

Review

Methodological approaches to using bivalve gaping behavior as bioindicator

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ABSTRACT

Bivalve mollusks are ecologically and economically important filter feeders which are considered useful bio-indicators of environmental change. Their sedentary lifestyle integrates local conditions over time, while their continuous filtering activity makes them sensitive to changes in water quality. Their filtration and physiological status are potentially reflected in their shell opening behavior. This behavior can be measured by so-called valvometry, which has been applied across diverse research fields. Here, we summarize existing research on valve gaping to provide an overview over valve gaping behavior as ecological indicator across different species, habitats and applications.

A systematic literature search was conducted, resulting in 196 studies on bivalve gaping behavior. For each study, we examined four categories of methodological decisions: species used, measurement approaches applied, employed methods for analyzing data, and study targets pursued.

The screened studies covered 64 species from 9 taxonomic orders, with a strong bias towards marine species. Sensors directly attached to individuals without additional measurement units were the most commonly used measurement approach (72.4%). Study targets were highly diverse, resulting in a classification with two major groups (technology vs. biology) and several subgroups. For data analysis, seven biological endpoints were identified as the most commonly used bases, alongside various additional analytical approaches.

We identified a lack of standardization in use of biological endpoints as a key challenge, and we propose the introduction of a minimum reporting standard for future studies. Additionally, we highlight interdependencies between methodological choices and discuss gaps and biases in the current literature, with the aim of connecting diverse research fields and supporting more cumulative scientific progress.

1. Introduction

Bivalve mollusks are an ecologically and economically important group in aquatic ecosystems (van der Schatte Olivier et al., 2020). As filter feeders, they filter and process large volumes of water continuously, playing a central role in nutrient cycling, water clarity, and the overall functioning of aquatic ecosystems (Vaughn and Hoellein, 2018). This includes the active removal of fine particulate matter from the open water (Lummer et al., 2016), as well as changes of physico-chemical and microbial properties of the substrate by increasing interstitial oxygen concentration and influencing the composition of bacterial communities in the hyporheic zone (Boeker et al., 2016). At the same time, they represent a major food source for human populations worldwide, with bivalve aquaculture accounting for a substantial share of global marine production (Wijsman et al., 2019). In addition, many species of mussels

are key target species of conservation (Geist, 2010) with intensive efforts devoted to their culturing and propagation (Geist et al., 2023). A direct consequence of their filter-feeding lifestyle is that bivalves are in constant physiological exchange with their surrounding water. Responses of bivalves to environmental stressors include changes in behavior, physiology, and health, with different levels of sensitivity depending on the stressor (Dobler et al., 2026a; Dobler et al., 2026b). Additionally, most bivalve species are sedentary or have very limited mobility and are exposed to a single set of local conditions. All of these aspects together make them useful bioindicators for detecting changes in aquatic ecosystems (Chahouri et al., 2023).

Since filtering activity is directly related to valve gaping behavior (Riisgård et al., 2003), i.e., the opening and closing of the shell, valve movements can reflect a wide range of physiological and behavioral states, making them a versatile and information-rich biomonitoring

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parameter (Hartmann et al., 2016; Ferreira-Rodríguez et al., 2023). This richness comes with a trade-off: because valve gaping reflects the combined influence of multiple internal and external factors, isolating the contribution of any single one can be challenging. The measurement of valve gaping behavior, also referred to as valvometry, can be conducted non-invasively and continuously, and has been applied across a broad range of research fields and contexts.

The most prominent application of valvometry has been in the development of Biological Early Warning Systems (BEWSs), which use real-time bivalve behavior to provide continuous, automated detection of water quality (Ferreira-Rodríguez et al., 2023). Bivalve-based BEWSs offer a complementary approach to traditional physical and chemical methods, and are now well established. They have been the subject of dedicated reviews (Kramer and Foekema, 2001; Bae and Park, 2014; Bownik and Włodkowiec, 2021; Gudimov and Komarova, 2021; Arroyo et al., 2022; Dvoretzky and Dvoretzky, 2023; Vereycken and Aldridge, 2023). However, valvometry extends well beyond BEWSs, not only covering real-time measurements with pre-set alarms but also asynchronous data recordings that are required for fundamental research on valve gaping.

Despite its breadth of application, conducting a valvometry study involves a considerable number of methodological challenges and decisions. Some of these follow naturally from the research question, but others require deliberate consideration: which species to use and whether to compare several species; which measurement approach to apply; which study targets to pursue; and how to analyze the resulting data. These decisions are rarely made in isolation, and the choices available to researchers have expanded considerably as the field has grown. Yet no systematic overview of the field as a whole has been published to date. Existing reviews are either focused on specific applications, most notably BEWSs as mentioned above, or limited to particular habitats (Salánki et al., 2003) or study targets (Clements and Comeau, 2019), and predominantly reflect a marine perspective, leaving it unclear which methodological options have been used in the entire field of research on valve gaping, how they relate to one another, and where gaps, biases, or limitations may exist across the field.

This work addresses this gap by presenting the first systematic review of research on bivalve valve gaping that is not limited to any single application, species group, or habitat type. Specifically, we examine four categories of methodological decisions made across the screened studies: the species used, the measurement approaches applied, the employed methods for analyzing data, and the study targets pursued. By mapping these decisions systematically across the literature, we aim to provide a comprehensive overview of the options that have been used to date, identify interdependencies between different methodological choices, and highlight gaps, biases, and limitations that may warrant reconsideration across the field. Based on our findings, we propose recommendations aimed at improving the comparability and usability of results across studies and disciplines, with the goal of connecting the diverse research fields that make use of valve gaping and hence supporting a more cumulative and interdisciplinary scientific progress.

2. Material and methods

2.1. Literature search

We conducted a systematic literature search via Google Scholar, for which we entered four different search keys: i) “Valvometry”, ii) “Valve gape”, iii) “Shell gape”, and iv) “Biological Early Warning Systems valve”. We evaluated all results listed on pages 1–10 for each search key separately and included suitable sources in our literature base with the search being conducted between January 12th and February 12th 2026. The publication date of articles was not restricted during the search. Additionally, review papers found via the search keys on Google Scholar served as further study sources (see Appendix A Table A.1 for list of reviews).

We included accessible original research (including new as well as re-analysis of data) using data of bivalve shell movement without restricting the used bivalve species, measurement approaches, methods for analyzing data, or study targets. We excluded duplicates of studies as well as preprints and abstracts of presentations. Furthermore, we excluded studies that did not research bivalves and their gaping behavior.

2.2. Identification and categorization of methodological decisions

For each screened study, we recorded the bivalve *Species* used, the *Measurement approaches* applied, the employed methods for analyzing data (more specifically, *Biological endpoints* examined), and the *Study targets* pursued, resulting in a structured dataset compiled in an Excel file (see Appendix B). The results are reported as percentages of all screened studies. Since individual studies could have more than one contribution within a methodological decision (see Fig 1), the percentages sum up to more than 100%.

As terminology is not standardized across the different fields involved and the range of options is considerable, we defined categories for each examined methodological decision, as detailed in the following for each parameter separately.

2.2.1. Habitat / Species

All *Species* names used in the studies were verified via the quick search function of LifeWatch Belgium's Molluscabase (<https://www.molluscabase.org/>). If a name used in a study was listed with an unaccepted status in the Molluscabase, the accepted name was used for further analysis instead. The potential habitats were taken over from Molluscabase's “Environment” information for each *Species* individually. Taxonomic results are mainly reported on the ordinal level rather than the *Species* level, except for some of the most recurrent *Species*. On average, each study used 1.2 different *Species* (for details see Appendix A Table A.2).

2.2.2. Measurement approach

We categorized *Measurement approaches* into three groups as described below. For details on the used measurement technologies, see Appendix A Table A.3 and Fig A.1.

1. Bivalve-borne (see Fig 2 A)

Per our definition, *bivalve-borne* sensors are directly attached to an individual. No additional units (beyond those needed for data transfer and power supply) are required to record valve gaping. With this approach, within-bivalve-movements are recorded.

2. Semi-bivalve-borne (see Fig 2 B)

We define *semi-bivalve-borne Measurement approaches* as one unit that is directly attached to an individual, while a second or several further units are not attached to an individual but are still necessary to record valve gaping behavior. With this approach, bivalve-to-external-unit-movements are recorded.

3. External (see Fig 2 C)

For this *Measurement approach*, we define that no measurement unit is attached to an individual. With this approach, bivalve movements are recorded from a distance, without any sensor unit being directly attached to a bivalve.

On average, each of the screened studies used only one *Measurement approach*.

2.2.3. Study target

The screened studies aimed for a high variety of *Study targets*, which reflect the purpose of the studies. For a comprehensive overview, we categorized *Study targets* with a hierarchical flow chart, as illustrated in Fig 3. In Appendix A Table A.4, all studies are listed in detail within the category structure of the *Study targets*, giving more information on the

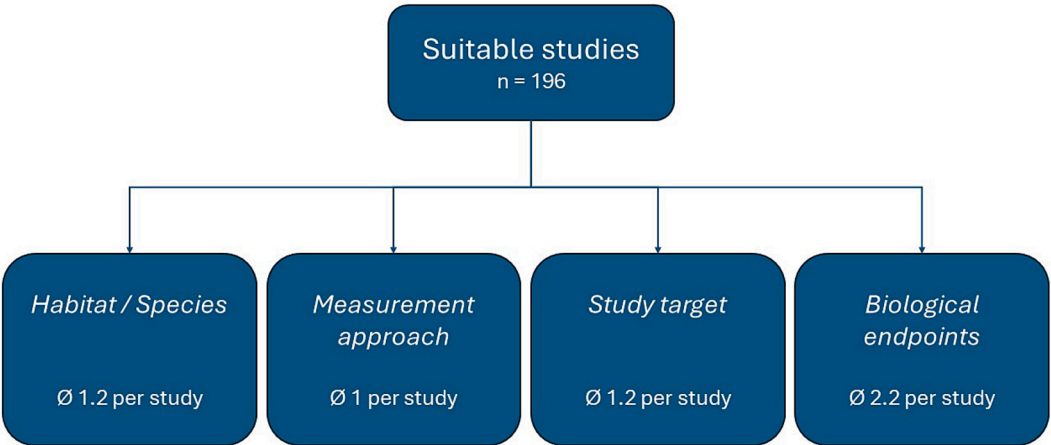


Fig 1. Methodological decisions. The literature search resulted in 196 suitable studies, for which four methodological decisions were recorded and evaluated: Habitat / Species, Measurement approach, Study target, and Biological endpoints (=part of data analysis). Individual studies could be assigned to more than one category per parameter, hence we report the average (Ø) number of categories used per study.

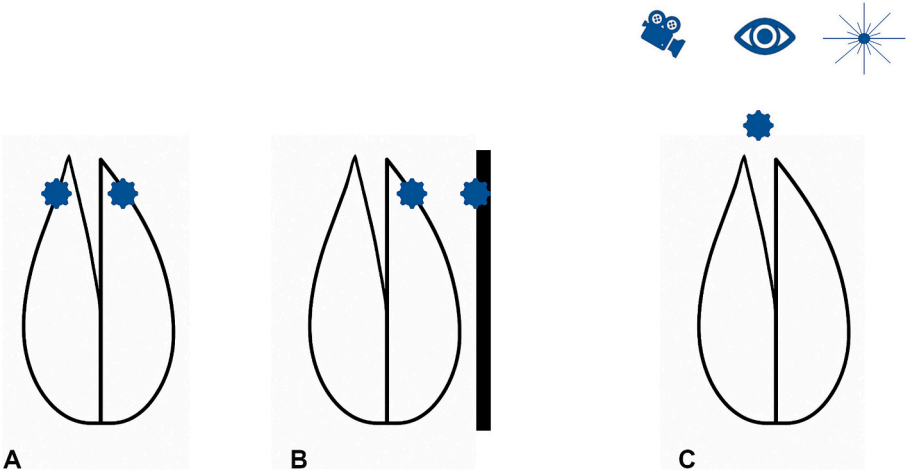


Fig 2. Visualization of measurement approach categories. Blue gear wheel indicates position of sensor units within measurement approach category. **A:** Bivalve-borne sensors. **B:** Semi-bivalve-borne sensors. **C:** External approaches. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

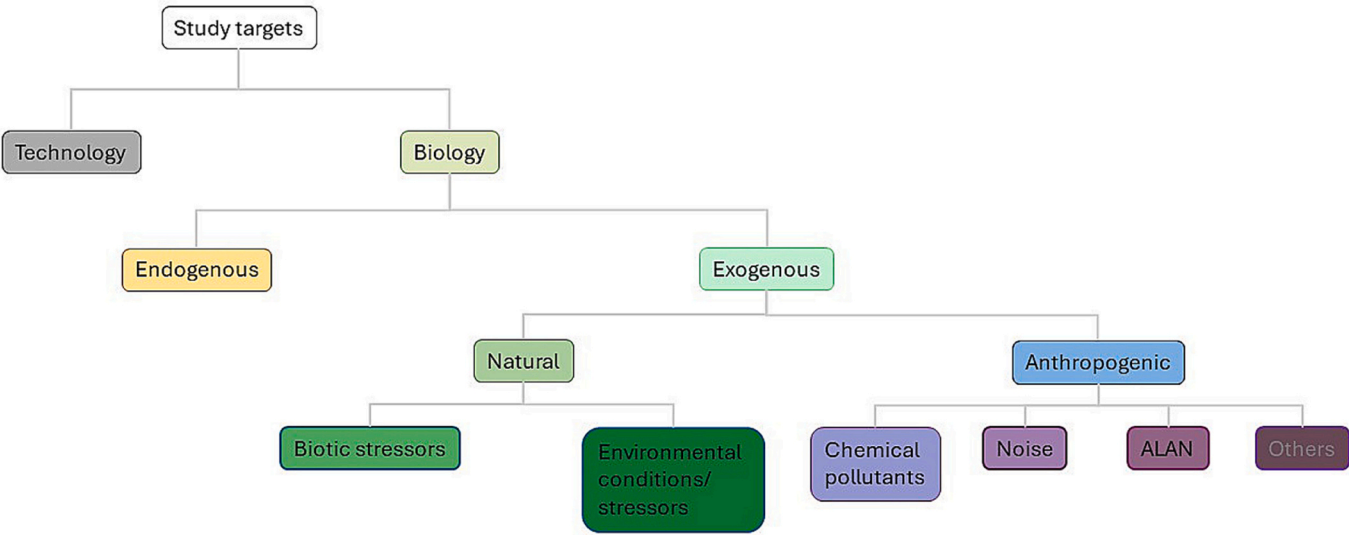


Fig 3. Flow-chart structure of study targets. Each branching indicates the subdivision of a study target group.

exact study aims. On average, each of the studies aimed for 1.2 different *Study targets*.

Study targets in the field of **Technology** included the introduction, optimization, and comparison of *Measurement approaches* as well as the report of experience with those, including approaches related to the development and application of Biological Early Warning systems. Additionally, all studies focusing on the implementation of data preprocessing, analysis, and modeling techniques were categorized as **Technology** studies.

All non-**Technology**-targets were categorized as targets in the field of **Biology**. We further subdivided this category into several subcategories, since the targets appeared to be very heterogeneous.

As **Endogenous** targets, we categorized all studies with focus on the examination of bivalves as organisms rather than an assessment of a stressor. Examples are changes in body temperature or burrowing behavior, identified via valve gaping. For more details, see Appendix A Table A.4.

As **Exogenous** targets, we categorized all non-**Endogenous** study targets, with further subcategories **Natural** and **Anthropogenic** targets.

Natural Study targets were further subcategorized into **Biotic stressors** and **Environmental conditions/stressors**. While **Biotic stressors** include several organisms that can induce stress or damage to the tested bivalves, **Environmental conditions/stressors** refer to environmental-specific effects like abiotic, water quality, or spatial parameters (for details see Appendix A Table A.4).

Anthropogenic Study targets were further subcategorized into **Chemical pollutants**, **Noise**, Artificial Light at Night (**ALAN**), and **Others** (7.1%).

Chemical pollutants included a high variety of chemicals that are introduced into waterbodies by humans. Those range from metals and pesticides to other pollutants such as crude oil (for details see Appendix A Table A.4).

Noise included human-caused sounds that can occur in natural habitats, like drilling, pile driving or ship noise; it also included intentional **Noise** exposure for better understanding of **Noise** reception, for example, with sinusoidal sounds.

ALAN included studies that tested the effect of artificial light at night, which is a form of environmental pollution introduced by humans.

Finally, the category **Others** summarized all remaining influences that did not fall in any of the previously mentioned categories of **Anthropogenic Study targets**, ranging from the effect of feeding regimes to fine sediment pollution (for details see Appendix A Table A.4).

2.2.4. Data analysis

The screened studies presented a high variety of methods for analyzing valve gaping data. In this work, we differentiate between the use of **Biological endpoints** and **other analysis methods**.

2.2.4.1. Biological endpoints. Since *Biological endpoints* were defined in various ways in the screened studies, we defined subgroups that reflect the different dimensions of valve gaping, including physiological parameters (reflected in *Distance*, *State*, *Angle*, and *Shell Gape Size* as defined below), timing (reflected in *Duration* and *Frequency* as defined below), and the combination of both (reflected in *Distance * Duration* as defined below). In Appendix A Table A.5, the used endpoints within the categories are detailed with example studies. We define the categories used here as follows:

Distance: The measured *Distance* between two valves of an individual (*bivalve-borne* measurement) or between one valve and an external fixpoint (*semi-bivalve-borne* or *external* measurement).

State: A categorical parameter that gives an interpretable name to observed *Distances*, for example defined by a (study-specific) threshold *Distance* that describes the transition point between different categories. The definition can also be conducted more intuitively, for example, by

defining the transition point based on biological visual cues as the extension or retraction of the siphon.

Duration: A timespan that is specified by the beginning and the end of a specific event.

Angle: The measured gape in degree or radians between two valves or between a valve and an external fixpoint.

Frequency: The number of observations of a specified event. This can either be the occurrence of a *State*, the occurrence of a *State* change, or the occurrence of specified *Distance* differences that are not defined as *States*.

Distance * Duration: The mathematical combination of *Distance* and *Duration*.

Shell Gape Size (SGS): SGS was defined by A.V. Gudimov to describe changes in the mean valve *Distance*, resulting in so-called “behavioral acts”. He distinguished between period of activity, period of quiescence, valve contraction, valve trembling, adduction, rapid rhythm, slow rhythm, open slow rhythm, and close slow rhythm.

On average, each study used 2.2 different *Biological endpoints*.

2.2.4.2. Other analysis methods. The screened studies employed a wide variety of data analysis, preprocessing, postprocessing, and modeling approaches, both to analyze the *Biological endpoints* described above and to examine valve gaping independently of *Biological endpoints*. The approaches are listed in detail in Appendix A Table A.6.

3. Results

3.1. Literature search

The search resulted in a total of 696 papers (386 Google Scholar, 310 cited in review papers), from which we finally considered 196 suitable for this review (see Fig 4 for PRISMA flowchart). Of those 196 studies, 145 were found directly via Google Scholar and another 51 studies were added from the sources of the related review papers. The earliest screened study dates back to 1956 with a notable increase in publications beginning in the early 2000s.

The Supplementary list in Appendix B contains a summary of all 196 screened studies, including the year of publication, bivalve *Species* used, common habitat(s) of the *Species*, *Study targets*, *Measurement approaches*, and methods for analyzing data (*Biological endpoints*).

3.2. Methodological decisions

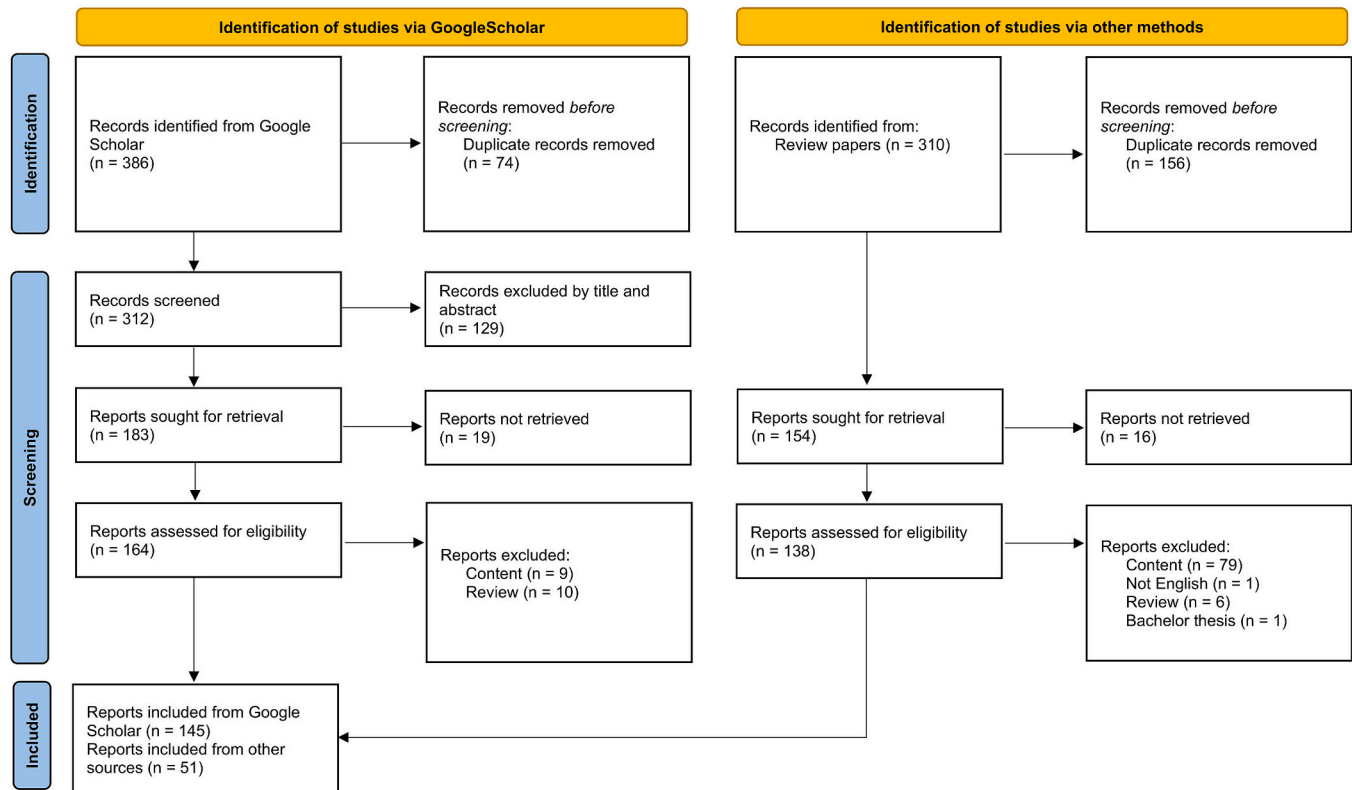
In this review, we examine four methodological decisions in research on bivalve gaping behavior, as depicted in Fig 1. In the following, the results will first be presented for each of the parameters individually and subsequently for interdependencies between the different parameters.

3.2.1. Habitat / Species

The screened studies included 64 different *Species* from 21 families and 9 orders, inhabiting marine (67.3%), freshwater (25.0%), or brackish water (one study, < 1%) habitats. Additionally, studies used *Species* that can inhabit brackish as well as marine habitats (11.2%) and *Species* that can inhabit brackish as well as freshwater habitats (12.2%), subsequently referred to as hybrid-marine and hybrid-freshwater *Species*, respectively. Only a few studies did not specify the bivalve *Species* used (3.0%).

Mytilida, including marine as well as hybrid-marine *Species*, were by far the most commonly used order (28.8% of all studies), followed by marine and hybrid-marine *Ostreida* (23.0%) and freshwater and hybrid-freshwater *Unionida* (21.4%). The most commonly used *Species* (> 5%) were marine *Mytilus edulis* (16.8%), marine *Mytilus galloprovincialis* (9.7%), hybrid-marine *Magallana gigas* and freshwater *Corbicula fluminea* (9.2% each), marine *Crassostrea virginica* (8.7%), and hybrid-freshwater *Dreissena polymorpha* (5.1%). For a detailed list of all used

PRISMA 2020 flow diagram for new systematic reviews which included searches of databases, registers and other sources



Source: Page MJ, et al. BMJ 2021;372:n71. doi: 10.1136/bmj.n71.

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Fig 4. Schematic of the literature selection process, based on the PRISMA 2020 flowchart. Left panels: Identification of sources based on Google Scholar search. Right panels: Identification of sources within review papers found during Google Scholar search. Total number of suitable studies: 196.

Species sorted by habitat including their total number of occurrences in the screened studies, see Appendix A Table A.2. Additionally, the Excel list in Appendix B can be filtered by taxonomic order, family, *Species*, and habitat separately.

3.2.2. Measurement approach

The most commonly used *Measurement approach* was *bivalve-borne* (72.4%), while *semi-bivalve-borne* (14.3%) and *external* (13.8%) approaches occurred with similar frequency. Of all studies, 1.5% did not specify their *Measurement approaches*. The differentiation between *bivalve-borne* and *semi-bivalve-borne* approaches was especially difficult for studies that did not describe their systems in detail, especially since the same technologies can be used in different ways. For example, a Hall sensor can either be used by attaching a magnet to one valve and the hall sensor to the second valve (*bivalve-borne*) or by attaching only one of the two parts to a valve and the second part to an external unit (*semi-bivalve-borne*), measuring the *Distance* between valve and external unit rather than the *Distance* between the two valves. We categorized the *Measurement approaches* to the best of our knowledge where descriptions were unclear.

3.2.3. Study target

Technology was pursued as a *Study target* in 21.4% of all studies, while **Biology** accounted for 97.4%. Within **Biology**, **Endogenous** targets were represented in 21.9% of all studies, while **Exogenous** targets were represented in 75.5%. The two subcategories of **Exogenous** studies, namely **Natural** (38.8%) and **Anthropogenic** targets (36.7%), were almost equally addressed. Among **Natural** targets, **Environmental conditions/stressors** (28.1%) were more common than **Biotic stressors** (10.7%). Among **Anthropogenic** targets, **Chemical pollutants**

dominated (23.0%), followed by comparably low shares for **Noise** (5.6%), Artificial Light At Night (**ALAN**, 1.0%), and **Other Anthropogenic** targets (7.1%). For details, see Appendix A Table A.4.

3.2.4. Data analysis

3.2.4.1. Biological endpoints

3.2.4.1.1. Distance. This endpoint can be used as a mathematical basis for most other endpoints but still is only the second most frequent endpoint observed over the screened studies (59.7% of all studies). The *Distance* can be displayed directly as the measured values, for example, for Hall sensors, the magnetic flux density. It can also be converted to absolute *Distance* in millimeters or centimeters or it can be given as proportion, for example, based on the maximum value observed during the recordings.

Within the screened studies, several variations of *Distance* were used, for example, maximum *Distance* observed or the difference of *Distance* between specified timepoints. For a detailed list of the *Distance* variations used, including example papers, see Appendix A Table A.5. For the full list of papers using specific *Distance* variations, see the Excel list in Appendix B and adapt the filter for “Endpoint variations” according to your variation of interest as detailed in Appendix A Table A.5.

3.2.4.1.2. State. *States* are the most frequently used *Biological endpoints* among the screened studies (62.2% of all studies). The most common *States* are “open” and “closed”, partly defined by a threshold *Distance* that describes the transition point between the two classes (with study-specific threshold values) but partly also defined by biological visual cues as the extension or retraction of the siphon. Besides the binary *States* open vs. closed, also other definitions of *States* are used, for example, differentiating between “widely open”, “narrowly open”, and

“totally closed” valves. Even though *States* are mostly defined for the entire range of measured values, the screened studies did not always examine all available *States* but focused only on parts of them. For example, for the binary *State* definition of open vs. closed, some studies only examined changes in the open *State* and some only examined changes in the closed *State*. For the full list of papers using specific state variations, see the Excel list in Appendix B and adapt the filter for “Endpoint variations” to “GSO” (Gape State Open), “GSC” (Gape State Closed) or “GS” (Gape State, used for all definitions of *States*). Since *State* was partly also evaluated on group level, you can also find the abbreviations “GrGSO”, “GrGSC”, and “GrGS”, indicating the *States* were examined on group level.

3.2.4.1.3. Duration. The screened studies used *Duration* to identify the timeframe in which a *State* remained (for every definition of *State*), for the length between a distinct time point and the onset of a predefined reaction, or for the time between the onset of a behavioral change and the change back to predefined “normal” behavior. *Duration* is the third most frequently used behavioral endpoint among all screened studies (45.4% of all studies).

3.2.4.1.4. Angle. The *Angle* was not used often (7.1% of all studies) but still three variations were established: the maximum observed gape *Angle*, the change in gape *Angle* equaling velocity, and the change in gape *Angle* per second (equaling velocity) with correction for the individual's size.

3.2.4.1.5. Frequency. *Frequency* was used in 35.7% of all studies as either the occurrence of a *State*, the occurrence of a *State* change, or the occurrence of specified *Distance* differences that are not defined as *States*.

3.2.4.1.6. Distance * Duration. While several studies examine both *Distance* and *Duration* separately, two studies (1% of all studies) introduced specific values to combine the two endpoints in one: the gaping index, which multiplies the average normalized gaping *Distance* with the *Duration* spent open; and the Shell integral, combining the valve opening *Angle* with the *Duration* spent open.

3.2.4.1.7. SGS. This endpoint appeared in four studies (2% of all studies), all written by A.V. Gudimov, who introduced these “behavioral acts”.

3.2.4.1.8. Combination of Biological endpoints. As described above and in Fig 5, *Biological endpoints* were frequently used in combination with each other. We evaluated the most frequently used combinations (used in $\geq 5\%$ of all studies) and report them in the following as proportion of all studies:

- Only *Distance* (21%)
- *Distance*, *Duration*, and *State* (12%)
- *Duration* and *State* (10%)
- *Duration*, *Frequency*, and *State* (10%)
- *Distance*, *Duration*, *Frequency*, and *State* (9%)
- Only *State* (7%)
- *Frequency* and *State* (5%)

These *Biological endpoints* were used in 75% of all studies. The remaining 25% are detailed in Appendix A Table A.7. Sixty-six percent of all studies simultaneously used multiple *Biological endpoints*, with the majority of them using two (26%), three (29%) or four (11%) of them.

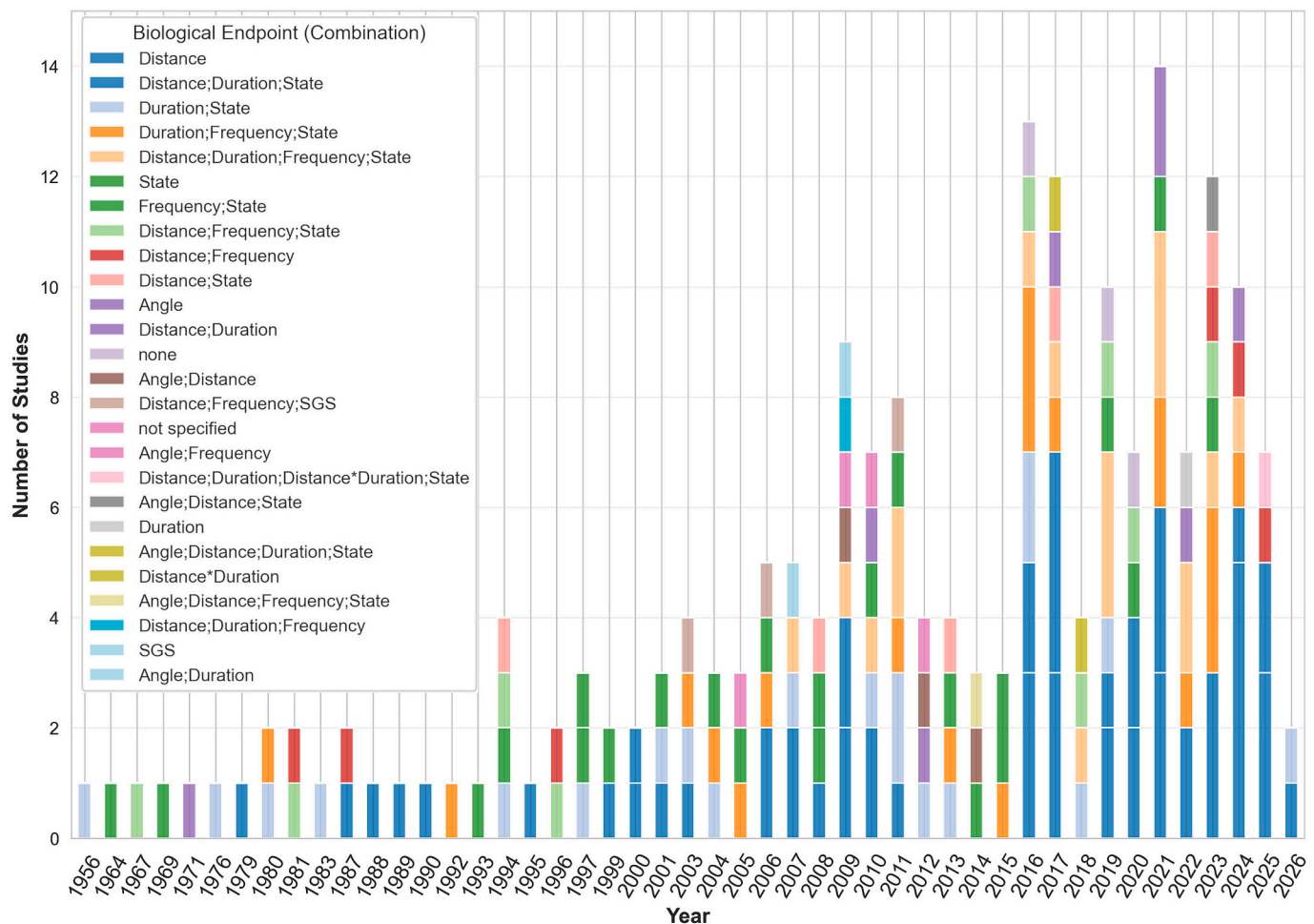


Fig 5. Bar plot showing (combinations of) Biological Endpoints. X-Axis indicates the year of publication; Y-Axis indicates the number of studies. Colors indicate the used Biological Endpoint or the combination of Biological Endpoints.

3.2.4.2. *Other analysis methods.* We differentiated all further analysis methods in 13 groups, which can be found in Appendix A Table A.6.

3.3. Interdependence of analyzed groups

3.3.1. Bivalves x Measurement approach

The most commonly used combinations were *bivalve-borne* sensors with Mytilida (25.5%), Ostreida (17.9%), and Unionida (15.3%), followed by *bivalve-borne* measurements of Venerida (9.7%), *external* measurements of Mytilida (9.2%) and *bivalve-borne* measurements of Pectinida (5.6%). For the counts and proportions of all combinations, see Appendix A Table A.8.

3.3.2. Bivalves x Study target

As illustrated in Fig 6, studies with *Environmental conditions/stressors* as *Study target* most commonly used Mytilida (12.2% of all studies), followed by Ostreida and Unionida (6.6% of all studies each). Studies examining *Chemical pollutants* most commonly used Venerida (9.2%), more specifically, *Corbicula fluminea* (8.2%). *Technology* is most often examined combined with Mytilida (5.6%). So are *Endogenous Study targets* (9.7%), which are second most frequently examined with Ostreida (7.1%). *Biotic stressors* are examined in comparable frequency with Mytilida (4.6%) and Ostreida (4.1%), while *Other Anthropogenic Study targets* are comparably often examined with Mytilida (3.6%) and Unionida (3.1%). *Noise* is most frequently tested with Mytilida (3.6%) and *ALAN* is tested once for Mytilida (0.5%) and once for Ostreida (0.5%). For the counts and proportions of all combinations, see Appendix A Table A.9.

3.3.3. Bivalves x Biological endpoints

Minor order-specific differences in the use of *Biological endpoints* for data analysis could be observed across all studies. While Mytilida and Pectinida data showed a tendency to be analyzed by *Distance* (27.0% and

5.1% of all studies respectively), Ostreida, Unionida, Venerida, and Mytilida data were preferably analyzed by *State* (15.3%, 14.8%, 10.2%, and 5.6% of all studies respectively). Using *Duration*, *Frequency*, *Angle*, *SGS*, *Distance * Duration* or none of the *Biological endpoints* was not preferred for any taxonomic order. For the counts and proportions of all combinations, see Appendix A Table A.10.

3.3.4. Measurement approach x Study target

In general, *bivalve-borne* sensors are most commonly used for all *Study targets*. Still, when comparing the use for different *Study targets* within each *Measurement approach*, it can be observed that *bivalve-borne* sensors are mostly used for *Endogenous Study targets* (17.3% of all studies), *external Measurement approaches* are mostly used for *Environmental conditions/stressors* (8.7%), and *semi-bivalve-borne* approaches are mostly used for *Chemical pollutants* (5.6%). For the counts and proportions of all combinations, see Appendix A Table A.11.

3.3.5. Measurement approach x Biological endpoints

Most commonly used *Measurement approaches* were observed to be used with most commonly used *Biological endpoints* and vice versa. Hence, no interdependence going beyond the frequency of use could be observed. For details see Appendix A Table A.12 and Fig A.2.

3.3.6. Study target x Biological endpoint

As illustrated in Fig 7, the combination of *Study Target* and *Biological endpoint* is diverse. *Environmental conditions/stressors* and *Chemical pollutants* are mostly analyzed by *State* (18.9% and 17.9% of all studies respectively). *Endogenous Study targets*, *Technology*, *Biotic stressors*, *Noise*, and *Other Anthropogenic* factors are mostly analyzed by *Distance* (13.8%, 11.2%, 8.7%, 5.6% and 5.1% respectively). *ALAN* is analyzed in both studies by *Duration* and *State* (1.0% each), and in one study additionally by *Frequency* (0.5%). For the counts and proportions of all combinations, see Appendix A Table A.13.

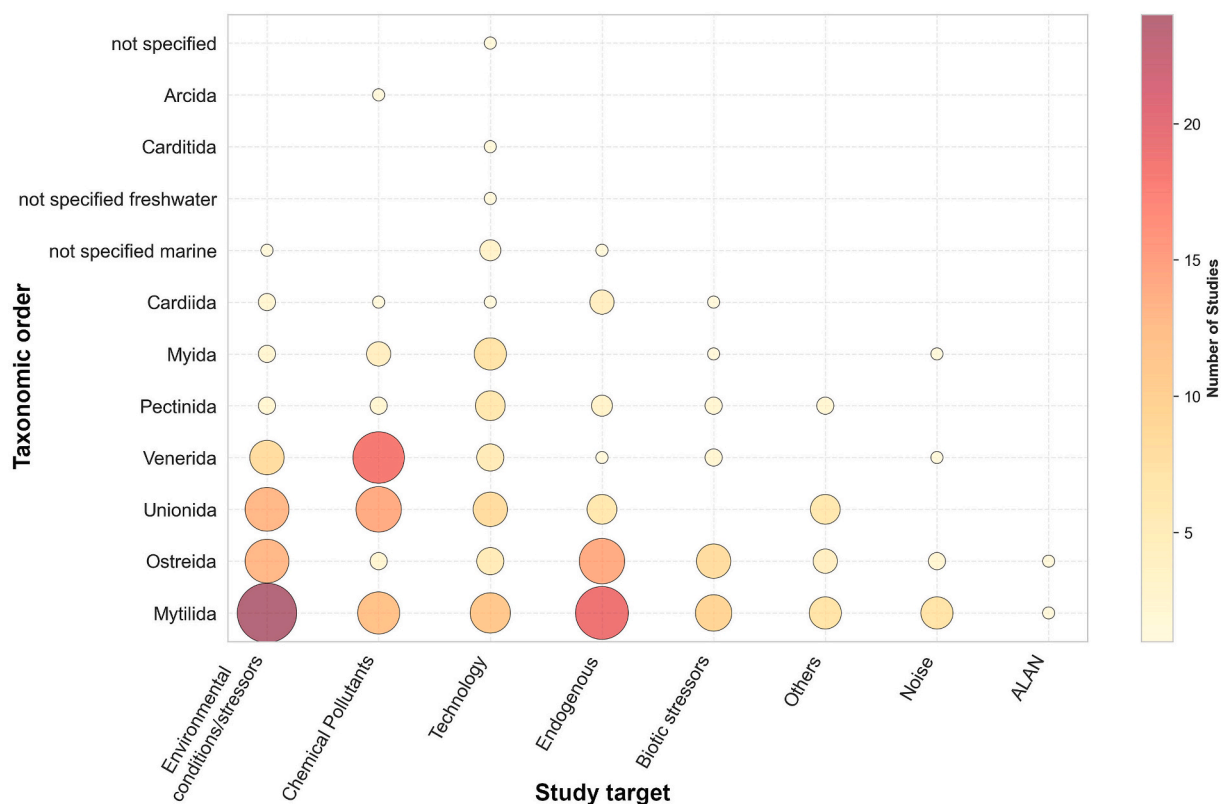


Fig 6. Bubble Chart Bivalves x Study Targets. X-axis indicates the study targets examined in the screened studies. Y-axis indicates, which taxonomic orders were used for examinations. The size and color intensity of the circles indicate the number of studies in the intersection of a taxonomic order and a study target.

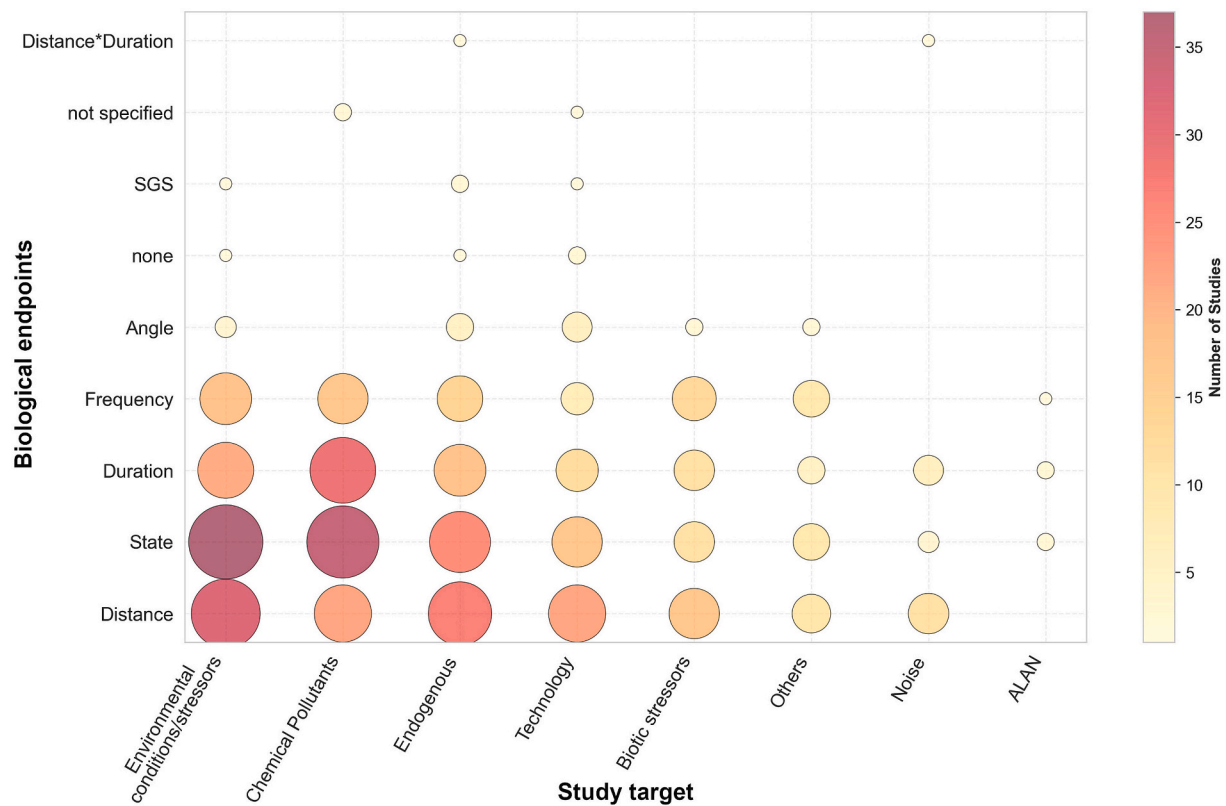


Fig 7. Bubble Chart Study Targets x Biological Endpoints. X-axis indicates the study targets examined in the screened studies. Y-axis indicates the used biological endpoints for data analysis. The size and color intensity of the circles indicate the number of studies in the intersection of a biological endpoint and a study target.

4. Discussion

The results of this work reflect the wide use and considerable potential of bivalve gaping behavior as a sensitive bioindicator in aquatic ecosystems, with direct relevance for early warning systems and water management. With a substantial number of *Species* and *Measurement approaches* used for a wide variety of *Study targets* that are analyzed with multiple methods, the field has clearly attracted sustained, diverse and increased scientific interest. By mapping the methodological decisions systematically across the literature, we provide a comprehensive overview of the options that have been used to date, covering a high diversity which reflects the versatility of valve gaping as an indicator, applicable across a wide range of research questions and hence research fields. Nevertheless, this diversity also comes with challenges that require thorough reconsideration to exploit the full potential of bivalve gaping.

One challenge can be found in the imbalance of *Species* used, with a strong focus on a small number of marine *Species*, namely *Mytilus edulis*, *Mytilus galloprovincialis*, *Magallana gigas*, and *Crassostrea virginica*. While their good availability due to successful cultivation and their economic as well as ecological relevance (Smaal et al., 2019) make them important *Species* both in general and for research on valve gaping specifically, they do not represent the full variety of bivalve *Species* in general, nor of marine *Species* in particular. While some of the screened studies used two to five marine *Species* and compared their valve gaping behavior for specific research questions, none has yet systematically investigated the comparability of valve gaping responses between the aforementioned frequently used *Species* and the high variety of other marine *Species*. Without such a broad comparative study, the ecological justification for the disproportionate focus on a small number of *Species* remains limited.

At the same time, freshwater *Species* in general represent a smaller share of the *Species* used in the screened studies, even though they provide considerable ecosystem services (Zieritz et al., 2025) and, due to their vulnerability and high potential for mass mortality events (Cossey

et al., 2026), require coordinated monitoring (Zajac et al., 2026). As for marine *Species* but on a smaller scale, here too the focus is set on few *Species*, namely *Anodonta cygnea* and *Corbicula fluminea*. This is especially relevant, since *Corbicula fluminea* is considered invasive (or potentially re-colonizing) in Europe and America (Sousa et al., 2008) and competes with generalist native *Species* (Geist et al., 2025). Even though this *Species* is perceived rather negatively due to its invasiveness, Sousa et al. (2008) describe it as a good bioindicator in general. Several of the reasons they put forward are directly applicable to research on valve gaping as well.

Its wide spatial distribution makes it possible to compare results across different freshwater systems with its high abundance, partly a consequence of its invasive status, facilitating access and sampling. It is also relatively easy to maintain in laboratory settings and can be successfully transplanted into the field. Furthermore, its high filtration capacity makes valve gaping a particularly relevant and informative parameter. Finally, its size is well suited for dissection and consequently also for the attachment of sensor units, which is a practical advantage for *bivalve-borne* and *semi-bivalve-borne* measurement. Overall, in countries where it is native, it is a very suitable *Species* for research on valve gaping, as demonstrated for example by Jou et al. (2016). In countries where it is invasive, however, even though ecologically the *Species* is problematic, its presence might offer a good opportunity for the use of gaping measurements in the laboratory as well as in the field without risking potential harm for native *Species* through handling and attaching sensor units. This would be an additional benefit if the results were transferable to other (native) *Species* and could hence contribute to their conservation.

For the knowledge transfer, as for the aforementioned frequently used marine *Species*, further studies comparing the valve gaping behavior of *Corbicula fluminea* and native *Species* are required, following the example of Bucci et al. (2008). An additional benefit could be its use in the detection of *Chemical pollutants*, which was the most common

Study target for which *Corbicula fluminea* was used in the screened studies. Whilst *Species*-specific differences in sensitivities and stressor responses among different bivalve *Species* need to be considered, the use of widely distributed and abundant *Species* such as *Corbicula fluminea* may be a useful approach for comparative stressor monitoring and the development of early warning systems (Chen et al., 2012), even if this *Species* is considered an alien pest in areas outside its original distribution.

This also applies to the hybrid-freshwater *Species Dreissena polymorpha*, which has already been used for a long time within the established Biological Early Warning System “*Dreissena-Monitor*” (Borchering, 2006). Whether its valve gaping response differs from pure brackish water *Species* is not tested in the screened studies but since only one pure brackish *Species* was used, namely *Corbicula japonica* (Moroishi et al., 2009), brackish habitats do not appear to be a primary focus for the research community. Still, due to the used hybrid-habitat *Species* (mainly *Dreissena polymorpha* and *Magallana gigas*) that occur in comparable amounts to freshwater *Species*, brackish habitats are covered, albeit not by *Species* that inhabit exclusively brackish habitats.

Beyond the choice of *Species*, the *Measurement approach* represents another key decision in research on valve gaping. Three classes of *Measurement approaches* were identified across the screened studies, of which the *bivalve-borne* sensors were by far the most commonly used category across the screened studies. This dominance likely reflects their ease of application to bivalves, which has been established over the last 20 years. Unlike *external Measurement approaches*, only individual-level data is recorded, in contrast to area-wide recordings covering multiple individuals simultaneously, for example by videos (Turco et al., 2025) or hydrophones (Coquereau et al., 2016). Additionally, unlike *semi-bivalve-borne* setups, *bivalve-borne* approaches do not require individuals to be fixed in place and hence allow them to display their full range of natural behaviors. However, it should be noted that attaching sensors directly to an individual may still influence some of its behaviors (Drainas et al., 2024).

External and *semi-bivalve-borne* approaches, while less popular, each offer distinct advantages that make them valuable in specific contexts, too.

External approaches can simultaneously capture information on several individuals at once without the need to handle them, while they are not limited to measuring *Distance* between shells. For example, parameters such as siphon extension can also be observed (Escobar-Calderón et al., 2022). Their main limitation is that they are less suitable for *Species* that move frequently, as individuals may move out of the observable range, unless movements are restricted by the experimental setting. Additionally, outside of controlled laboratory conditions, data noise can be higher than for other approaches, for example caused by the recording of other animals crossing the image field. Hence, evaluation and interpretation of the recorded data might require advanced computational resources, particularly for automated video analysis.

Semi-bivalve-borne approaches, on the other hand, place a very clear focus on valve gaping, as fixation of the individual largely prevents other movements. This setup also simplifies the technical requirements, since measurement units do not need to accommodate free movement and noise introduced by movements other than valve gaping is largely eliminated. The trade-off, however, is that fixation limits the range of natural behaviors that can be displayed, making this approach less suitable for *Study targets* that aim to examine general behavior under natural conditions, for example, increased mobility as an adaptation to avoid dry conditions (Dobler et al., 2026b).

While there has been a preference for *bivalve-borne* sensors over the last 20 years, all three approaches have their merits, and which one is most suitable depends on the study environment, the *Species* used, and the *Study target*. In general, it appears that *bivalve-borne* sensors are suitable wherever handling of individuals is possible, while *external* approaches are more appropriate when handling is not an option (for example for endangered *Species* or field conditions that do not allow for

the attachment of sensors to individuals). *Semi-bivalve-borne* sensors appear to be a suitable approach for settings that require noise-free measurements of valve gaping and are not affected by the restricted range of natural behaviors that fixation entails.

Within all three groups, considerable variation exists in the specific technologies and methods used. Unifying the naming conventions across studies, or grouping approaches into clearly defined functional categories, would improve comparability without requiring readers to understand technological details. Additionally, including a sample of raw data as a standard supplement could help readers better understand the format of the output and hence the basis on which data analysis is conducted, as the input is a crucial factor for the output of an analysis.

The choice of *Measurement approach* is partly driven by the *Study target*, which determines what needs to be measured and under which conditions. The relationship between *Measurement approaches* and *Study targets* also shows some interpretable patterns. *Endogenous* studies predominantly use *bivalve-borne* sensors, which is logical given that this approach captures individual-level data most directly. Studies on *Chemical pollutants* show a tendency towards *semi-bivalve-borne* approaches, possibly because fixation helps to isolate responses in valve gaping from confounding movement-related factors, allowing a cleaner attribution of observed changes to the pollutant in question. *External* approaches appear most commonly in studies on *Environmental conditions/stressors*, though this may be less directly driven by the *Study target* itself and more by the fact that *external* approaches are predominantly used in marine *Species*, which in turn dominate this *Study target* category.

Technological Study targets accounted for a relatively minor share of the screened studies, which is expected given that studies with a purely technological focus were outside the scope of this review, since only studies that applied technological approaches directly to bivalves and/or shell movement data were included. Nevertheless, the screened studies do contain some developments regarding both hardware and software, indicating that technological progress is an ongoing and embedded part of the field, covered in this work by studies from 1969 (Véró and Salánki, 1969) to 2024 (de Bruyn et al., 2024).

Endogenous targets, the first subcategory of *Biological Study targets*, accounted for a relatively small share of this broader group. This may reflect the fact that *Endogenous* research is bivalve-centric in nature and does not yield direct benefits for humans, which might reduce its appeal for funding or publication. However, understanding *Endogenous* processes is an important foundation for further research: knowing how internal processes influence shell movements allows this knowledge to be incorporated into the interpretation of other *Study targets*. In particular, it helps to establish baseline data for valve gaping behavior, which has been concluded to be an important first step before characterizing responses to external stressors (Andrade et al., 2016).

Natural targets (examining how bivalves react to *Biotic* and *Environmental conditions/stressors*, one of the subgroups of *Exogenous* targets) appear to play a dual role in research on valve gaping: In field settings, they contribute directly to the establishment of baseline data, capturing the full range of natural responses under realistic conditions. As mentioned above for *Endogenous* targets, this is concluded to be an important first step in research on valve gaping (Andrade et al., 2016). Given that especially freshwater bivalves are facing increasing pressure from natural threats (Lopes-Lima et al., 2018), there is an urgent need for improved understanding of the favorable and the current situations. In laboratory settings, however, natural conditions must be introduced deliberately as experimental parameters. In this context, *Natural* targets cease to be part of baseline data and instead become distinct, testable variables in their own right. This distinction between field and laboratory interpretation of *Natural* targets has direct consequences for how results should be interpreted and compared across studies and should be considered carefully in the research question. Still, inclusion of controls in laboratory studies can be useful to collect baseline data for facilitating the extraction of exposure effects.

Anthropogenic targets accounted for a comparable share to **Natural** targets and were dominated by the subcategory of **Chemical pollutants**: They cover a wide range of substances, including metals, pesticides, and other partly very specific pollutants, that can be tested explicitly in the laboratory or as one of many relevant factors in the field. The strong research interest in this area is likely driven by two factors: on one hand, the high variety of potential **Chemical pollutants** means that each requires individual testing, as well as testing for interactive effects with other substances (Di Poi et al., 2018; Gekière et al., 2024). On the other hand, chemical pollution is a major concern for water quality globally, as humans continuously introduce these substances into water bodies worldwide (Häder et al., 2020). Besides the strong negative effects for aquatic ecosystems, **Chemical pollutants** also carry a high potential for direct harm to humans, making it a subject of considerable interest for Biological Early Warning Systems. Those can be applied to monitor water quality in general (Vereycken and Aldridge, 2023) as well as drinking water quality in particular (Ferreira-Rodríguez et al., 2023). For this, distinct reactions of bivalves to pollutants need to be known to be able to set alarm criteria, based on which further measures can be conducted. The implementation and use of Biological Early Warning Systems represents an important and well-established application within research on valve gaping and has received considerable attention (Kramer and Foekema, 2001; Salánki et al., 2003; Kuklina et al., 2013; Bae and Park, 2014; Andrade et al., 2016; Clements and Comeau, 2019; Bownik and Włodkowiec, 2021; Gudimov and Komarova, 2021; Arroyo et al., 2022; Dvoretzky and Dvoretzky, 2023; Ferreira-Rodríguez et al., 2023; Vereycken and Aldridge, 2023). Nevertheless, it is only one application within the field of research on valve gaping in general but also when it comes to chemical pollution in particular: in addition to Biological Early Warning Systems, the understanding of the influence of **Chemical pollutants** on bivalve gaping behavior is also relevant to understand ecological developments. For example, relative resilience to heavy metal pollution might be a potential advantage in *Magallana gigas* compared to *Mytilus edulis* (Kelleghan et al., 2023). This specific study contributes to understanding the competition between a native and an invasive *Species*, which is ecologically highly relevant and does not require a Biological Early Warning System with specified alarm criteria but rather an exploratory, fundamental research approach.

Currently, these two research directions (use of Biological Early Warning Systems and biomonitoring with the aim of fundamental research) appear to operate largely in parallel, with limited exchange of results, as differences in methods for analyzing data render findings difficult to compare. Even though this difference is most prominent in these contrasting approaches, it actually applies to the entire field of research on bivalve gaping: approaches for data analysis vary considerably across studies, even though some basic *Biological endpoints* have been established from the very beginning in principle.

The analysis of those *Biological endpoints* across the screened studies revealed a landscape of considerable diversity with limited standardization. Seven distinct *Biological endpoints* were identified - *Distance*, *State*, *Duration*, *Angle*, *Frequency*, *Distance * Duration*, and *SGS* - used either individually or in various combinations, with only 1.5% of studies not using any of the listed endpoints at all (see Appendix A Table A.6 for other analysis methods).

The use of combinations of *Biological endpoints* in 66% of the studies suggests that single endpoints are often considered insufficient on their own and hence studies reporting only one endpoint risk missing important dimensions of valve gaping behavior. Still, no formal standards could be identified governing which endpoints should be applied to which research questions, nor which combinations are most appropriate for particular study designs or *Species*. It is important to note that the *Biological endpoints* identified in this work summarize several mathematical approaches each, meaning that this lack of standardization goes even beyond the seven categories listed here. The approaches are manifold and the comparability of study results deteriorates with each newly introduced modification of those *Biological endpoints*. Not

only comparability, but also usability is curtailed: when, for example, results from Biological Early Warning studies could be used for fundamental research and vice versa, both fields could be advanced and the generation of knowledge across both fields could be accelerated substantially. To address this, we propose the introduction of a minimum reporting standard for *Biological endpoints* in research on bivalve gaping. Such a standard should specify a core combination of endpoints that all studies in the field are expected to report, while leaving researchers free to conduct additional analyses beyond this baseline. The standard should be designed to encompass as diverse a set of endpoints as possible, so as to meet the varying methodological requirements of different target *Species*, *Measurement approaches*, and research objectives.

While the establishment of such a standard is a task for an expert commission drawn from the different fields of research on bivalve gaping, the following is put forward as a temporary standard:

We propose using *Distance*, *State*, and *Duration* as a minimum reporting standard. *Distance* and *State* were the two most widely used endpoints across the screened studies, and their combination with *Duration* (which adds a complementary temporal dimension not captured by either alone) was the most common endpoint combination identified in the screened studies. Taking the frequency of prior use into account for the choice of a minimum reporting standard improves the comparability of future studies with those already conducted. However, the most commonly used approaches may not necessarily be the most appropriate ones, and inclusion of novel and meaningful endpoints should by no means be hampered by the argument of backward compatibility with previous studies.

For practicability reasons, we propose to use all three endpoints as simple as possible, with *Distance* being represented by the proportional opening of each individual (i.e. minimum value of an individual equals 0, maximum value of an individual equals 1, all values in between are scaled accordingly), *State* being represented by open vs. closed (with the threshold determined by matching visual observations of *States* with the related data), and *Duration* being represented by the time an individual spends in an open or closed *State*.

With this proposal, we address one of the gaps identified in this work. Improving the comparability and usability of results across studies and disciplines remains an overarching challenge. Ultimately, the goal is to connect the diverse research fields that make use of existing measurements and to establish valve gaping as a standardized ecological indicator applicable across fields and monitoring contexts. Achieving this connection will require coordinated effort from experts across all fields involved. This work, with its thorough overview of methodological approaches, provides a starting point for discussions and decisions towards interdisciplinary scientific progress in the research of bivalve gaping behavior.

5. Conclusion

Despite decades of development and a wide variety of research topics, the research field of bivalve gaping lacks agreed reporting conventions. A clear reporting of the bivalve species used, including individuals' size and source, should become standard, alongside proper technical descriptions of the measurement methods including a classification of the used *Measurement approach* for more intuitive understanding by non-technicians, for example, by explicit graphical representation of the approach. Complementing this reporting, a minimum reporting convention of *Biological endpoints* could help harmonize the diverse *Study targets*, advancing the field as a whole without hindering progress in analytical approaches. With standardized reporting conventions in place, research on bivalve gaping has the potential to develop into a robust, widely applicable ecological indicator framework, capable of supporting both aquatic ecosystem monitoring and water management across disciplines and habitat types.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used Claude (Anthropic) in order to support the revision process, including checking language, grammar, and logic. No changes were made directly by Claude (Anthropic). All suggestions for changes by Claude (Anthropic) were reviewed and edited before inclusion in the manuscript. The authors take full responsibility for the content of the published article.

CRedit authorship contribution statement

Konstantina Drainas: Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Juergen Geist:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

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Data availability

All data sources used in this study are provided in the supplementary material.

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