions we drew are that a wide range of protocols and organisms have been used but there is no standardised method for assessing the quality of aquatic ecosystems on a more global scale. Additionally, the most commonly used developmental stages have been juveniles and adults. At these stages, the most frequently used species were the fathead minnow (*Pimephales promelas*) and two salmonids: rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*). Few studies used earlier stages of development (embryos or larvae), mostly due to the difficulty of obtaining fish embryos and caging them in the field. Finally, we identified research gaps in active biomonitoring for water quality assessment which could indicate useful directions for future research and development.

1. Introduction

Aquatic ecosystems are confronted with a wide range of contaminants including metals, hydrocarbons, detergents, pesticides and pharmaceutical compounds. Furthermore, although new potentially toxic substances arrive regularly on the market, knowledge about the extent of contamination by these substances and their repercussions remains limited (Reid et al., 2019). In Europe, the objective of the Water Framework Directive (WFD), adopted by members of the European Union in 2000 (European Commission, 2000), is for water bodies to reach and maintain a good ecological and chemical status. To achieve this, water contamination must be monitored and controlled. Evaluation of such contamination is made by establishing a list of substances to monitor in the water, biota or sediment. Chemical analyses can provide valuable information on the contaminants present in aquatic systems. However, because of their large number, sometimes low concentration and the fact that many of them are unknown, the present capacities and efficacy of chemical analyses remain limited (Brack et al., 2016). The recent paper by Persson et al. (2022) emphasises that, because increasing emissions and synthesis of new compounds surpass our current monitoring and assessment capabilities, the planetary limit for new chemicals has been exceeded, leaving a significant gap in our knowledge about the presence and effects of these substances in ecosystems. Existing testing methods need to be improved and new ones developed for better monitoring and of these substances and their toxicity to aquatic organisms, since aquatic systems are the main sinks for pollutants (Brack et al., 2016).

The urgent need to address this environmental challenge has led to an exploration of innovative approaches, including the integration of biomonitoring into environmental management tools. Biomonitoring can be defined as the use of living organisms as sentinels in the surveillance of water quality to evaluate temporal or spatial changes in contamination and toxicity in an effluent or receiving water body (Wepener, 2013). The use of living sentinel organisms, makes it possible to integrate the diversity of bioavailable pollutants present in the environment with the assessment of their toxicity (Besse et al., 2012; Crane et al., 2007). We generally distinguish two approaches: passive biomonitoring (PBM) and active biomonitoring (ABM).

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In passive biomonitoring, indigenous organisms are used as indicators of environmental quality. These can provide information on the amount and fluctuation of pollutants over time through measurement of biomarker responses and bioaccumulation levels. However, this approach has limitations, as described by Smolders et al. (2003). The capture of organisms in the wild can be difficult and depends on their geographical distribution, particularly in the present context of global biodiversity decline. The history and passive exposure of these sentinel organisms is unknown, which complicates interpretation. Some factors such as age, size, reproductive cycle or nutritional status may affect the response of several commonly used toxicity indicators (van der Oost et al., 2003). Additionally, PBM has so far been mainly used in marine environments and far less in freshwater systems (Besse et al., 2012; OSPAR Commission, 2013).

Active biomonitoring (ABM) is a more recent approach and is defined as the translocation of organisms from a pristine site to a more impacted one, followed by the quantification of their biological, physiological and biochemical responses to the water quality (Wepener, 2013). Active biomonitoring allows measurements of life-history traits such as feeding, growth and survival to be used as toxicity markers (Dedourge-Geffard et al., 2009; Lopes et al., 2020). By using organisms from a known reference population, this approach minimises the influence of potentially confounding factors (such as exposure time or differing life histories of wild individuals) and permits us to use calibrated organisms, allowing a better replicability and comparison between sites (Smolders et al., 2003; Wepener, 2013). It provides an integrative evaluation of environmental changes, making it a relevant method for early warning, risk assessment and ecosystem conservation. There has been much development of ABM methods using invertebrates. In marine environments, for example, methods of ABM using mussels (*Mytilus galloprovincialis*) have been implemented (Goldberg, 1975). In continental ecosystems, species groups that can be used include gammarids (e.g. *Gammarus fossarum*) and bivalves (e.g. *Dreissena polymorpha*) (Besse et al., 2012; Binelli et al., 2015). Their diverse taxa, wide distribution and easy maintenance allow valuable insights in ecosystem surveillance (Ferrari et al., 2013).

Active biomonitoring methods using fish exist for freshwater system evaluation but remain difficult and limited, as described by several authors (Besse et al., 2012; Liber et al., 2007; Oikari, 2006). Fish represent an interesting model for ABM as they are widely distributed throughout aquatic ecosystems. They play a key ecological role in maintaining ecosystem balance and are considered a biological quality element (BQE), monitored by the WFD (European Commission, 2000). Additionally, fish are physiologically and metabolically closer to mammals than are invertebrates. As the WFD also aims to protect human health, the use of fish rather than invertebrates can offer relevant information about the impact of pollution on vertebrates. Fish populations are already considered as indicators of aquatic ecosystem health, as changes in their abundance or diversity can indicate environmental disturbances (European Commission, 2000; Roset et al., 2007). However, for ethical and population density reasons, fish sampling approaches are increasingly limited and constrained. Moreover, results from sampled fish cannot be directly related to specific sources of stress such as chemical contamination and toxicity. Thus, it seems crucial to improve ABM methods and techniques using fish species, as these would enable a more comprehensive understanding and evaluation of aquatic system quality.

In this context, the purpose of the present paper is a literature review of publications concerning the use of fish in active biomonitoring. We focused on how fish are presently used and what environmental questions their use is intended to answer.

2. Review method

For this study, we retrieved all relevant publications in English referenced in Web of Science starting from 2005, as the last review on fish caging for environmental assessment dates from 2006 (Oikari, 2006). The literature extraction was performed in January 2023, using the PRISMA method (Preferred Reporting Items for Systematic reviews and Meta-Analyses) for the systematic review, in order to reduce the risk of error and increase transparency about the research and screening of literature conducted (Page et al., 2021).

Literature extraction was performed by using the following combinations of requests and keywords to extract all papers related to the use of fish for the evaluation of environmental contamination using active biomonitoring methods.

– Fish (topic) AND contaminant/contamination (topic) AND caged/caging (all)
– Fish (topic) AND contamination/contaminant (topic) AND bypass/by-pass (all) AND exsitu/ex-situ (all) OR semi-field.

From these two queries, we obtained a total of 346 results, among which 341 were retained (five duplicates and non-accessible papers were removed). After a quick reading, we excluded 216 more papers based on several criteria (PRISMA analysis is detailed in Supplementary Material S1). Of these, 61 papers were excluded because they were published before 2005 and we wished to confine our analysis to literature published after the analysis by Oikari (2006), 5 were reviews, 59 were studies about fish farming, 24 were about passive rather than active biomonitoring approaches, and 36 used taxa other than fish. Finally, 6 papers not dealing with contamination, 6 with a lab-only approach and 19 with a chemistry-only approach were excluded, leaving 126 experimental papers for our analysis.

Given that this first extraction provided us with a very limited number of papers dealing with early life stages (only 2), we performed a second extraction specifically to obtain papers on studies using fish early life stages. We made this second extraction in February 2023 on Web of Science, without applying any publication date limitations. We used the following requests (see S1: Identification of studies via other methods): (i) embryos AND fish AND caged or caging, (ii) embryos AND fish AND field AND contamina* (iii) early AND life AND stage AND fish AND field AND contamina*, (iv) early AND life AND stage AND fish AND *in situ* AND contamina* and, finally, (v) early AND life AND stage AND fish AND caged or caging. This extraction provided 23 new papers using fish early life stages in ABM (published between 1993 and 2023), leading to a final paper corpus of 148 studies. These 148 papers were analysed using five criteria (the complete list of 148 references is given in S2, and an exhaustive table for literature analysis in S3). Our aim was to provide exhaustive information on the remaining articles. We defined these criteria according to the five scientific questions we address in this work: (i) What are the characteristics of the organisms used (species, family, developmental stage, origin) and reason for this choice? (ii) What questions did the authors set out to answer? More specifically, what kind of pressure did they want to study?, (iii) What devices and tools (experimental design, reference) did the authors use to answer this question? (iv) From a technical viewpoint, are there any similarities or differences across the experimental designs used? (v) Were the authors subject to any experimental constraints and, if so, what were they?

3. Use of fish in environmental biomonitoring

3.1. Species

An important criterion in the choice of species is the local and temporal availability of organisms (Oikari, 2006). Using non-native species can present a risk in case of escape to the wild, with potential effects on the ecosystem; their use may even be prohibited by law. Furthermore, the use of native species improves ecological relevance. Fish farming makes it possible to obtain individuals on a regular basis with control over certain characteristics (gender, size, reproductive status, etc.). It has also been suggested as a way to obtain calibrated organisms with a known background (Oikari, 2006) to avoid any influence of past exposure on fish responses. In our review, we observed that the species used were mainly native to the countries where the experiments were conducted. In such cases, it is recommended to choose species available close to the experimental site to reduce the time taken and stress generated by transport and handling. Of the retrieved studies, 76% used fish from farms, while 19% used wild organisms. The choice of the latter could sometimes be explained by a particular interest that authors had in a species (e.g. endemic species) that cannot be easily bred or maintained in captivity. Some other criteria, such as size, season or stress tolerance could influence species choice, depending on the experimental design. For example, using warm-water or tropical species, such as zebrafish or Nile tilapia seems impossible during the winter or in cold parts of the world.

Of the 64 species used across the studies in the review, 22 were used more than once, accounting for 101 of the studies (Fig. 1). The three most frequently used species were the fathead minnow (*Pimephales promelas*), rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*). The fathead minnow was exclusively used in North America (USA, Canada), and featured in 40% of the studies in our dataset where experiments were carried out. Fathead minnow is found widely in the wild and is easily bred in captivity. Moreover, this species is well known,

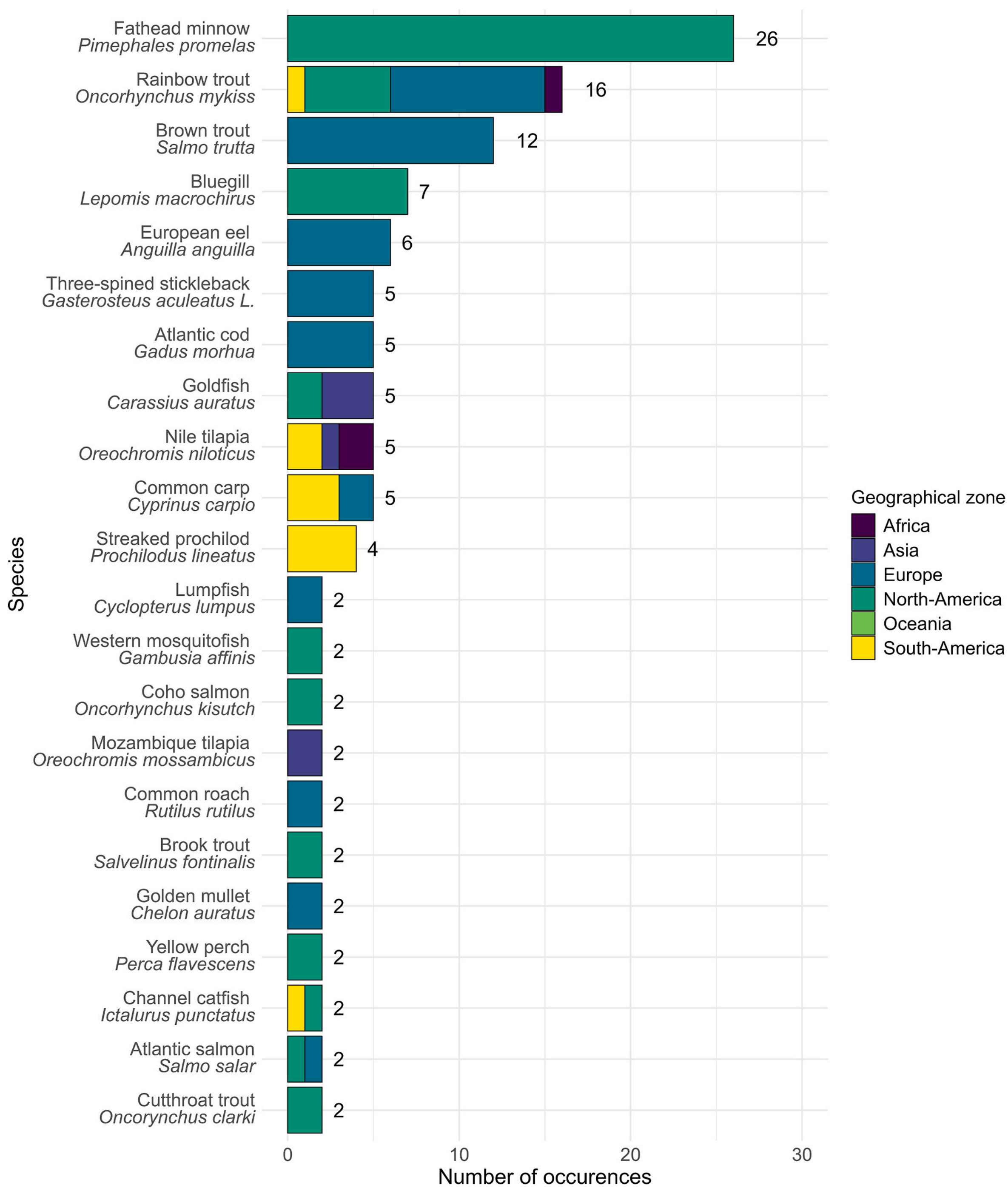

Fig. 1. Number of active biomonitoring studies using fish species (including all species used more than once). Each colour corresponds to the continent where the experiment was conducted. Total numbers of studies for each continent in this review: Africa (3), Antarctica (1), Asia (11), Europe (55), North America (59), Oceania (3), South-America (16). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

commonly used in ecotoxicological and ecological studies in North America and has many available biomarkers (Ankley & Villeneuve, 2006). This species is used in various ecotoxicological tests, particularly for assessing endocrine disruption (OECD, 2012) and is thus extensively deployed across North America for such evaluations. For example, Writer et al. (2010) assessed water quality of 11 lakes in Minnesota using this species, revealing endocrine disruption in a majority of the sites, whatever the local human activities. Moreover, as waste-water treatment plant effluents can be a source of endocrine disruptors in the environment, several studies used fathead minnows and their biomarkers to evaluate associated water contamination (Lazaro-Cote et al., 2018; Lefebvre et al., 2017). Rainbow trout is native to the North Pacific but has been widely introduced in other parts of the globe (including Europe) for consumption and fishing (Toussaint et al., 2016). Its widespread presence and ease of breeding, as well as its frequent use in ecotoxicology and lab studies, could explain why this species has so often been used in field caging experiments on several continents. Rainbow trout biomarkers used in ABM include cytochrome P4501A (CYP1A) expression or activity (Abrahamson et al., 2007; Brammell et al., 2010; Jonsson et al., 2010) and endocrine disruption (Franco et al., 2020). They may be used in multi-biomarker approaches (Beghin et al., 2022; Orrego et al., 2006; Schweizer et al., 2022). Brown trout was the third most commonly used species in our review. It is native to Europe and is farmed for human consumption. It is also frequently used in ecotoxicology studies, which explains its frequent use in active biomonitoring approaches. In the review we found this species had been used in Norway (Allan et al., 2013), France (Bony et al., 2008) and Switzerland (Burkhardt-Holm et al., 2008).

Model species such as zebrafish (*Danio rerio*) and Japanese medaka (*Oryzias latipes*), are widely used in laboratory ecotoxicology and easily purchased, which are important criteria in species choice, but these fish are rarely used in *situ* monitoring. Their natural distributions are limited to Asia, which decreases their interest and ecological relevance for the rest of the world. This could be the reason why zebrafish and Japanese medaka were each only used once among the studies covered by our review (Luo et al., 2009; Rodriguez-Fuentes et al., 2012).

Another interesting observation that emerged from our review is that, for ABM, salmonids (trouts, salmons) and cyprinids (minnows, goldfishes, carps) are the most two commonly used families (following Linnaeus' classification), with each one representing one-third of the total species occurrences. Cyprinids and salmonids are frequently among the most abundant fish in freshwater ecosystems, especially in North America and Europe (Nelson et al., 2016). These families have wide geographical distributions and can be found in a variety of aquatic systems, making them useful for biomonitoring studies. Their species are also frequently fished or reared for consumption. They are extensively bred and farmed for the same reasons, making them easy to purchase, even at early life stages. This finding also highlights the striking differences in numbers of ABM studies among the continents: 114 of the studies were realized in Europe and North America whereas in Africa and Oceania only three each were conducted.

Across the 148 different studies we retrieved, 64 fish species were used in field caging experiments to assess water quality. Of these 64 species, 47 were freshwater and 15 marine, according to the environments authors wanted to study. The European eel (*Anguilla anguilla*) and coho salmon (*Oncorhynchus kisutch*) are the only two species that were used in both habitats, depending on the study. These two species are diadromous migratory fish that can live in either fresh or marine water, according to their developmental stage.

3.2. *Applications of active biomonitoring in fish*

We particularly wanted to know whether the authors of the studies in our review had specific primary objectives, especially whether their experiments targeted predetermined sources of pollution on a local scale or whether their studies were designed to help improve field exposure methods. There were no differences in the main tendencies among continents.

3.2.1. *Habitats studied*

Fish are used in active biomonitoring in all types of environments, such as lakes, rivers, estuaries or the sea. The majority of studies in our review were, however, conducted in continental aquatic ecosystems (85%), corresponding to the greater number of freshwater species used mentioned above. This could be due to the continental locations of the majority of contamination sources, which concentrate pollutants more in fresh than in marine waters. Only 22 studies were conducted in marine waters, four were conducted in estuaries and the remainder along the coast or in known polluted sites. A large proportion of these focused on areas with a significant major input of freshwater and, consequently, the contaminants associated with continental human activities. Among the studies, the potential contamination sources were varied: effluents from chemical plants (Guilherme et al., 2008a, 2008b; Pereira et al., 2010), offshore oil installations (Abrahamson et al., 2008; Brooks et al., 2011), harbours (Kerambrun et al., 2012) or bays/estuaries directly connected to rivers from the continent (Bugel et al., 2011; Daverat et al., 2012; Jung et al., 2008; Kazour et al., 2020; Kelley et al., 2011). The only experiments conducted in open water examined offshore oil installations, facilities that are often located far from the coast (Abrahamson et al., 2008; Brooks et al., 2011; Hylland et al., 2008).

One factor that can also influence the choice of both experimental site and equipment design is the possibility of vandalism, tampering or theft, which can lead with biases or destruction of the experimental devices during exposure (Oikari, 2006). For example, in the study of Gauthier et al. (2006), experimental sites were chosen because of the privacy they offered in order to limit the possibility of vandalism. Vandalism risk was also cited as a limitation for *in situ* exposures in the study of Burton et al. (2005). It has been identified as one of the major constraints for authors designing ABM studies because it limits the sites where experimentation is possible (Wepener, 2008).

3.2.2. *Study goals*

Among the 148 studies, the objective of more than half was toxicity assessment of waters for fish health. A small proportion (15%) were designed to reveal the presence of just one or a few specific pollutants in water. A smaller number (10%) were conducted with regard to specific technological accidents, such as the Fukushima nuclear accident (Teien et al., 2021; Yamamoto et al., 2014) or accidental oil spills (Roberts et al., 2006).

Various types of pollution source were studied, with wastewater treatment plant (WWTP) effluents being the most frequent. This objective accounted for 25% of the studies designed to examine a specific type of pressure. Because these plants are not able to entirely remove all pollutants from wastewater, they represent one of today's greatest sources of contamination (Kolpin et al., 2002). Questions have been raised about the toxicity of these effluents for aquatic ecosystems and fish populations in every part of the world. In our review, 22 studies were devoted to the impact of WWTP effluents in North America alone, mainly on native species such as fathead minnow (Cavallin et al., 2021; Perkins et al., 2017; Sellin Jeffries et al., 2009), rainbow trout (Franco et al., 2020; Ings et al., 2011) and bluegill (Baker et al., 2014; Du et al., 2019; McLean et al., 2019).

We also retrieved seven papers on WWTP effluent toxicity in Europe that used other species: brown trout (Burki et al., 2006; Vincze et al., 2015) and the three-spined stickleback (*Gastrosteus aculeatus)* (Catteau et al., 2021). The latter is a European fish species (Nelson et al., 2016) commonly used in ABM, particularly in France. Biomarkers for endocrine disruption were developed for this species, making it suitable for effluent toxicity evaluation (Sanchez et al., 2007, 2008). In our review, three-spined stickleback was used in two studies that were part of a research project aiming to develop a multi-biomarker approach in France.

In South America, we found only one similar study, which assessed the toxicity of untreated sewage effluent using a native species, the streaked prochilod (*Prochilodus lineatus*) (Pérez et al., 2018). We did not find any studies made on the African continent in our literature search. Toxicity assessments of other types of effluents, such as those from mines (Bougas et al., 2016) or industry (Al-Arabi et al., 2005; Lunardelli et al., 2018; Santos et al., 2006) were less frequent. Considering pollution over larger geographical zones, water toxicity in agricultural (Vieira et al., 2017; Whitehead et al., 2005) or urban areas (Camargo & Martinez, 2007; Kelley et al., 2011; Schweizer et al., 2022) was also assessed by several authors on several continents.

In all, the vast majority of studies focused on a single source in a relatively small geographical area. A very small number of studies had the goal of developing new markers or biotests for larger-scale evaluations of water quality. One example of this is Roberts et al. (2005), who conducted a study to develop new biomarkers in three salmonid species: rainbow trout (*Oncorhynchus mykiss*), cutbow trout (*Oncorhynchus clarkii x mykiss*) and Atlantic salmon (*Salmo salar*). The authors used species from different regions of the USA to increase the number of potential study areas. Kolok et al. (2012) also proposed an exposure method using fathead minnows for large-scale evaluations of water quality, focusing on the presence and effects of endocrine disruptors. This method involves fish deployment for surveillance, primarily to monitor the toxicity associated with WWTPs, which are a major source of endocrine disruptors in the environment.

3.2.3. Endpoints

Knowing that the objective of most of the studies reviewed was the evaluation of toxicity to fish, we examined the types of analyses that had been done. We divided their endpoints into four categories: biomarkers (mostly corresponding to endpoints at a sub-individual scale), pollutant bioaccumulation, life traits and survival.

Biomarkers were the most frequently used parameters of the three categories. Out of the studies in our review, 55 used one or several biomarkers, representing around a third of all the studies we retrieved. Several studies used only one type of biomarker. These were generally made for the development and suitability assessment of the biomarker for *in situ* toxicity evaluation. For example, Abrahamson et al. (2008) examined the suitability of the EROD assay (7-ethoxyresorufin O-deethylase) in contamination monitoring. Another approach with the same purpose, based on the use of new *cyp1* transcripts, was used by Jonsson et al. (2010) on rainbow trout. Vitellogenin, CYP1A and other toxicant defence genes expression are often used as biomarkers (Burki et al., 2006; Roberts et al., 2006). Histopathology, or the study of histological lesions, is a less specific biomarker but one more relevant to health assessment as it is clearly related to tissue integrity (Camargo & Martinez, 2007; van der Oost et al., 2003). This marker was used alone on several organs of the streaked prochilod (*Prochilodus lineatus*) to assess the toxicity of an urban river in South Brazil (Camargo & Martinez, 2007). Generally, the use of a single biomarker, or only one type, remains rare as this provides only limited information. It is often recommended to use several biomarkers in parallel to improve the quality of evaluation (Galloway et al., 2004). In most studies of our review, several biomarkers were used for this reason. Biological responses can be analysed separately (McGovarin et al., 2018) or with a more integrative approach, such as principal component analysis (PCA) (Catteau et al., 2021), or by index calculation as in Integrated Biomarker Response (IBR) (Beghin et al., 2022). In our review, 24 studies used both biomarkers and bioaccumulation approaches, to correlate biomarker responses with the presence of contaminants in organisms. Winter et al. (2005) showed that concentrations of contaminants from industrial sources (PCBs and HAPs) were correlated with EROD activity in caged chub (*Leuciscus cephalus*). The combination of biomarker response and pollutant content in tissues can also allow discrimination between sites and type of contamination (Klaverkamp et al., 2006). Biological responses and pollutant bioaccumulation can also be analysed to facilitate data analyses, e.g., with a PCA (Gagnaire et al., 2015) or Generalised Procrustes Analysis (Ballesteros et al., 2017). Such analyses are often combined with water or sediment analyses to assess the presence of contaminants in water. In our review, about half of the studies also included chemical analyses of water or sediments. This type of approach confirms that most studies focused on a particular type of contaminant, such as PAHs (Barbee et al., 2008), PCBs (Brammell et al., 2010), metals (Le Guernic et al., 2016a) or, at least, a particular source of contamination such as agricultural, urban (Ankley et al., 2021) or WWTP (Defo et al., 2021; Du et al., 2019).

In the life traits category, we included all endpoints referring to growth, reproductive quality, behaviour, development and feeding. Only a small number of papers in our review used just life traits for toxicity assessment (deBruyn et al., 2007; McLean et al., 2019). These types of endpoints are generally less sensitive but are considered more ecologically relevant than molecular biomarkers (Adams et al., 1989; van der Oost et al., 2003). In the same way as for biomarkers, life traits are often used in combination with pollutant bioaccumulation and water and sediment analyses to detect organism exposure. In the Gironde watershed, growth in terms of weight was monitored in parallel with metal concentrations in otoliths of caged European eels (*Anguilla anguilla*) to evaluate whether metal contamination impacted organism growth (Daverat et al., 2012). Condition indices of juvenile fish, including growth, were evaluated by Kerambrun et al. (2012) who used caged sea bass and turbot in a French harbour. Their results showed a decrease in growth and other health indicators associated with a higher metal tissue content compared with a reference site.

Mortality is a relevant and significant indicator of toxicity, especially for adult fish. A few papers in our review measured survival in their toxicity assessments. Hewitt et al. (2006) used this marker, combined with growth and contaminant bioaccumulation, in caged Cape Fear shiner (*Notropis mekistocholas*) to assess habitat quality for this endangered species. In the study by Todd et al. (2007), survival of rainbow trout (*Oncorhynchus mykiss*) was directly correlated with metal concentration in water in an area subject to acid rock drainage.

Bioaccumulation is defined as the monitoring of contaminant levels in biota for exposure assessment (van der Oost et al., 2003). Bioaccumulation markers were used in 40 studies of our review to complement toxicity indicators previously described. This mostly involved determining whether measured toxicity responses were correlated with the amount of bioavailable contaminant accumulated by the organisms (Klaverkamp et al., 2006; Winter et al., 2005). A smaller number of studies used bioaccumulation alone to evaluate the potential exposure of organisms to various pollutants (Kazour et al., 2020).

3.2.4. Use of other species or taxa in ABM

For environmental monitoring and assessment of effects on aquatic organisms, it is recommended to use several species or taxa to better integrate their differences in sensitivity (Catteau et al., 2022). However, the vast majority of active biomonitoring studies (85%) in our review used only one species or taxon. Only 13 studies used more than one species of fish, and these had several different objectives. For conservation, the study of Cope et al. (2011) aimed to evaluate habitat quality for the shortnose sturgeon (*Acipenser brevirostrum*), an endangered species in the USA. The authors caged shortnose sturgeons and fathead minnows (*Pimephales promelas*) to compare responses between species and found a higher sensitivity in the sturgeon. Different species can also be exposed at the same time to assess fish health for species of economic interest (Al-Arabi et al., 2005; Alvarado et al., 2021; Yamamoto et al., 2014). Some studies used a ‘standardised’ species and a native species in parallel for a better comparison and toxicity evaluation. For example, (Scarcia et al., 2014), comparing common carp with native *Pimelodella laticeps*, showed that these species had different responses to pollutant exposure.

Only four experimental studies used another group of organisms in addition to fish and in all cases these were aquatic invertebrates, mainly mussels (Brooks et al., 2011; Hylland et al., 2008; Jasinska et al., 2015). Techniques for ABM with invertebrates are better developed and more frequently used than those with fish. The use of both invertebrate and vertebrate taxa allows a better evaluation of water quality, integrating their differences in sensitivity. This is especially the case in marine environments, for which methods are available and standardised for mussels (Besse et al., 2012; OSPAR Commission, 2013). For example, through the RINBIO surveillance network, an overall assessment of contamination and its effects (condition index) was conducted on mussels along the entire French Mediterranean coast. This allowed researchers to compare areas in a reliable manner, regardless of their physical and trophic characteristics (Andral et al., 2004). Catteau et al. (2022) are the only researchers who used more than two taxa in ABM. To assess the toxicity of effluents from different WWTPs in Europe, these authors used three-spined stickleback (*Gastrosteus aculeatus*), a bryophyte (*Fontinalis antipyretica*) and two invertebrate species: a bivalve (*Dreissena polymorpha*) and an amphipod crustacean (*Gammarus fossarum*). These different taxa were chosen because of their physiological differences and different ecological compartments, giving them different responses to effluent toxicity. Their complementarity provided an integrative assessment of the biological effects of WWTP effluents on a freshwater aquatic ecosystem.

3.3. Experimental designs used for active biomonitoring with fish

3.3.1. References/controls

The use of a reference is essential to compare fish response in a situation of stress (polluted environment) with stress-free conditions. A response of an exposed individual or group can only be associated with toxicity or effect by comparing it with the same individual or group maintained under optimal conditions (Rykiel, 1985).

Oikari (2006) recommended using geographically close sites presenting physico-chemical properties similar to those of the experimental site as references in ABM. The majority of authors (75% of the studies in our review) used at least caged fishes on a reference site considered as clean or weakly contaminated in a similar experimental design to those exposed at the site of interest (polluted site). As many of the studies were designed to evaluate toxicity of a particular point source of contamination, the authors mainly chose a site upstream of the effluent source, but not far from the exposure site, thus providing a control group in conditions close to those of the exposed group. Use of this approach included studies on effluents from WWTPs (Beghin et al., 2022; Catteau et al., 2021; McGovarin et al., 2018), industry (Fenet et al., 2006; Lunardelli et al., 2018) and mines (Gagnaire et al., 2015). However, it is often difficult to find a site that meets all of these requirements and is free from anthropogenic pressures. To improve reliability, it is therefore recommended to increase the number of control sites (Oikari, 2006). It is also common to assess toxicity of an effluent along a distance and thus a toxicity gradient. This is the case for example in studies focusing on effluents of pulp mills (Al-Arabi et al., 2005), waste disposal sites (Dale et al., 2019), mines and WWTPs (McCallum et al., 2017; Simmons et al., 2017). In heavily developed areas, it might be difficult to find pristine sites (Burton et al., 2005; Crane et al., 2007). For example, the reference site used by Beghin et al. (2022) was upstream of a WWTP but their results indicated that the water there was also contaminated, although differently from the water downstream, which complicated interpretation of the results.

3.3.2. Study duration

In our review, experiment duration was from 2 to more than 300 days, but most trials lasted less than one month (83%). We did not find any trends of exposure duration and suppose that those used were chosen to be sufficient to obtain clear signals in terms of expected biomarker and bioaccumulation responses by the end of the experiment. In most studies, fish response was measured only at the end of the experiment (70% of our review). Oikari (2006) recommended taking into account the organism's diet when deciding experiment duration. This aspect can often be avoided by using a reference group if experimental conditions are similar, but appears to have been handled differently among the studies in our review, depending on the species used, biomarkers measured, duration of exposure required, and cage location. Indeed, it was often assumed that fish are able to feed naturally when exposed in the field (Kerambrun et al., 2012; Winter et al., 2005). Nevertheless, starvation can occur and influence biomarker responses, leading to biases in results interpretation. To avoid this problem in experiments requiring an exposure lasting more than a few days, organisms were usually fed once a week (McGovarin et al., 2018; Simmons et al., 2017) or every day (Al-Arabi et al., 2005). Below one week of exposure, the nutritional status of the animals is not considered as a relevant factor to be considered (Oikari, 2006). In these cases, the organisms were not usually fed during the experiments (Souza-Bastos et al., 2017; Vieira et al., 2017).

3.3.3. Caging biases

Limitations and biases associated with experimentation and experimental design have been described by several authors (Besse et al., 2012; Crane et al., 2007; Liber et al., 2007; Oikari, 2006). These studies identified feeding/starvation, confinement stress and fish density as the principal biases. In our review, only three studies had the primary goal of identifying and evaluating the influence of environmental and physiological factors on the responses of organisms. For example, Le Guernic et al. (2016b) studied the effects of caging constraints on three-spined stickleback (*Gastrosteus aculeatus*) and showed that 14 days of starvation could influence responses commonly monitored in toxicity assessment, such as immunity biomarkers and the condition index. Moreover, parameters linked to oxidative stress and immunity were impacted by stress linked to transport and high fish density in cages. Trevisan et al. (2013) also studied the influence of confinement in Nile tilapia (*Oreochromis niloticus*). For both contaminated and reference sites, their results showed a disturbance in antioxidant biomarker responses, as well as in blood glucose and lactate levels, compared with free-swimming individuals. Influence of feeding procedure on fish response has also been reported in rainbow trout (*Oncorhynchus mykiss*) (Hanson & Larsson, 2007).

3.3.4. Experimental devices

Fish caging is the most commonly used exposure method in pollution biomonitoring, mainly for its ease of use. It represented 93% of the papers in our review (138 studies). However, the design of fish caging itself restricts organism manipulation and the regular collection of biological samples. Some authors have suggested the use of flow-through systems as a way to avoid some of these limitations, for example at reference sites (Dubé et al., 2002; Liber et al., 2007). This kind of approach might be useful in some cases but is expensive and quite difficult to use on a large scale because it is not easily movable. Roberts et al. (2005) used a 'flow-through, onshore exposure method' to expose Atlantic salmon (*Salmo salar*) in the St John River (Canada) because there was a legal prohibition against placing this species in the river. The difficulty of placing cages in areas with strong water currents has also been mentioned. Hence, (Hanson & Larsson, 2007) experimented with a 'flow through tank system' and Kolok et al. (2012) proposed a novel assessment method they called a 'mini-mobile environmental monitoring unit'. This field mini-lab device aims to expose organisms directly by flow-through and allows the control of water parameters such as temperature to avoid some known limits of fish caging trials. This method has primarily been used to assess the effects of effluents from WWTPs with adult fathead minnow (*Pimephales promelas*).

3.3.5. Developmental stages

Of the studies in our review, 83% (123 studies) used juvenile or adult fish for contamination assessment. The use of these stages offers several advantages. They are large enough to take many samples, at the organ scale if needed. As they are already developed, a wide range of biomarkers can be used. They are also relatively easy to obtain from fish farms or the wild. Juveniles can be used to avoid the influence of sex or reproductive cycle on monitored parameters (Pereira et al., 2010). Moreover, it is possible to monitor their growth or sexual maturation (Kerambrun et al., 2012). Finally, the use of juveniles is relevant for studies focusing on water quality in nurseries (Kazour et al., 2020; Kerambrun et al., 2012).

Limitations such as confinement stress or diet primarily affect free-swimming larvae, juveniles and adults, i.e. later developmental stages feeding on an exogenous diet and considered sensitive to stress factors. Such caging biases can be avoided by using early life stages. These stages are highly sensitive to environmental factors, particularly contamination, making them a valuable tool in environmental monitoring (McKim, 1977). Their use in the field is still rare: in our initial bibliographic search request (detailed in S1), only 2 studies used fish early life stages. Using the same requests on the 1993–2023 period, we were able to retrieve 23 more studies, which is still quite low (detailed in S1). All were conducted in the Northern hemisphere (1 in Asia, 8 in North America and 14 in Europe). The following section will discuss the use of these stages in active biomonitoring, including advantages, disadvantages and trends.

4. Use of fish early life stages in environmental biomonitoring

The term 'early life stages' refers to fertilized organisms that have not yet begun to feed exogenously, or what (Balon, 1975) referred to as eleutheroembryos. These developmental stages are frequently used in laboratory toxicological studies and several sets of guidelines exist for their use (OECD, 1998, 2018). The OECD 212 guidelines (Fish, Short-term Toxicity Test on Embryo and Sac-fry Stages) recommends the use of five freshwater species: rainbow trout (*Oncorhynchus mykiss*), zebrafish (*Danio rerio*), common carp (*Cyprinus carpio*), Japanese medaka (*Oryzias latipes*) and fathead minnow (*Pimephales promelas*). It is possible to use other species, but the implementation of this standardised test would need to be adapted (OECD, 1998). The main condition for the use of early life stages is the availability of eggs. Reproduction in captivity is not controlled for all fish species, restricting the capacity to provide organisms at the desired developmental stage. Additionally, it is particularly difficult to obtain fish embryos directly from the wild. Parental exposure can also influence offspring response and needs to be controlled as much as possible (Burt et al., 2011). Choice of species is influenced by other factors such as thermal tolerance, development time, breeding season and geographical distribution. These characteristics are summarized in Supplementary Material 5 (S5) for several freshwater fish species that are recommended in OECD guidelines.

4.1. Species used at early life stages

Fifteen different fish species were used in the 23 studies that used early life stages for biomonitoring, representing a significant diversity. There were 11 freshwater species and four marine ones, corresponding to the habitats studied. As previously stated, the use of embryos or sac-fry larvae of a particular species is heavily influenced by whether controlled reproduction is possible in captivity. When it comes to Japanese medaka or zebrafish, reproduction is controlled, making it possible to obtain well-balanced, high-quality embryos almost year-round. Other factors, such as the thermal optimum, must be taken into consideration depending on the study site. Due of their behavior, some species are not very compatible with caging approaches. For instance, cannibalistic behaviors have been observed in the larvae of the Northern pike (*Esox lucius*) and european perch *(Perca fluviatilis*) (e.g. Schäfers & Nagel, 1993). The western mosquitofish (*Gambusia holbrooki*) is ovoviviparous, meaning that eggs are incubated directly in the female's abdomen, limiting the obtention of freshly fertilized eggs (Krumholz, 1948).

In our review, the two species most frequently used at early life stages were brown trout (*Salmo trutta*) and fathead minnow (*Pimephales promelas*) (Fig. 2). Brown trout was only used in Europe, in Sweden (Norrgren & Degerman, 1993; Serrano et al., 2008) and France (Bony et al., 2008). Fathead minnow was exclusively used in North America (Gauthier et al., 2006; Parrott et al., 2003; Pyle et al., 2001). More broadly, the most commonly used species were salmoniforms (6 different species, including coregoninae and salmoninae subfamilies), which were used in more than half of the studies (12 out of 23). As previously mentioned, salmonids are a diverse family of cold-temperate fish species, inhabiting a wide range of aquatic habitats (Nelson et al., 2016). They also have significant economic and heritage value because they are highly farmed, fished and consumed (Ankley & Villeneuve, 2006; Teletchea, 2011). As a result, their reproduction in captivity is relatively well controlled and eggs are easy to obtain. Moreover, their eggs are large in size, making them easy to handle, and they have a long embryonic developing period, allowing longer-term exposures (Arola et al., 2019).

4.2. Applications of ABM using early life stages of fish

4.2.1. Study goals

Almost all of the studies using early life stages chose native species from the study areas. This is an interesting and crucial issue because early development is a critical stage in a populations' health and recruitment (Jonsson & Jonsson, 2014; Kamler, 1992). The exposure of embryos and larvae at specific sites of interest (e.g. spawning grounds) makes it possible to assess the suitability of sites for the reproduction, development and growth of threatened species for conservation purposes. Out of the 23 studies, most were conducted to determine whether ecosystems were suited to species development, which is vital for their conservation. This contributes to the improvement of conservation efforts and the long-term health of species and their ecosystems. Sources of pollution studied included agriculture (Bony et al., 2008), mine effluents (Pyle et al., 2001), industrial effluents (Vehniäinen et al., 2015) or technological accidents (Incardona et al., 2012). For example, Chalmers et al. (2014) exposed embryos of cutthroat trout (*Oncorhynchus clarkii*) on the bed of a river to study the potential effects of a mine in Canada. In Germany, the VALIMAR project studied the impact of the water quality of two differently contaminated streams (urbanisation, agriculture) using brown trout (*Salmo trutta*) (Luckenbach et al., 2003; Luckenbach, Kilian, et al., 2001a; Luckenbach, Triebskorn, et al., 2001b). deBruyn et al. (2007) assessed water quality of the spawning grounds of lake whitefish (*Coregonus clupeaformis*) following an accidental oil spill in Alberta, Canada. One recurrent issue with the use of early life stages is that they omit exposure during the later growth periods or reproduction, which would otherwise be helpful to increase ecological relevance (Gauthier et al., 2006).

4.2.2. Endpoints

Compared with studies on adults and juveniles, the amount of biological material available from eggs or larvae makes analysis at the molecular level much more difficult. Furthermore, as they are not yet fully developed, some physiological or metabolic processes are not yet activated, making certain biomarkers unusable (Wiegand et al., 2000). Molecular biomarkers are generally more sensitive at these stages, providing short-term responses to pollutant exposure, but the sensitivity of early life stages to pollution also facilitates the use of individual markers of toxicity (Murl Rolland, 2000; van der Oost et al., 2003). Endpoints such as survival or developmental abnormalities are easier to implement with early life stages and allow a more comprehensive evaluation at the population level (Kamler, 2002; Schuijt et al., 2021). The toxicological endpoints studied in the 23 papers using early stages are mostly related to survival and life traits such as quality of development, hatching success and growth. Mortality during exposure is one of

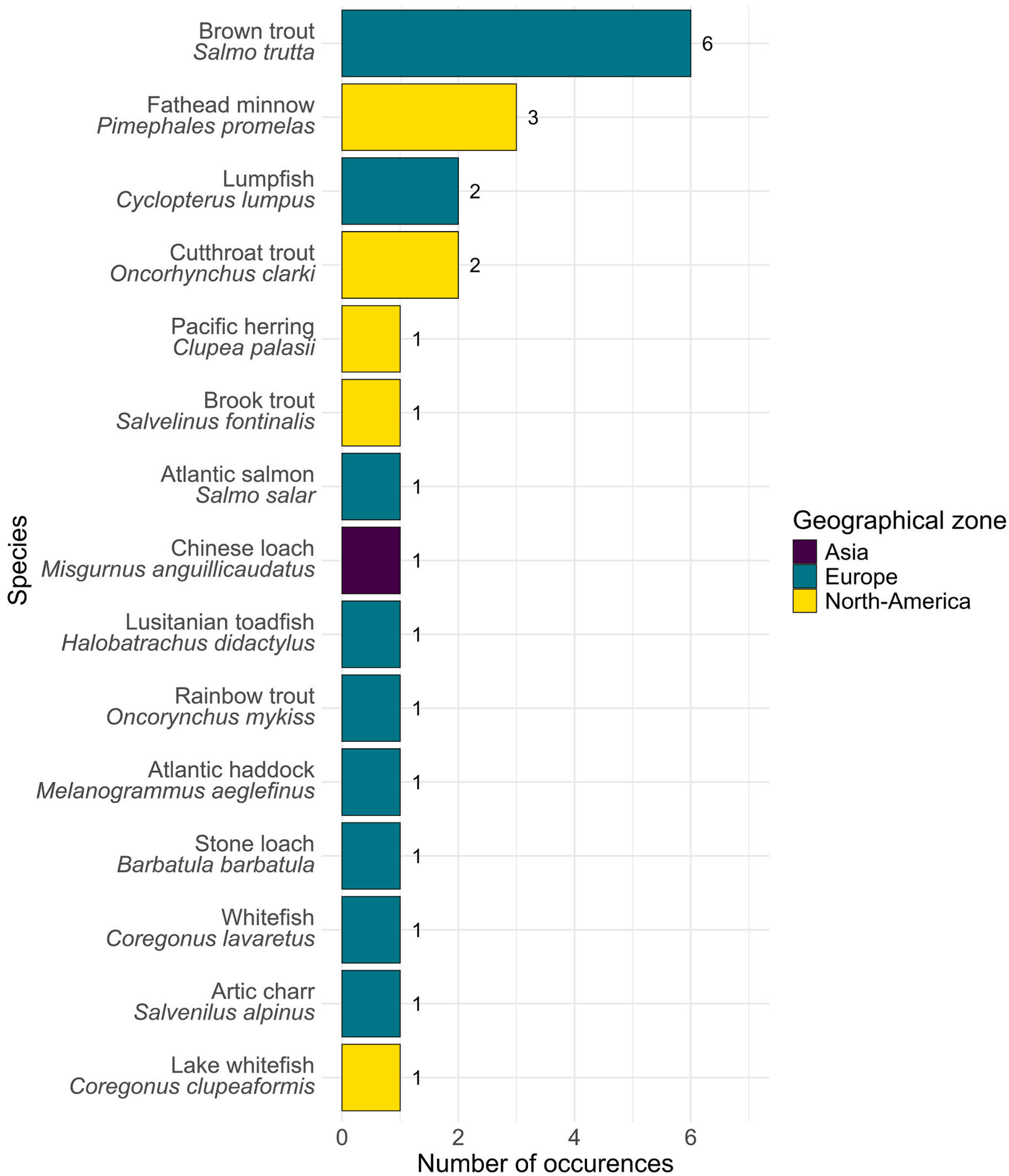

Fig. 2. Number of studies using species at early life stages. Each colour corresponds to the continent where the experiment was conducted. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the main indicators monitored in the studies of our review, being used in Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*) (Norrgren & Degerman, 1993), brook trout (*Salvelinus fontinalis*) (Fiss & Carline, 1993), whitefish (*Coregonus lavaretus*) (Arola et al., 2019) and fathead minnow (*Pimephales promelas*) (Pyle et al., 2001). Incardona et al. (2012) were able to assess toxicity related to the presence of polycylic aromatic compounds in coastal waters after an oil spill by monitoring survival and sublethal abnormalities of Pacific herring (*Clupea pallasii*) embryos.

It has already been demonstrated that an exposure to pollutants can cause developmental abnormalities or disruption, such as malformations, modification of duration of embryonic period or hatching rate (McLachlan, 2001; Murl Rolland, 2000). In our review, PAH concentration in water was linked to a higher rate of malformations in lumpfish (*Cyclopterus lumpus*) embryos (Hansen et al., 2022). In the same way, hatching time was monitored to evaluate toxicity of metals (cadmium and nickel) on fathead minnow embryos (Gauthier et al., 2006). At a sublethal level, biomarkers such as EROD activity were used after a two-month embryonic exposure on Arctic charr (*Salvelinus alpinus*) to assess levels of contamination in several tributaries of a Swiss' lake (Gillet & Monod, 1998). For some species, it is also possible to apply multi-biomarker approaches with gene expression for endocrine disruption (vitellogenin), metallothioneins and xenobiotic metabolism (Marlatt et al., 2016). Other indicators used on early life stages included DNA damage (Bony et al., 2008), swimming speed (Cresci et al., 2020), hatching rate (Chalmers et al., 2014) and bioaccumulation (Sørensen et al., 2023).

4.3. Experimental designs used for ABM with fish early life stages

4.3.1. Study duration

The duration of studies using early life stages ranged from 7 to more than 150 days, depending on the scientific question, species and outside temperature (which influences the length of embryonic development). For instance, since salmonids reproduce in winter, they have a long embryonic development period, which enables longer studies (Arola et al., 2019). The embryonic period of rainbow trout (*Oncorhynchus mykiss*) is one of the shortest among salmonids, lasting approximately 300°-days until hatching (Billard, 1992). It lasts 400°-days in brown trout (*Salmo trutta*) and 430°-days in Atlantic salmon (*Salmo salar*) (Billard, 1992; Teletchea, 2011). For example, at 5 °C, the embryonic period lasts 60, 80, 86 days in rainbow trout, brown trout and Atlantic salmon, respectively. For fathead minnow (*Pimephales promelas*), which reproduces during spring at warmer temperatures, Gauthier et al. (2006) conducted a study on the effects of metals in contaminated lakes that lasted 7 days from fertilisation to larval stage. Duration of a study depends on the time necessary for development but also on the stage of development exposed. Through the embryonic and larval period, sensitivity to contamination can differ depending on the precise stage of development (Burggren & Mueller, 2015). As embryos are static, they passively undergo environmental stressors (Kamler, 2002). Thus, some authors started exposure soon after fertilisation to cover all sensitivity windows and increase ecological relevance (Arola et al., 2019; Fiss & Carline, 1993; Hansen et al., 2022). However, because eggs in early development can be extremely sensitive to handling and transport, making it difficult to start experiments very early in the development process, some authors started exposure on eyed embryos, which are considered less sensitive to handling (Marlatt et al., 2016; Norrgren & Degerman, 1993).

In Europe, the directive 2010/63/EU on the protection of animals used for scientific purposes considers fishes as animals from the start of exogenous feeding (European Commission, 2010), leading some authors to stop exposure at this precise moment (Luckenbach et al., 2003). Longer durations of exposure remain quite rare but provide relevant information on long-term effects of contamination on organisms. Parrott et al. (2003) conducted an exposure of fathead minnows (*Pimephales promelas*) to pulp mill effluents from fertilisation to sexual maturity, showing that early exposure could lead to developmental impairments such as changes in several sex characteristics or growth disruption.

4.3.2. References/controls

The main strategy for reference in studies with fish early life stage was to use reference sites in the field (13 papers out of 23). Seven papers in our review used laboratory exposure as a control, and three did not fully describe their form of reference. Beyond the challenge of finding a comparable site free from anthropic pressures, the use of early life stages poses an additional challenge. Water temperature has a significant influence on both the quality and duration of embryonic development (Burggren & Mueller, 2015). Consequently, study sites with different temperatures complicate result comparison and interpretation. Some authors expressed data in degree-days to allow site comparison (Fiss & Carline, 1993), but this requires a good knowledge of the kinetics of embryonic development in the species at different temperatures. It also implies careful temperature monitoring at each location. For example, exposures of embryos of brown trout (*Salmo trutta*) in the study of Luckenbach et al. (2003) lasted between 110 and 150 days between the two field sites and the control run in the laboratory. This was due to differences in temperature between sites and because the experiment was set up to end at the exogenous feeding stage. Such a choice complicates site comparisons, particularly for time- and temperature-dependent endpoints like timing of hatching. As it is difficult to precisely predict the timing of development with regard to temperature, regular monitoring of organisms is necessary.

4.3.3. Experimental devices

Limitations linked to temperature can be avoided without caging directly in the field, as in the studies by (Hanson & Larsson, 2007; Kolok et al., 2012) mentioned above. By using flow-through circulation, such methods could allow environmental exposure of more sensitive organisms under more controlled physico-chemical conditions. To our knowledge, only six studies used this type of exposure method with fish early life stages. Several authors have used what they called a 'by-pass system' to avoid temperature impact and allow more frequent monitoring of the organisms (Luckenbach, Kilian, et al., 2001a; Luckenbach, Triebskorn, et al., 2001b). All these studies were part of the VALIMAR project, which aimed to investigate the effects of WTTP effluents in Germany in the 2000s. This kind of device is interesting since it represents a significant improvement for biomonitoring by allowing the exposure of more sensitive organisms. However, one identified limitation is the significant cost of such devices, in terms of both budget and logistics. The thermoregulation of the exposure units requires more equipment than caging and an electrical supply, which is not always possible, especially at a large scale.

5. Conclusion and perspectives for future work

This literature review revealed wide variation in protocols and exposure systems used in active biomonitoring, as well as in the fish species chosen. All of these aspects depended on the scientific issue addressed, geographical location, species available and existing knowledge about these species. Given the number of studies using each species and the origin of the organisms, it is challenging to draw conclusions about the advantages and limits of each and their respective sensitivity. Considerations of the choice of species, experimental design and experimental protocols more generally have already been assessed and discussed in the literature. The choice of exposure method, species and developmental stages used, as well as study duration and

Table 1
Advantages and limitations of using early life stages of fish for environmental monitoring compared with juveniles and adults.

Advantages	Limitations
Small size, hence requires less space and we can use more individuals per replicate	Sensitivity to environmental parameters, hence physico-chemical parameters must be tightly controlled
Highly sensitive to pollutants, hence requires lower exposure time	Small size, thus less biological material is available
Less artefacts related to caging stress	Less toxicological endpoints available (eg: longterm effects on reproduction, cancer development)
Less concerned by ethical regulations	Embryos and larvae are usually not directly available in the field outside the breeding season
Usually transparent chorion and skin	
Endogenous feeding, hence less biases related to diet	
Less biases related to life history	
Can be produced in large quantities during the breeding season or all the year round for species with controlled reproduction	

biomarkers of exposure or effects can influence the conclusions of studies and thus need to be selected carefully depending on the questions researchers wish to address (Liber et al., 2007; Oikari, 2006; Crane et al., 2007).

The use of early life stages in ABM for *in situ* toxicity assessment remains scarce, despite their numerous advantages over adults and juveniles (Table 1). Early life stages are critical for the health and recruitment of fish populations and need to be considered in environmental quality assessments. Because of their developmental stage, small size and endogenous feeding, they are not prone to the biaises associated with caging (starvation, confinement) and technical aspects (size, transport) that can be encountered with adults or juveniles. Also, for some species it is possible to obtain large quantities of high-quality embryos, avoiding limits related to the life history of organisms. Some are already widely used in laboratory for toxicity assessment, and for which reproduction is controlled. Several species with varying thermal tolerances are recommended by the OECD 212 guideline (Fish, Short-term Toxicity Test on Embryo and Sac-fry Stages), which can be selected based on the region and season. Some are better suited for cold water (e.g. rainbow trout, *Oncorhynchus mykiss*), warm water (e.g. Japanese medaka, *Oryzias latipes*), and more temperate water (e.g. common carp, *Cyprinus carpio* or bluegill, *Lepomis macrochirus*). For ease of application, it could be worthwhile to use species with a wide thermal tolerance at early life stages. For all these reasons, along with their high sensitivity to pollutants, they represent a good model for large-scale monitoring. As they are sensitive to environmental parameters, "lab-on-field" approaches that enable environmental parameters control (such as temperature) may be useful for their application in the field. This kind of approach had already been used and shown success for early life stages exposure but it was not intended to be mobile. Therefore, one line of work would be the development of exposure devices that are relatively easy to transport, manipulate, and energy-autonomous, to allow the exposure on the field of embryos and larvae under semi-controlled conditions at a larger scale.

Recently, pollution has been shown to be one of the major drivers of biodiversity loss (Sigmund et al., 2023). Further efforts are needed to assess the impact of contamination, considering the wide variety of contaminants present in aquatic ecosystems. It is necessary to develop non-targeted methods that take into account the wide diversity of pollutants that could be present in aquatic environments. Since the last review on the subject, there these has been no methodological study on active biomonitoring with fish and no standardised method for large-scale assessment of contamination. To better compare and assess water quality between areas, it is also important to develop fish ABM methods that can be used at a larger scale. Additionally, we advise using native species whenever possible to improve ecological relevance. When few informations on native species are available, it is useful to use model species as a complementary approach. Furthermore, it is crucial to address the gap in ABM studies in under-studied countries and continents. South-America and Africa, in particular, are considered as biodiversity hotspots, but while the extinction rate of species there is estimated as being far higher than in other parts of the globe, studies assessing the impact of pollution there remain scarce (Di Marco et al., 2017; Dirzo and Raven, 2003). To conclude, it is necessary to bridge theses gaps to improve environmental quality monitoring and significant measures must be taken at a global scale drastically reduce the amount of hazardous chemical releases into the environment.

CRediT authorship contribution statement

Sarah Bancel: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Jérôme Cachot:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Corentin Bon:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Éric Rochard:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Olivier Geffard:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

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Data availability

All data used for the literature review are in Supplementary Information.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.124661.

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