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A review of physical environmental enrichment with a focus on overhead cover and vertically-suspended structures

Abstract

Environmental enrichment is increasingly used in aquaculture to improve growth, reduce stress, and promote natural behaviors. Structural (or physical) enrichment is the addition of structures to increase environmental heterogeneity and complexity or provide shelter. At a production level, conventional structural enrichment strategies, such as adding materials to a rearing unit, are often impractical because of the associated increase in labor, waste accumulation, and elevated disease risks. However, structural enrichment techniques have been recently developed that do not interfere with routine hatchery operations and frequently increase fish growth. This review focuses on the relatively recent structural enrichment techniques of non-submerged overhead cover and vertically-suspended structure, and their effects on growth, health, and behavior in production-scale systems. Additionally, key factors influencing enrichment effectiveness and practical considerations for implementation are discussed. These methods of structural enrichment show promise as economically-efficient tools to enhance fish rearing performance and welfare without negatively impacting hatchery procedures.

Keywords: environmental enrichment, structural enrichment, overhead cover, vertically suspended structures, fish welfare, fish behavior, hatchery rearing, aquaculture

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Introduction

Aquaculture is expanding worldwide because of the increasing demand for food, recreation, ornamental trade, and ecosystem restoration.[1–4] As such production intensifies, differences between hatchery-reared and wild fish have become more apparent and animal welfare concerns have been raised. In typical production systems, fish are reared at high densities in barren environments that differ significantly from natural habitats.[5–8] Fish reared in these conditions differ in behavior, morphology, and physiology from wild conspecifics, potentially leading to issues if such fish are being reared for recreational fisheries or species restoration.[6–12]

Environmental enrichment is a strategy to address the issues associated with typically-barren hatchery rearing conditions by increasing environmental complexity and introducing elements that more closely resemble natural habitats.[13,14] Environmental Enrichment can improve fish welfare by enhancing physiological and behavioral conditions.[10,15,16] However, its implementation is often constrained by economic considerations, including labor requirements, material costs, and compatibility with routine hatchery operations. Despite these limitations, some forms of environmental enrichment have cost-effectively provided both welfare and production benefits.[6,13,14,17,18]

Environmental enrichment is often categorized into five types: Physical (structural), social, nutritional, sensorial, and occupational.[14,17,19] Particularly, physical enrichment is defined as the addition of structure to provide shelter or increase environmental heterogeneity and complexity.[6,14,19–21] Prior studies of physical enrichment have added woody debris, substrate, or combinations of these structures to fish rearing units.[15,22–30] These techniques are often impractical in production systems, because their placement in or at the bottom of rearing units hinders routine fish culture activities, such as tank cleaning, as well as increases the risk of potential disease outbreaks by trapping food and feces.[27,31,32] However, other forms of physical enrichment, such as non-submerged overhead cover and vertically-suspended structure, have been identified as both beneficial to fish and compatible with routine hatchery operations.[33–38] This review focuses on these two forms of environmental enrichment that can safely and effectively be used in production fish hatcheries. It will not examine other forms of physical enrichment that are used in laboratory or experimental situations or those that cannot be used effectively in production hatcheries.

Non-submerged overhead cover

Introduction

For this review, non-submerged overhead cover environmental enrichment is defined as any structure or material that provides shade or concealment above or at the top of the water surface of a rearing unit. This cover can either partially (Figure 1) or near-completely (Figure 2) cover the rearing unit. The primary function of non-submerged overhead cover is to provide a refuge area, reduce light intensity, or offer shelter while not being submerged under the water surface of the rearing unit, be it a tank, raceway, trough, or pond. Overhead cover is widely recognized as an essential element of natural aquatic environments.[39–50] Its presence can reduce stress, improve growth, provide refuge, and mitigate light exposure.[14,42,51–53] Despite these benefits, hatchery rearing units are often left completely uncovered to allow for periodic tank cleaning and observations that are considered critical for monitoring fish health and rearing performance.[49,54–56] However, the use of overhead cover can improve hatchery economics by enhancing fish growth and improving fish behavior and health, making it a cost-effective mechanism for increasing production efficiency.[16,33,53,57] The post-stocking benefits of overhead cover in hatchery-reared fish have also been documented.[13,22,58]

Figure 1 Photograph of a circular tank partially covered with a non-submerged wooden structure. Note the location of the fish clustered under the partial cover.

Figure 2 Photograph of a tank near-completely covered with a non-submerged structure made of corrugated plastic.

A wide variety of materials have been used to make overhead cover, including wood, plastic, saran cloth, and netting.[17,33,49,59,60] Each differs in functionality and suitability depending on the fish species being reared and the rearing context.[46,53,58,61–63] Coverage percentage, position relative to the water surface (i.e. distance above or floating), location and configuration of the rearing unit (i.e. indoor or outdoor, circular or rectangular), and material type are all important variables that influence the efficacy of overhead cover on fish rearing.[14,33,37,46,53,60]

While the use of overhead cover in conjunction with a number of different rearing unit types has been evaluated, the benefits appear to be more pronounced in circular tanks than in rectangular units or ponds.[14,33,49,63–65]

Circular tanks

Overhead tank covers with circular tanks have consistently improved growth and feed conversion in salmonids, although the effectiveness of these results can depend on both species and trial duration. Juvenile rainbow trout (*Oncorhynchus mykiss*) reared under partial (29%) plywood covers exhibited significantly greater weight gain and improved feed conversion compared to fish in uncovered tanks[33]. However, these differences were only detected in longer trials (55 days) and not in shorter 34-day experiments. Similar improvements in growth and feed conversion were observed in juvenile brown trout (*Salmo trutta*) reared under the same partial cover configuration over a 51-day period.[62] More recent studies in circular tanks using partial and near-full overhead covers constructed with corrugated plastic report comparable improvements in growth and feed efficiency for both rainbow trout and brown trout in trials ranging from 63 to 84 days.[37,60] However, the effects, if any, of overhead cover may not be consistent among different fish species. For example, channel catfish (*Ictalurus punctatus*) reared in similar conditions to the rainbow trout and brown trout that experienced positive effects from overhead cover[37,60] did not show significant improvements in growth.[61] Additionally, steelhead trout (*Oncorhynchus mykiss*) reared in outdoor circular tanks under partial, floating cover showed a significant increase in growth, but no response was observed in rainbow trout and brown trout reared under the same covers.[46] Krebs et al.,[37] did not observe any difference in viscerosomatic index, hepatosomatic index, splenosomatic index, and relative fin lengths in brown trout reared with or without overhead cover. Similar results were reported by Walker et al.,[60] who also did not observe any difference in hematocrit between covered and uncovered rainbow trout. These findings suggest that partial and near-full tank covers can enhance the rearing performance of salmonids in circular rearing systems, particularly when used for extended rearing periods, but responses likely vary by species and experimental conditions.

Behavioral changes have been observed in fish reared with overhead cover, although these appear to be species-specific and potentially influenced by fish age and cover configuration. In response to an external stimulus, rainbow trout reared in partial cover (66% and 33%) showed significant retreating behavior, whereas uncovered fish tended to scatter.[66] Additionally, fish reared under partial covers were more likely than those reared in uncovered tanks to seek cover when introduced to a new environment with overhead cover.[66] McCrimmon and Kwain[67] reported that fish age influenced the behavioral response to rearing in circular tanks under floating cover, with behavioral changes only observed in trout at least a year old. Overhead cover preferences appear to increase with the age of rainbow trout.[68] In contrast, Nile tilapia (*Oreochromis niloticus*) reared in tanks in a recirculation aquaculture system under partial cover exhibited significantly more distress behaviors than those fish reared under no cover or full cover[53]. Full cover, however, significantly reduced stress and aggression behaviors compared to no cover and partial cover.[53] Based on the few studies available, the influence of overhead cover during hatchery rearing on fish behavior appears to be species-specific and life-stage specific.

While in general the use of overhead cover during fish rearing is beneficial, expanding the percentage of the tank covered appears to yield limited additional benefit. For example, rainbow trout reared in 33% and 66% overhead cover both exhibited improved retreat and stress behavior compared to open tanks, yet the two partial cover treatments did not significantly differ from one another.[66] Similarly, juvenile brown trout reared under 65% or 98% cover demonstrated greater growth than fish in uncovered tanks, but growth did not significantly differ between the two cover treatments.[37] However, juvenile rainbow showed significantly greater weight gain under 98% cover compared to 65%, although other measured variables did not differ between treatments.[60] Together, these findings suggest that while the presence of overhead cover is beneficial, increasing the percentage of coverage is not necessarily needed.

Rectangular units and ponds

In contrast to circular tanks, the use of overhead covers in rectangular rearing units, like raceways, or rectangular or ovoid ponds, appears to have no impact on fish growth. Rainbow trout reared in covered and uncovered concrete raceways showed no significant differences in growth or feed conversion after 215 days.[65] Similar results were observed in cutthroat trout (*Oncorhynchus clarkii*) reared under similar conditions after 250 days.[49] Growth of juvenile rainbow trout, Japanese sea bass (*Lateolabrax japonicus*), and Asian sea bass (*Lates calcarifer*) in ponds was also unaffected by the use of partial covers.[63,64] In contrast, the use of covers in troughs increased the growth and whole brain weights of lake trout (*Salvelinus namaycush*).[58] When tilapia (*Tilapia rendalli*) were reared in ponds with under 80% overhead coverage, the results were mixed. Fish in one trial grew significantly better with covers, but a subsequent trial found no effect of overhead cover on growth.[57] Although there have been few studies, they suggest that the effects of overhead cover in rectangular rearing units and ponds on fish growth are limited and inconsistent.

In general, the use of overhead cover in raceways and ponds has produced noticeable physiological and health benefits. For example, cutthroat trout reared in raceways with overhead cover showed an improvement in health and physiological indices. Further, Nile tilapia reared in ponds under net cover resulted in hematological and biochemical profiles that indicated reduced stress levels.[49,69] However, rainbow trout in raceways with overhead cover had similar health and physiological indices as those reared in uncovered raceways.[65] The use of overhead cover in ponds also eliminated sunburn in yearling Atlantic salmon (*Salmo salar*)[70] and its use in raceways reduced the incidence of cataracts.[71] The positive fish health and physiological effects associated with the use of covers in raceways and ponds, which have not been reported for cover use in circular tanks, is likely because circular tanks are typically indoors, while raceways and ponds are outside and subject to direct sunshine.

Fish reared in raceways and ponds with overhead cover have notable behavioral changes. Silver carp (*Hypophthalmichthys molitrix*) reared in ponds under a small percentage (approximately 0.5%) of overhead, floating cover, showed a distinct preference for cover, reduced swimming activity, and less-coordinated schooling behavior[72]. Similarly, lake trout reared in covered troughs had stronger startle responses and reduced brain serotonin levels, indicating increased behavioral reactivity.[58] In addition, rainbow trout and cutthroat trout previously reared under overhead cover in a raceway, displayed significantly greater, yet temporary, improvements in a predator model behavioral analysis study.[65,49]

Other considerations

Multiple studies also report that overhead cover causes little disruption to regular tank cleanings and fish observations, suggesting that it does not interfere with daily operations.[33,37,62] Wagner et al.[49] reported that raceways with cover were cleaner than those without any cover. Overhead cover may also reduce avian predation risks in outdoor rearing units such as raceways and ponds.[49,63,71] A major benefit to almost completely covering the rearing unit, leaving just enough space for an automatic feeder, is that fish are prevented from jumping out of the tank.[37]

Recommendations

The use of overhead cover, either partially or totally covering the entire rearing unit surface, is recommended during the rearing of various fish species at different life stages.[33,37,49,62,63,66,70,71] Furthermore, covers should be constructed from mostly-inert and waterproof materials, such as plastic, fiberglass, or fiberglass-reinforced plastic, for ease of tank accessibility, material cleanliness, and durability.[37] The cost of these materials is negligible in relation to the improvements in fish growth and potential improvements in fish health, physiology, and post-stocking survival.[33,62] Overall, overhead cover provides an affordable and practical mechanism for enhancing fish production without disrupting hatchery operations.

Vertically suspended structure

Introduction

For this review vertically-suspended environmental enrichment is defined as any structure or material that is suspended from the top of the rearing unit and does not touch the bottom of the tank (Figure 3). Within the tank, vertically-suspended environmental enrichment increases the physical complexity, alters tank hydrodynamics, and influences fish behavior and spatial distribution. Although vertically-suspended structures differ from natural forms of structural complexity, they provide environmental heterogeneity that is often lacking in hatchery environments.[5,6,19,36,73–75]

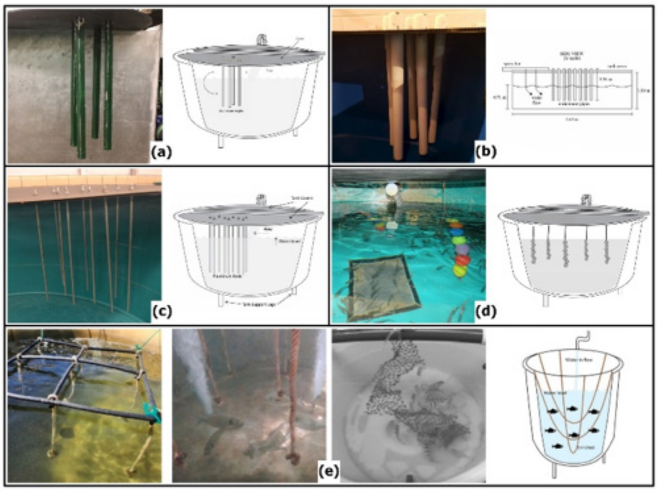

Figure 3 Vertically suspended structure types: (a) aluminum angles (80), (b) conduit pipe (38; 100), (c) aluminum rods (78), (d) spheres (34), (e) rope and netting (97; 99;96)

Vertically-suspended environmental enrichment was developed because of difficulties with earlier forms of within-tank structural enrichment that included the addition of woody debris, substrate consisting of gravel, rock, or concrete, and natural or artificial vegetation directly into the rearing unit.[23–25,28] However, these approaches often disrupt routine hatchery operations by impeding hatchery staff tank cleaning, impeding the hydraulic self-cleaning of circular tanks, increasing waste accumulation, and reducing tank carrying capacities.[14,27,36,38,76–78] In contrast, vertically suspended structures generally do not interfere with routine hatchery operations, do not affect hydraulic self-cleaning (when appropriately configured), and actually increase tank carrying capacities.[34,79–82]

Many different types and arrays of vertically-suspended structure have been evaluated, including aluminum rods, strings of plastic spheres, plastic conduit, and aluminum angles. The differences in material, density, and configuration within the rearing unit can influence the effectiveness of vertically-suspended environmental enrichment by altering the fluid dynamics within the tank and fish behavior.[74,77,80–86]

Types of vertically-suspended structure in circular tanks

Aluminum rods: Aluminum rods were the first type of vertically-suspended structure evaluated. Kientz and Barnes[36] examined the growth and condition of juvenile rainbow trout reared in nearly fully covered circular tanks containing nine vertically oriented round aluminum rods (compared with that of trout reared in almost fully covered tanks with no rods (control) at two water velocities (2.0 body length (BL)/s and 2.75 BL/s). After 51 days, total tank weight gain was significantly higher in the structurally complex tanks than in the control tanks, regardless of water velocity. The feed conversion ratio of 1.25 in the structurally-complex tanks was also significantly better than the feed conversion ratio of 1.66 observed in the unenriched tanks. Kientz and Barnes[36] also reported no significant differences in hepatosomatic index, splenosomatic index, and viscerosomatic index between the fish from the structurally complex and the control tanks. Subsequent multiple studies rearing rainbow trout with an array of nine or more aluminum rods indicated significant improvements in growth.[34,36,78,85,87]

Some studies have not reported positive impacts on fish growth from the use of vertically-suspended environmental enrichment, however. Huysman et al.,[86] reported no difference in rainbow trout growth between enriched and unenriched tanks but also indicated that the extremely high rearing densities likely influenced the results. Growth of landlocked fall Chinook salmon (*Oncorhynchus tshawytscha*) and Atlantic salmon was not impacted by rearing with an a suspended array of nine aluminum rods.[88] Matthew et al.[82] reported that bluegill (*Lepomis macrochirus*) growth was negatively impacted by rearing with an array of thirty-two aluminum rods. These results indicate that the effects of using aluminum rods as environmental enrichment may be species, size, and rearing density specific.

Spheres: Only three studies have examined the use of vertically-suspended strings of colored plastic spheres. During the rearing of juvenile rainbow trout, Kientz et al.[78] evaluated spherical structures comprised of seven colored plastic balls vertically-stacked and suspended on a string from an overhead tank covers and reported significantly improved weight gain and feed conversion ratios relative to control tanks. Similar results were reported by Crank et al.[34] and Voorhees et al.[85] In a related study, the presence and density of plastic spheres did not significantly alter rainbow trout predator avoidance behavior, although limitations in experimental design may have contributed to the lack of measurable results.[89] While suspended strings of plastic balls appear to be beneficial during trout rearing, they are also difficult to clean, making them somewhat impractical for routine hatchery use

Aluminum angles: Vertically-suspended arrays of aluminum angles have been consistently associated with improved growth in salmonids. Multiple studies have documented significantly greater growth in rainbow trout reared with arrays of four aluminum angles.[80,87,90,91] Similar results have been reported using a suspended array of aluminum angles during Chinook salmon rearing.[35]

In addition to the aluminum angle arrays themselves, several studies have also investigated the influence of angle color on fish growth. In comparison to silver (unpainted), red, and black angles, the use of green angles significantly increased growth in Chinook salmon.[92] However, there were no differences in rainbow trout or Chinook salmon growth using either blue and silver vertically-suspended angles,[93] as well as no differences in rainbow trout grown with either red, blue, and green angles.[79] These inconsistent results suggest that species-specific biological requirements and the visual environment likely mediate responses to color, rather than color alone being the main contributing factor.[79,92,93]

In addition to improving growth, vertically-suspended angles may influence fish behavior. Huysman et al.[74] reported that an array of four angles significantly influenced spatial distribution of rainbow trout within the rearing unit. However, a similar study found no differences in location preference between rainbow trout with prior exposure to angles and naïve fish.[84]

Conduit pipe: Vertically-suspended arrays of plastic conduit pipe in circular tanks were evaluated in two studies. Growth was significantly improved in rainbow trout and Chinook salmon reared with an array of twenty conduit pipes in comparison to barren tanks.[38]

Similarly, Jones et al.,[94] used a vertically-suspended array of 20 plastic conduit pipes as enrichment in 3.63 m circular tanks during Atlantic salmon rearing. They reported a significant improvement in feed conversion ratio after 168 days of rearing and recommended the use of vertically-suspended structures to improve the hatchery rearing performance of Atlantic salmon in circular tanks.

Rope and string: Vertically- suspended rope and string structures have not been shown to improve growth but generally improve fish stress and behavior. Although growth was not affected, exposure to an array of nine suspended ropes improved stress levels and behavior in Gilthead seabream (*Sparus aurata*).[95,96] Similarly, ropes hanging across a rearing unit improved behavior European seabass (*Dicentrarchus labrax*).[97] However, in a much shorter duration study with European seabass, suspended ropes had no impact on growth or behavior.[98] Vertically-suspended netting improved exploratory behavior in rock bream (*Oplegnathus fasciatus*) but did not impact stress levels.[99] In contrast to other vertically suspended structures, rainbow trout growth was unaffected by rearing with vertically-suspended arrays of 28 rubber strings[100] However, arrays of rubber strings reduced rainbow trout stress and improved health responses.[100]

Rectangular rearing units

Unlike circular rearing units, the use of vertically-suspended structure has not been extensively studied in rectangular rearing units. Rosburg et al.,[101] An array of five rods with six golf balls in semi-square tanks significantly improved the growth of juvenile landlocked fall Chinook salmon after 90 days of rearing. In contrast, juvenile pikeperch and sterlet reared in square tanks under three arrays of five conduit pipes had significantly improved survival, growth, and morphological development compared to those reared in unenriched tanks.[102] The presence of structure also impacted pikeperch spatial distribution, but did not change the frequency of abnormal behaviors in sterlet, suggesting species-specific biological requirements.[102] Overall, these limited studies indicate that while vertically- suspended structures in rectangular systems may enhance fish welfare, they appear dependent on species and experimental design, and remain difficult to interpret because of the small number of studies.

Practical considerations

The use of vertically suspended structural environmental enrichment in production systems requires consideration of its effects on tank hydraulics, material properties, and operational feasibility. Across studies, aluminum angles, aluminum rods, PVC pipes, spherical structures, and rope structures do not interfere with the hydraulic self-cleaning of circular tanks, do not require additional cleaning, and generally do not interfere with routine hatchery operations.[34-36,38,78,79,85–87,90,94,100] However, structure density and configuration are critical, and if the arrays are excessive or poorly arranged, water flow can be disrupted and self-cleaning reduced.[34,77,80,82,83] Combining different vertically-suspended enrichment structures appears to produce outcomes similar to single structure designs.[34,78,85] Aluminum angles have become the preferred form of vertically-suspended environmental enrichment in circular tanks because they are easy and inexpensive to make, easy to clean and maintain, have been shown to consistently improve fish growth, and do not impact circular tank hydraulic self-cleaning dynamics.[35,80,87,90,91] Overall, vertically suspended structures can be utilized without disrupting routine hatchery operations with the correct density and configuration, with aluminum angles most recommended due to their effectiveness, minimal material use, and ease of maintenance.

Conclusion

Non-submerged overhead covers and vertically suspended structures are practical and economically-efficient methods of physical enrichment in hatchery systems. Both have documented benefits on fish growth, behavior, and health, although fish physiological and behavior responses with overhead cover more extensively studied. The effectiveness of these techniques is dependent upon the rearing unit, structure configuration, material type, duration, and species being reared. Generally, most improvements have been observed during salmonid rearing in circular tanks for longer durations. More studies are needed with other species in other types of rearing units.

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Conflicts of interest

The authors declare that there are no conflicts of interest.

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