

Development of a biological early warning system based on the reactions of the bivalve mollusc *Pecten jacobaeus* (Linnaeus, 1758) to unfavourable conditions

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Abstract

Bivalve molluscs (Bivalvia) are a group of invertebrates that can be found in freshwater and saltwater habitats. Due to their filter-feeding and sessile lifestyle, bivalve molluscs have been the subject of numerous studies to monitor their response to environmental changes, thereby developing potential early warning systems for aquatic pollution based on living organisms. Such systems often record the closing of bivalve mollusc shells as an indicator of the molluscs' reaction to changing environmental conditions. This study analysed the possibility of using the bivalve mollusc *Pecten jacobaeus* (Linnaeus, 1758) in a pilot early warning system. Four experiments were conducted on six specimens to study the reactions of *P. jacobaeus* specimens to the presence of selected substances in the environment. Three specimens were assigned to both the experimental and control groups. In the first experiment, the reactions of the shellfish to gradually reduced salinity for twenty minutes were monitored. In the second experiment, the responses of the shellfish to an increase in the amount of alcohol in seawater for fifteen minutes were observed. In the third experiment, the reaction of the scallops to the addition of microplastics was monitored for twenty minutes. In the fourth, the responses to the addition of sunflower oil to seawater were monitored. A custom system utilising Hall sensors and an Arduino microcontroller was developed to monitor the opening and closing of the shells. The system registered each closing of the shells on a personal computer. The experiments recorded the reaction of the shellfish to a decrease in salinity and the presence of alcohol, which was manifested by the closure of the shells. No response to microplastics and oil was recorded in the experiments. This pilot study has demonstrated the potential of using the closure of scallop shells as an indicator of environmental changes.

Keywords: *Pecten jacobaeus*, early warning system, Hall sensor, bivalve molluscs

1. Introduction

Bivalve molluscs (Bivalvia) are a group of organisms that live in marine or freshwater habitats, and two fused shells surround their bodies. They feed by filtering water, extracting plankton and organic matter, and are therefore at the bottom of the food chain (Jørgensen, 1996; Peharda Uljević *et al.*, 2022). Most species of bivalve molluscs are immobile or have limited mobility in their adult form. Therefore, they cannot migrate from the area that they occupy in the event of unfavourable living conditions. Due to their relatively sessile lifestyle, bivalve molluscs are attractive species for conducting various types of biological research in the natural environment and represent model organisms for assessing the state of the environment (Vereycken and Aldridge, 2022). For example, one of the earliest monitoring systems based on bivalve molluscs is the "National Mussel Watch Program", implemented in the USA since 1986, which monitors the presence and fluctuations of chemical pollutants and biological stressors in national coastal waters (<https://coastalscience.noaa.gov/science-areas/pollution/mussel-watch/>; accessed 24.03.2025).

In addition to long-term environmental monitoring, there is considerable interest in using bivalve molluscs to monitor changes in the aquatic environment in real time (Comeau, 2018; Rana, 2020; Retaillieu *et al.*, 2023; Shakspeare *et al.*, 2023). The basis for such use is the easily detectable activity of opening or closing the shells of bivalve molluscs. Closed shells serve to protect the molluscs from predators or to isolate the animal from poor water quality conditions. On the other hand, the shells must be open to allow gas exchange, feeding, waste product excretion, spawning, and secretion of byssus filaments (Miller, 2022). Automated monitoring of shell positioning presents a technological challenge, and various devices have been developed for this purpose; the historical development of these devices is described by Miller (2022). Modern devices used today to record the position of shells most often work by attaching a magnet to one shell and a Hall sensor to the other, which records the strength of the magnetic field, or the distance between the shells (Miller and Dowd, 2017; Dvoretzky and Dvoretzky, 2023; Retaillieu, 2023). Such devices that convert non-electrical biological values into electrical signals are often referred to as biosensors (Rana, 2020; Vereycken and Aldridge, 2023).

In the 1990s, a biological early warning system for detecting pollution in the aquatic environment, called Dreissena-Monitor, was developed in Germany (Borcherding, 2006). This system is based on the shell movements of the freshwater mussel *Dreissena polymorpha*. Forty-two zebra mussels with attached sensors, located in two flow systems, were connected to a computer that records whether the mussels are open or closed. Taking into account the expected behaviour of the mussels, as well as the system's response to several toxicity tests, reliable alarm thresholds were established based on the proportion of open and closed mussels at any given time. Borcherding (2006) states that such a system was used at thirteen water pollution control stations in Germany in 2006. In addition to monitoring water quality in freshwater environments, pilot biological monitoring studies have been conducted using a system with biosensors attached to mussels under marine farming conditions. This system is designed for monitoring both animal welfare and the response of shellfish to changes in environmental factors (Andrewartha *et al.*, 2015). Experimental devices based on measuring the distance between shells, changes in the opening or closing pattern, or changes in the shellfish's heart rate have also been developed, and are used to indicate possible changes in the environment in which the shellfish are found (Lyubimtsev *et al.*, 2019; de Vargas Guterres *et al.*, 2020).

In light of the above, it can be concluded that the use of shellfish, equipped with various sensors, for monitoring the state of the environment and changes caused by environmental

pollution's impact on marine and freshwater habitats is a promising method of biological monitoring. The advantages of such systems are reflected in the lower cost of production and use, compared to traditional monitoring methods, the ability to obtain information about the state of the ecosystem in real time, reliable operation, ease of operation, low maintenance requirements, and very rapid detection of alarming situations (Borcherding, 2006; Dvoretzky and Dvoretzky, 2023).

Although various studies have been conducted in recent years on the use of sensors to record the reactions of bivalve molluscs to different environmental conditions (Comeau, 2018; Rana, 2020; Retailleau *et al.*, 2023; Shakspeare *et al.*, 2023), according to the available data, none of the studies conducted have been done on the species of bivalve mollusc, Mediterranean scallop (*Pecten jacobaeus*, Linnaeus, 1758). The Mediterranean scallop is an endemic species, and the largest species of the Pectinidae family that inhabits the Mediterranean Sea (Ríos *et al.*, 2002; Peharda Uljević *et al.*, 2022; Wagner, 1991). It is most widespread in the northern Adriatic; however, since the 1980s, a significant population decline has been recorded throughout the Mediterranean due to overfishing (Katsanevakis, 2005; Peharda Uljević *et al.*, 2022). Specimens of the species have a flat upper shell that is usually lighter in color than the lower, rounded shell (Wagner, 1991; Mattei and Pellizzato, 1996; Peharda Uljević *et al.*, 2022). Like most species of the Pectinoidea family, they are hermaphrodites, meaning that each specimen contains both male and female gametes (Mattei and Pellizzato, 1996; Peharda Uljević *et al.*, 2022). Specimens can grow up to sixteen centimeters in length, reaching sexual maturity at a length of approximately five centimeters (Mattei and Pellizzato, 1996). They grow seasonally, with the highest growth intensity recorded during the winter months (Peharda Uljević *et al.*, 2022).

Scallops are considered mobile bivalves, and by vigorously closing their shells and expelling seawater, they can move and thus avoid predators and local unfavourable environmental conditions (Peharda Uljević *et al.*, 2022). Most bivalves react to unfavorable conditions by reducing filtration and wholly or partially closing their shells (Jørgensen, 1996). Therefore, this research hypothesized that, given their ability to move, Mediterranean scallops would react more strongly to changes in environmental conditions; that is, in the presence of adverse conditions or pollution, they would respond by closing their shells and/or moving. In order to monitor the closing of bivalve shells, a device based on the Arduino platform was created, to which sensors were connected to record the position of the shells. These and similar devices have already been successfully used in monitoring the behavior of other species of shellfish, specifically their reactions to changes in environmental parameters (Dvoretzky and Dvoretzky, 2023).

2. Materials and Methods

2.1. Bivalve molluscs used in the study

Six specimens of the species *Pecten jacobaeus* were obtained in collaboration with local fishermen. After being removed from the sea, the specimens were immediately placed in plastic containers, covered with a towel soaked in seawater, and transferred to the research station within thirty minutes. Upon arrival, the width, length, and height of each specimen were measured with a sliding ruler. All specimens met the size requirements of the Rulebook on the protection of fish and other marine organisms and criteria for determining the amount of compensation for damages (Official Gazette 64/2023), which stipulates a minimum catch length of a specimen to be greater than ten centimetres. According to available literature data, the age of the specimens can be estimated to be ten years or more (Peharda Uljević *et al.*, 2003).

Table 1. Shell sizes of scallops were measured with a sliding ruler.

	Width (cm)	Length (cm)	Height (cm)
Specimen 1	15.4	13.1	3.6
Specimen 2	14.9	12.3	3.3
Specimen 3	15.2	12.9	3.3
Specimen 4	15.6	13.1	3.7
Specimen 5	15.2	12.5	3.3
Specimen 6	15.9	14.5	3.8

2.2. Tank systems for bivalve housing and experiments

A set of two closed recirculating systems was constructed to house the specimens. Each system consisted of a central tank with a volume of 62 L and an auxiliary tank with a volume of 65 L, from which seawater was pumped back to the main tank (Figure 1). To provide optimal conditions for the shellfish, 45 L of seawater were drained from the auxiliary tank three times a day and replaced with fresh seawater. A HI-98129 Combo pH/EC/TDS/temperature tester (HANNA instruments) and OxyGuard Polaris C DO probe were used to monitor seawater parameters. Throughout the experiment, the pH ranged from 8.10 to 8.15, and oxygen saturation ranged from 88 % to 94 %.

Two smaller tanks with a volume of 30 L were used to conduct the experiments, in which the bivalves were exposed to conditions of reduced salinity, alcohol, microplastics, and oil. One tank was intended for the control group, and the other was intended for the experimental group. The tanks in which the experiments were conducted were carefully cleaned, rinsed with distilled water, and dried before use in the following experiment. Meanwhile, the bivalves were transferred to the tank system to recover from the effects of the substances to which they were exposed.



Figure 1. Scallops (*Pecten jacobaeus*, Linnaeus, 1758) in one of the tanks of the recirculation system

2.3. Shell position recording system

A system for controlling the position of the shells was designed to ensure automated recording of the shell movement of the studied specimens. The system consisted of an Arduino Uno R3 microcontroller, a six-meter-long cable, Seed Studio Hall sensors, magnets, and a laptop computer. The microcontroller enabled the simultaneous operation of six Hall sensors.

To enable the sensor to work, a program code was written in the C programming language. The code was then loaded into the Arduino IDE program on a personal computer, which was used to transfer the code to the microcontroller itself. Using the code, the microcontroller converted the Hall sensor signals into digital states 0 (closed shell) and 1 (open shell). The obtained signals were transmitted in real-time from the microcontroller to a laptop computer, which was used to control the position of the shells using the "Serial monitor" option available in the Arduino IDE program (Figure 2).

```
Sensor 1: 0
Sensor 2: 1
Sensor 3: 0
Sensor 4: 1
Sensor 5: 1
Sensor 6: 1
Sensor 1: 0
Sensor 2: 0
Sensor 3: 0
Sensor 4: 1
```

Figure 2. Example of the "Serial Monitor" option available in the Arduino IDE

To assess the sensitivity and accuracy of the shell movement recording system based on Hall sensors, a series of preliminary calibration trials were conducted using empty shells from several specimens of *Pecten jacobaeus*. The Hall sensors were attached to the upper shell of each specimen using glue, while a permanent magnet measuring 18×3 millimeters was attached to the lower shell. The upper and lower valves were manually positioned in controlled states. Corresponding digital output from the Hall sensor was recorded via the Arduino serial monitor. In each configuration, the system reliably detected shell positions and returned consistent digital values: '0' for closed shells and '1' for open shells. These measurements were repeated across multiple shell pairs to confirm reproducibility. Although the current setup was binary, it was sufficiently sensitive for detecting complete closures, which represent the primary behavioral endpoint of interest in the context of a biological early warning system.



Figure 3. Hall sensor attached to the specimen of scallop (*Pecten jacobaeus*, Linnaeus, 1758). A red light indicates that the sensor is working and the shells are closed.

After waterproofing, the Hall sensor and permanent magnet were attached to each experimental specimen of *P. jacobaeus* as described above (Figure 3). The specimens and the sensors on them were numbered with the same number. Specimens marked with the numbers one, two, and three were subjected to experiments, while specimens marked with the numbers four, five, and six served as a control group.

2.4. Conducting the experiments

After seven days of acclimation of the shellfish to the conditions in the recirculation system, the experiments were conducted. After being transferred to the experimental tanks, the individuals were allowed a five-minute acclimation period during which their behavior was observed, after which the each experiment was initiated. Four experiments were performed, each of which is described in detail below. A three-day break was made between each experiment.

2.4.1 Experiment 1. - reactions of scallops to a decrease in salinity

In the first experiment, the response of scallops to a gradual reduction in salinity was monitored by adding distilled water to 20 L of seawater in the experimental tank. After being transferred to the experimental tanks, the individuals were allowed a five-minute acclimation period during which their behavior was observed, after which the experiment was initiated. To ensure the same conditions in the experimental and control tanks, the same amount of seawater was added to the control tank simultaneously. The distilled water and seawater were the same temperature as the water in the tanks, which was 14.6 °C. Distilled water and seawater were added four times, 2.5 L at a time. At the beginning of the experiment and after each addition of distilled water in the experimental tank, salinity was measured. A five-minute break was allowed between each addition of distilled and seawater. After the last addition of water, the scallops were left in the tanks for an additional five minutes before being transferred to the holding tanks. Throughout the experiment, sensors placed on the scallops recorded the movements of the shells as they closed and opened.

2.4.2 Experiment 2. - Reactions of scallops to the addition of alcohol

In the second experiment, the reaction of shellfish to the presence of alcohol in seawater was monitored. The experiment was conducted like the previously described experiment using distilled water. Three 100 mL portions of 96 % ethanol were added to the experimental tank, totaling 300 mL, while three 100 mL portions of seawater were added to the control tank, also totaling 300 mL. A five-minute break was allowed between each addition, and after the last addition, the shellfish were left in the tanks for an additional 5 minutes, after which they were transferred to holding tanks.

2.4.3 Experiment 3. - Reactions of scallops to the addition of microplastics

The third experiment used microplastic particles ranging in size from 1 mm to 5 mm, prepared by shredding polyethylene bags of different colours. The bags were shredded to the appropriate size using scissors and then added to a plastic container containing 200 mL of seawater. The plastic particles were then mixed with seawater and added to the experimental tank, while 200 mL of seawater was added to the control tank. The shellfish's reactions were then recorded for twenty minutes. After the experiment, the shellfish were transferred to holding tanks.

2.4.4 Experiment 4. - Reactions of scallops to the addition of sunflower oil

The fourth experiment investigated the reaction of shellfish to the addition of 100 mL of sunflower oil to an experimental tank containing 20 L of seawater. To ensure the most even distribution of oil in the experimental tanks, 100 mL of oil were first mixed with 100 mL of seawater in a 2-liter plastic bottle. The bottle was then closed, and the contents were shaken until the oil droplets were finely dispersed in the water, specifically, until an emulsion was formed. The contents of the bottle were added to the experimental tank, while 200 mL of

seawater were added to the control tank. The reaction of the specimens was then recorded over 20 minutes.

3. Results

3.1 Reactions of scallops to reduced salinity

At the beginning of the experiment, seawater salinity was measured at 37.6 ‰. After adding 2.5 L of distilled water to 20 L of seawater, the salinity dropped to 33.5 ‰, and the sensors on the shellfish did not record any reactions from the shellfish over five minutes. Additionally, no difference in the behaviour of the shellfish between the experimental and control tanks was observed by direct observation. After adding another 2.5 L of distilled water, the salinity dropped to 30 ‰, and the specimens began to close their shells and retract their sensory tentacles. The sensors recorded the rapid movements of opening and closing the shells, as well as the specimens moving within the experimental pool. After adding the third dose of distilled water, the salinity dropped to 27 ‰, and the sensors continued to record the closing and opening of the shells of all three specimens in the experimental pool. In contrast, the specimens in the control pool remained completely open at all times. Within forty-five seconds of adding the third dose, specimen number 3 completely closes and remains closed until the end of the experiment. After adding the fourth dose, the salinity drops to 25 ‰, and within ten seconds of adding the fourth dose, the sensors record the closing of specimens 1 and 2, and all specimens remain completely closed until the end of the experiment. The sensors on the specimens in the control pool did not record the closing of any specimens during the entire duration of the experiment (Figure 4).

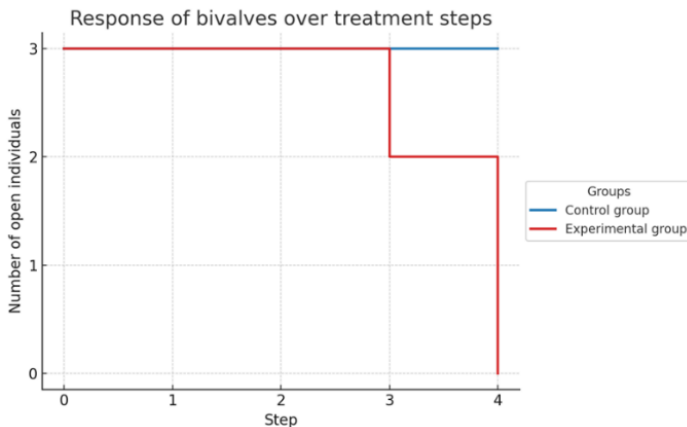


Figure 4. Response of specimens of scallop (*Pecten jacobaeus*, Linnaeus, 1758) to decreasing salinity over four steps. At each step, 2.5 L of distilled water was added to the system (initial volume 20 L; initial salinity = 37.6 ‰).

3.2 Reactions of scallops to the addition of alcohol

Within ten seconds after adding the first dose of 100 mL of 96 % ethanol, the sensors recorded intensive opening and closing of the shells and movement of all three specimens in the experimental pool. After 90 seconds, the scallops stop closing and opening their shells and remain open until the next addition of alcohol. Five minutes after adding the first 100 mL, another 100 mL of 96 % ethanol were added. Immediately after adding the second dose, the sensors again recorded intensive opening and closing of the shells and the movement of the specimens within the tank. After one minute, specimen number 3 closes and remains closed until the end of the experiment. In specimens 1 and 2, after the initial intensive movements, a sedated phase occurs, and they remain open until the third dose of alcohol is added. Immediately after adding the third dose of alcohol, specimens 1 and 2 also close and remain closed until the end of the experiment. When designing the experiment, we planned to add a fourth dose of 100 mL of alcohol. However, since the specimens had already closed completely after three doses, i.e., 300 mL of alcohol, we decided to return them to the holding tanks after five minutes. Sensors did not record any closing of shells of specimens in the control pool throughout the experiment (Figure 5).

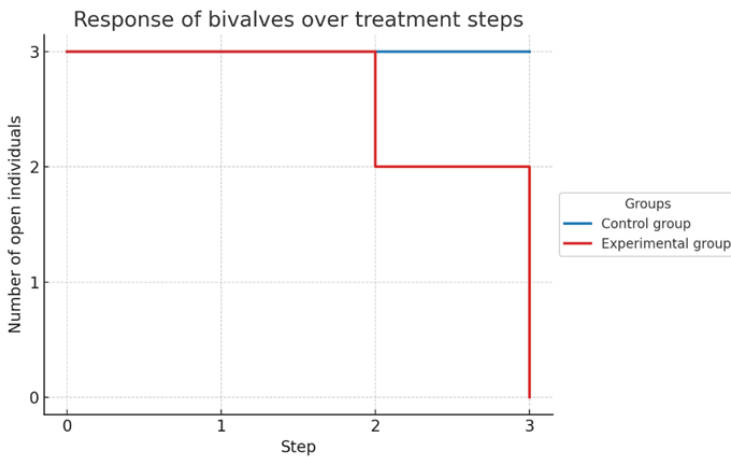


Figure 5. Response of specimens of scallop (*Pecten jacobaeus*, Linnaeus, 1758) to stepwise addition of ethanol. At each step, 100 mL of 96 % ethanol was added to the system (initial volume 20 L; initial salinity = 37.6 ‰).

3.3 Reactions of scallops to the addition of microplastic particles

After adding microplastic particles mixed in 200 mL of seawater to the experimental pool, the sensors did not record any movements of the scallops. Direct observation revealed that while some plastic particles remained on the surface and some sank, the shellfish did not react. Instead, the shellfish shells were completely open with their sensory tentacles extended. Specimen number 2 even pulled plastic particles inside the shells (Figure 6). The specimens in the control pool remained open throughout the experiment.



Figure 6. Specimens of scallops (*Pecten jacobaeus*, Linnaeus, 1758) during the microplastic experiment

3.4 Reactions of scallops to the addition of sunflower oil

After adding 200 millilitres of an emulsion of sunflower oil and seawater to the experimental pool, the sensors did not record any movements of the shellfish shells (Figure 7). During the twenty minutes of the experiment, the bivalves in both the experimental and control pools remained open.



Figure 7. Specimen of scallops (*Pecten jacobaeus*, Linnaeus, 1758) during the sunflower oil experiment

4. Discussion

4.1 Reactions of scallops to reduced salinity

The responses of scallops to reduced salinity recorded in this study are consistent with the results of other studies that have shown that bivalve molluscs reduce the amount of filtered seawater or completely close their shells if the surrounding salinity is at the limit of their tolerance (McFarland *et al.*, 2013). It is known that salinity fluctuations can affect vital physiological parameters of bivalve molluscs. Suboptimal salinity conditions result in a weakening of the defence functions of bivalve molluscs and slow down their growth and filtration rate (Pourmozaffar *et al.*, 2019). Domínguez *et al.* (2020) found that four bivalve mollusc species (*Ruditapes decussatus*, *Venerupis corrugata*, *Cerastoderma edule*, *Ruditapes philippinarum*) dramatically reduce the level of filtration at salinities below fifteen ppm. A study conducted on the species *Perna viridis* showed that within five minutes of placing the specimens in a tank at a salinity of 35 ‰, 100 % of the mussels were open with their gills exposed to the external environment. When exposing specimens of the same species to a salinity of 25 ‰ for 1 hour, only 10 % of the specimens were fully open (McFarland *et al.*, 2013). From the presentation of these two studies (McFarland *et al.*, 2013; Domínguez *et al.*, 2020), it is evident that the tolerance limit for lower salinities is at different salinity values in different species. The results obtained from our study on the Mediterranean scallop, which showed that all specimens closed completely at a salinity of 25 ‰, align with the findings of studies conducted on the species *Perna viridis*.

4.2 Reactions of scallops to the addition of alcohol

Despite an extensive literature search, we have not found a single study that has examined the reaction of shellfish to the presence of alcohol in seawater. The study described in this paper showed that scallops reacted by intensive closing and opening, as well as by moving, at the first instance of alcohol presence in the seawater, that is, when the alcohol concentration was 4.8 ‰. At a concentration of 14.2 ‰, all specimens were tightly closed. As we have already mentioned, specimens isolate their tissues from adverse environmental conditions by closing their shells (Miller, 2022). Therefore, we can conclude that scallops recognise the presence of alcohol in seawater, at the concentrations as mentioned above, as adverse environmental conditions.

4.3 Reactions of scallops to the addition of microplastics

Due to their diet, shellfish can ingest and bioaccumulate plastic particles of various sizes from the aquatic environment in which they are found (Wright *et al.*, 2013; Huffman Ringwood, 2021). The size of microplastic particles directly affects their movement in water and consumption by shellfish. Research has shown that smaller particles will be more often ingested by shellfish and will have a greater negative impact on shellfish (Wang *et al.*, 2021). Namely, larger plastic particles will be excreted in the form of pseudofeces and faeces, while smaller microplastic and nanoplastic particles will accumulate in tissues (Huffman Ringwood, 2021). Song *et al.* (2020) state that the duration of exposure to microplastic particles also affects the intensity of adverse reactions in shellfish. Abidli *et al.* (2021) state that the level of filtration of the shellfish *Mytilus galloprovincialis* decreases after two weeks of exposure to microplastic particles. Microplastics typically cause sublethal effects that accumulate over more prolonged exposures. For instance, oxidative stress, energy depletion, and histopathological changes have been observed after days to weeks of microplastic exposure, but not within an hour. Bour *et al.* (2018) found no changes in survival, condition, or burrowing behaviour in *Ennucula tenuis* and *Abra nitida* species, even after 4 weeks of microplastic exposure. However, subtle impacts on energy reserves were detected. In our study, we measured changes in the

behaviour of the shellfish *P. jacobaeus* in response to short-term exposure to microplastic particles. The shellfish did not react to the presence of microplastics in the environment, but continued to filter seawater normally. This is consistent with all the previously mentioned studies that indicate that shellfish ingest microplastic particles through filtration. Furthermore, the results of this pilot study showed that scallops do not change the intensity of filtration, i.e., they do not close their shells in the presence of microplastics in the environment. From the data above, we can conclude that short-term exposure to microplastic particles is not recognised by shellfish as deteriorated environmental conditions. These results should be interpreted with caution, as longer exposure durations and a broader range of microplastic characteristics may be necessary to evaluate the species' sensitivity to such pollutants fully.

4.4 Reactions of scallops to the addition of sunflower oil

Unfortunately, we did not find any studies in the available literature that would address shellfish reactions to the presence of vegetable oils in the seawater surrounding them. All available studies researched the impact of crude oil and diesel on shellfish physiology (Neff *et al.*, 1987; da Silva *et al.*, 2005; Baussant *et al.*, 2009). A common factor among all the studies mentioned is that small oil droplets can be filtered out of the water and consumed by shellfish during their everyday feeding habits. We created a fine oil emulsion during our study by vigorously mixing the seawater and sunflower oil. After pouring the emulsion into the experimental tank, the small oil droplets were evenly distributed inside the tank, while the larger droplets floated to the surface. Since the shellfish continued to filter the seawater normally with no observable behavioural response after the oil emulsion was added, we can assume that the short-term exposure to a fine emulsion of sunflower oil did not represent an unfavourable environmental factor for them. It is important to note that the oil used was a commercially available, sunflower oil intended for human consumption. Given its chemical profile and limited exposure time, the absence of a reaction should not be interpreted as evidence of insensitivity to all types of oil-based pollution. Instead, these findings underscore the need for further studies involving various types of oils, different concentrations, and longer exposure durations to more accurately assess the suitability of *Pecten jacobaeus* for detecting oil-derived contaminants in early warning systems.

4.5 Potential of Mediterranean scallops as bioindicators and biosensors for early-warning environmental monitoring systems

Biological early warning systems monitor the behaviour or physiology of living organisms as an indirect mechanism for recording local changes in the environment. Such systems have become an increasingly used tool for monitoring water pollution (Vereycken and Aldridge, 2022). Some systems have been in use for over thirty years, most often using shellfish as a model organism (Borcherding, 2006). Namely, the reaction to unfavourable biotic and abiotic factors is crucial for the survival of shellfish, which, as sessile or poorly mobile organisms, have developed numerous adaptations and responses that enable them to survive (Dzierżyńska-Białończyk *et al.*, 2019; Miller, 2022). Furthermore, the advantage of using bivalve molluscs in early warning systems lies in their continuous filtration of large amounts of water, sensitivity to various pollutants, longevity of particular species, and physical responses to environmental changes (Vereycken and Aldridge, 2022). One of the techniques used to monitor the reactions of bivalve molluscs in early

warning systems is tracking the position of their shells (Andrewartha *et al.*, 2015; de Vargas Guterres *et al.*, 2020; Dvoretzky and Dvoretzky, 2023).

Through this pilot study using a system for recording the position of shells, which we constructed ourselves, we tried to determine the possibility of using the specimens of the species of Mediterranean scallop as an organisms for creating a biological early warning system for changes in environmental factors, i.e. possible environmental pollution, using shell closure behavior as a measurable endpoint. The constructed system demonstrated the possibility of monitoring the movement of bivalve mollusc shells and recording their reactions to unfavourable environmental conditions. It has been previously known that strong shell movements enable scallops to swim in the event of danger (Peharda Uljević *et al.*, 2022). Through this research, we have determined that strong and intense shell movements also occur in cases where specimens of this species find themselves in unfavourable environmental conditions. The constructed experimental movement recording system successfully recorded clear behavioural responses, such as rapid shell movement and closure, in reaction to acute stressors like reduced salinity and ethanol, suggesting that *P. jacobaeus* is capable of perceiving and reacting to sudden changes in water quality.

Despite the recorded reactions of scallops to a decrease in salinity and the addition of alcohol in the pilot study, there was no reaction at all to the addition of plastic particles and sunflower oil. However, the absence of any observable response to microplastic particles and sunflower oil under the tested conditions needs cautious interpretation. In the case of microplastics, exposure lasted only twenty minutes. It involved relatively large particles (1–5 mm), which may not have been perceived as threatening by the scallops or may have been processed as inert suspended matter. Since previous studies have shown that effects of microplastics in bivalves tend to manifest after longer exposure durations (days to weeks) (Bour *et al.*, 2018; Abidli *et al.*, 2021) our findings do not exclude the possibility of physiological impacts, but rather suggest that *P. jacobaeus* may not be suitable for early and rapid detection of microplastics in real-time monitoring systems.

Similarly, no behavioural changes were observed during short-term exposure to a fine emulsion of sunflower oil intended for human consumption. The chemical composition and relatively benign nature of the tested oil likely contributed to the lack of response. It remains unclear whether more chemically complex or industrial oil pollutants would provoke detectable reactions in scallops. Therefore, further research is necessary to evaluate the sensitivity of *P. jacobaeus* to a broader range of oil-derived contaminants, including petroleum-based substances and oil mixtures containing surfactants and additives.

Taken together, the results of this study should be regarded as preliminary. While *P. jacobaeus* demonstrated responsiveness to specific acute stressors, its capacity to serve as an effective sentinel species in biological early warning systems remains contingent on pollutant type, concentration, and duration of exposure. Future research should incorporate extended exposure periods and additional pollutant classes to characterise the species' potential in environmental monitoring applications more precisely.

5. Conclusion

This pilot study explored the behavioral responses of *Pecten jacobaeus* to selected environmental stressors using an in-house-built sensor system designed to monitor shell valve

movement. The tested individuals exhibited detectable behavioral responses, such as rapid shell movements and shell closure, in reaction to acute changes in salinity and ethanol concentration, indicating the potential of this species to respond to specific short-term environmental changes. No behavioral reaction (i.e., shell closure) was observed in response to short-term exposure to microplastic particles or sunflower oil. These findings are consistent with previous literature indicating that such substances may not induce immediate or observable behavioral responses within short exposure periods.

The in-house-built sensor system, based on Hall sensors, successfully recorded valve movement and proved capable of detecting full closures, thereby validating its basic functionality for behavioral monitoring in bivalves. While the results demonstrate some promise for the application of *P. jacobaeus* in biological early warning systems, the current study was limited to a small number of individuals, a restricted range of stressors, and short exposure durations. Therefore, the outcomes should be interpreted as preliminary, serving primarily as a proof of concept for future research. Further investigations involving more extended exposure periods and a wider range of environmental contaminants are necessary to fully assess the suitability and reliability of *P. jacobaeus* as a sentinel species for biological early warning systems.

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Conflict of interests

The authors affirm that they have no competing interests to disclose.

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