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Comparative study of fabricated conventional aerator models for enhancing oxygenation efficiency in Aquafarm

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Abstract

In fact Aerators plays an important role in maintaining optimum dissolved oxygen level within aquaculture setups, particularly in shrimp farming. Despite of abundance aerator options are available; but their relative efficiencies remain poorly understood. To address this gap, it has been planned, designed, fabricated and evaluated the aerator models through a series of aeration experiments conducted in the tanks measuring (5 × 5 × 1 m). The fabricated aerator models included Single Perforated Sheet Aerators, Two Tier Perforated Sheets Aerators, Wooden Perforated Aerators and Wooden Flat Surface Aerators were used for the study. The main aim was to compare their performance in terms of the Overall Oxygen Transfer Coefficient (KLa)T and Standard Oxygen Transfer Rate (SOTR). The calculated average values of the Overall Oxygen Transfer Coefficient $(KLa)_T$ ranged from 0.82 h^{-1} to 1.48 h^{-1}, while the corresponding average Standard Oxygen Transfer Rate (SOTR) values varied from 0.072 kg O_2/h to 0.133 kg O_2/h among the above mentioned aerator models, notably, the two tier perforated sheets aerators demonstrated the highest Overall Oxygen Transfer Coefficient $(KLa)_T$ and Standard Oxygen Transfer Rate (SOTR) values compared to the other aerator designs, with the Single Perforated Sheet Aerator, Wooden Flat Surface Aerator and Wooden Perforated Sheet Aerator models following in descending order of efficiency. These findings provide valuable insights into the performance of various aerator models, aiding aquaculture practitioners in making informed decisions regarding aerator selection for their shrimp farming activities.

Keywords: Aeration efficiency, aeration, dissolved oxygen, fabricated aerators

Introduction

The aquaculture industry is poised to play a crucial role in addressing global food and nutritional needs (Kobayashi *et al.*, 2015) [16], accounting for nearly half of the world's fish consumption. With substantial growth potential remaining, alongside agriculture (Troell *et al.*, 2014), [36] this sector is expanding rapidly. The efficacy of intensive and semi-intensive aquaculture systems hinges on various water quality parameters, with dissolved oxygen (DO) concentration being paramount for maintaining optimal aquatic health (Baylar *et al.*, 2006; Roy *et al.*, 2020a) [4, 24]. Fishes and other aquatic species' growth metrics directly correlate with DO levels within the culture system. To foster suitable fish and aquatic species cultivation, DO levels should ideally exceed 5 mg/L in culture water. When DO levels plummet below 3 mg/L, fish experience stress, potentially leading to significant mortalities (Boyd and Hanson, 2010; Nguyen *et al.*, 2020) [8, 20]. Insufficient DO levels drastically diminish fish feed consumption, with prolonged exposure to very low levels, such as 0.5 mg/L, resulting in widespread fish fatalities (Eltawi and ElSbaay, 2016) [13]. Two primary methods, natural aeration and artificial aeration, are employed to elevate dissolved oxygen levels in aquatic environments (Tien *et al.*, 2019) [35]. Natural aeration relies on atmospheric diffusion and plant photosynthesis to enhance DO levels organically. However, due to the escalating demands for productivity in aquaculture, there has been a surge in intensifying fish farming, exacerbating the need for higher DO levels. Additionally, natural aeration encounters challenges during nighttime when DO concentrations decline, impacting species respiration (Tanveer *et al.*, 2018; Boyd, 1998) [34, 6]. To mitigate these issues, artificial aerators have gained widespread adoption in aquaculture operations (Roy *et al.*, 2021a, b, c) [25, 26, 27].

Essentially, artificial aeration systems augment the air-water interface; facilitating increased oxygen transfer from the air into the water through agitation. Mechanical aeration has become a standard practice to mitigate low dissolved oxygen levels in intensive culture ponds. Surface aerators, predominantly paddlewheel types, have been widely used in aquaculture ponds to establish an oxygen-rich environment. However, aeration entails significant initial investment costs, following land and pond construction. Moreover, aeration consumes the majority of energy on farms, accounting for 90-95% in India (Jayanthi *et al.*, 2020) [15] and approximately 80% in Australia (Peterson and Patterson, 2000) [23]. Aeration cost is the third largest cost in intensive aquaculture system after post larvae and feed cost representing about 15% of total production cost (Avinash *et al.*, 2013) [3]. In light of these challenges, the current study aimed to develop a fabricated aeration system; specifically a splashing aerator has been planned, designed and fabricated for tank-based operations. This fabricated aerator comprises a series of perforated sheets arranged horizontally, with pipelines positioned above the water surface at an average height of 0.85 m for water distribution. A centrifugal pump serves as a key component of the fabricated aeration system, elevating the water to the desired height and dispersing it into fine spray droplets from the showers, effectively absorbing oxygen from the atmosphere. This process increases the water surface area in contact with air, facilitating oxygenation before the water returns to the tank (El-Zahaby and El-Gendy, 2016) [14]. The efficiency of aeration hinges on the surface area of water droplets in contact with air, primarily determined by the size of the shower opening and the dispersion of water molecules. Research indicates that water volume also influences oxygen transfer rates, with Elliott (1969) [12] recommending an aerator power to water volume ratio of less than 0.1 kW/m^3. These showers were meticulously designed and fabricated to ensure thorough mixing of water, aiming to achieve DO de-stratification in the water column. Salim *et al.* (2016) [28] conducted a study using Nile tilapia in a showering aeration system, yielding satisfactory results in terms of feed conversion ratio, relative growth rate, specific growth rate, and dissolved oxygen levels, with minimal energy consumption and higher net profit compared to other aeration systems.

2. Materials and Methods

2.1 Experimental setup

Three uniform square shaped experimental cement concrete tanks with inner dimension of 5 × 5 × 1 m (without soil base) located at the Research and Instructional Fish Farm of College of Fisheries, Mangaluru were selected for conducting the experiment. Four aerator designs namely i) Single Perforated Sheet Aerators ii) Two Tier Perforated Sheets Aerators iii) Wooden Perforated Aerators and iv) Wooden Flat Surface Aerators models were planned, designed and fabricated. Each aerator designs were fabricated in triplicate. These aerators were used to check their oxygenating efficiency. The system was operated with the 0.5 HP pump, which was manufactured by V-Guard company. A control valve was provided to manage the flow of water. The system consists of the arrangement of pipes and showers at an average height of 0.85 m from the water surface. These tanks were initially drained completely and neatly cleaned the sides and bottom of the tank. These tanks were filled with fresh water up to the level of 0.5 m depth. One side of the tank is provided with an outlet for draining out the water whenever required.

2.2 Experimental design

2.2.1 Single perforated sheet aerator model

Using the GI (Galvanized Iron) perforated sheet, single perforated tray aerator designs with a dimension of 81 × 72 × 5 cm were fabricated. This model typically refers to an aeration device that consists of a single flat surface made up of a material with perforations or holes. This type of aerator model is designed to introduce oxygen into liquid, facilitating processes such as oxygen transfer, promoting biological activity, or improving water quality.

The shower is made up of a sheet which is perforated into small holes; size of the shower is 30 × 30 cm. The water falling from the shower has been made to fall on the top of the perforated tray and it passes through the pore of perforated tray before falling into the pond water. When it passes through the pores of the tray, it splits into minute particles and observes the oxygen content present in the atmosphere before reaching the pond water.

Single perforated sheet aerator model

2.2.2 Two Tier Perforated Sheets Aerator

Two Tier perforated sheets aerator designs with adimension of 81 × 72 × 5 cm were fabricated. Eachsheet has perforations or holes that allow air to be introduced into the water as it passes through the sheets. The purpose of using multiple sheets is to increase the contact area between the air and the water, which maximizes the effectiveness of the aeration process.

Two Tier Perforated Sheets Aerator

2.2.3 Wooden perforated sheet aerator

A wooden perforated sheet aerator is a type of aeration device, made up of wooden planks, designed and fabricated with the dimension of (90 cm x 90 cm x 2.5 cm. These planks have perforations or holes in it (76 x 71 cm). These holes allow the water to pass through it, and naturally it increases aeration efficiency.

Wooden perforated sheet aerator

2.2.4 Wooden Flat Surface Aerator model

A wooden flat surface aerator is (88 cm x 85 cm x 2.5cm) made up of wooden planks joined with each other. When the water falls on the surface of the planks, it splits into minute particles, and it enhances the oxygen transfer capacity of the aerator model. Aerator is commonly used in various applications to enhance oxygen transfer, promote biological processes, and improve the overall quality of the liquid.

Wooden Flat Surface Aerator model

Standard tests for aerators were conducted in the cement concrete tanks with clean tap water at standard temperature and pressure (20 °C and 760 mm Hg). The water is first deoxygenated using a sodium sulfite (Na_2SO_3) solution along with cobalt chloride ($CoCl_2\ 6H_2O$) as a catalyst (APHA, 1980) [2]. The change in DO concentration is measured as the water is re-oxygenated with the aerator being evaluated. This procedure is termed as unsteady-state testing, since the amount of oxygen transferred and the DO concentration change during the test. Two sampling stations were selected in the test tanks. The sampling points were located away from the walls and floor of the tank. For deoxygenating the tank water 7.88 mg/L of sodium sulfite (Na_2SO_3) was used to remove 1.0 mg/L of oxygen. The cobalt chloride at a concentration of 0.25 mg/L was used as a catalyst. Chemical slurries were first made by mixing the respective chemical with a small amount of pond water. The chemical slurries are mixed until the tank water DO drops to below 0.5 mg/L. The cobalt chloride catalyst is added to the tank water first and mixed the pond water manually for a period of 30 minutes to ensure complete mixing. The sodium sulfite solution is then splashed into the tank and mixed thoroughly with the help of man power. After 20-30 minutes of mixing the DO of the tank water was measured and ensured to be less than 0.5 mg/L. The aerator is turned on to increase DO concentration of the tank water. Dissolved oxygen readings are then taken simultaneously at timed intervals (0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 120, 150 and 180 minutes) while the DO increases to at least 90% saturation.

The DO deficit is computed for each interval that DO was measured during re-aeration

$OD = DO_s - DO_m$

Where,
DO_s = Theoretical oxygen saturation concentration (mg/L)
DO_m = Measured oxygen saturation concentration (mg/L)

The natural logarithms of DO deficits (Y) are plotted versus the time of aeration (X); the best fit line is computed with regression analysis. The oxygen transfer coefficient is computed using the above graph at points representing 10% and 70% oxygen saturation (Lawson, T. B. 1995) [18] as follows

$$(K_L\ a)_T = \frac{\ln(OD_{10}) - \ln(OD_{70})}{(t_{70} - t_{10})/60}$$

Where,
$(K_L\ a)_T$ = Overall Oxygen Transfer Co-efficient (hr^{-1}) at temperature T
ln = Natural logarithm
OD_{10} = Oxygen deficit at 10 % saturation (mg/L)
OD_{70} = Oxygen deficit at 70 % saturation (mg/L)
t_{10}= Time taken to reach 10 % dissolved oxygen concentration saturation (min.)
t_{70} = Time taken to reach 70 % dissolved oxygen concentration saturation (min.)

The Oxygen Transfer Coefficient is adjusted to 20 °C with the following equation

$K_L\ a_{20} = K_L\ a_T \div 1.024^{T-20}$

Where,
$K_L\ a_{20}$ = Overall Oxygen Transfer Coefficient at 20 °C ($hour^{-1}$)
$(K_L\ a)_T$ = Overall Oxygen Transfer coefficient at t °C ($hour^{-1}$) and
T = Test water temperature (°C).

The SOTR (Standard Oxygen Transfer Rate) is the amount of oxygen that an aerator will transfer to water per hour under standard conditions. Standard conditions are 0 mg/L DO, 20 °C temperature and clean water. The overall oxygen transfer coefficient is used to estimate the standard oxygen transfer rate for an aerator.

$SOTR = (K_L\ a_{20})\ (Cs_{20})\ (V)\ (10^{-3})$

Where,
SOTR = Standard Oxygen Transfer Rate (kg Oxygen h^{-1})
$K_L\ a_{20}$ = Overall oxygen transfer coefficient
Cs_{20} = DO concentration at saturation and 20 °C (gm^{-3} which equals mg/L)
V = Tank volume (m^3) and
10^{-3} = Factor for converting g to kg.

3. Results and Discussion

The performance of fabricated aerator models have been tested by measuring the increasing dissolved oxygen level in the experimental cement ponds after dropping the dissolved oxygen to below 0.5 mg/L. At the beginning of the experiment, the dissolved oxygen level increased sharply and then it decreased slowly until it reached the final value. The increase of D.O content in the pond water shows the similar trend of all other aerators.

3.1 Without using aerator (Control)

Experiment was conducted in triplicate; the ponds were denoted as P_1, P_2, and P_3. Initially, the pond water was de-oxygenated, the dissolved oxygen content measurement recorded as 0.43 mg/L, 0.43 mg/L, and 0.50 mg/L in the respective ponds. The D.O level was measured at regular intervals and after three hours, D.O levels were re-assessed, resulting in final values of 4.20 mg/L 4.15 mg/L, and 4.16 mg/L respectively in the above ponds. The overall oxygen transfer coefficients $(K_L\ a)_T$ obtained were denoted as 0.25 h^{-1}, 0.24 h^{-1} and 0.21 h^{-1} respectively. Furthermore, the Standard Oxygen Transfer Rate (SOTR) in each pond was recorded as 0.024 kg O_2/h, 0.023 kg O_2/h, and 0.020 kg O_2/h respectively.

3.2 Single perforated sheet aerator model

Experiment was conducted in triplicate in three cement cisterns; the ponds were labeled as P_1, P_2, and P_3. The pond water was initially deoxygenated, the dissolved oxygen levels measured was 0.35 mg/L in all the three ponds. The D.O level was measured at regular intervals and after three hours, D.O content was re-measured, which shows final values of 7.60 mg/L, 7.50 mg/L, and 7.50 mg/L in the aforementioned ponds respectively. The overall oxygen-transfer coefficients $(K_L\ a)_T$ obtained was 1.27 h^{-1}, 1.38 h^{-1}, and 1.36 h^{-1},while the Standard Oxygen Transfer Rates (SOTR) achieved was 0.116 kg O2/h, 0.124 kg O2/h, and 0.120 kg O2/h, correspondingly.

3.3 Two tier perforated sheets aerator model

Following the procedure of initial de-oxygenation of the pond water, the dissolved oxygen level was measured as 0.45 mg/L,0.40 mg/L, and 0.50mg/L in ponds P_1, P_2, and P_3 respectively. Subsequently, the pond water was re-oxygenated using the aforementioned aerator models for a period of three hours, resulting in D.O levels reaching 7.45 mg/L, 7.55 mg/L, and 7.60 mg/L in the respective ponds. The Overall oxygen-transfer coefficient $(K_L\ a)_T$ values were calculated as 1.44 h^{-1}, 1.518 h^{-1}, and 1.48 h^{-1}, with the Standard Oxygen Transfer Rates (SOTR) calculated as 0.13 kg O2/h, 0.136 kg O2/h, and 0.134 kg O2/h.

3.4 Wooden perforated sheet aerator

The Dissolved Oxygen content in ponds P_1, P_2, and P_3 was initially recorded as 0.4 mg/L, 0.5 mg/L, and 0.4 mg/L respectively. After three hours of aeration, the increased DO levels measured as 6.85 mg/L, 6.95 mg/L, and 7.0 mg/L in the respective ponds. The Overall oxygen transfer coefficient $(K_L\ a)_T$ values were calculated as 0.80 h^{-1}, 0.77 h^{-1}, and 0.89 h^{-1}, while the measured Standard Oxygen Transfer Rate (SOTR) values were 0.071 kg O2/h, 0.069 kg O2/h, and 0.078 kg O2/h.

3.5 Wooden flat surface aerator

The pond's water oxygen content was initially recorded as 0.55 mg/L, 0.45 mg/L, and 0.5 mg/Lin ponds P_1, P_2, and P_3 respectively. After three hours of oxygenation using above-mentioned aerator models, the DO levels notably increased to 7.5 mg/L, 7.3 mg/L, and 7.4 mg/L respectively. The overall oxygen transfer coefficient $(K_L\ a)_T$ values were computed as 0.89 h^{-1}, 0.96 h^{-1}, and 0.85 h^{-1}, while the corresponding SOTR measurements were 0.083 kg O2/h, 0.089 kg O2/h, and 0.080 kg O2/h.

A variety of aerator models are commercially available to maintain optimum oxygen level in shrimp pond water. However, it has been a scarcity of conclusive data regarding their aeration efficiency and energy usage across different environmental conditions. Consequently, several new aerator designs were introduced in this study to assess the average Overall Oxygen Transfer Coefficient $(K_L\ a)_T$ values and average Standard Oxygen Transfer Rate (SOTR) of various models, including Single Perforated Sheet Aerator, Two tier Perforated Sheets Aerator, Wooden Perforated Aerator and Wooden Flat Surface Aerator models. The calculated average $(K_L\ a)_T$ values were 1.335 h^{-1}, 1.48 h^{-1}, 0.82 h^{-1}, and 0.90 h^{-1} respectively, with corresponding average SOTR values of 0.12 kg O2/h, 0.133 kg O2/h ,0.073 kg O2/h, and 0.084 kg O2/h. These findings were largely consistent with those of Mohan Maloth *et al.* (2020) [19], who reported similar $(K_L\ a)_T$ values and SOTR values for different types of aerator. Research results indicated that oxygen transfer rates initially peaked among all types of aerator but gradually declined over time. Scholars have observed that the rate of oxygen transfer to water decreases as the dissolved oxygen level in the pond water increases (Boyd, 1998) [6].

Based on the observations of the study, Shukla B K and G Oel A, 2018 [30], concluded that maximum value of oxygen-transfer efficiency of 21.53 kg-O_2/kW-hr was obtained for the discharge of 1.11 L/s for single nozzle aerator; however the maximum oxygen-transfer factor of 2.0 x 10^{-2} s^{-1} was obtained at the discharge of 4.69 L/s for aerator having eight numbers of openings having area of 594.96 mm^2. On the other hand, maximum oxygen transfer efficiency of 10.93 kg-O_2/kW-hr was demonstrated by aerator with single opening at a discharge of 1.11 L/s and maximum oxygen transfer factor of 7.83 x 10^{-3} s^{-1} was obtained from aerator with eight openings at a discharge of 4.69 L/s corresponding to set of aerators with area of openings equal to 246.30 mm^2.

Chonmapat Torasa and Nichanant Sermsri, 2019 [10] observed from their study that the solar energy paddle wheel can increase oxygen level dissolved in the water about 0.16 mg/L in one hour. The furrowed model blade was able to improve the aeration efficiency of the paddlewheel. Roy *et al.* 2020 [24] based on their results concluded that the optimum number of trays in a perforated tray aerator should be three to achieve the maximum SAE. Finally, it may be said that the developed RSM/CCRD model is an effective tool for predicting the optimized geometric variables of a perforated tray aerator.

Based on the study conducted to optimize the geometric and dynamic parameters of a spiral aerator, the following conclusions were drawn by the authors that SOTR increases with the increase in number of handles and rotational speed of a spiral aerator and SAE decreases with the increase in rotational speed from 70 to 250 rpm (Roy *et al.* 2020) [24]. Performance test carried out showed that the overall oxygen transfer co-efficient (KLa) was observed to be as high as 8.19 hr^{-1} and standard oxygen transfer rate (SOTR) and standard aerator efficiency (SAE) ranged from 1.1-1.2 kg O_2 hr^{-1} and 1.1-1.3 kg O_2/Kw hr. respectively (Omofunmi O. E. and Adewumi J. K.2017) [22]. The optimized values of SAE (0.616 kg O_2/kWh) and SOTR (0.429 kg O_2/h) were obtained at $\alpha = 75^o$ and d = 350 mm. The respective values before optimization were 0.320 kg O_2/ kWh and 0.346 kg O_2/h. Thereby, the SAE of the submerged aerator increased by 92.5% after modification (Jayraj *et al.* 2018) [17].

Roy *et al.*, 2021 [25] concluded from their study that to achieve the maximum standard aeration efficiency, N, h and α should be 1,000 rpm, 0.50 m, and 12° respectively. Under the optimum operating conditions, the maximum SAE was found to be 1.711 kg O_2/kWh. The results demonstrated that the type-A PKW created maximum oxygen transfer efficiency of the three PKW types. In addition, the results showed that the aeration efficiency of all PKW models increases with drop height but decreases with increasing discharge over the weirs (Deepak Singh and Munendra Kumar, 2022) [11].

Paddle wheel aerators and propeller aspirator pumps are widely employed to enhance the dissolved oxygen concentration in pond water. Previous studies have evaluated numerous electric aerators, such as paddle wheel aerators, propeller-aspirator pumps, vertical pumps, pump sprayers, and diffused-air systems, to assess their oxygen transfer efficiency. SOTR and SAE values ranged from 0.6 to 23.2 kg O2/h and 0.7 to 3.0 kg O2kW/h respectively (Boyd CE and Ahmad T, 1987) [7]. Additionally, tractor-powered pump sprayers and paddle wheel aerators were tested, with SOTR values ranging from 7.8 to 73.8 kg O2/h (Omofunmi., *et al.* 2016) [21]. Furthermore, a low-cost prototype paddle wheel aerator was developed, demonstrating an overall oxygen transfer coefficient $(K_L a)_T$ as high as 8.19 h^{-1},with SOTR and SAE ranging from 1.1-1.2 kg O2/h and 1.1 - 1.3 kg O2kW/h respectively (Boyd CE, 1990) [9]. Another study reported SOTR and SAE values for twenty-four types of paddle wheel aerators ranging from 1.9 - 8.5 kg O_2/h and 1.2 - 5.2 kg O2 kW/h respectively (Ahmad and Boyd, 1988) [1]. Various designs of paddle wheel aerators were tested, with a 91 cm diameter paddle wheel with triangular paddles showing the highest SAE of 2.96 kg O2 kW/h.

4. Conclusion

The experiments were conducted using the above mentioned conventional fabricated aerators. The findings indicated that the two tier perforated sheets aerator model exhibited superior $(K_L a)_T$ and SOTR values compared to the single perforated sheet aerator, wooden perforated aerator, and wooden flat surface aerator models, in descending order. The enhanced dissolved oxygen content observed may be attributed to increased area of contact between water and air, facilitated by smaller bubbles generated within the two tier perforated sheets aerator model. Aeration efficiency relies on the extent of air-water interface, primarily influenced by the size of water droplets or air bubbles. Aeration constitutes a significant portion of expenses in intensive aquaculture systems, ranking third after post-larvae and feed costs, accounting for approximately 15% of total production costs. Mechanical aerators incur higher initial and operational expenses. The study suggests that the aforementioned conventional fabricated aerators could effectively boost dissolved oxygen levels in small-scale fish ponds. Selecting the appropriate type and quantity of aerator model can lower the overall expenses of shrimp farming and decrease energy consumption. Since aeration accounts for a significant portion of energy usage in shrimp aquaculture, efficiently managing aerator usage can lead to substantial savings in both production costs and energy consumption.

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