

Impact of Vertically-Suspended Environmental Enrichment and Two Densities of Fish on Circular Tank Velocity Profiles

Joshua M. A. Caasi¹, Joseph M. Barnes¹, Michael E. Barnes² 

¹Benedictine College, School of Engineering, Atchison, Kansas, USA

²South Dakota Department of Game, Fish and Parks, McNenny State Fish Hatchery, Spearfish, South Dakota, USA

Email: mike.barnes@state.sd.us

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Abstract

Vertically-suspended environmental enrichment has been shown to produce improvements in fish growth during hatchery rearing in circular tanks. This study documented the effects of a novel suspended structure on the velocity profile of a 3.63-m diameter circular tank containing juvenile landlocked fall Chinook salmon (*Oncorhynchus tshawytscha*) at two different densities (9.0 and 34.3 kg/m³). The addition of vertically-suspended structure to the tank significantly decreased velocities at nearly every sampling point, with velocities typically dropping from 15 cm/s without structure to less than 6 cm/s when structure was present. Fish density also significantly impacted in-tank velocities, with an inverse relationship observed between the density of fish and water velocity. Significant interactions were present among the presence or absence of structure and fish density. When structure and fish were absent, the velocity at the edge of the tank was 15.63 cm/s, which was significantly higher than the 4.75 cm/s velocity when both structure and the lower fish density were added, which was in turn significantly higher than the 2.29 cm/s velocity observed with structure and higher fish density. Despite the potentially unique features of this study, vertically-suspended environmental enrichment and the presence of fish clearly alter circular tank water velocities, which may at least partially explain the improvements in fish rearing performance observed with the use of suspended structure.

Keywords

Circular Tank, Velocity, Environmental Enrichment, Fish Density

1. Introduction

Circular tanks are commonly used in aquaculture and are well-suited for fish

production [1] [2] [3]. They are inherently self-cleaning with relatively uniform water quality because of the rotational flows resulting from water entering through a tangential spray bar and exiting through a central drain [1] [2] [3] [4]. The rotational flows can also be adjusted to optimize likely beneficial fish exercise [5] [6] [7] [8].

Timmons *et al.* [1], Tvinnereim and Skybakmoen [9], Davidson and Summerfelt [10], Oca and Masalo [3], Lekang [11], and Plew *et al.* [12] have all documented the water velocity profiles in circular tanks. In general, water rotating tangentially to the tank wall creates a second radial rotation which is fastest towards the edge of the tank, and if fast enough, carries the fish waste from the bottom of the tank to the drain [1]. However, circular tank water flow patterns can be influenced by tank dimensions, water inlet structure geometry, outlet structure numbers and locations, fish numbers and sizes, and incoming water velocity and flow [3] [9] [10] [12] [13]. Environmental enrichment present in the circular tank can also significantly affect velocity profiles [14] [15].

Environmental enrichment is the modification of typically barren hatchery rearing tanks to simulate natural habitats or make more complex rearing environments [16]. In practice, environmental enrichment has included placing rocks, plant and root materials, or cement bricks in tanks [17]-[24]. However, placement of objects on the tank bottoms can severely affect flow patterns and directly reduce or eliminate the effectiveness of tank self-cleaning, leading to increased tank-cleaning labor and increased fish health risks from trapped organic matter [1] [3] [9] [24] [25] [26] [27]. The use of structures suspended from the top of circular tanks has allowed for the addition of environmental enrichment without the loss of hydraulic self-cleaning [28]. Vertically-suspended environmental enrichment has been shown to improve the growth and hatchery rearing efficiencies for numerous salmonid species [28]-[35].

The effects of vertically-suspended structures on circular tank water velocity profiles have been reported by Moine *et al.* [14] and Muggli *et al.* [15]. However, both studies used 1.8-m diameter tanks and suspended arrays of small aluminum rods. Neither Moine *et al.* [14] nor Muggli *et al.* [15] examined the interaction of fish and vertically-suspended enrichment; all of their measurements were in tanks devoid of fish. Given that tank size, the presence of fish, and environmental enrichment structures can all impact within-tank water velocity profiles [9] [12] [14] [15] [36], additional information on circular tank water flow patterns in larger tanks containing fish with different environmental enrichment structures is needed. Thus, the objective of this experiment was to document water velocities in circular tanks larger in diameter than 1.8-m, with and without the presence of fish, and with and without the presence of a novel vertically-suspended environmental enrichment structure.

2. Methods

All data was collected in a 3.63-m diameter, 0.71-m water-depth stainless-steel sided, cement bottom, circular tank fitted with a square central drain and a ho-

horizontal spray bar (**Figure 1** and **Figure 2**) at McNenny State Fish Hatchery in rural Spearfish, South Dakota, USA. Water height was maintained in tank at a height of 0.7 m, and the incoming water flow rate was 288 L/min. Water velocity profiles for the tank were developed under six different scenarios: 1) fish absent from the tank and no vertically-suspended environmental enrichment, 2) fish absent with enrichment, 3) fish present at a lower density and no enrichment, 4) fish present at a lower density with enrichment, 5) fish present at a higher density and no enrichment, and 6) fish present at a higher density with enrichment (**Table 1**). The vertically-suspended environmental enrichment consisted of a 43×117 cm array of 20 pieces (diameter = 4.34 cm; length = 0.94 m) of polyvinyl chloride electrical conduit protruding downward from an overhead plastic cover as described by White *et al.* [35]. The conduit pieces were evenly spaced, approximately 16.5 cm apart. The array was approximately 58 cm from the tank edge and was located 90° from the spray bar where water entered the tank (**Figure 3**).

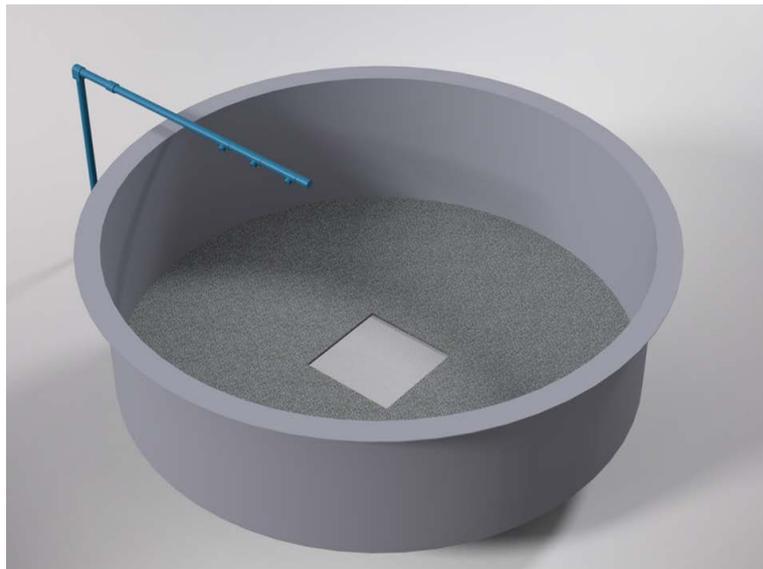


Figure 1. Diagram of a circular tank with horizontal spray bar and centralized drain.



Figure 2. Picture of the tank in situ at McNenny State Fish Hatchery.

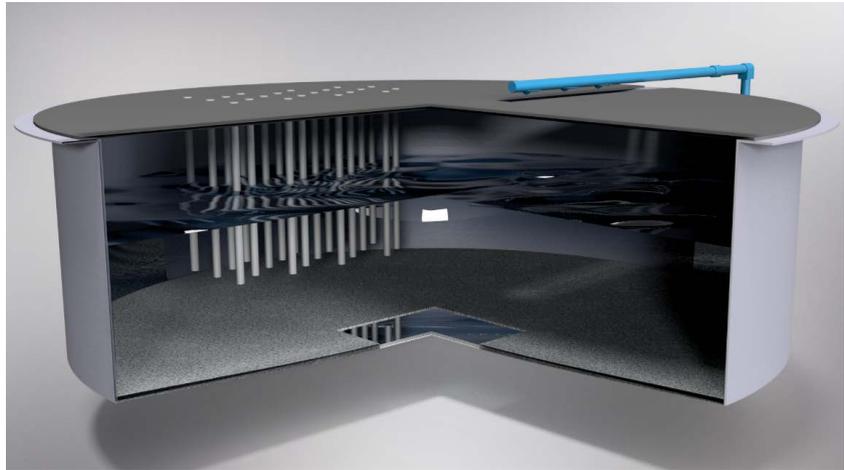


Figure 3. Model of the circular tank interior with a view of vertically-suspended structure array.

Table 1. Scenarios for sampling velocities in a circular tank with and without vertically-suspended structure with or without the presence of fish at two densities.

Scenario	Structure	Fish
1	No	None
2	No	Low density
3	No	High density
4	Yes	None
5	Yes	Low density
6	Yes	High density

To measure in-tank velocities, a grid system was overlaid on the overhead view of the tank (**Figure 4**). The 0° axis was the location of the horizontal spray bar and the 90° axis was the location of enrichment structure. On each axis (0° , 90° , 180° , and 270°), velocity samples were taken at three locations: near the edge of the tank, in the middle of the axis, and near the central drain. At each of these locations, data was collected at three depths: near the top of the water column, in the middle, and near the bottom (**Figure 5**; **Table 2**). Two replicates for each sampling location were recorded. Velocity measurements were taken with a JDC Electronics Flowwatch Flowmeter (JDC, Yverdon-les-Bains, Switzerland).

In addition to collecting velocity data with or without the presence of vertically-suspended structure, sampling also occurred with or without the presence of fish at two different densities. At the first sampling date (March 31, 2020), the tank contained 9.3-cm long (total length) landlocked fall Chinook salmon (*Oncorhynchus tshawytscha*) at a density of 9.0 kg/m^3 . Sampling occurred again on June 3, 2020 when the same fish had grown to approximately 13.8-cm long and the tank density was 34.3 kg/m^3 . Thus, the two densities did not contain the same size of fish; fish size increased as density increased.

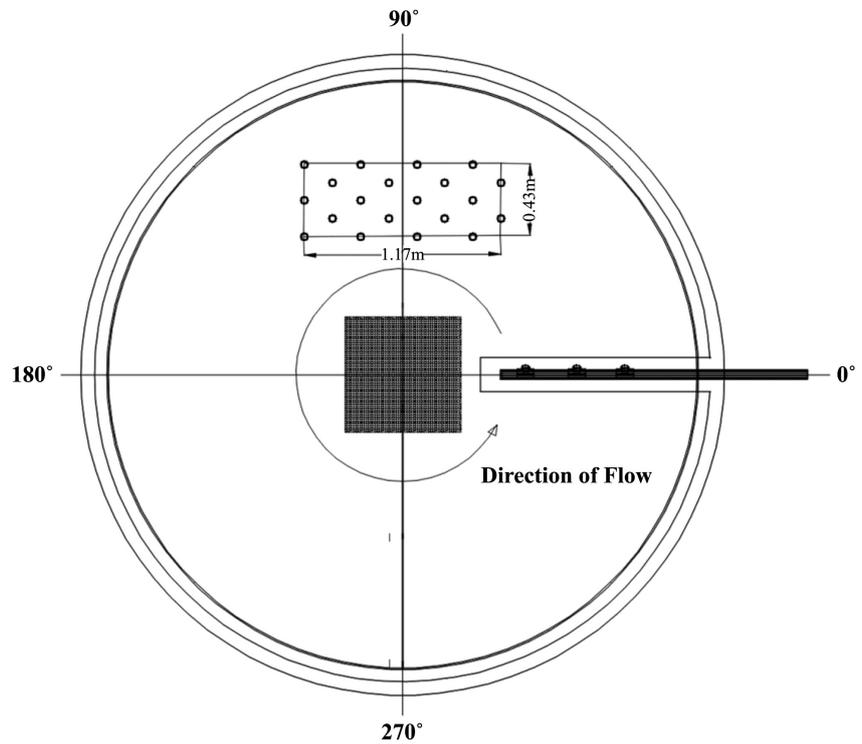


Figure 4. Overhead view of the salmon rearing tank showing sampling location degrees and array size.

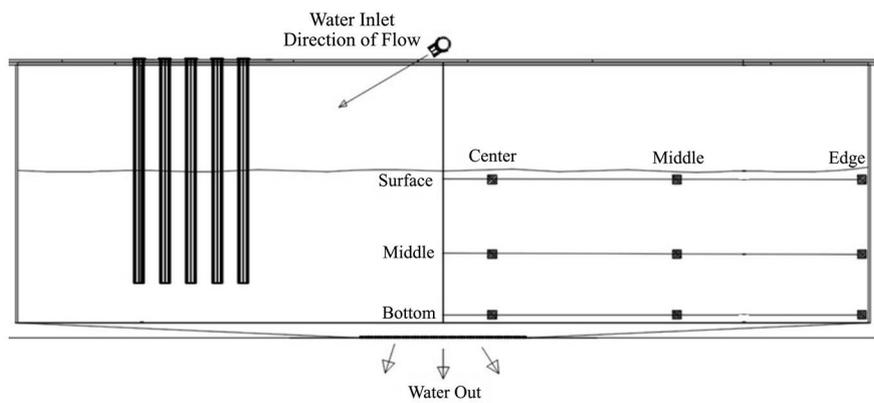


Figure 5. Cross-sectional view of the salmon rearing tank with sampling locations.

Table 2. Velocity sampling locations.

		Distance (cm)
Radial position ^a	Center	20
	Middle	122
	Edge	173
Depth ^b	Surface	4
	Middle	35
	Bottom	66

^aDistance is from midpoint of water column; ^bDistance is from surface of water column.

Data were initially analyzed by analysis of variance and covariance using the SPSS (24.0) statistical analysis program (IBM, Armonk, New York, USA). Because of the large number of interactions, subsequent analysis used one-way analysis of variance. Tukey's mean comparison procedure was used for post-hoc analysis. The significance level for all tests was predetermined at $P < 0.05$.

3. Results

The addition of vertically-suspended structure to the tank significantly decreased velocities at nearly every sampling point. Specifically, velocities at the three radial locations were at least 15 cm/s in the absence of structure but decreased to less than 6 cm/s when structure was present (Table 3). Fish density also significantly impacted in-tank velocities. In general, an inverse relationship between the density of fish and water velocity was observed (Table 4). Significant interactions were observed among the presence or absence of structure and fish density. When structure and fish were absent, an edge velocity of 15.63 cm/s was observed, which was significantly higher than the 4.75 cm/s velocity when structure was added at the lower fish density (Table 5). This in turn was significantly higher than the 2.29 cm/s velocity observed with structure and higher fish density. At the fish density of 9.0 kg/m³, cross-sectional profiles of the circular tank indicated reduced velocities at each depth with the presence of structure in comparison to the absence of either fish or structure, the presence of only fish, or the presence of both fish and structure (Figures 6-11). In contrast, the combination of both structure and fish produced the slowest velocity profiles at the fish density of 34.3 kg/m³, with slightly higher velocities observed with just the presence of structure in Figures 12-17. The highest velocities occurred with either the presence of only fish or the absence of both fish and structure.

Table 3. Mean (\pm SD) overall water velocities (cm/s) at three radial positions in a circular tank with or without vertically-suspended structures, all sampling depths combined. Means with different letters in same columns are significantly different ($P < 0.05$).

Structure	Radial position		
	Center	Middle	Edge
Absent	20.04 \pm 4.35 z	22.88 \pm 2.77 z	15.63 \pm 2.22 z
Present	4.75 \pm 2.64 y	5.71 \pm 2.56 y	4.75 \pm 2.33 y

Table 4. Mean (\pm SD) overall water velocities (cm/s) at three radial positions in a circular tank with three different fish densities, all sampling depths combined. Means with different letters in same column are significantly different ($P < 0.05$).

Fish	Radial position		
	Center	Middle	Edge
Absent	20.04 \pm 4.35 z	22.88 \pm 2.77 z	15.63 \pm 2.22 z
9.0 kg/m ³	17.33 \pm 4.68 z	17.25 \pm 3.05 y	11.21 \pm 1.91 y
34.3 kg/m ³	10.25 \pm 2.54 y	14.38 \pm 4.52 x	15.25 \pm 4.53 z

Table 5. Mean (\pm SD) overall water velocities (cm/s) at three radial positions in a circular tank, with and without vertically-suspended structure, and three different fish densities, all sampling depths combined. Means with different letters in the same column are significantly different ($P < 0.05$).

Fish	Structure	Radial position		
		Center	Middle	Edge
Absent	Absent	20.04 \pm 4.35 z	22.88 \pm 2.77 z	15.63 \pm 2.22 z
9.0 kg/m ³	Present	4.75 \pm 2.64 y	5.71 \pm 2.56 y	4.75 \pm 2.33 y
34.3 kg/m ³	Present	3.92 \pm 2.04 y	4.13 \pm 1.87 y	2.29 \pm 1.97 x

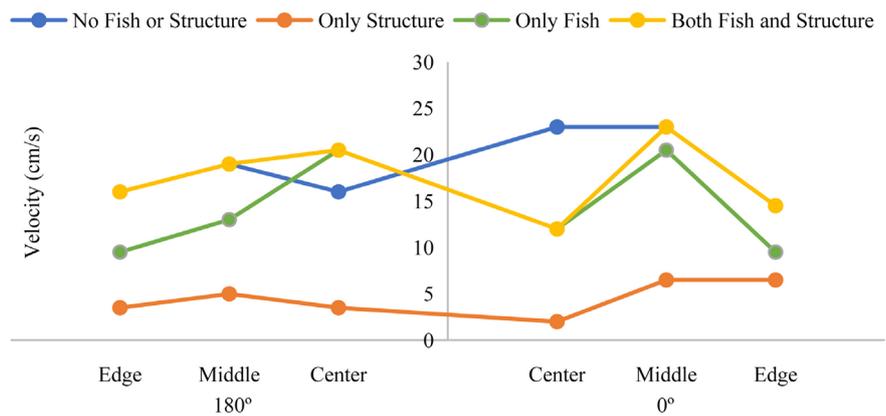


Figure 6. Cross-sectional velocity profiles at a depth of 4 cm (surface) of a 3.63-m diameter circular tank parallel to the incoming water supply (spray bar—location 0) and across to the other side of the tank (location 180). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 9.0 kg/m³ or an array of vertically-suspended structure, or with the tank containing both fish and structure.

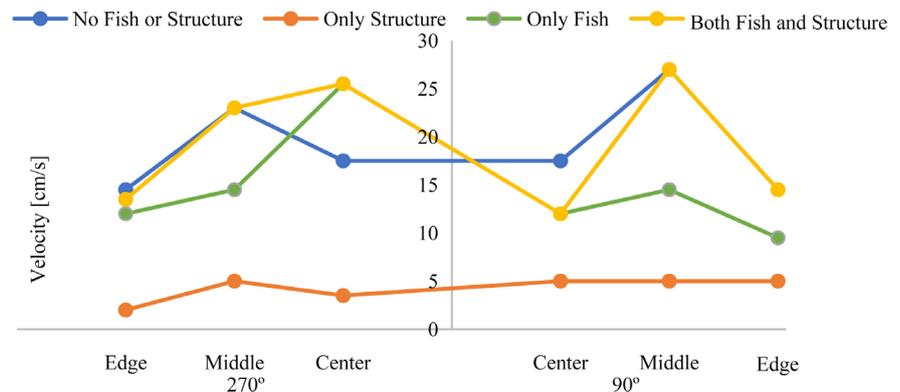


Figure 7. Cross-sectional velocity profiles at a depth of 4 cm (surface) of a 3.63-m diameter circular tank perpendicular to the incoming water supply from the location of an array of vertically-suspended structure (location 90) and across to the other side of the tank (location 270). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 9.0 kg/m³ or structure, or with the tank containing both fish and structure.

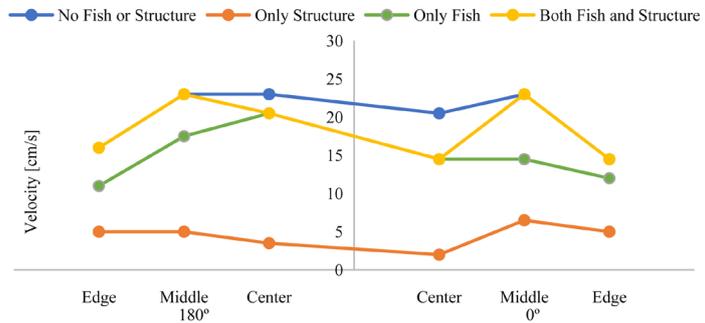


Figure 8. Cross-sectional velocity profiles at a depth of 35 cm (middle level) of a 3.63-m diameter circular tank parallel to the incoming water supply (spray bar—location 0) and across to the other side of the tank (location 180). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 9.0 kg/m³ or an array of vertically-suspended structure, or with the tank containing both fish and structure.

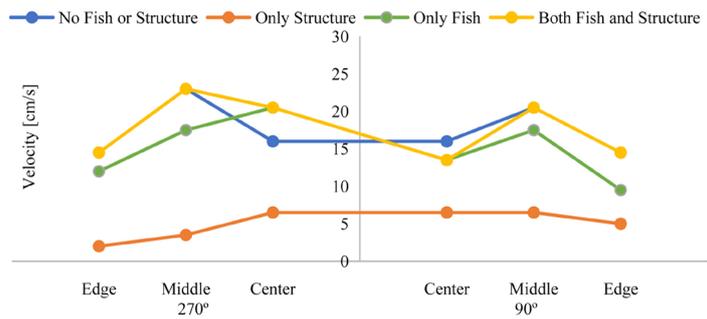


Figure 9. Cross-sectional velocity profiles at a depth of 35 cm (middle level) of a 3.63-m diameter circular tank perpendicular to the incoming water supply from the location of an array of vertically-suspended structure (location 90) and across to the other side of the tank (location 270). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 9.0 kg/m³ or structure, or with the tank containing both fish and structure.

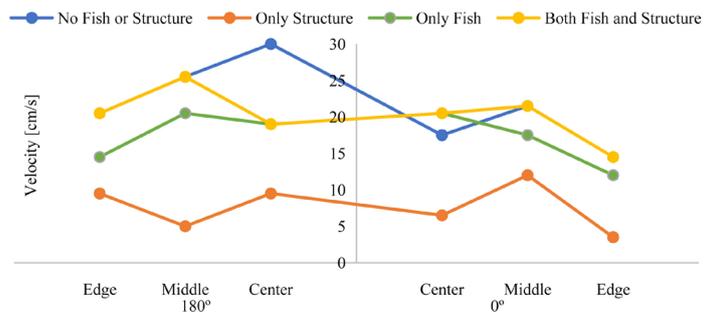


Figure 10. Cross-sectional velocity profiles at a depth of 66 cm (bottom) of a 3.63-m diameter circular tank parallel to the incoming water supply (spray bar—location 0) and across to the other side of the tank (location 180). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 9.0 kg/m³ or an array of vertically-suspended structure, or with the tank containing both fish and structure.

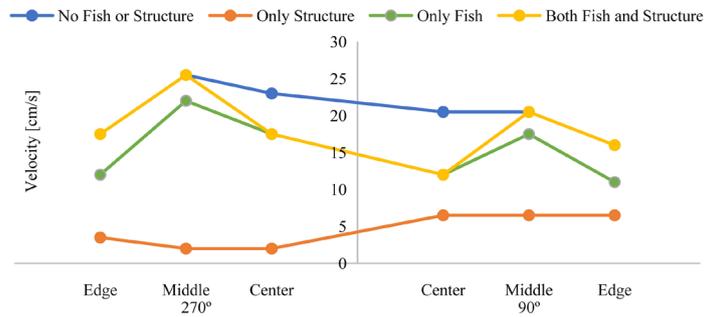


Figure 11. Cross-sectional velocity profiles at a depth of 66 cm (bottom) of a 3.63-m diameter circular tank perpendicular to the incoming water supply from the location of an array of vertically-suspended structure (location 90) and across to the other side of the tank (location 270). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 9.0 kg/m³ or structure, or with the tank containing both fish and structure.

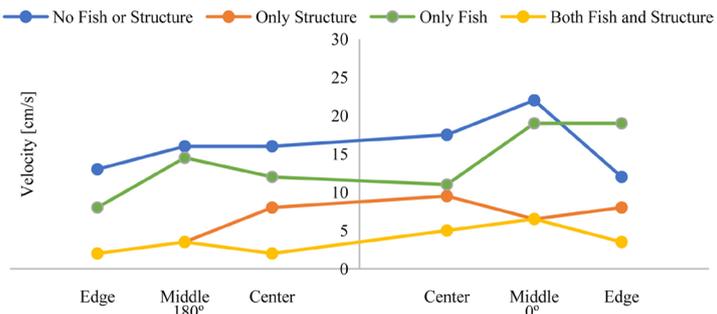


Figure 12. Cross-sectional velocity profiles at a depth of 4 cm (surface) of a 3.63-m diameter circular tank parallel to the incoming water supply (spray bar—location 0) and across to the other side of the tank (location 180). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 34.3 kg/m³ or an array of vertically-suspended structure, or with the tank containing both fish and structure.

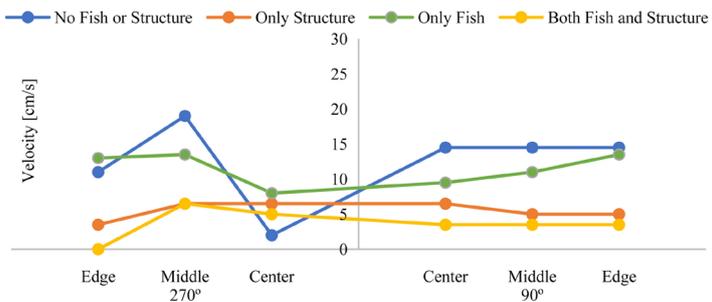


Figure 13. Cross-sectional velocity profiles at a depth of 4 cm (surface) of a 3.63-m diameter circular tank perpendicular to the incoming water supply from the location of an array of vertically-suspended structure (location 90) and across to the other side of the tank (location 270). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 34.3 kg/m³ or structure, or with the tank containing both fish and structure.

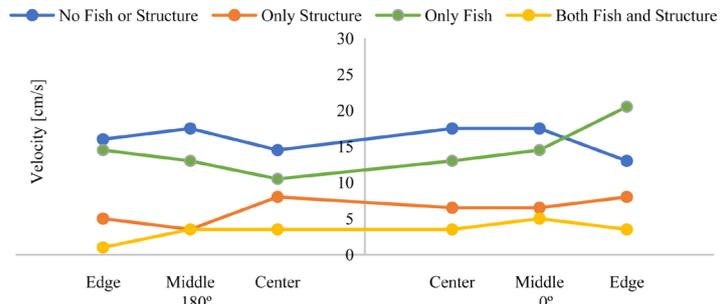


Figure 14. Cross-sectional velocity profiles at a depth of 35 cm (middle level) of a 3.63-m diameter circular tank parallel to the incoming water supply (spray bar—location 0) and across to the other side of the tank (location 180). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 34.3 kg/m³ or an array of vertically-suspended structure, or with the tank containing both fish and structure.

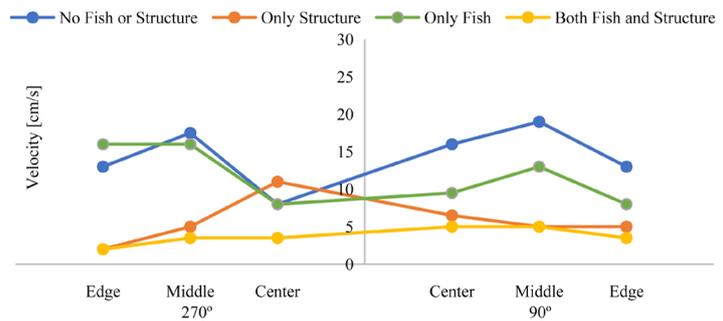


Figure 15. Cross-sectional velocity profiles at a depth of 35 cm (middle level) of a 3.63-m diameter circular tank perpendicular to the incoming water supply from the location of an array of vertically-suspended structure (location 90) and across to the other side of the tank (location 270). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 34.3 kg/m³ or structure, or with the tank containing both fish and structure.

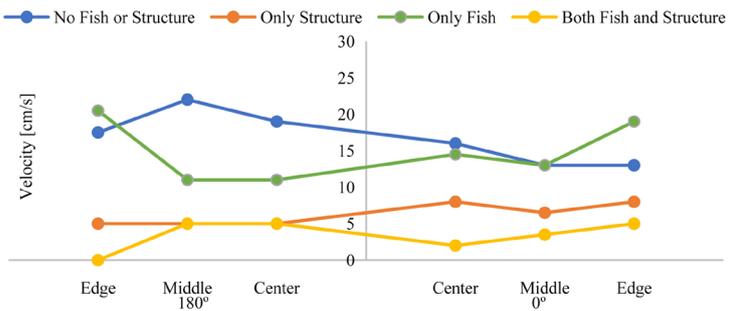


Figure 16. Cross-sectional velocity profiles at a depth of 66 cm (bottom) of a 3.63-m diameter circular tank parallel to the incoming water supply (spray bar—location 0) and across to the other side of the tank (location 180). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 34.3 kg/m³ or an array of vertically-suspended structure, or with the tank containing both fish and structure.

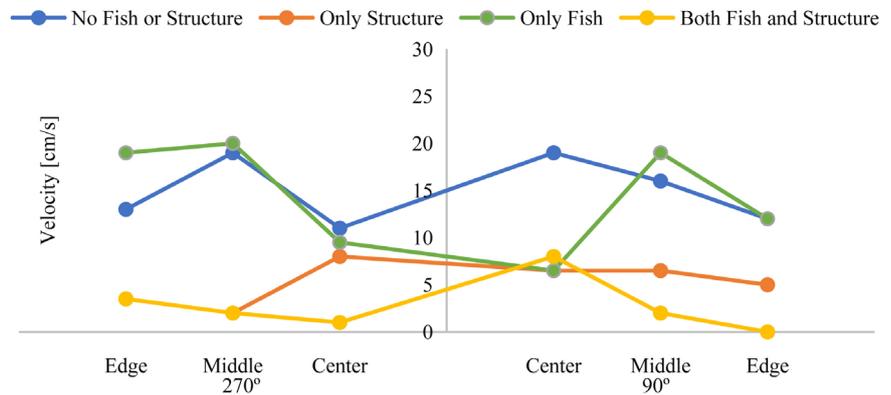


Figure 17. Cross-sectional velocity profiles at a depth of 66 cm (bottom) of a 3.63-m diameter circular tank perpendicular to the incoming water supply from the location of an array of vertically-suspended structure (location 90) and across to the other side of the tank (location 270). Sampling locations from the center of the tank were 20 cm (Center), 122 cm (Middle), and 173 cm (Edge—2 cm from the outer edge of the tank). Velocities were recorded with the tank void of fish or structure, with the tank containing either fish at a density of 34.3 kg/m^3 or structure, or with the tank containing both fish and structure.

4. Discussion

In the absence of structure or fish, the velocity profile of the circular tank follows the pattern described by Timmons *et al.* [1] and Sumida *et al.* [37] of a large central vortex and irrotational zone. These features are instrumental in creating the self-cleaning nature of circular tanks during fish rearing. However, reductions in water velocity can hinder this beneficial self-cleaning [11] [36]. Lekang [11] suggests that if water velocity at the bottom of the tank is below 8 cm/s, the self-cleaning effect is nonexistent. The presence of structure in the tank, and particularly the presence of both structure and either of the fish densities produced velocities at or below this threshold. However, Lekang [11] also suggests that at higher fish densities, lower velocities could be acceptable because fish movement increases resuspension of solids to allow the secondary flow pattern to carry particles to the drain. Unlike Lekang [11], velocities in the present study were not highest at the edge of the tank. Nor was there a consistent trend of higher velocities at the top of the tank.

The reduction in water velocity resulting from the placement of structure in the tank in this study supports the observations of Moine *et al.* [14] and Muggli *et al.* [15]. However, there is a difference in velocity-reduction magnitude. Moine *et al.* [14] and Muggli *et al.* [15] reported that structure decreased the overall tank velocity from highs of 21 to 24 cm/s to as low as 0 to 3 cm/s. In contrast, this study had high velocities of 17 to 20 cm/s which decreased in the presence of structure down to as low as 4 to 7 cm/s. The differences between this study and Moine *et al.* [14] and Muggli *et al.* [15] could be due to differences in the structural arrays used and the size of the circular tanks. This study used longer rods in a 20-rod array in a 3.63-m diameter tank, compared to the shorter nine-rod and 15-rod arrays in 1.8-m tanks used by Moine *et al.* [14] and Muggli *et al.* [15].

This study confirms the reduction of tank velocities with the presence of fish as described by Plew *et al.* [12] and Oca and Masalo [36]. In this study, average tank velocity was reduced by 25% at the lower density of 9 kg/m³ and 10% at the higher density of 34.3 kg/m³. Plew *et al.* [12] reported a 15% reduction in velocity at stocking densities of 15.3 kg/m³ and 35.6 kg/m³, and a 57% reduction at 79.4 kg/m³. However, Oca and Masalo [36] reported a significant loss in velocity in the center of the tank at a stocking density of 14 kg/m³. No such velocity loss was observed in this study. This discrepancy could possibly be because of differences in the tank sizes and fish densities used. Plew *et al.* [12] used considerably larger, 15-m diameter tanks, whereas Oca and Masalo [36] used smaller, 1.44-m diameter tanks containing fewer fish. In addition, compared to the present investigation, Oca and Masalo [36] examined in-tank velocities in much more detail than the present study.

The effect of fish density is greatly impacted by the presence of structure. In this study, at a fish density of 9.0 kg/m³ water velocity remains virtually unchanged, if not slightly slower. However, when the density is increased to 34.3 kg/m³, velocity is reduced drastically. Fausch [38] indicated that fish are more likely to dwell in the lower velocity regions of the tank during non-feeding periods, thereby avoiding the higher-velocity, more energy-intensive areas where food becomes available. It is likely that the fish associate with the lower-velocity areas of the vertically-suspended structure, and at higher fish densities, the combination of fish and structure becomes almost like a wall impeding water flow. In other words, the more fish that congregate next to the structure, the more impact they will have in reducing the tank velocity, and this effect would be multiplied at higher densities. The results from the present study support this hypothesis.

The positive effects of vertically-suspended environmental enrichment structures on fish growth are well documented [28] [29] [30] [31] [33] [35]. It is likely that at least some of these positive effects occur because of the reduction in water velocities. Although high-velocity-induced exercise can benefit fish growth in the short term [5] [6] [39] [40] [41] [42], long periods of exercise can be harmful [7] [8]. Thus, by providing non-uniform within tank velocities, the suspended structures are likely providing refuge areas from continual exercise and also allowing the fish to minimize their energy expenditures during feeding [38]. By altering within-tank velocities, vertically-suspended structures may also be improving fish growth by providing more uniform oxygen concentrations throughout the tank [43]. Although dissolved oxygen levels are relatively uniform in circular tanks, particularly in comparison to rectangular fish rearing tanks [2] [3]; there is still variation in dissolved oxygen levels throughout circular tanks [10] [12] [13].

The results of this study may be unique to the size of tank, spray bar configuration, and suspended structure used, as well as by the size and species of fish. Tvinnereim and Skybakmoen [9], Davidson and Summerfelt [10], Oca and Masalo [3], Plew *et al.* [12], Gorle *et al.* [13], and Muggli *et al.* [15] all indicate that

circular tank velocity profiles can be influenced by multiple factors, including tank size, water inlets and outlets, incoming water velocities, number and size of fish in the tank, and type and size of suspended enrichment structure. However, despite the potentially unique features of this study, vertically-suspended environmental enrichment and the presence of fish clearly decrease circular tank water velocities.

5. Conclusion

This study using a specific size of circular tank demonstrated that a unique form of environmental enrichment and two distinct fish densities can act alone and also interact to dramatically alter within tank water velocity profiles. These changes in water velocity affect the hydraulic self-cleaning of the circular tank and may at least partially explain the improvements in fish rearing performance observed with the use of suspended structures.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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