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Original Research Paper

Improving Domestic Fish Welfare in Aquaculture Through Environmental Enrichment and Social Structure Management

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Stress reduction,
Sustainability.

Abstract

Fishing is an integral part of the worldwide seafood production, known as aquaculture. Nevertheless, fish welfare in domestic fish farming is an increasing concern due to overcrowding, inadequate environmental conditions, and a lack of enrichment. In this paper, the author discusses how the welfare of farmed fish can be enhanced by environmental enrichment and social structure. Environmental enrichment is a process in which the aquatic environment is modified to stimulate natural behaviors, e.g., by adding hiding places and substrates. The practices aid in stress reduction, aggression prevention, and increase fish health. In the same way, social structure plays a crucial role in maintaining a steady hierarchy and reducing aggressive interactions. The lack of space may interfere with these social processes and have adverse behavioral and physiological effects. This paper represents the ways to enhance social structures, such as size-based grouping and segregation. The case studies demonstrate effective aquaculture practices that have adopted welfare-enhancing methods, with benefits including healthier fish, higher growth rates, and increased disease resistance. Although these have been listed, high costs, space constraints, and behavioral variability are among the challenges that hinder broad adoption. To sum up, environmental enrichment and social structure are crucial elements of ethical and sustainable aquaculture practices. These practices need to be standardized by future research and policy modifications, which will ultimately improve the sustainability and ethics of the aquaculture industry.

Introduction

Aquaculture refers to the cultivation of aquatic living organisms (aquatic life) and nonliving objects (aquatic arable land) under regulated conditions (Senthil, 2024). Nevertheless, this has not been the case, as, despite its significance, the welfare of fish in aquaculture is often negatively affected by factors such as overcrowding, a lack of environmental complexity, and deprivation of natural behaviors (Macaulay et al., 2021). Most traditional fish farms are economically efficient, but they do not account for essential factors such as water quality, habitat structure, social life, and behavioral requirements (Venkadeshwaran et al., 2025). The outcome may be long-term stress, vulnerability to disorders, deviant behaviors, trauma, and poor health and development.

Environmental enrichment, the intentional provision of captive environments with sensory, physical, social, and cognitive stimulation, has become an essential part of recent decades as a means of enhancing the welfare of fish in

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aquaculture (Jones et al., 2022). The objectives of enrichment include satisfying behavioral, physiological, morphological, and psychological needs of fish as well as alleviating stress and aberrant behavior (Shelton et al., 2024; Trebilco et al., 2022). Physical enrichment can be by the use of substrates (gravel, sand, natural like bottoms), shelters (rocks, plants, hiding structures), structural complexity; sensory enrichment can come in the form of variable background color, tank covers and variable water flows; occupational enrichment can be through varying currents or water movement and social and dietary enrichment play a role as well.

There are numerous welfare benefits of enriching the environments of farmed fish, supported by experimental research (Wicaksono et al., 2021). In many cases, fish that are raised under enriched conditions exhibit decreased stress responses, fewer fin injuries, better fin health and development, increased behavioral repertoire (exploration, shelter use), and recovery from stressors than fish raised in unfilled tanks. In a review under investigation, broodstock fish fed suspended organic-cable structures in one study registered much reduced heart rates when subjected to routine stressful husbandry routine activities (feeding, netting, cleaning) (Mason et al., 2022). They healed more quickly than fish in unenriched tanks, indicating that enrichment alleviates stress and enhances welfare in conditions that approximate realistic production-related conditions (Kitole et al., 2023; Gustavsson et al., 2021).

However, enrichment is challenging to apply in commercial aquaculture. The majority of the positive results come from laboratory or small-scale studies; however, there is a significant gap between controlled experiments and on-farm application under realistic production conditions. Species, life stage, rearing system, and the trade-off between welfare gains and economic costs are critical factors that determine the viability of various enrichment strategies (Beacham & Laake, 2025). For example, substrates or structural features can disrupt maintenance processes (cleaning, harvesting, or sorting), and enriching can increase labor or reduce production efficiency. In addition to enhancing the environment, another fundamental yet often neglected element of fish welfare is the social structure (Arechavala-Lopez et al., 2022). Fish are not solitary creatures; in most cases, consistent social order or group processes are significant factors that lessen aggression, competition, and tension (Zhang et al., 2022; Hidayat et al., 2022). These dynamics are disrupted by overcrowding or poor grouping, leading to high levels of aggression, resource competition, stress, and disease. Even though one of the enrichment groups (rearing with conspecifics or compatible species, or careful grouping by size or species) is considered, it remains under-researched. It is hardly adopted as a regular practice in aquaculture.

Combined, environmental enrichment and social-structure control provide a direction for solving the problem of mutualism between the requirements of aquaculture and the ethical and biological needs of fish (Xu et al., 2022). Through habitat enrichment and the promotion of natural social processes, fish farms can reduce

stress, injuries, and disease, improve behavioral welfare, and possibly enhance long-term health and development, and be provided in a more humane, sustainable manner (Jones et al., 2021; Jayasinghe et al., 2024; Onozaka et al., 2023). But to achieve this promise at a broader scale, additional research is needed, particularly in natural commercial settings and across different species and life stages, to devise viable, cost-effective enrichment protocols. Aquaculture should also be subject to the inclusion of welfare standards (such as environmental and social enrichment) in the guidelines by policymakers and industry participants, to encourage the production of sustainable, ethical, and high-quality seafood (Al-Jame et al., 2024; Arechavala-Lopez et al., 2022; Vaishnav & Kumar, 2025).

Key Contribution

- The paper highlights the importance of environmental enrichment and social structure in maximizing fish welfare, alleviating stress, and stimulating natural behaviors in aquaculture conditions.
- It examines viable options for applying enrichment methods and social arrangements and provides insights into how these can be incorporated into commercial aquaculture activities.
- The paper focuses on the value of pursuing humane, sustainable approaches to fish farming, which raises ethical issues and the long-term sustainability of the aquaculture sector.

The paper explains how environmental enrichment and social structure are very crucial in enhancing the welfare of farmed fish. The paper examines how these elements can help reduce stress, promote health, and stimulate natural behaviors by focusing on incorporating natural habitat elements and stable social processes. It discusses different methods of enrichment, the importance of social hierarchy in reducing aggression, and the practical implementation issues of these measures in commercial aquaculture. The necessity of future research and policy formulation to ascertain the sustainable, morally and welfare-friendly development of the aquaculture industry is also highlighted in the paper.

Environmental Enrichment in Aquaculture

Environmental enrichment is an ecological alteration that stimulates natural behavior and enhances the mental and physical health of animals. In aquaculture, it entails the provision of an environment that is close to the natural environment of the fish, which gives them the room to explore, forage, and socialize in a manner that is in line with the needs of the fish species. These nutritional situations are more conducive to counter the pressure which, as a rule, develops upon dull, sterile tanks, and to healthier, hardier fish. Enrichment has become an essential part of humane and sustainable aquaculture as fish farming becomes popular all over the world. Introduction of hiding places is one of the significant methods in environmental enrichment.

Fish, especially captive fish, whose lives are at risk, enjoy the capacity to escape to safe areas.

Herbs, shelters, or rocks can be the hiding places that fish seek when they feel threatened, reduce stress, and avoid aggressive interactions. This is a mere introduction to the aquaculture environment, which imitates natural environments that fish are usually exposed to in the natural environment, and which provides safety and solace. Besides, the introduction of substrates, such as sand or gravel, promotes natural activities, such as digging and foraging. Social interaction and encouraging exploration take place in complex habitats, such as artificial reefs. A combination of these factors enhances fish welfare by giving them a more exciting and active environment.

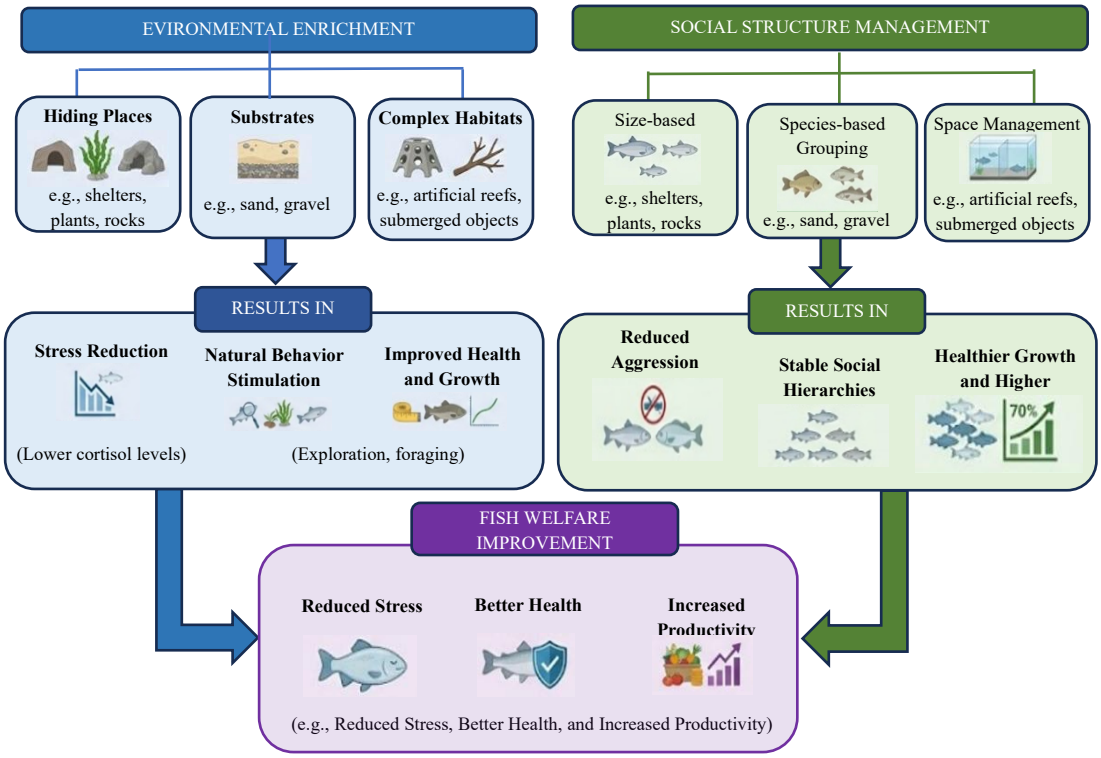

Figure 1: Improving Fish Welfare in Aquaculture - Environmental Enrichment and Social Structure Management

The visualization of the relationship between Environmental Enrichment and Social Structure Management as the means of enhancing fish welfare in aquaculture is presented in Figure 1. Each strategy has been subdivided into significant methods, and the direct advantages of these methods are depicted in the diagram. Environmental enrichment (e.g., hiding places, substrates, and intricate habitats) results in a lowered stress level, enhancement of natural behaviors, and increased health and growth. Management of Social Structure (e.g., size-based grouping, species-based grouping, and space management) leads to less aggression, less variable social hierarchies, and healthier and more successful growth. The resultant effect would be in improving Fish Welfare and consequently reducing stress, improving health, and promoting productivity.

A second technique is that of using substrates. Inclusion of materials like gravel, sand, or any other bottom environment gives the animal a

more natural environment, which promotes behaviors like digging, foraging, and nesting. Most fish species do these activities in the wild, which are essential to their well-being. Substrates do not just provide a physical habitat to the fish, but also facilitate the natural changes in behavior, which will enhance the sense of enrichment that is otherwise unavailable to the barren aquaculture systems. The other important issue of environmental enrichment is a complex habitat. These habitats have diverse structures, i.e., plant growth, artificial reefs, or objects submerged in water, which promote exploration and social interaction. These kinds of features mimic the natural aquatic habitat where species can exercise the freedom to move around and interact with each other as would be expected of them in the natural environment. Complex habitats also contribute to avoiding boredom and behavioral problems due to boredom and the inability to stimulate the fish, thus making them more active and healthier. The advantages of such environmental enrichment methods are immense for the welfare of the fish. Enriched environments have been found to help enhance immune functioning by reducing stress and providing chances to engage in natural behaviors, decreasing disease risk, and decreasing the occurrence of adverse behaviors, such as aggression, cannibalism, or lethargy. When given the right kind of stimuli, fish tend to display a broad spectrum of natural behaviour, and not only increase their welfare, but also improve their growth and development. Also, the practices have the potential to improve the survival rates, decrease the use of antibiotics and other medications, and eventually have a more sustainable and ethical approach to aquaculture.

Social Structure in Aquaculture

Importance of Social Structure

The social structure is central to the health and well-being of fish in aquaculture systems, where fish are usually kept in small areas. Fish are very social creatures that communicate with each other in a manner that will aid in the formation of a natural social order within their groups. Fish have been known to establish intricate social structures in the wild, and these ties are based on size, age, species, and social affiliations. These structures are natural mechanisms that control the competition within the environment, minimize aggression, and encourage cooperative behaviors that are paramount in ensuring the overall well-being of the fish population. A stable social structure is fundamental in aquaculture because it facilitates favorable behaviors and also ensures that fish thrive in their captive setting.

Table 1: Social Structure and Aggression in Aquaculture

Social Structure Type	Aggression Level (Incidents per 100 Fish)	Average Fish Growth Rate (g/day)	Survival Rate (%)	Stress Indicators (Cortisol Level)
Stable Hierarchy	5	0.4	95	Low (2-3 ng/g)
Overcrowding	50	0.2	75	High (10-15 ng/g)
Incompatible Groupings	30	0.25	80	Moderate (5-8 ng/g)
Social Segregation	10	0.35	90	Moderate (5-6 ng/g)

Table 1 below is a summary of the correlation between various social groups in aquaculture and some of the key welfare parameters, including aggression, growth rate, survival rate, and level of stress. It makes a comparison between how various conditions, such as anchoring hierarchies, overcrowding, incompatible groupings, and social segregation, influence the behavior and general health of farmed fish. Stable hierarchies are linked to low levels of aggression, increased rates of growth, and less stress; and overcrowding and incompatible groupings result in much more aggression, less growth, and higher levels of stress. Social segregation, on the other hand, assists in reducing aggression and making fish healthier and productive by giving enough space to natural social processes.

Stable Hierarchy and Reduced Aggression

Proper social organization in fish farming can also be used to diminish negative traits that tend to manifest themselves in the crowded areas, e.g., aggression, territorial conflicts, and resource struggles. These behaviors are easily increased in aquaculture systems where a large population of fish is kept together, and this causes stress, injury, and even death. These problems can be enhanced by the lack of an organized or insecure social structure and result in an increase in the levels of stress, a reduction in growth rates, and an increase in mortality rates. Consequently, social structure has to be comprehended, and to manage the well-being of farmed fish, it is necessary. A stable hierarchy is one of the most crucial issues concerning social structure in aquaculture. Fish in most species automatically have a social hierarchy within their groups, with the larger or more aggressive creatures taking up the upper place in the social structure. This segmentation aids in controlling relationships among fish so that they do not have much competition for resources and space. The less aggressive tendencies of fish to keep a natural hierarchy will mean that fish are less likely to compete in a fight over food, leading to a relatively peaceful environment. Aquaculture operations can reduce stress-related behavior, including fin nipping or fighting, by offering environments in which fish can establish and support such social relationships that lead to healthier and more productive fish.

Table 2: Strategies for Managing Social Structure

Management Strategy	Average Aggression Level (Incidents per 100 Fish)	Growth Rate (g/day)	Survival Rate (%)	Cortisol Levels (ng/g)	Labor/Cost Increase
Size-based Grouping	10	0.35	90	4-6	Moderate (10-15%)
Species-based Grouping	15	0.3	85	5-7	Low (5-10%)
Environmental Segregation	8	0.4	92	3-5	High (15-20%)
Behavioral Monitoring	12	0.33	88	4-6	High (20-25%)

Table 2 gives an overview of different ways of managing social structure in aquaculture, such as size-based grouping, species-based grouping, environmental segregation, and behavioral monitoring. It emphasizes the effects of every

strategy on aggressiveness, growth rate, survival rate, cortisol levels (stress indicators), as well as labor/cost increase. An example is size-based grouping, which minimizes aggression and allows healthy development through keeping fish of a similar size together. Environmental segregation and behavioral monitoring necessitate an increase in labor and resources, and higher survival rates and less stress. The table allows assessing the effectiveness and viability of every strategy in enhancing fish welfare whilst weighing the resources of operation.

The Issue of Overcrowding

Having a healthy social structure depends on another serious aspect, which is not being overcrowded. One of the most prevalent problems in most aquaculture activities is overcrowding, which causes the high stocking densities that result in the disturbance of the natural social hierarchy and space, food, and oxygen competition. Fish tend to be more stressed and aggressive in crowded environments, as they cannot assert their dominance and find a place in the group. This may cause various adverse effects, such as injuries, epidemics, and low growth rates. Aquaculture farms must manage and monitor the stocking rates of aquaculture so as to ensure that fish do not experience stress from overcrowding, and that they are allowed to socialize with others in the aquaculture without feeling overcrowded. Group Management Strategies.

Group Management Strategies

Grouping fish by size and species is one of the strategies that can be applied in order to improve social structure in aquaculture. With proper care (placing fish with other fish of an equivalent size and similar species), aquaculture activities can minimize the possibilities of aggression and ensure that the social order within the group is not affected. The size-based organization is an especially significant factor since large fish tend to be the most dominant and may bully and harm smaller fish or be able to injure them. The division of fish into various groups according to their size simplifies the control of interactions and eliminates bullying and competition over resources. Besides, the coexistence of compatible species may lessen the risks of interspecies aggression and ensure the coexistence of all fish in the system.

Environmental Segregation

The other important measure is the environmental segregation employed in the aquacultural system. It could be helpful to partition the space into smaller parts in large tanks or ponds so as to avoid overcrowding of fish, while permitting social interaction. This segregation may be brought about by the use of physical barriers or by the space arrangement that brings natural barriers between groups of fish. The aquaculture operations can enable this by restricting the quantity of fish in each section to make sure that every group of fish has the required space to develop a stable social environment, lessening aggression and stress.

Behavioral Monitoring

Lastly, behavior surveillance is a mandatory component in the control of social organization in aquaculture. Through continuous monitoring

of the behavior of the fish, the operators of the farms will be able to detect cases of stress, aggression, and social disturbance of the fish early enough to prevent the problem before it deteriorates. Monitoring also aids operators to identify when there is a change in the social dynamics of a group, and alterations can be made, including re-grouping fish or changing the stocking densities. Consistent behavioral analyses also offer great information that could be leveraged to optimize management, humanize fish, and make sure that the aquaculture regime is functioning in the most effective manner.

Enhancing Fish Welfare Through Environmental Enrichment and Social Structure

The environmental enrichment and social structure control are significant determinants of the welfare of farmed fish in aquaculture systems. These behaviors benefit the natural requirements of fish and assist in performing activities that alleviate stress and improve health.

Environmental Enrichment

Environmental enrichment refers to the provision of an environment to the fish to facilitate natural behaviors and alleviate stress. These can involve the provision of hiding spots, either in the form of rocks or natural shelters, where the fish can hide to get out of possible danger and to cut short aggressive interactions. In the same manner, the addition of substrates, e.g., gravel or sand, can be used to promote such natural activities as digging and foraging that are essential to fish health. The complicated habitats, like submerged formations or artificial reefs, further stimulate fish by providing them with a chance to explore and have an opportunity to socialize and form a more stimulating environment. Such environmental improvements have been found to help reduce stress, increase immune capability, and make fish healthier to grow, as well as help in nurturing social bonds within a group.

Social Structure in Aquaculture

Naturally, fish tend to form a social hierarchy, which tends to control the competition, decrease the aggression, and make the social processes more effective. It is essential in aquaculture to ensure a stable social setup in order to reduce stress and aggression. When fish can establish and sustain this natural hierarchy, their competition over resources becomes minimal; therefore, there are fewer chances of injuries and diseases. The interference with this social order that is usually brought about by congestion or improper grouping can result in increased aggression, stress, and lack of good health.

Size and Species Grouping

The use of grouping of fish in terms of size and species is one of the effective methods through which the social structure can be improved. The habit also aids in limiting aggression because bigger and stronger fish have fewer chances of bullying the smaller ones. When similar-sized fish are kept within the same environment and in complementary species, there will be more advantageous interactions between them than when they are placed in groups that do not match.

Overcrowding and Space Management

The problem of overcrowding is a significant issue in most aquaculture systems, where the problem may result in competition among the stock in terms of space and other resources and eventually affect the social system and welfare of the fish. Monitoring and controlling stocking densities are fundamental in ensuring that the store is not overcrowded. Ensuring that the fish have enough room to interact in a natural way and build steady hierarchies will assist in eliminating stress and lead to improved health and development. Moreover, space management (division of tanks or ponds into smaller parts) could be used to control the situation with environmental segregation so that the fish would not be affected by the adverse consequences of overcrowding, and social interactions could still be offered.

Conclusion

To sum up, environmental enrichment and management of the social structure are necessary to enhance fish welfare in aquaculture. Such measures are beneficial in imitating the natural environment of the farmed fish and enable them to respond intuitively, including foraging and socializing, which alleviates stress and increases wellness. Improving the immune system of fish by enriching the living environment with hiding spots, texture, and complexity can help prevent disease, raise healthier and more productive fish. On the same note, two further ways of ensuring that social structure is addressed as it is through grouping fish according to size and species, and avoiding crowding them together, are to ensure that natural hierarchies are observed, and thus aggression and resource competition are minimized. What comes out is a healthier and more balanced environment, which helps in the well-being of fish and the increase of farm output. In the future, there is a need to conduct more research that will fine-tune and streamline these welfare-enhancing practices, especially in large-scale commercial aquaculture. To break the existing limitations, innovations in the cost-effective enrichment approaches will be essential, and plans should be made for further improvements in the monitoring technologies. With the increase in the industry, it will be necessary to include fish welfare as a part of traditional farming to not only promote ethical considerations but also sustainability. As more is researched and policy developed, aquaculture will become more humane and environmentally aware to fulfill the needs of seafood across the globe, one that puts the health of the farmed fish first.

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