

1 Managing Aquaculture Noise: Impacts on Fish Hearing, Welfare, and Mitigation Strategies

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30     Abstract

31     As intensive aquaculture continues to develop, substantial investments have been made in  
32     equipment to sustain high-density farming. However, this has resulted in elevated noise levels  
33     within these aquaculture environments, particularly below 2000 Hz, matching the hearing range  
34     of most cultured species. Fish under noise conditions may experience hearing loss and  
35     physiological stress, which can negatively affect their growth, foraging efficiency, reproductive  
36     success, and increase their susceptibility to diseases. These adverse effects compromise the  
37     welfare of farmed fish, potentially decreasing production quality and increasing mortality rates.  
38     Despite these notable effects, the understanding and management of noise conditions in  
39     aquaculture systems lag behind other environmental parameters in terms of recognition and  
40     control.

41     In this review, we cover the fundamentals of fish auditory systems, the hearing range of key  
42     farmed fish species, and the most common noise sources and levels prevalent in current  
43     intensive aquaculture systems. Additionally, we examine recent discoveries on the effects of  
44     anthropogenic noise on fish hearing, physiological responses and behavior. Finally, we provide  
45     strategies for noise monitoring and management in aquaculture industry, while also highlighting  
46     open questions for future research. Our goal is to assist researchers and practitioners in  
47     comprehending underwater noise and its effects on cultured organisms, providing a valuable  
48     resource for promoting healthy and sustainable development of intensive aquaculture.

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50     **Keywords:** Fish welfare, Aquaculture, Underwater noise, Auditory sensitivity, Noise control

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## 1. Introduction

The United Nations predicts that by the year 2100, the global population will reach at least 11 billion. Therefore, any industry capable of producing sustainable food will need to expand and become more efficient than ever to meet the growing human demand for food and nutrients <sup>[1]</sup>. The Food and Agriculture Organization of the United Nations (FAO) reported that in 2020, the total production of both fisheries and aquaculture sectors reached a record of 214 million tons, with per capita consumption standing at 20.2 kg (excluding algae), more than double the consumption rate of 9.9 kg per capita observed 50 years ago.<sup>[1]</sup> Currently, nearly 90% of wild caught species are facing overfishing, and the global capture from marine fisheries is no longer sufficient to meet demand growth sustainably<sup>[1-3]</sup>. Populations will increasingly depend on aquatic products from aquaculture, which continues to grow at a rate of 7.8% annually, surpassing pork, dairy, beef, and cereals. This highlights the importance of aquaculture in enhancing the resilience of the global food system <sup>[4]</sup>.

In the face of pressing challenges such as rapid population growth, resource constraints, eutrophication and climate change, aquaculture must adapt to foster healthy, diverse, and highly productive practices <sup>[5,6]</sup>. In recent times, various aquaculture models have rapidly emerged, with intensive aquaculture farms demonstrating extensive potential owing to their controlled environment, enhanced efficiency, and reduced energy consumption. Intensive aquaculture requires advanced instrumentation and management techniques to achieve high-density cultivation, substantial product yields, and significant economic benefits. Currently, notable methods within this category include the recirculating aquaculture systems (RAS), deep-sea cage system, and in-pond raceway systems (IPRS). However, the aquaculture industry still faces considerable challenges related to spatial constraints, fish diseases, food safety, environmental pollution, and consumer acceptance <sup>[7-9]</sup>. To achieve sustainable production and cope with the growing consumer demand, it is crucial to prioritize animal welfare and ethical aquaculture practices <sup>[10]</sup>. In intensive aquaculture systems, such as RAS models, several potential stressors related to water quality and noise conditions are difficult to manage due to the pursuit of high yields. These stressors are often exacerbated in high-density farming, as fish have limited space

to escape from their impact within the tank, resulting in compromised fish welfare and affecting economic profitability<sup>[11]</sup>. While current studies on stressors in intensive aquaculture systems primarily focus on parameters like culture density, lighting, and water quality, there is comparatively less attention given to noise conditions.

In intensive aquaculture, equipment like pumps, aerators, and filtration systems are necessary to maintain high-density aquaculture environments, inevitably generating low frequency underwater noise<sup>[12-22]</sup>. Most fish and invertebrates, including those used in aquaculture industry, show best hearing sensitivity and sound production with this frequency range<sup>[23-25]</sup>.

Extended exposure to elevated noise levels imposes a persistent burden on organisms. This ultimately results in the deterioration of various bodily functions, compromising growth and even survival<sup>[14,25-27]</sup>. Multiple studies have demonstrated that long-term exposure to anthropogenic noise can impact fish hearing, physiological responses, growth, reproduction, and behavior<sup>[28-32]</sup>.

Notably, close to the noise source, where noise levels are highest, a variety of significant and permanent effects can occur simultaneously. In contrast, at greater distances from the noise source, fewer physiological impacts are observed, and no permanent damage is detected (Figure 1). Understanding such negative consequences from chronic noise exposure and how they impact fish well-being at the species level is crucial for developing effective soundscape management and noise mitigation strategies.

This review provides a comprehensive overview of the fish auditory system, including its structure and sensitivity across major cultured species. It highlights the importance of the hearing sense for these animals and discusses the audiometry methods for measuring auditory thresholds and detecting hearing impairments in future research. Besides, it also covers non-auditory effects of noise exposure, ranging from general physiological effects to behavioral changes and impact on reproduction.

Finally, this review proposes strategies for effectively regulating noise within aquaculture settings. The ultimate goal is to inform aquaculture scientists and farmers with theoretical guidance for creating more sustainable and healthier aquaculture systems for intensive farming.

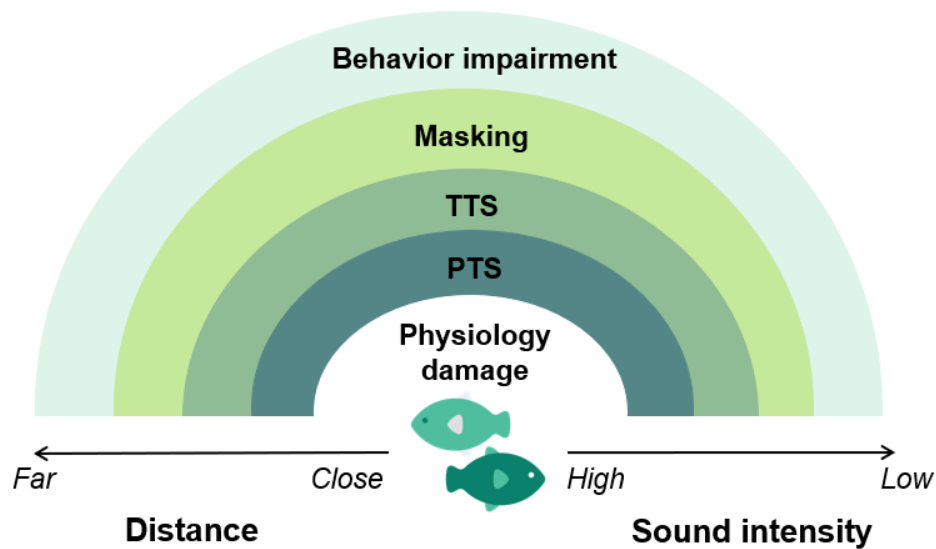


Fig.1 Multiple effects of anthropogenic noise on fishes considering their distance to the noise source. Simultaneous effects including physical damage and mortality occur closer to the noise source, whilst mild or temporary effects are typically found at greater distances. (TTS, Temporary auditory Threshold Shifts; PTS, Permanent auditory Threshold Shifts).

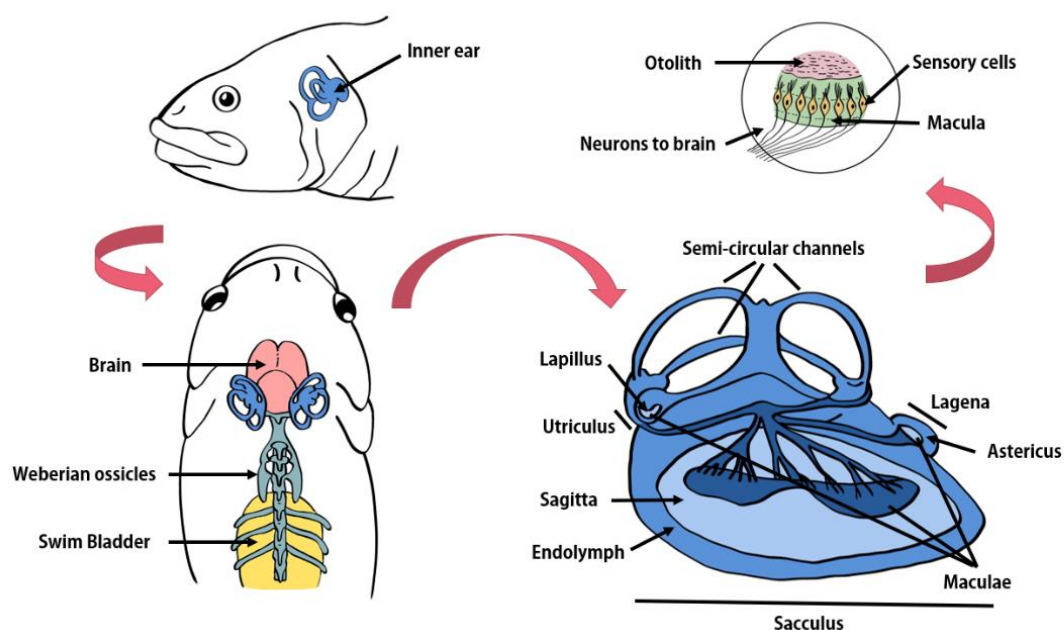
## 2. Fish Sensing: Detecting Sound and Vibrations

Fish species have undergone adaptive evolutionary processes to develop a wide range of sensory structures specifically for detecting underwater sound and vibrations. These specialized adaptations enable fish to effectively navigate and interact within their aquatic environment. The peripheral auditory organs of fish include the inner ears and, in some species, accessory morphological hearing structures to enhance their auditory sensitivity and expand their sensitive frequency range. Besides, most fish species possess a lateral line system for detecting vibrations and water movement, which aids in spatial orientation and playing a critical role in behaviors such as schooling.

## 2.1. The auditory system

Ray-finned fishes (Actinopterygii), representing over half of extant vertebrates, exhibit remarkable diversity in hearing structures and sound-producing mechanisms. These adaptations serve orientation and communication within their highly diverse and acoustically rich environments<sup>[33,34]</sup>. Considerable variation exists in the shape and size of the inner ears across the over existing 30,000 fish species. This diversity likely results in differences in their sensitive ranges, auditory thresholds, and directional hearing<sup>[35]</sup>.

The inner ear comprises of three perpendicular semicircular canals that respond primarily to body movement and postural changes, and three otolithic endorgans - utricle, saccule, and lagena, each containing a single dense calcium carbonate otolith<sup>[36-39]</sup> – see Fig. 2. Each endorgan contains a sensory epithelium populated with auditory receptors called hair cells, which are covered by a gelatinous membrane and mechanically linked to the calcareous otolith. Movement of these hair cells triggers the opening of transduction channels, generating a receptor potential and stimulating afferent fibers along the axis of movement. The differential inertia between the sensory macula and the attached otolith enables these endorgans to function as biological accelerometers, encoding linear acceleration and particle motion<sup>[40,41]</sup>.



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149 Fig. 2 Position and structure of the fish inner ears and their relative distance to the swimbladder  
150 and connecting Weberian ossicles (left). Detail of the inner ear showing the three otolithic  
151 endorgans – sacculus, utricle and lagena. Each otolithic endorgan contains a macula with  
152 auditory sensory hair cells that detect acoustic stimuli through stereocilia bending caused by  
153 otolith vibrations (right). Adapted from illustrations by Carlyn Iverson and Antoni Lombarte.

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155 At the top of each sensory hair cell, there is a bundle of cilia, and the arrangement of cilia is  
156 related to the polarization of each hair cells. When the stereocilia bend towards the kinocilium  
157 cause depolarization or excitation of the sensory cell, while bending to the opposite direction  
158 causes hyperpolarization. Fish rely on these polarity-related responses to discriminate sound  
159 features including directionality <sup>[42,43]</sup>. Sensory hair cells communicate with the auditory nerve  
160 (VIII cranial nerve) and information is then transmitted to the central nervous system for further  
161 auditory processing <sup>[44]</sup>.

162 Sound waves in the water environment have both a pressure and a particle motion component. A  
163 sound wave propagates because particles next to a vibrating source move back and forth in the  
164 same location but transmitting their oscillatory motion to their neighboring particles. The  
165 particles oscillate along the direction of sound propagation and are followed by waves of  
166 compression and rarefaction corresponding to increase and decrease in pressure, respectively.  
167 This phenomenon is termed sound pressure. Particle motion, on the other hand, can be specified  
168 in terms of particle displacement, velocity, or acceleration <sup>[24,45]</sup>.

169 Particle oscillations in the water can either be detected directly by hair cells present along the  
170 fish lateral line or by the inner ear hair cells due to the relative motion (impedance difference)  
171 between the fish body and the denser otoliths <sup>[46]</sup>.

172 Most aquatic animals, including fish and invertebrates primarily sense sound using particle  
173 motion <sup>[47-50]</sup>. However, several fish species exhibit higher auditory sensitivity and/or an extended  
174 frequency bandwidth, due to accessory structures that enhance hearing by acoustically coupling  
175 air-filled cavities to the inner ear, converting sound pressure into movements that can be  
176 detected by otoliths <sup>[51]</sup>. Examples include the Weberian apparatus in Ostariophysi, enhancing

hearing in fish like carp (*Cyprinus carpio*) and goldfish (*Carassius auratus*), and adaptations like the air-breathing organ in Anabantoidei. The inner ear's connection to the swim bladder varies, influencing hearing sensitivity. These connections can be direct or proximate, such as in Herringiformes and Stenopterygians, or absent, as in cod and salmon, resulting in lower auditory sensitivities.

## 2.2. The lateral line system

In addition to their auditory system, fish also possess a specialized sensory system known as the lateral line, which detects water motion and pressure gradients, and mediates capabilities such as predators and prey detection, hydrodynamic imaging and various behaviors such as rheotaxis, schooling, and courtship displays <sup>[52-58]</sup>. The lateral lines are linear structures running along both sides of the fish's body, comprising numerous canal neuromasts that open to the environment through multiple pores. These neuromasts, also distributed across the head, trunk, and tail fin, are sensory structures consisting of hair cell epithelia and a cupula connecting the ciliary bundles of the hair cells with the surrounding water<sup>[59,60]</sup>.

Neuromasts exist in various configurations and integumental positions, typically categorized into superficial neuromasts, which are located on the surface of the epidermis, and canal neuromasts, situated in subdermal canals that form through invagination of the epidermis <sup>[61]</sup>. While surface neuromasts have cupulas that extend beyond the boundary layer and move proportionally to water velocity, canal neuromasts align with the canal axis and their cupulas move in response to fluid velocity within the canal, which is determined by pressure differences between canal pores. Thus, neuromasts detect both fluid velocity and acceleration, providing the central nervous system with a three-dimensional pattern of fluid flow across the body surface <sup>[62-64]</sup>.

The oscillations perceived by the lateral line receptors are in the low-frequency range, typically from 1-5 to 100-200 Hz <sup>[59,60]</sup>. The maximum sensitivity differs between canal neuromasts, which are most sensitive at 20-30 to 100 Hz, and superficial neuromasts, which are most sensitive at 2-5 to 10-15 Hz. <sup>[65,66]</sup>. For example, In the sculpin *Cottus bairdi*, canal neuromasts are most sensitive



at 50 Hz, while free neuromasts show maximum sensitivity at 10 Hz<sup>[67]</sup>. The trunk lateral line of the plainfin midshipman fish, *Porichthys notatus*, only has superficial neuromasts, which responded maximally to frequencies of 20-50 Hz<sup>[68]</sup>. The spectral sensitivity ranges of the inner ear and lateral line system partially overlap, but their peak sensitivities differ significantly. The primary distinction is that the lateral line system's receptors respond to displacement waves, whereas the inner ear's receptors respond to pressure waves. The lateral line cannot detect sound oscillations because the fish body, neuromast cupulae, and surrounding water oscillate simultaneously. However, the inner ear receptors are stimulated by the inertia of the otolith, which is nearly three times denser than the fish body<sup>[59]</sup>.

### 2.3. Acoustic and vibrational sensitivity

The auditory capabilities of most fish species have been reported between 50 to 1000 Hz, with some species demonstrating the capacity to perceive sounds exceeding 3 kHz<sup>[41]</sup>. Remarkably, only a very small fraction of species exhibit the ability to detect sounds above 100 kHz<sup>[69]</sup>. The hearing ranges of most well-known farming fish are detailed in Table 1.

Table 1: Auditory Sensitivity of Key Farmed Fish Species for Human Consumption and Ornamental Purposes. All data were obtained using the Auditory Evoked Potential recording technique and thresholds given in dB re 1  $\mu$ Pa, unless otherwise stated.

Order	Species	Frequency range (Hz)	Best Response Frequency (Hz)	Minimum Threshold (dB re 1 µPa)	Reference
Perciformes	Pacific bluefin tuna ( <i>Thunnus orientalis</i> )	325 ~ 800	500	83	Poper et al. <sup>[70]</sup>
	Large yellow croaker ( <i>Larimichthys crocea</i> )	600 ~ 800	600		Liu et al. <sup>[71]</sup>
	Red drum ( <i>Sciaenops ocellatus</i> )	100 ~ 1k	400	95	Horokvskv et al. <sup>[72]</sup>
	Jack mackerel ( <i>Trachurus japonicus</i> )	200 ~ 800			Babaran et al. <sup>[73]</sup>
	Black sea bream ( <i>Sparus macrocephalus</i> )	100 ~ 600	600		Chen et al. <sup>[74]</sup>
	Red sea bream ( <i>Pagrus major</i> )	100 ~ 2k	300	80	Kojima et al. <sup>[75]</sup>
Cypriniformes	Silver carp ( <i>Hypophthalmichthys molitrix</i> )	300 ~ 2k	750 ~ 1.5k	104.2	Lovell et al. <sup>[76]</sup>
	Bighead carp ( <i>Aristichthys nobilis</i> )	300 ~ 2k	750 ~ 1.5k	105.7	
	Common carp ( <i>Cyprinus carpio</i> )	100 ~ 500	100 ~ 505	70	Kojima et al. <sup>[77]</sup>
		1000 (by ECG)	100 (by ECG)	75 (by ECG)	
	Crucian carp ( <i>Carassius auratus</i> )	300 ~ 1k	800	70	Wang et al. <sup>[78]</sup>
Clupeiformes	Pacific herring ( <i>Clupea pallasii</i> )	200 ~ 5k			Mann et al. <sup>[79]</sup>
	Scaled Sardine ( <i>Harengula jaguana</i> )	100 ~ 2k		120 – 130	
	Round sardinella ( <i>Sardinella aurita</i> )	100 ~ 1k			
Salmoniformes	Chinook salmon ( <i>Oncorhynchus tshawytscha</i> )	100 ~ 1k	250	105	Oxman et al. <sup>[80]</sup>
Siluriformes	Bullhead catfish ( <i>Ictalurus nebulosis</i> )	100 ~ 5k	700	35 (dB below 1	Weiss et al. <sup>[81]</sup>

				dyn/cm <sup>2</sup> )	222
Gadiformes	Walleye pollock ( <i>Theragra chalcogramma</i> )	40 ~ 450	100 ~ 200	75	Mann et al. <sup>[67]</sup>
Pleuronectiformes	Olive flounder ( <i>Paralichthys olivaceus</i> )	60 ~ 700	100	94.1	Xing et al. <sup>[82]</sup>
Acipenseriformes	Yangtze sturgeon ( <i>Acipenser dabryanus</i> )	100 ~ 500	300	133	Xiang et al. <sup>[83]</sup>

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For decades, researchers used to classify fish into two distinct categories based on their auditory abilities – “hearing generalists” (or “non-specialists”) and “hearing specialists”. The former group, including salmonids and tunas, typically exhibited a narrower frequency detection range or bandwidth and poor sensitivity (high auditory thresholds). On the other hand, the latter group, comprised of *Ostariophysi* and *Clupeiformes*, as well as some members of *Holocentridae* and *Sciaenidae* <sup>[51,84]</sup>. This divergence in hearing abilities is attributed to the presence of specialized morphological structures, such as the Weber apparatus, in the latter group, that facilitate sound transmission from the swim bladder to the inner ear to increase hearing sensitivity. Nevertheless, further research on fish hearing has revealed that the aforementioned classifications fail to encompass all fish species and lack clarity and evolutionary support <sup>[40] [85]</sup>. More recently, Popper et al. proposed another strategy of using the terms specialist and non-specialist together with information on the specific structure of function that is considered a specialization<sup>[40]</sup>.

It is equally important to understand that although we know that all fish and many invertebrates are sensitive to the particle motion components of sound<sup>[86]</sup>, and only some fish can detect sound pressure, we know very little about the sensitivity of aquatic animals to the vibrations produced inside and near substrates <sup>[87,88]</sup>. At present, research on the vibration sensitivity of aquatic animals mostly focuses on invertebrates and crustaceans, while research on fish only involves some benthic fish. Berghahn et al. investigated the vibrational sensitivity of plaice (*Pleuronectes platessa*), sole (*Solea solea*), and lemon sole (*Microstomus kitt*), exposed the fishes to between 40 and 300 Hz. The gill ventilation, eye movement and burial behavior demonstrated that the sensitivity of the fishes was greatest between 100 and 200 Hz, with sole being the most sensitive at 170Hz (10 cm s<sup>-2</sup> at 20–170 Hz) <sup>[89]</sup>. As for invertebrates, there is evidence to suggest that mussels (*Mytilus edulis*) and hermit crabs, are sensitive to physical vibrations at frequencies of 5-410 Hz <sup>[88,90,91]</sup>. The North Sea shrimp (Crangon Crangon) is sensitive to vibrations from water, sand, and buried animals themselves, reaching its maximum at 170 Hz.

#### 2.4. Importance of the underwater Soundscape and Vibroscape

Sensory channels like vision, olfaction, and touch have limitations in aquatic environments, especially when providing rapid, long-distance, and three-dimensional information. As a result, sound becomes an exceptionally effective vehicle for transmitting information among aquatic organisms, particularly in waters with low visibility<sup>[24,92]</sup>.

Sound is crucial for the survival of marine organisms, and research has shown that aquatic acoustic signals between 50 Hz and 10 kHz play a vital role in fish communication, orientation, foraging, and defense<sup>[93]</sup>. Furthermore, the auditory structures of most fish species are fully developed within a few days post-hatching, highlighting the importance of sound detection in their life history<sup>[94]</sup>.

The aquatic soundscape can be defined as a combination of sound sources known as geophony, biophony, and anthrophony<sup>[95,96]</sup>. Geophony, known for its intensity and variability, includes sounds such as those generated by wind, rain, hydraulic turbulence or sediment transport with frequencies spanning up to 25 kHz<sup>[97-101]</sup>. Biophony, on the other hand, is produced by a wide range of taxa, from large cetaceans producing loud, long-travelling calls and fish choruses to small invertebrates, such as snapping shrimps<sup>[102-104]</sup>.

Over 989 fish species spanning 175 families have been found to actively produce sounds so far<sup>[105,106]</sup>. Fish primarily produce sound in two ways: by vibrating their swim bladder using sonic muscles<sup>[107]</sup>, and by using modified pectoral fins and pectoral girdles for sound production<sup>[108]</sup>.

They produce sounds for various purposes, including communication, courtship, territorial defense, and group coordination. For example, some fish produce sounds during courtship rituals to attract mates or establish dominance within their territory. These self-generated sounds can vary in frequency, duration, and intensity depending on the species and the specific behavior being exhibited<sup>[109,110]</sup>. Additionally, the ability to differentiate between the sounds of prey, predators, and conspecifics aids fish in finding food and avoiding threats<sup>[69,111,112]</sup>.

Altogether, the acoustic environment can be extremely rich in information for fish species, offering essential cues for orientation and habitat identification.<sup>[113-117]</sup> For instance, coral reef fishes rely on these cues after spawning, when fertilized eggs drift away with the current.

Juveniles' survival depends on their ability to navigate back to the reef, guided by acoustic signals generated by fish and invertebrate populations <sup>[118-121]</sup>.

The vibrational component of aquatic environments, termed vibroscape, plays a crucial role in addition to soundscapes <sup>[122]</sup>. Growing evidence shows that vibrational signals are produced and detected by several benthic and demersal species, including salmonids and sculpins <sup>[123]</sup>. On the seabed, there is evidence to suggest that deep-sea shrimp use vibration to detect falling prey <sup>[124]</sup>, flatfish (such as *Pleuronectes platessa* and *Solea spp.*) may use vibration to detect predators <sup>[89]</sup>. Even though there is limited knowledge in this field, studies, particularly on invertebrates, suggest that vibrational stimuli induce physiological and behavioral responses <sup>[125]</sup>. Roberts et al. exposed blue mussels (*Mytilus edulis*) and marine hermit crab (*Pagurus bernhardus*) in cages to a pile driver. The sound and vibration during the pile driving process were quantified using water-borne particle motion sensor, hydrophones, and tri-axial geophone. Animals exposed showed changes in oxygen consumption (*M. edulis*) and behavior, such as environmental sampling and anti-predator responses (both species) <sup>[88]</sup>. Vibrations may be crucial to communication and environmental sensing, providing an additional sensory channel when other modalities are less effective. The vibroscape is thus an essential part of the sensory world of fish, overlapping with the soundscape.

With various anthropogenic activities altering the acoustic and vibrational features of underwater environments - crucial for fish sensory adaptation, communication, and orientation - it is vital to fully understand the stimuli fish respond to. This requires considering substrate vibration alongside sound pressure and particle motion when characterizing a sensory environment. <sup>[123]</sup>.

### **3 Noise in the aquaculture environment**

The modern aquaculture industry comprises various large-scale artificial rearing systems, such as Recirculating Aquaculture Systems (RAS), Deep-sea Cage System, In-Pond Raceway System (IPRS).

In contrast to natural habitats, these environments require extensive equipment, including air compressors, aerators, ventilation devices, water pumps, filtration equipment, and other maintenance equipment, to maintain in high-density cultures. The operation of this equipment generates substantial noise within these rearing systems <sup>[15,126]</sup>. Consequently, it is essential to characterize the acoustic and vibrational aquaculture settings to understand the potential impact of noise as a stressor on cultured species <sup>[127]</sup>.

### 3.1 Noise sources in aquaculture

The impact of underwater sound in aquaculture facilities is influenced by both the species being farmed and the specific design and location of the facility. Different fish farms may have different machinery and equipment based on their production needs, influencing sound generation and propagation, and creating a unique soundscape and vibroscape for each facility. Despite its recognized importance, the acoustic features of most aquaculture environments remain insufficiently understood.

In RAS, high-frequency noise generally arises from electric equipment such as filters, oxygenators, air compressors and pumps, as well as from collapsing air bubbles. On the other hand, low-frequency noise typically originates from water currents and vibration of ground and tank walls <sup>[15,126]</sup>.

To increase aquaculture density, it becomes crucial to elevate dissolved oxygen levels to inhibit anaerobic bacteria and improve water quality. This requires aeration and oxygenation systems, which typically include a Roots blower, an aeration pipeline, and gas stones. The vibration and acoustic radiation of the Roots blower is commonly the main source of underwater noise in RAS <sup>[128,129]</sup>. Although modern systems often locate the Roots blower outside the facility or in a separate isolated room, vibrations from the blower can still propagate into the farm through the aeration pipeline. Moreover, the high-speed gas flow within the pipeline generates noise due to fluctuations in flow rate or pressure, and interactions between gas and the pipe wall<sup>[15]</sup>.

Pumps are also a major source of underwater noise in aquaculture. Tanks are typically placed directly on concrete surfaces with pumps located near at the bottom and adjacent to the same concrete slab. This design allows pump noise to propagate directly through the water and from

the air-water interface, while also allowing vibrations to travel through the underlying concrete slab<sup>[15]</sup>.

When the blower is turned off, the primary background noise comes from the water flow and aeration process. In flow-through or RAS, continuous water flow generates considerable noise, especially when large volumes create air gaps under the inflow pipe. Gutscher et al. found that water flowing above the surface produces high-frequency noise, with external filters contributing more noise than submerged ones, suggesting that more air entering the water raises sound pressure levels (SPLs) <sup>[16]</sup>. Craven et al. and Yin et al. identified that high-frequency noise (>1000 Hz) mainly comes from surface bubbles and aeration stones, with finer stones producing smaller bubbles and thus higher-frequency noise and SPLs <sup>[15,130]</sup>.

It is important to note that activities by facility staff, though not yet empirically proven, may significantly impact fish. Unlike the consistent noise from machinery, these sounds are usually brief, occurring during daylight hours - such as the use of specific tools or impacts on tank walls. Fish cannot anticipate these unpredictable noises, which may trigger fear or flight responses <sup>[131,132]</sup>.

While RAS systems are a markedly louder environment for species otherwise held in earthen ponds, the deep-sea cage environment clearly represents the most variable and loudest aquaculture system, reaching noise levels capable of eliciting a measurable physiological response in many species and revealing a likely source of chronic stress<sup>[127]</sup>. The pronounced variability exhibited by deep-sea cage systems can be ascribed to the inherent openness of the system itself, the site-specific and external sound sources originating from the surrounding environment, as well as the aquaculture production system itself. These sources of sound encompass abiotic, biotic, and anthropogenic factors. Abiotic or physical sources encompass elements such as wind, rain, and water turbulence. Additionally, anthropogenic sources included access vessels, an associated feed barge, oxygen storage, compressed air automated feeder and a temporary handling facility linked to the site contribute to the overall soundscape. Among the more notable impacts observed, the effects stemming from vessel noise generated by service



vessels or other transiting ships have been identified as particularly significant <sup>[127]</sup>.

Pond aquaculture systems are characterized by the lowest noise levels among all aquaculture systems, primarily due to their limited utilization of mechanical equipment <sup>[127]</sup>. Nevertheless, in outdoor pond systems, motorized paddlewheel aerators have been identified as a significant contributor to noise levels <sup>[127]</sup>.

### 3.2 Relevant noise frequencies and sound pressure levels

Researchers have conducted studies to monitor the frequency range and sound pressure levels of noise generated by aquaculture systems or associated activities. In intensive aquaculture systems, the average broadband sound pressure levels can vary significantly. For example, in pond without aerators, the average sound pressure level is around 70 dB, while in circular fiberglass tanks, it can reach up to 130 dB re 1 $\mu$ Pa <sup>[126]</sup>. These noises exist in all aquaculture water bodies, and their frequencies match the hearing sensitivity range of most aquaculture fish species (10-2000Hz) (Fig. 3) <sup>[133]</sup>. The main acoustic environment of the aquaculture system is the comprehensive product of the acoustic contribution of each component. By measuring the acoustic properties of individual components, it is possible to separate which components dominate and quantify the acoustic recognition of each component. This is important because it can directly compare the acoustic characteristics of individual device components with the hearing ability of fish.

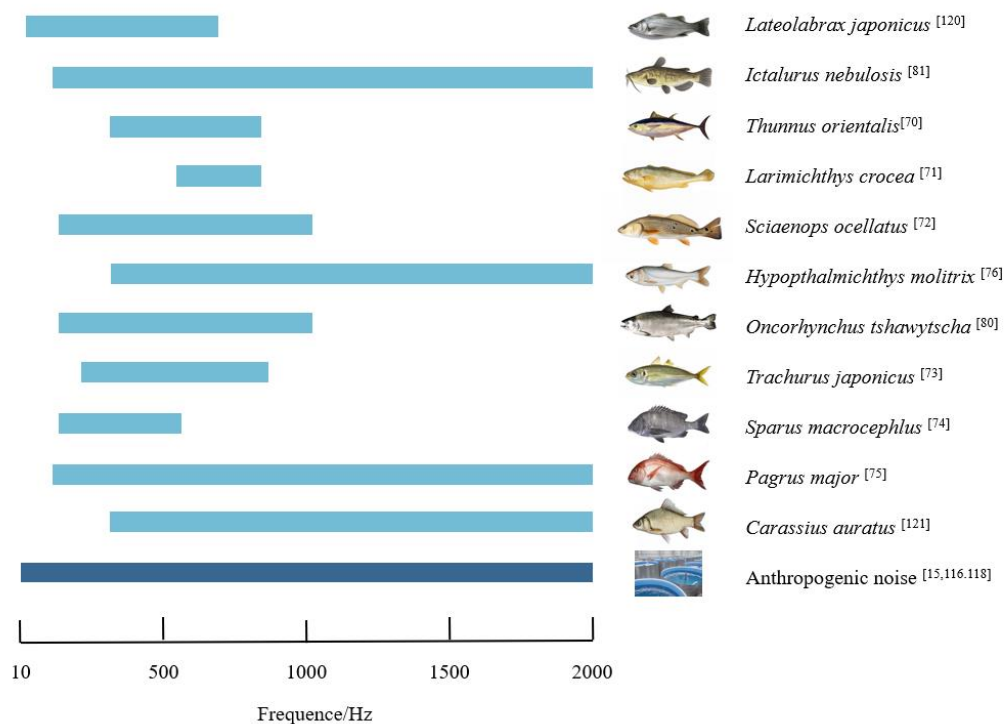


Fig. 3 The auditory frequency range of major farmed fish species and the overlap with the noise conditions in the farmed environment (Data based on Huang et al.<sup>[134]</sup>; Weiss et al.<sup>[81]</sup>; Poper et al.<sup>[70]</sup>; Liu et al.<sup>[71]</sup>; Horokvskv et al.<sup>[72]</sup>; Lovell et al.<sup>[76]</sup>; Oxman et al.<sup>[80]</sup>; Babaran et al.<sup>[73]</sup>; Chen et al.<sup>[74]</sup>; Kojima at al.<sup>[75]</sup>; Van et al.<sup>[135]</sup>; Bart et al.<sup>[126]</sup>; Craven et al.<sup>[15]</sup>; Yin et al.<sup>[130]</sup>).

Yin et al. conducted a study to record the aquaculture environmental noise in open fiberglass tanks, and their findings indicated that the SPLs of aquaculture environmental noise were around 87.48 – 90.65 dB. This noise was a combination of low-frequency resonance noise generated by aquaculture working equipment and the inner walls of the tanks, with the main frequency peak at 100 Hz, bubble noise from the surface water body at 1,250 Hz, and working noise from aeration stones, aerators, and air compressors at 1,600 to 2,500 Hz<sup>[130]</sup>. This result is same as Bart et al., high-frequency noise (1~2 kHz) from electric equipment such as motors, oxygenators, and air compressors, as well as low-frequency noise (25~100 Hz) from water flow, ground vibration, and pool wall vibration. Yao et al. found that the maximum SPLs corresponded to a frequency of 125 Hz at Chinese sturgeon nursery workshop, which is a low-frequency noise ( $\leq 200$  Hz)<sup>[128]</sup>. Low-frequency noise has the characteristics of long wavelengths, making it easy to cross obstacles, propagate over long distances, and attenuate slowly. The low-frequency noise

generated by working equipment can easily propagate through the integrated pipe gutter in the breeding area to the roof, where it reflects and produces a very long reverberation. The superposition of direct and reverberant acoustic energy enhances indoor low-frequency noise, making it crucial to control low-frequency noise <sup>[128]</sup>.

Previous research has highlighted the significant influence of structural design and distance between tanks and mechanical equipment on the SPLs of underwater noise in land-based aquaculture systems. Lara et al. conducted a study on zebrafish housing homes and found that the SPLs ranged from 122 to 143 dB, predominantly at frequencies below 1000 Hz. The SPLs were notably affected by the proximity of pumps and filters, with fish experiencing higher noise levels as these units moved closer together. Comparison of the soundscape spectral curves with the zebrafish hearing sensitivity revealed significant overlap within the zebrafish hearing range of 100 to 8000 Hz, which was 22.4 dB above the hearing threshold <sup>[21]</sup>. Barnes et al. reported an ambient noise level of 50 dB in a salmonid hatchery breeding room. When water flowed into the two mentioned rooms, the noise level increased to 73 dB <sup>[18]</sup>. In the tanks investigated by Craven et al., the main contributor to the peak at 187.5 Hz was the sound generated by the pumps. Aeration sounds ranged from >7600 Hz up to 22 kHz, and the maximum sound pressure level produced by coarse air stones was 119 dB, with larger and stronger bubbles generated below 8 kHz <sup>[15]</sup>. Yao et al. conducted a study on the indoor and outdoor noise of a Chinese sturgeon nursery workshop. The average sound pressure level in the outdoor unit area reached 94-98 dB, and the unit noise transmitted to the outer wall of the breeding area was 77 dB. The average indoor noise in the breeding area was 83 dB <sup>[128]</sup>.

The cleaning of rearing ponds and filtration systems has been found to significantly increase underwater noise levels. Voorhees et al. found that the noise level during the cleaning of the tank in the salmon hatchery was as high as 77dB, compared to 68dB under normal water flow conditions. Noise levels in the rearing pavilion were highest in the proximity of the power washer, reaching upwards of 83 dB<sup>[20]</sup>. Similarly, Stone et al. found that noise SPLs could increase up to 80 dB during the cleaning of the filtration system <sup>[136]</sup>. Heise et al. monitored noise levels in the Vancouver Aquarium rearing tanks and found that the average SPLs across all frequencies were 91.9 dB (range 87.0-104.5 dB). They also discovered that the highest sustained pressure levels

were observed during cleaning activities, increase of approximately 25 dB <sup>[19]</sup>.

In aquaculture systems, the SPLs and frequency of underwater noise vary depending on the depth. Craven et al. investigated the soundscape in RAS tank. The highest SPLs were found to be 124 dB at the bottom of the tank and 115 dB at the shallowest level. The soundscape in the tank was stratified and positively correlated with depth <sup>[15]</sup>. However, the effects of noise on cultured species in aquaculture systems vary considerably due to differences in their physiological ability to perceive sound, as well as their behavior. For instance, shrimp and flounder tend to stay the bottom and walls of tanks, which exposes them to different acoustic environments and may result in more significant noise effects from vibrations in the tank itself compared to upper fish <sup>[137]</sup>. Nevertheless, the correlation between water depth and noise level is not always absolute. Yin et al. and Craven et al. observed different results with the main peak of background noise at 187.5 Hz at different depths, and there was no change in the noise frequency with increasing water depth <sup>[15,130]</sup>. The reason is that Craven used closed, covered tanks, while Yin used open tanks. The transmission and attenuation of sound in a closed body of water are significantly different from those in open conditions. In closed tanks, the SPLs of the background noise gradually decrease from the bottom to the surface, but there is no change in the frequency of the main peak. However, in open tanks, the transmission of equipment noise from the air to the water is attenuated, and the SPLs of high-frequency noise in the surface layer are relatively high, while the low-frequency resonance of the bottom layer of equipment with the inner wall of the tank is the highest, and high-frequency noise is relatively low. An alternative explanation for the vertical stratification of sound is that the propagation of sound through the water is also affected by bubbles rising from the aeration stone, an effect similar to that of bubble curtains used to reduce the propagation of sound from pile driving <sup>[138]</sup>.

The combination of materials and structural design of tanks indeed plays a significant role in determining the acoustic conditions within them. Terhu et al. discovered that noise levels in fiberglass tanks were, on average, 4 to 16 dB higher than those in concrete tanks <sup>[14]</sup>. Bart et al. found that fiberglass tanks being noisier than concrete tanks <sup>[126]</sup>. Craven et al. investigated an aquaculture facility with concrete rearing tanks, where mean peak spectral levels ranged from 105 to 117 dB, and the peak frequency remained at 187.5 Hz <sup>[15]</sup>. Davidson et al. characterized

the acoustic environment of fiberglass tanks and reported a sound pressure range of 105 to 130 dB for the highest spectral levels below 100 Hz <sup>[139]</sup>. Bart et al. discovered that SPLs reached 120 dB in concrete raceways and 130 dB in fiberglass tanks. Overall, concrete tanks were found to be the least noisy, while fiberglass tanks exhibited the highest sound pressure levels <sup>[126]</sup>. In a study conducted by Radford et al. showed that sound levels in cage farms were consistently higher, ranging from 107 to 112 dB, and exhibited more variability compared to RAS, while ponds were found to be the quietest <sup>[127]</sup>. In modern aquaculture, where aquatic animals may transition between different aquatic systems during their life cycle, it is important to understand how these species adapt to sudden changes in the perceived environmental sound. For example, when juveniles reared in RAS are transferred to cage, it is not yet known how they might respond to the altered soundscape. All cage cultured fish, including salmon, seabass, and snapper, are typically raised in cage after being bred in land-based tanks and RAS. However, the relatively loud sounds of RAS may cause stress in more sensitive species or early life stages. These animals may experience significant stress due to inappropriate soundscapes, which can potentially affect their health and growth rates <sup>[137]</sup>.

#### **4. Effects of environmental noise on fish in aquaculture**

In the natural environment, fish obtain a large amount of information by listening to the sounds of their surroundings. In aquaculture environments, sustained noise may lead to shielding, increased stress levels, and changes in fish behavior. Generally speaking, aquaculture noise does not cause fish death, but long-term noise may reduce the growth rate, immunity, survival rate, and spawning and reproduction rate of fish, ultimately affecting the welfare of aquaculture animals <sup>[26,120,140-142]</sup>.

At present, people mainly use hydrophones to monitor the noise in aquaculture environments. After detailed analysis of the noise, it is compared with the sensitive threshold of aquaculture species. At present, the main research work on the impact of noise on fish is focused on laboratory conditions. The collected aquaculture noise is replayed through underwater speakers,

and short-term or long-term noise exposure experiments are conducted on fish to study the effects of noise on their hearing, behavior, physiology, and other aspects (Fig. 4). It should be noted that the research mentioned in this review focuses on the impact of human noise on rearing species, and does not pay too much attention to other wild species.

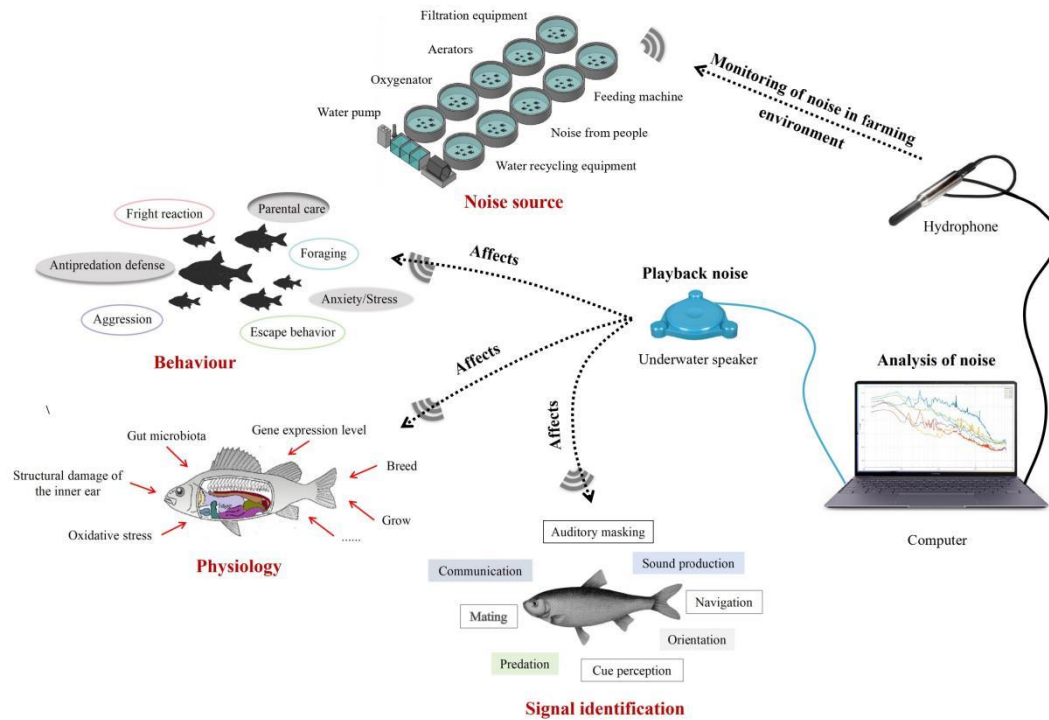


Fig. 4 Experimental method for the impact of aquaculture noise on fish

#### 4.1 Effects on hearing and communication

The impact of noise on fish hearing can be categorized into two types: PTS and TTS <sup>[143]</sup>. Fish exposed to low-intensity noise over an extended period or high-intensity noise for a brief period may encounter temporary auditory threshold displacement <sup>[144]</sup>. If the hearing loss is not fully restored prior to subsequent noise stimulation, a portion of the loss may become permanent, resulting in a condition known as PTS. The PTS is irreversible and accompanies the death of auditory HCs and the loss of synaptic connections within the inner ear of fish <sup>[145-147]</sup>. In current studies on the impact of noise on fish hearing, various noise sources are utilized. These include single-frequency sounds, white noise <sup>[148,149]</sup>, and the playback of anthropogenic noise

recordings<sup>[150]</sup>. Enger et al. revealed that exposure to intense pure sound caused damage to sensory HCs in Atlantic cod (*Gadhus morhua*)<sup>[151]</sup>. Similarly, Oscar fish (*Astronotus ocellatus*) exposed to a continuous tone of 180 dB re 1μPa for one hour exhibited impairment in HCs function<sup>[28]</sup>. Goldfish (*Carassius auratus*) demonstrated susceptibility to aquarium filtered noise, with a maximum threshold change of 15 to 19 dB in hearing at 100 and 300 Hz<sup>[16]</sup>. Exposed common roach (*Rutilus rutilus*) and sand goby (*Pomatoschistus minutus*) to continuous broadband noise, the TTS in common roach at 250 Hz and 1000 Hz (11.9 and 13.4 dB, respectively), while sand goby exhibited a non-significant shift of 6.6 dB at 125 Hz<sup>[152]</sup>. Breitzler et al. subjected adult zebrafish to white noise at varying SPLs (130, 140, and 150 dB) for 24 hours, results indicated TTS up to 33 dB along with increased response latency. Fish exposed to 130 and 140 dB noise levels experienced restored hearing function within 7 days, whereas those exposed to 150 dB noise levels required 14 days for their auditory thresholds to return to baseline. HCs loss was only observed significantly in the 150 dB noise treatment, and sensory tissue (number of hair cell receptors) fully regenerated within 7 days<sup>[153]</sup>. Andrew et al. assessed the auditory thresholds of silver (*Hypophthalmichthys molitrix*) and bighead (*H. nobilis*) carp before and after exposure to high-intensity (155 dB) broadband sound, revealing TTS in both species<sup>[154]</sup>. Caiger et al. exposed snappers to low-intensity noise of 120 dB for a duration of 2 weeks, resulting in increased auditory thresholds at 100, 200, and 400 Hz<sup>[155]</sup>. Amoser et al. subjected goldfish (*Carassius auratus*) to white noise of 158 dB, yielding a significant decrease in sensitivity of 26 dB<sup>[156]</sup>. Smith et al. raised goldfish under white noise conditions ranging from 160-170 dB. Even after a mere 10 minutes of noise exposure, goldfish exhibited significant changes in their hearing thresholds, which linearly increased to approximately 28 dB after 24 hours of continuous exposure. Subsequent noise exposure did not lead to further threshold shifts. After 21 days of noise exposure, it took goldfish 14 days to fully recover to normal hearing levels<sup>[157]</sup>. Gutscher et al. explored the repercussions of filter noise (110-114 dB) in aquaculture systems on goldfish, resulting in masking of hearing thresholds by up to 20 dB (0.1 kHz) and up to 24 dB (0.5 kHz)<sup>[16]</sup>.

#### 4.2 Masking effects on signal recognition

One potential barrier to acoustic communication is increasing levels of background noise, which

reduces the ability of fish to detect important signals related to the environment and other animals <sup>[15,128]</sup>. Artificial noise is different from natural environmental sounds and cannot provide useful survival information for fish. The frequency of artificial noise is partially consistent with the aquatic organism vocalizations and may disrupt their communication. When reducing the presence of other sound waves, the ability of fish to detect related sound waves is significantly affected, forcing the auditory threshold of fish to increase. This phenomenon is called masking <sup>[158]</sup>. Usually, only noise within a critical frequency band around the signal frequency can effectively mask the signal. Generally speaking, within the sensitive frequency range, the sound pressure of the signal is 15-30dB higher than the environmental noise sound pressure, so that fish can distinguish the signal sound <sup>[158]</sup>.

Lara et al. recorded higher SPLs (122-143 dB), predominantly below 1000 Hz, with more spectral peaks in noise recordings from zebrafish housing systems, indicating a potential for significant auditory masking effects <sup>[21]</sup>. Radford et al. found that noise generated by both RAS and cage culture systems exceeded the auditory thresholds of common carp, Atlantic salmon, and European perch at 100 Hz. Zhang et al. discovered that underwater noise from wind turbines overlapped with the auditory sensitivity and vocalization of zebrafish, suggesting a potential masking effect on their acoustic communication <sup>[159]</sup>.

#### 4.3 Impact on Physiology

Fish are often stimulated by various stressors in their living environment, leading to acute or chronic stress <sup>[160,161]</sup>. External (environmental) and internal (disease, metabolic imbalance) stressors can significantly alter certain biochemical parameters, which may reveal poor animal welfare conditions. Stress stimuli induce major neuroendocrine responses in fish, manifested as an increase in corticosteroids (especially cortisol) and catecholamines. As a direct consequence of its high levels in the circulatory system, extensive secondary stress responses can be observed, such as elevated blood sugar levels from tissue glycogen reserves. In addition, in adaptive stress response, the hematopoietic activity of the spleen increases, as well as other related parameters such as hematocrit value and hemoglobin content. Even in the medium or long term, the tertiary stress response can have destructive effects on fish by inhibiting growth rate and interfering with



reproductive processes. Noise has always been considered a stressor, and its impact on fish may be as severe or more severe as hearing or behavior.

Ship noise has been shown to cause a significant increase in cortisol stress in various freshwater fish species (*Cyprinus carpio*, *Gobio gobio*, and *Perca fluviatilis*)<sup>[162]</sup>. Carp (*Carassius auratus*, Linnaeus, 1758) and goldfish (*Carassius auratus*, Linnaeus, 1758) showed a brief peak in plasma cortisol levels after 24 hours of noise exposure<sup>[157]</sup>. The plasma cortisol levels of milkfish (*Chanos chanos*) exposed to offshore wind farm noise were higher during the first 24 hours<sup>[163]</sup>. Exposure to continuous ship noise also amplified plasma cortisol levels in large yellow croakers (*Pseudosciaena crocea*) and Japanese sea bass (*Lateolabrax japonicus*) for up to 6 days<sup>[164]</sup>.

Filiciotto et al. observed that fish exposed to noise from land-based aquaculture systems had higher levels of serum cortisol, glucose, red blood cell count, red blood cell pressure, and hemoglobin content, while lower levels of white blood cells<sup>[165]</sup>.

Prolonged exposure to offshore wind farm noise (138 dB) resulted in heightened levels of ROS in the plasma of black porgy (*Acanthopagrus schlegelii*)<sup>[166]</sup>. Zhang et al. revealed that artificial acoustic landscapes (RAS: 107 dB, IPRS: 115 dB) had deleterious effects on the immune, antioxidant, and digestive enzymes of largemouth bass (*Micropterus salmoides*)<sup>[167]</sup>. Hang et al. discovered that environmental noise from RAS (115 dB) adversely affected the antioxidant and immune systems of largemouth bass (*Micropterus salmoides*)<sup>[142]</sup>. Wysocki et al. demonstrated that aquaculture noise can induce long-term stress in rainbow trout (*Oncorhynchus mykiss*). Following 8 months of exposure to noise (115 dB, 130 dB, and 150 dB), plasma chloride and sodium ion concentrations decreased, while glucose concentrations increased<sup>[12]</sup>. Filiciotto et al. examined the impact of offshore aquaculture systems' environmental noise on gilthead sea bream (*Sparus aurata*) juveniles. The results showed that the total oxidation state, lysozyme activity, anti-protease activity, and white blood cell levels of the fish significantly increased, while the albumin/globulin ratio significantly decreased<sup>[168]</sup>. Short-term exposure to 150 dB of noise significantly increased the levels of lactate and red blood cell accumulation in gilthead sea bream (*Sparus aurata*, Linnaeus 1758) and European sea bass (*Dicentrarchus labrax*, Linnaeus 1758), while glucose levels in the gilthead sea bream significantly decreased<sup>[169]</sup>. Hang et al. observed that the liver tissue of largemouth bass (*Micropterus salmoides*) showed elevated levels of

587 oxidative stress after exposure to underwater noise <sup>[142]</sup>. Trabulo et al. exposed Meagre  
588 (*Argyrosomus regius*) larvae to ship noise and observed an increase in lipid droplet consumption,  
589 a decrease in body depth, a slight decrease in superoxide dismutase (SOD) activity, and no  
590 change in DNA damage or electron transfer system (ETS) activity in the 2dph larvae <sup>[170]</sup>. Lara et  
591 al. studied the effects of continuous exposure to 130 and 150 dB of continuous white noise on  
592 zebrafish juveniles (*Danio rerio*). At 3 and 5 days after fertilization, heart rate, yolk sac  
593 consumption, and cortisol levels significantly increased with rising noise levels <sup>[26]</sup>. After 10 days  
594 of exposure to ship noise (123-136 dB), the ACTH, cortisol, glucose, lactate, hematocrit, Hsp70,  
595 cholesterol, triglycerides, and osmotic pressure values of the gillhead sea bream (*Sparus aurata*,  
596 Linnaeus 1758) significantly increased, indicating the primary and secondary stress responses of  
597 fish to ship noise <sup>[171]</sup>.

598 Furthermore, several scholars have delved into the impact of noise on the inner ear, gut  
599 microbiota, and other factors. Wong et al. conducted an exposure experiment on zebrafish  
600 subjected to 150 dB white noise, observing a significant decrease in presynaptic Ribeye b protein  
601 in the inner ear <sup>[172]</sup>. Peled (*Coregonus peled*) exposed to a 300 Hz noise ranging from 176 to 186  
602 dB for 18 days, acoustic exposure resulted in ultrastructure changes to otoliths, morphological  
603 damage to sensory hair cells of the macula sacculi, and a gradual decrease in the number of  
604 functionally active mitochondria in the red blood cells but no changes to telomeres <sup>[173]</sup>. Following  
605 short-term noise stimulation at 120 dB, *Larimichthys crocea* and *Nibeal albiflora* displayed a sharp  
606 increase in physiological indicators. Conversely, after prolonged stimulation, growth and immune  
607 indicators exhibited significant decreases. The proportion of intestinal microbiota became  
608 severely imbalanced, with *Vibrio* and *Pseudomonas* dominating, while the abundance of other  
609 genera was notably low, particularly some common intestinal probiotics <sup>[174]</sup>.

610 The employment of histological techniques enables the systematic exploration of diverse  
611 responses and regulatory pathways in organisms under stress, providing a comprehensive  
612 understanding of intricate biological phenomena <sup>[175]</sup>. Transcriptomics has played a pivotal role in  
613 illuminating the comprehensive landscape of gene expression and its interconnections <sup>[176]</sup>. In the  
614 case of small yellow croakers (*Larimichthys polyactives*) exposed to 120 dB ship noise, there is an  
615 upregulation observed in synaptic membranes, receptor-mediated endocytosis, and

neurotransmitter secretion processes in brain tissue. This phenomenon is particularly noteworthy in the context of impaired extracellular matrix (ECM) composition<sup>[177]</sup>. Wei et al. noted elevated plasma cortisol levels in milkfish (*Chanos chanos*) exposed to wind farm noise within the first 24 hours. Additionally, the mRNA levels of head kidney star (steroidogenic acid regulation) and hsd11b2 (11-b-hydroxysteroid dihydrogenase 2) showed significant increases<sup>[163]</sup>. Continuous exposure to wind farm noise (138dB) resulted in changes in the mRNA levels of antioxidant related genes (sod1, cat, and gpx) in the liver of Black Porgy (*Acanthopagrus schlegelii*) (downregulation of cat and upregulation of gpx)<sup>[166]</sup>. Andrew et al. conducted a comprehensive study on the gene expression levels of Atlantic salt (*Salmo salt*) before and after noise exposure, and found transcriptional expression differences related to cell energy, cell respiration, oxygen transport, glycolytic pathways, TCA cycle (tricarboxylic acid cycle), and electron transport chains<sup>[178]</sup>. Shuck et al. found that after noise exposure, there were significant differences in the biological functions regulated by the inner ear of zebrafish, including cancer, cell growth and proliferation, and inflammation. The neuroendocrine system responded to physiological environmental pressure to restore the homeostasis of the entire body organs and cells<sup>[179]</sup>. Under noise stress, hybrid sturgeon liver tissue cell apoptosis and cell movement are enhanced, DNA replication, RNA transcription and translation, protein synthesis are inhibited, and lipid metabolism, nucleotide metabolism, and vitamin D3 metabolism pathways are also inhibited. However, the initiation of some immune responses ensures their normal immune ability<sup>[180]</sup>. After exposure to ship noise, transcripts of metabolic related pathways such as the citric acid cycle (TCA cycle pathway), pentose phosphate pathway, and oxidative phosphorylation pathway in the liver tissue of Marbled rockfish (*Sebastes marmoratus*) were upregulated<sup>[181]</sup>.

#### 4.4 Effects on growth and reproduction

As the development of the auditory vesicle occurs in fish during the embryonic period, the impact of noise on fish can manifest as early as the embryonic stage, influencing embryos and larvae through direct (albeit potentially silent) acoustic activity. This, in turn, affects the growth and development of the adult fish. Increased mortality of eggs and embryos has been noted in

environments where the ambient noise level is only 15 dB higher than the natural environment. However, in surviving fry, excessive noise can also result in slower growth rates<sup>[27]</sup>. For longnose killifish (*Fundulus similis*) and sheepshead minnow (*Cyprinodon variegates*), reductions in egg viability and growth rate occurred when the sound level in the aquarium was approximately 20 dB higher than that in the control aquarium<sup>[27]</sup>. Terhune et al. found that the growth rate of Atlantic salmon (*Salmo salar*, Linnaeus 1758) was diminished in high-noise environments<sup>[14]</sup>. Wysocki et al. observed a reduction in feeding and a slight slowing of growth in rainbow trout at the onset of noise exposure<sup>[182]</sup>. Kusku et al. discovered that urban noise adversely affects the growth and feed efficiency of Koi fish (*Cyprinus carpio*)<sup>[183]</sup>. The mean body weight of largemouth bass (*Micropterus salmoides*) was significantly lower than that of the control group under the influence of IPRS (115.1 dB) noise<sup>[167]</sup>. Hang et al. also reported that RAS noise significantly reduced the weight gain rate of larval largemouth bass (*Micropterus salmoides*)<sup>[142]</sup>. Nonetheless, some studies have indicated that noise may not exert a significant impact on the growth of certain fish species, or that fish can gradually adapt to noisy environments. Wysocki et al. conducted an exposure experience on rainbow trout (*Oncorhynchus mykiss*), subjecting them to long-term exposure to varying decibel levels of farm noise. The findings revealed that the noise did not exacerbate rainbow trout's susceptibility to pathogens, and it had no discernible effects on growth or hearing. The authors suggested that this lack of impact might be linked to genetic variations among different populations of rainbow trout and the absence of a hearing sensitivity advantage relative to carp and catfish<sup>[182]</sup>. Lara et al. found no significant effects of continuous exposure to 130 and 150 dB continuous white noise on the development and hatching of larval zebrafish (*Danio rerio*)<sup>[26]</sup>. Intensive culture noise (149 dB) negatively affected the growth of rainbow trout (*Oncorhynchus mykiss*) in the first month, resulting in lower mean body weights, lengths, specific growth rates, condition factors, feed factors, and survival rates. However, after five months of exposure, no significant differences in growth parameters were observed between the noise-exposed and control groups<sup>[13]</sup>. Larval Atlantic cod (*Gadus morhua*) exhibited lower growth rates and higher yolk sac depletion than controls after two days of noise disturbance from intensive culture. Cod larvae subjected to 16 days of noise disturbance had a lower body length, impacting their survival rate. However, as the duration of noise disturbance

increased, the fish's growth performance gradually returned to normal, indicating long-term adaptation to noise <sup>[184]</sup>. Sound plays a crucial role in the reproductive success of fish, as acoustic signals often convey information about characteristics such as male size and condition, influencing female spawning behavior and, consequently, mating success. Consequently, fish reproduction relying on acoustic communication may be particularly vulnerable to anthropogenic noise. Butler et al. found that under the influence of pure tones in the range of 100 to 2000 Hz, male African cichlid fish (*Astatotilapia burtoni*) altered the location of their courtship behavior, resulting in a decreased likelihood of females detecting them <sup>[193]</sup>. Jong et al. tested the impact of continuous noise on the courtship behavior of the painted goby (*Pomatoschistus pictus*) in an aquarium, and the results indicated a lower likelihood of female painted goby yielding under noise conditions. This suggests that reproductive success may be sensitive to noise pollution, potentially reducing adaptability <sup>[194]</sup>. Blom et al. found that continuous noise exposure increased nest guarding and egg-laying latency in female common goby (*Pomatoschistus microps*) and decreased the probability of egg-laying Crovo et al. found that growling signals facilitated the onset of spawning behavior in female blacktail shiner (*Cyprinella venusta*), and this response might be inhibited by anthropogenic noise pollution <sup>[195]</sup>.

#### 4.5 Effects on behavior

Noise serves as a distraction for fish, diverting their limited attention from their primary tasks towards the environmental noise stimuli. Anthropogenic noise not only induces physiological damage to fish but also exerts profound effects on their behavior. Fish perceive noise as a threat, leading to the development of avoidance behaviors, instigating fear responses, and causing a loss of control over their normal behavior. Moreover, noise has the potential to mask communication signals among animals, hindering effective communication within and between groups. This disruption in communication may alter the way individuals interact within a group, potentially impacting the group dynamics or even the entire ecosystem. Engås et al. discovered that fish exhibited a fleeing response from noise sound sources, impacting

their normal feeding and mating behaviors<sup>[185]</sup>. Codarin et al.'s study also revealed that ship noise affected the auditory sensitivity of various fish species, subsequently influencing mate searching, foraging, and individual communication behaviors in these fish<sup>[186]</sup>. Short-term exposure to 150 dB noise significantly increased the locomotor performance of gilthead sea bream (*Sparus aurata*, Linnaeus 1758) and European sea bass (*Dicentrarchus labrax*, Linnaeus 1758)<sup>[169]</sup>. Moderate sound levels (112 dB) can affect zebrafish swimming behavior by altering school cohesion, swimming speed, and swimming height, while artificial noise of 120-140 dB elicited a startle response and caused many individuals to dive to the bottom<sup>[187]</sup>. Exposure of zebrafish to white noise of 150 dB significantly induced anxiety and stress<sup>[172]</sup>. Different temporally structured sounds (both continuous and intermittent at 165 dB) increased startle response, swimming speed, group cohesion, and submarine diving in European seabass (*Dicentrarchus labrax*)<sup>[188]</sup>. Sabet et al. exposed adult zebrafish to noise conditions around 122 dB and found significant increases in startle response, swimming speed, and foraging ability, especially with intermittent treatments<sup>[189]</sup>. Lavral zebrafish (*Danio rerio*) consistently exposed to continuous white noise at 130 and 150 dB / 1  $\mu$ Pa showed enhanced dark avoidance and impaired spontaneous alternation behavior in an anxiety-related dark/light preference test<sup>[26]</sup>. Due to the ability of fish to perceive various sound stimuli through the inner ear and lateral line, resulting in various behavioral responses such as phonotaxis, fish's phonotaxis is divided into positive phonotaxis and negative phonotaxis<sup>[190]</sup>. Positive phonotaxis is manifested by the tendency to move toward the sound source under external acoustic stimulation. For example, in recent years, the emergence of "sound-induced fisheries" and "ocean ranching" is based on the positive phonotaxis of fish. Sound-induced fishing technology is a novel fishing technique that applies acoustic principles to lure fish. It involves playing back recorded biological sounds of fish (such as feeding, mating, schooling, etc.) underwater using specific instruments. This method clusters fish and induces them to enter a predetermined fishing area, thereby achieving the purpose of fishing<sup>[191]</sup>. Michael et al. used audio frequencies in the range of 50 to 400 Hz to train mahi-mahi and rainbow trout, intending to control the aggregation of fish in net cages and attract escaped fish back to the cages through acoustic training. The study showed that when the audio frequency was adjusted to 250 Hz, both mahi-mahi and rainbow trout could be simultaneously

controlled to feed on bait. The trained fish could be gathered and maintained long-term memory<sup>[192]</sup>. Negative phonotaxis is manifested by fish swimming away from the direction of the sound source under sound stimulation. Researchers often use this negative phonotaxis of fish to deter and drive them using sound. Hawkins experimentally demonstrated that fish exhibit different behavioral responses to different frequencies of sound<sup>[190]</sup>. Nestler et al. studied the response of herring to sound frequency and intensity. When the sound intensity was in the range of 160 to 175 dB and the frequency was in the range of 100 to 1000 Hz, the startled response of herring was short. When the sound intensity was in the range of 187 to 200 dB and the frequency was in the range of 124.6 to 130.9 kHz, the herring fled from the sound source to a distance of 60 meters, lasting for 1 hour<sup>[193]</sup>.

In recent years, numerous scholars have delved into the behavioral repercussions on fish induced by the playback of ship or land-based culture system noise under captive conditions. Price et al. observed that ship noise reduced the reaction latency and duration of grouper and black sparrow, while aquaculture noise had a mitigating effect on the reaction speed of black sparrow. Interestingly, ship noise exhibited a more pronounced impact on anti-predator behavior compared to aquaculture noise<sup>[194]</sup>. Vessel noise has been found to decrease swimming behavior in spottail shiner (*Notropis hudsonius*) and bluegill sunfish (*Lepomis macrochirus*). However, spottail shiner demonstrated true avoidance behavior, indicating a more extreme response in species with refined auditory abilities<sup>[195]</sup>. Small yellow croaker (*Larimichthys polyactis*) exposed to 120 dB of vessel noise exhibited escape behavior from the noise source. By the end of the exposure, *L. polyactis* was motionless on the water's surface, losing the ability to maintain balance<sup>[177]</sup>. Zhang et al. observed more discrete polarity and cohesion in fish under the influence of RAS (107.7 dB) and IPRS (115.1 dB) compared to controls<sup>[167]</sup>. Hang et al. assessed the effects of commercial industrial RAS noise on the swimming behavior of larval largemouth bass (*Micropterus salmoides*) and found that the mean angle and distance between the focal fish of the noise group and its nearest neighbor fish were greater than those of the ambient group. This indicates a more dispersed and less cohesive population<sup>[142]</sup>. Hasan et al. placed fathead minnows (*Pimephales promelas*) into airstones and filter noise and found that exposure to novel filter noise resulted in decreased boldness, with a return to bolder behavior when placed back

into the original noisy environment <sup>[196]</sup>. Sabat et al. discovered that under captive conditions, noise induced significant startle response behavior in zebrafish (*Danio rerio*), increased swimming speed, caused Lake Victoria cichlids (*Haplochromis piceatus*) to move downward, and stay longer at the bottom of the tank <sup>[197]</sup>.

## **5 The impact of noise on other aquatic species**

In recent years, numerous scholars have investigated the multifaceted impacts of noise on the growth, development, behavioral response, and physiological aspects of other aquatic species. The summary of the impact of human noise on other aquatic species in recent years is presented in Table 2.



768 Table2 The impact of human noise on other aquatic species

Species	Noise level	Influence	Reference
Brown shrimp ( <i>Crangon crangon</i> )	25 - 400Hz 30 dB $\mu V^{-1} \mu bar^{-1}$ above habitat	significant reduction in growth and reproduction rates, increase aggression (cannibalism) and mortality rate and to decrease food uptake	Lagardère et al. [198]
	average increase 30 dB $\mu bar^{-1} Hz^{-1}$	22% increase of the ammonia excretion rate, 15% of increase of the O <sub>2</sub> consumption rate	Regnault et al. [199]
Sea hare ( <i>Stylocheilus striatus</i> )		reduced successful development of embryos by 21% and increased mortality of recently hatched larvae by 22%	Nedelec et al. [200]
Cephalopods ( <i>Loligo vulgaris</i> , <i>Sepia officinalis</i> , <i>Octopus vulgaris</i> , <i>Illex coindetii</i> )	50 - 400Hz	permanent and substantial alterations of the sensory hair cells of the statocysts	André et al. [201]
Cuttlefish ( <i>Sepia officinalis</i> )	315 - 400Hz 139 - 142 dB re 1 $\mu Pa^2$	injuries in statocysts, the damage degree increases with the decrease of distance from the sound source and the increase of time	Solé et al. [202]
	80 – 300 Hz 140 dB re. 1 $\mu Pa$ rms	escape responses (inking, jetting), body patterning changes and fin movements	Samson et al. [203]

	particle accelerations of $0.01 \text{ m s}^{-2}$		
Razor clams ( <i>Sinonovacula stricta</i> )	80 - 100 dB re $1 \mu\text{Pa}$	alteration in the O:N ratios and the expression of ten metabolism-related genes from the glycolysis, fatty acid biosynthesis, tryptophan metabolism, and Tricarboxylic Acid Cycle (TCA cycle) pathways, induced avoidance response	Peng et al. <sup>[204]</sup>
Longfin squid ( <i>Doryteuthis pealeii</i> )	80 – 100 Hz	a range of behavioral responses to sound include fleeing, deimatic and protean behaviors	Mooney et al. <sup>[205]</sup>
Blue mussel ( <i>Mytilus edulis</i> )	140- 155 dB re $1 \mu\text{Pa}^2\text{Hz}^{-1}$ Particle acceleration peaked at 160–175 dB re $1 (\mu\text{ms}^{-2})^2 \text{Hz}^{-1}$	changes in DNA integrity (six-fold higher DNA single strand-breaks in haemocytes and gill epithelial cells) and oxidative stress (68% increased TBARS in gill cells), physiological and behavioral changes (12% reduced oxygen consumption, 60% increase in valve gape, 84% reduced filtration rate)	Wale et al. <sup>[206]</sup>
European spiny lobster ( <i>Palinurus elephas</i> , Fabricius, 1787)	$125 \pm 5 \text{ dB re } 1 \mu\text{Pa/V re } 1$	Total haemocyte count (THC) and haemolymphatic protein concentration, phenoloxidase (PO) activity decreased significantly, whereas total protein and heat shock protein 27 (Hsp27) expression increased significantly	Ceill et al. <sup>[140]</sup>
Mediterranean spiny lobster		increased significantly locomotor activities and	Filiciotto et al. <sup>[207]</sup>

<i>(Palinurus elephas)</i>		haemolymphatic bioindicator of stressful conditions such as glucose, total proteins, Hsp70 expression and THC	
Red swamp crayfish ( <i>Procambarus clarkii</i> )	148 dB <sub>rms</sub> re	behavioral pattern changes, altered blood immune parameters	Ceil et al. <sup>[208]</sup>
Linear seahorse (Hippocampus erectus)	137.3 ± 0.7 dB re: 1 µPa	significant increases in immune indicators, sharp decreases in body weight (ΔWt), Fulton condition factor (ΔK), liver body index, and sex gland index	Anderson et al. <sup>[141]</sup>
Shore crabs ( <i>Carcinus maenas</i> )		consumed more oxygen, indicating a higher metabolic rate and potentially greater stress	Wale et al. <sup>[209]</sup>

770

## 771 **6 Noise control**

772 There are two main measures for noise control in intensive aquaculture systems: sound source  
773 control and propagation control. Sound source control should consider using special devices from  
774 the beginning of the design of the breeding workshop or facility to reduce noise at the source. If  
775 the cost of sound control is relatively high for breeding facilities that have already been put into  
776 use, it is possible to consider using isolation and sound absorption measures to control noise  
777 transmission. The "quality law" of sound insulation states that the density of sound insulation  
778 materials is directly proportional to the amount of sound insulation, meaning that the higher the  
779 quality of the material, the better the sound insulation effect. The "resonance principle" of sound  
780 absorption indicates that when the frequency of the incident noise sound wave is consistent with  
781 the natural frequency of the sound absorbing material, the sound absorbing material will  
782 undergo resonance phenomenon, which can efficiently reduce sound energy <sup>[128]</sup>.  
783 In section 3.1, it is highlighted that machinery, particularly electric motors and air compressors,  
784 stands as prevalent and highly impactful noise sources within aquaculture facilities. When  
785 designing aquaculture systems, thoughtful consideration must be given to the scientific  
786 utilization and arrangement of aquaculture equipment with the aim of minimizing noise  
787 disruptions in fish farming operations. Lara et al. conducted a study revealing that aquaculture  
788 tanks linked to autonomous water treatment units exhibit significantly lower noise levels  
789 compared to tanks integrated with water treatment systems <sup>[21]</sup>. Consequently, in the strategic  
790 planning of indoor aquaculture sites, it is advisable to position aquaculture tanks away from  
791 noise-prone zones, such as those housing water treatment units. Presently, most RAS position  
792 blowers outside the breeding workshop sans any sound insulation measures, resulting in  
793 elevated sound pressure levels when transmitted indoors <sup>[128]</sup>. For established RAS setups,  
794 outdoor blowers should be outfitted with a composite structure incorporating sound insulation  
795 and absorption, complemented by the installation of exhaust silencers in the workshop's  
796 ventilation openings. The application of sound insulation and absorption materials on indoor

ceilings and walls is also recommended. In the case of newly planned RAS, due consideration should be given to isolating blowers through elastic brackets and enclosing them within insulated spaces. Moreover, it is imperative to ensure that doors leading to rooms housing such equipment remain consistently closed <sup>[136]</sup>. Other types of aquaculture environments, such as outdoor ponds, etc., can be equipped with noise reduction devices outside of electric equipment.

The combination of materials and structural design in aquaculture ponds plays a significant role in determining the acoustic conditions inside the pond. As stated in section 3.2, the noise level of fiberglass tanks is significantly higher than that of tanks made of other materials. Therefore, if conditions permit, indoor aquaculture systems should choose tanks with lower noise levels such as concrete tanks.

Most machinery will transmit low-frequency noise to the breeding pond through various pipelines. Therefore, in addition to isolating the breeding pond from these mechanical equipment, soundproofing materials can also be installed on the pipelines or brackets can be set up under the noisy equipment. According to Lawrence and Mason, in order to minimize noise sources in zebrafish housing systems, dampers should be included on supports for pumps or other vibration and noise equipment <sup>[210]</sup>. Davidson et al. <sup>[139]</sup>, Craven et al. <sup>[15]</sup>, and Gutscher et al. <sup>[16]</sup> provided some strategies to modify the design of the water tank and pipeline system to reduce noise, including avoiding physical contact between the inlet and outlet pipes and the water tank, insulating the connecting pipes with foam fillers, and directly connecting the water tank and the support to prevent neoprene isolation pads to raise the water tank above the floor.

Yin et al. suggested that the following measures can be taken for fiberglass aquaculture tanks: (1) the inlet pipe should avoid contact with the inner wall of the tank; (2) Separate the outlet pipe from the main drainage pipe; (3) The water outlet pipe under the sink should avoid contact with the wall; (4) The sink should be fixed on shock-absorbing material<sup>[130]</sup>.

After turning off the blower, the background noise in the breeding workshop is mainly generated by the interaction between the aquaculture water and the pool water, as well as the interaction between the aeration airflow and the pool water. According to the sound energy formula, the sound energy of water droplet impact is directly proportional to the radius of the water droplet and the water droplet falling velocity. Due to the limitation of aquaculture scale, reducing the

flow rate is not advisable. Reducing the radius of water droplets contributes significantly to reducing water splashing noise and does not affect the total water consumption. Therefore, a flexible porous noise reduction net can be added before the aquaculture water impacts the pool. After passing through the noise reduction net, the radius of the aquaculture water decreases, which not only reduces noise, but also allows water droplets to disperse and fall into the pool, bringing in more air <sup>[130]</sup>. Gutscher et al. suggested that (1) the outlet of the inlet pipe of the sink should be placed near or below the water surface; (2) The water flow should not enter the water surface vertically (should be angled); (3) The external filter should not come into contact with the table or bracket where the sink is located<sup>[16]</sup>

The aeration tube directly enters the water, and the airflow generates bubbles. The bubbles rise to the water surface and burst, producing noise. Craven et al. suggested using open top water tanks and fine air stones (instead of coarse air stones) in aquariums to reduce environmental noise <sup>[15]</sup>. To reduce noise and sound energy, multiple rows of porous aeration grilles can be connected at the outlet of the aeration pipe. From the perspective of energy conservation, the friction between the airflow and the small holes in the gas grid will result in energy consumption and a reduction in sound energy. Moreover, after the airflow passes through the small hole, the volume and quantity of bubbles decrease, increasing the contact area between water and air, which is beneficial for dissolved oxygen <sup>[128]</sup>. Alternatively, Radford et al. suggest that oxygenation can be carried out in cone systems separate (and distant) from holding tanks <sup>[127]</sup>.

## **7. Conclusion and prospect**

So far, the impact of chronic noise on the welfare of fish farming is still an emerging research topic. More and more evidence suggest that the impact of underwater noise on fish has become a serious ecological problem. With the gradual increase in underwater noise levels, it is necessary to fully recognize and manage noise before it causes irreversible damage to the welfare of farmed aquatic organism and the underwater ecosystem. This article provides a comprehensive overview of the auditory organs and mechanisms of fish, as well as their growth, physiology, and behavioral responses to noise. It also elaborates on the noise control strategies for aquaculture

environments in existing literature, providing strategies for regulating anthropogenic noise in intensive aquaculture.

Although significant progress has been made in the impact of anthropogenic noise on aquatic animals such as fish in the past few decades, there is currently a relative lack of research on the effects of noise on fish in artificial aquaculture environments, and the following problems still exist:

1. The underwater soundscape in intensive aquaculture system remains uncertain. Although many studies have shown that noise in intensive aquaculture systems do not have adverse effects on the hearing sensitivity, growth, survival, and disease susceptibility of farmed fish. It is important to note that these results cannot be universally applied to all farmed fish, given the species-specific variations in auditory sensitivity and tolerance to potential stressors.

2. While low-intensity noise in intensive aquaculture environments may have a relatively modest short-term impact on the welfare of farmed fish, its long-term effects cannot be ignored. Striking a balance between aquaculture density, mechanical operations, and noise reduction is a crucial direction that warrants exploration.

3. Considering the increasing number of intensive aquaculture systems being applied, meeting the natural biological needs of farmed fish becomes increasingly challenging. It is important not only to determine the characteristics of individual fish species, but also to choose the most appropriate combination of technologies and methods. Therefore, given that the environmental requirements of each fish species are unique and vary according to their biological age, it must be emphasized that their health level at any time is the result of the interaction of many biological and environmental factors.

4. The characteristics of noise in artificial aquaculture environments are low intensity and long-term, and it is difficult to visually observe the damage to farmed fish through behavior and organizational observation alone, especially the potential and long-term effects caused by noise exposure. With the development and widespread and low-cost application of molecular biology, molecular biology methods can be fully utilized to more accurately assess and comprehensively analyze the impact of noise exposure on fish.

5. Detecting the movement of particles in water to determine the direction of the sound source

is indispensable for the hearing of all fish. Popper pointed out that the main challenges in investigating the impact of particle movement on fish are the difficulty in measuring particle movement, modeling particle movement, and the lack of experimental data on the potential adverse effects of particle movement on fish <sup>[86]</sup>. Calibrated sensors should be used to measure particle movement in different water environments, model particle movement, better understand the mechanical and physiological mechanisms of fish in detecting particle movement, and explore the adverse effects of high particle movement levels on fish.

In the context of increasingly tight environmental policies and shrinking aquaculture space, environmentally friendly intensive aquaculture systems have become one of the important ways to solve the contradiction between fishery development and environmental protection. The increase in intensive production and the demand for scientific and precise aquaculture will further stimulate the research and application process of welfare based aquaculture noise and environmental regulation for fish farming.

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