www.theajfarm.com

Volume 7, Issue 2, 2022/23
ISSN: 2672-4197 (Print)
ISSN: 2627-4200 (Online)
Pages 1-11

Optimization of Paddle Wheel Aerator Parameters for Enhanced Aquaculture Water Quality Using Response Surface Methodology Techniques

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Abstract

Water quality plays a pivotal role in the efficient management of aquaculture systems, particularly through the regulation of dissolved oxygen (DO) levels. This study focuses on the modification and performance evaluation of a locally fabricated mechanical paddle wheel aerator for optimizing fish pond agitation and oxygenation. Key operational parameters investigated include rotational speed (300–600 rpm), paddle submersion depth (0.1–0.2 m), and inclination angle (15°–45°). The aerator was tested in a 2,000 L concrete pond (1×2×1 m) with a stocking density of 300 fish/m³ using unsteady-state aeration tests. Results were statistically analyzed using Design Expert Software (2022) with ANOVA at $p< 0.05$. Maximum Standard Aeration Efficiency (SAE) of 5.856 kg O/kWh was achieved at 450 rpm, 0.2 m depth, and 45° inclination, while the highest Standard Oxygen Transfer Rate (SOTR) was 5.656 kg O/h at 600 rpm. The findings demonstrate that optimized paddle wheel design and configuration significantly improve aeration performance, offering a cost-effective solution for enhancing water quality in pond-based aquaculture systems.

Keywords: Parameter, oxygen, mechanical, transfer rate, standard aeration efficiency.

Introduction

Aquaculture has become a key pillar of global food security, contributing nearly 50% of the world's fish consumption (FAO, 2022). The rapid expansion of the sector is driven by rising demand for protein sources, placing immense pressure on production systems to enhance efficiency, sustainability, and economic viability. Among the critical factors influencing aquaculture productivity, water quality, particularly dissolved oxygen (DO) availability, plays a fundamental role in fish metabolism, growth, immune response, and overall survival (Boyd et al., 2018). Inadequate oxygen levels lead to stunted growth, increased disease susceptibility, and higher mortality rates, thereby negatively impacting economic returns and environmental sustainability in fish farming operations (Rahman et al., 2020).

To mitigate oxygen depletion, mechanical aeration systems such as paddle wheel aerators are widely employed to enhance oxygen diffusion and improve water circulation in pond-based aquaculture. These aerators generate surface turbulence, facilitating gas exchange between the water and atmosphere, which in turn increases DO levels. However, despite their effectiveness, conventional paddle wheel aerators are characterized by significant energy consumption, often accounting for up to 50% of total farm energy costs (Hargreaves and Boyd, 2022). The efficiency of oxygen transfer in these systems is influenced by multiple design and operational parameters, including rotational speed, submergence depth, and blade inclination angle (Tanveer et al., 2018). Poorly optimized settings result in suboptimal oxygen transfer efficiency (OTE), excessive power consumption, and reduced aerator lifespan, making aeration both economically and environmentally unsustainable (Roy, et al. 2021).

Despite the widespread adoption of paddle wheel aerators, several critical research gaps persist in their design, optimization, and operational efficiency. Most existing studies focus on isolated factors affecting aeration efficiency without addressing the interactions between key parameters such as rotational speed, blade submergence depth, and inclination angle (Roy et al., 2021). Inefficient aeration settings significantly increase operational costs, particularly in automated aquaculture systems, where aeration accounts for up to half of the total energy consumption (Hargreaves and Boyd, 2022). Existing aeration studies are also often region-specific and do not account for diverse environmental conditions, water chemistry variations, and different stocking densities, particularly in developing regions like Nigeria (FAO, 2022). Given these critical gaps, there is an urgent need to develop a data-driven, systematic approach for multi-objective optimization of paddle wheel aerator parameters.

To address these challenges, this study integrates Response Surface Methodology (RSM) techniques to provide a quantitative framework for assessing the impact of aerator design parameters on oxygen transfer rates, standard aeration efficiency (SAE), and energy use (Roy et al., 2021). Through a combination of experimental trials and computational modeling, this research aims to determine the optimal combination of aerator parameters that maximize oxygen transfer efficiency while minimizing energy consumption. Additionally, it seeks to develop predictive models to guide aquaculture practitioners in selecting appropriate aeration settings under varying environmental and operational conditions.

The findings from this research have significant implications for both small-scale and commercial aquaculture systems, particularly in regions with limited technological access and high energy costs. By applying optimization to paddle wheel aeration systems, this study contributes to reducing energy consumption through efficient aeration strategies, enhancing fish health and survival rates via optimized DO levels, promoting environmental sustainability by minimizing carbon footprints associated with excessive energy use, and supporting policy and decision-making by providing data-driven recommendations for energy-efficient aeration systems.

The optimization of paddle wheel aerator parameters is essential for advancing sustainable aquaculture practices. By leveraging optimization techniques, this study seeks to bridge existing knowledge gaps and establish a scientific basis for improving aerator performance, reducing operational costs, and enhancing environmental sustainability. The findings will serve as a valuable resource for aquaculture practitioners, policymakers, and researchers, ensuring the adoption of efficient and sustainable aeration practices for global fish production.

MATERIALS AND METHODS

Study Location and Pond Description

The experimental study was conducted using a rectangular concrete fishpond with internal dimensions of 1.0 m × 2.0 m × 1.0 m was used. The pond was filled with 2000 L of groundwater and stocked with African catfish (Clarias gariepinus) juveniles at a density of 300 fish/m^3, representing high-intensity culture conditions. Water temperature was monitored continuously using a laboratory-grade mercury thermometer to capture environmental variability during operation.

Aerator Design and Modification

A mechanical paddle wheel aerator was locally constructed and modified for enhanced dissolved oxygen (DO) transfer efficiency. The design featured: A stainless-steel shaft (8 cm in length); Six plastic paddles, each 40 cm in length; A 1.12 kW (1.5 hp), single-phase electric motor operating at 600 rpm. A gear reduction system with a speed ratio of 2:4 for torque optimization. The system was integrated with a variable frequency drive (ABB ACS800-01, 4 hp, 460 V) to control motor speed during tests. Materials were sourced locally to ensure replicability and cost efficiency for smallholder applications. The schematic layout of the paddle wheel system is provided in Figure 1.

Figure 1: Mechanical paddle wheel aerator

Experimental Procedure

To evaluate DO distribution performance, the paddle wheel was tested under three submersion depths: Position A: 0.2 m below water surface; Position B: 0.5 m below water surface and Position C: 0.8 m below water surface. Each treatment was replicated thrice, with trials conducted under consistent weather and water conditions. The system was allowed to run for 15 minutes prior to measurements to ensure uniform mixing. Water volume was kept constant at 2000 L across all trials.

DO Measurement and Data Collection

Dissolved oxygen concentrations were measured using a calibrated RE347 TX Microprocessor DO Meter. Readings were collected at three equidistant horizontal points along the pond and at two vertical layers: surface (0.05 m) and mid-depth (0.5 m). Measurements were recorded at 0-, 5-, 10-, and 15-minutes following aerator activation. The theoretical saturation DO concentration (Cs) was obtained from McGhee's standard reference table, with a value of 9.17 mg/L at 20 °C and atmospheric pressure of 760 mmHg. Ambient environmental parameters, including air temperature, relative humidity, and wind speed, were recorded using a portable digital weather station.

Theoretical Analysis

The theoretical framework for evaluating the performance of the mechanical paddle wheel aerator was based on standard aeration parameters under controlled conditions. The Standard Oxygen Transfer Rate (SOTR) represents the amount of oxygen transferred to water per unit time under standard conditions (20 °C), one atmosphere pressure, clean tap water, and an initial dissolved oxygen (DO) concentration of 0 mg/L (APHA, 1980). It is expressed as:

Oxygen Transfer and Aeration Performance

The Standard Oxygen Transfer Rate (SOTR) was calculated as follows (Subha et al., 2015):

$$\mathrm{SOTR} = K_L a_{20}\,(C^{*} - C_0)\,V = K_L a_{20} \times 9.07 \times V \times 10^{-3} \qquad (1)$$

where:

- SOTR = standard oxygen transfer rate (kg O_2 h^{-1}),
- $K_L a_{20}$ = overall oxygen transfer coefficient at 20 (h^{-1}),
- C^{*} = saturated dissolved oxygen concentration at test conditions (mg L^{-1}),
- C_0 = initial dissolved oxygen concentration (mg L^{-1}),
- 9.07 = DO saturation at 20 and 1 atm (mg L^{-1}),
- V = volume of water (m^3),
- 10^{-3} = conversion factor from g to kg.

The temperature correction for the oxygen transfer coefficient is given by:

$$K_L a_T = K_L a_{20}\,\theta^{T-20} \qquad (2)$$

where:

- $K_L a_T$ = oxygen transfer coefficient at temperature T (C),
- θ = temperature correction factor for clean water (typical value $\theta \approx 1.024$).

To provide a performance-specific metric that allows comparison across aerator sizes, the Standard Aeration Efficiency (SAE) was calculated as:

$$\mathrm{SAE} = \mathrm{SOTR}P \qquad (3)$$

where:

- SAE = Standard Aeration Efficiency (kg O_2 kW^{-1} h^{-1} or commonly written kg O_2 kWh^{-1}),
- P = power input to the aerator shaft (kW).

The oxygen transfer coefficient at the test temperature, $K_L a_T$, was determined from the slope of the natural logarithm of the oxygen deficit over time:

$$K_L a_T = -\ln(Y_2) - \ln(Y_1) t_2 - t_1 \qquad (4)$$

with

$$Y = C^{*} - C \quad (DOdeficit), \qquad t = time(h).$$

Finally, to standardize the coefficient to 20, equation eq:KLaT can be rearranged as:

$$K_L a_{20} = K_L a_T \theta^{T-20}. \qquad (5)$$

This theoretical framework provides the parameters required to compute both SOTR and SAE, enabling objective comparison of aerator performance under different operational conditions.

Data Analysis

Statistical analysis of the experimental data was performed using Design-Expert® Software version 13.0 (Stat-Ease Inc., 2022). In this study, Response Surface Methodology (RSM) employing the Optimal (Custom) design approach was applied to model and optimize the Standard Aeration Efficiency (SAE) and Standard Oxygen Transfer Rate (SOTR) of the mechanical paddle wheel aerator. The independent variables investigated were: Rotational speed of the shaft (N); submergence depth of the paddle wheel (h) and inclination angle of the paddle blade (). The levels of independent variables used in the custom RSM design are presented in Table 1. Each variable was evaluated at three numeric levels.

Table 1: Independent variables and their levels for optimal (Custom) design

Factor	**Symbol**	**Unit**	**Level 1 (L1)**	**Level 2 (L2)**	**Level 3 (L3)**
Rotational Speed	D	rpm	300	450	600
Submergence Depth	h	m	0.10	0.15	0.20
Inclination Angle	α		15	30	45

The design matrix generated contained 22 experimental runs, strategically distributed to capture both linear and interaction effects while minimizing the number of experiments required for reliable model development (Table 2). A second-order polynomial model was fitted to the data to describe the relationship between the independent variables and the two responses (SAE and SOTR). Model adequacy and statistical significance were determined through analysis of variance (ANOVA), with diagnostic statistics including the coefficient of determination (R^2), adjusted R^2, predicted R^2, and lack-of-fit tests. Numerical optimization using desirability functions was used to determine the optimal combination of speed, submergence depth, and blade inclination for achieving maximum aeration performance. Response surface plots and contour plots were generated to visualize the interaction effects of the input variables on each response parameter. From the regression equation shown in Equation 4, the independent factors such as depth and angle of inclination were positive. Therefore, an increase in depth (x_2) and angle of inclination (x_3) increases the standard oxygen transfer rate of the mechanical paddle wheel aerator.

It was observed that at a maximum depth of 0.8m and angle of inclination of $45°$, the optimum oxygen transfer rate of 5.8was achieved. Similar findings were reported in the design and construction of a solar-powered aeration system for fish farms by Gebremedhen (2016).

$$\mathrm{Y}_{SOTR} = 2.60 + 0.2109x_1 + 1.25x_2 + 0.8053x_3 - 0.3742x_1x_2 + 1.16x_2x_3$$

4 (6)

The 3D surface plot in Figure 2 shows that depth (x_1) and angle of inclination (x_2) has significant effect on the standard oxygen transfer rate of the paddle wheel aerator. At minimum depth of 0.1 m and angle of inclination ($15°$) the minimum standard oxygen transfer rate was achieved. It was observed that angle of inclination is highly significant for all runs. Thus, the maximum Standard oxygen transfer rate was obtained at the depth (0.2m), angle of inclination ($45°$) and speed (450rpm). Similar findings were observed in the performance evaluation of the propeller aspirator pump aerator by Kumar et al (2010); Chen, et al. (2015).

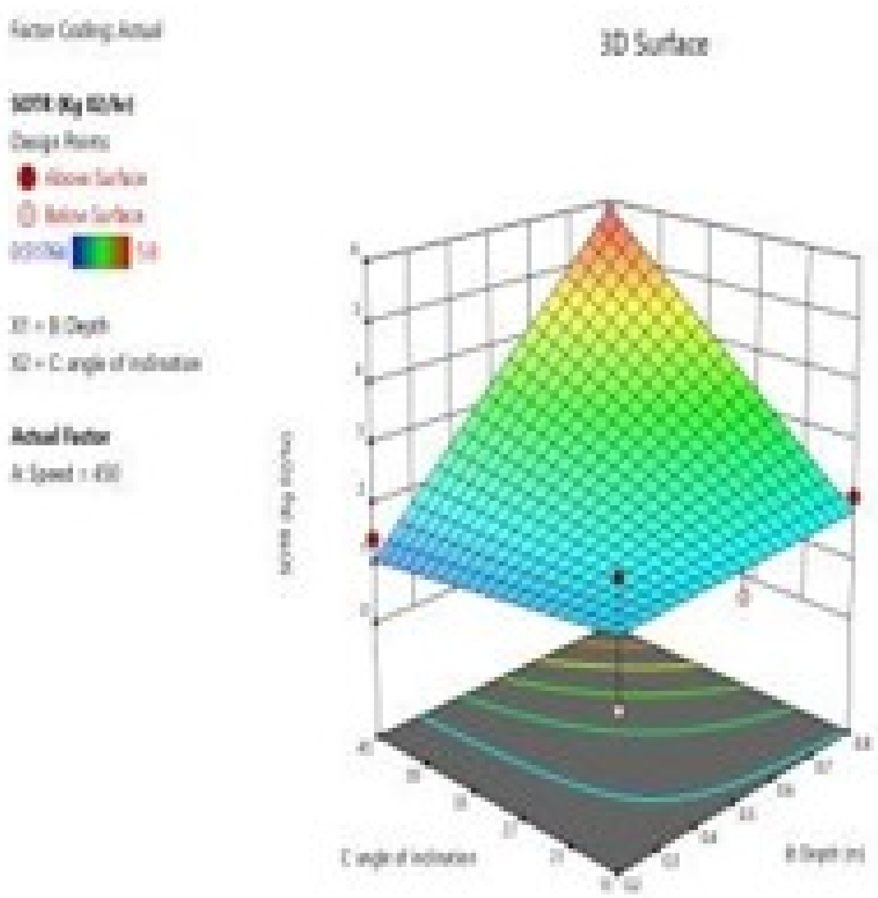

Figure 2: The 3D surface depth (xx_1) and angle of inclination (x_2) on the standard oxygen transfer rate

Effect of independent variable on Standard Aeration efficiency

The speed does not have a significant impact on the dependent variable. This implies that the speed does not contribute to the model's performance. The small sum of squares, low F-value, and high p-value indicate the speed does not explain much about the variability in the dependent variable. It was observed and noted that depth has a substantial impact on the dependent variable in the model. This indicates that there is a statistical significance at ($p<0.05$). The angle of inclination is statistically significant at ($p< 0.05$). This shows that there is a substantial impact on the dependent variable in the model.

$$Y_{SAE} = 2.32 + 0.1839x_1 + 1.11x_2 + 0.768x_3 - 0.3381x_1x_2 + 1.03x_2x_3 5(7)$$

From the regression equation shown in Eq. eq:SAE, the interaction term $-0.3381(x_1x_2)$ has a negative coefficient, indicating that the combined effect of speed (x_1) and depth (x_2) is inversely related to Standard Aerator Efficiency (SAE). This implies that the projected value of SAE decreases as the interaction between speed and depth increases.

Positive coefficients: Depth (x_2) and the angle of inclination (x_3), as well as the interaction

Table 2: Experimental design matrix for the paddle wheel aerator test

Run	**Speed,** D **(rpm)**	**Depth,** h **(m)**	**Inclination,** α **(°)**
1	450	0.15	30
2	600	0.10	30
3	300	0.10	45
4	600	0.15	45
5	300	0.10	15
6	450	0.15	15
7	600	0.10	30
8	600	0.15	15
9	600	0.20	15
10	600	0.10	30
11	600	0.10	45
12	450	0.10	30
13	450	0.15	15
14	300	0.20	30
15	450	0.10	45
16	450	0.15	30
17	450	0.20	45
18	450	0.15	15
19	450	0.10	15
20	450	0.20	30
21	300	0.20	30
22	450	0.20	30

Table 3: Experimental results

Run	**SOTR (kg O_2/hr)**	**SAE (kg O_2/kWhr)**
1	1.2940	1.1547
2	1.4142	1.2638
3	3.0000	2.6785
4	1.2941	1.1565
5	0.5176	0.4000
6	2.5000	2.2321
7	1.5176	1.3562
8	2.5000	2.2321
9	4.0000	3.5746
10	1.4142	1.2717
11	1.4142	1.2710
12	2.5176	2.2478
13	2.5000	2.2321
14	2.0706	1.8487
15	1.0000	0.8937
16	3.5355	3.1595
17	2.0706	1.8504
18	2.5000	2.2321
19	0.5176	0.4625
20	4.0000	3.5746
21	5.6569	5.0507
22	5.8432	5.1700

between depth and angle (x_2x_3), positively affect SAE. The projected SAE rises with increasing depth or the interplay between depth and inclination.

Magnitude of coefficients: The size of the coefficients reveals the strength of influence on SAE. Depth (x_2) appears to have the greatest effect ($0.1839, 1.11, 0.768, -0.3381, 1.03$), followed by the interaction terms (x_2x_3 and x_1x_2). The inclusion of interaction factors highlights that SAE is influenced not only by individual parameters but also by their combined effects.

In summary, speed (x_1), depth (x_2), and the interaction between depth and angle of inclination (x_2x_3) positively affect SAE, while the interaction between speed and depth (x_1x_2) negatively affects SAE. Similar findings were observed by Peterson (2002) in the effect of speed on Taiwanese paddlewheel aeration.

The 3D surface plot in Figure 2 illustrates the effect of speed (450 rpm) on SAE. An optimal depth of 0.10 m and inclination of $15°$ was obtained at the minimum. The maximum oxygen transfer rate was achieved at depth 0.20 m, angle $45°$, and speed 450 rpm. SAE increases with the linear terms of speed (x_1) and inclination (x_3). Comparable results were reported by Roy et al. (2021) in the prediction of SAE for a propeller-diffused aeration system using response surface methodology and artificial neural networks.

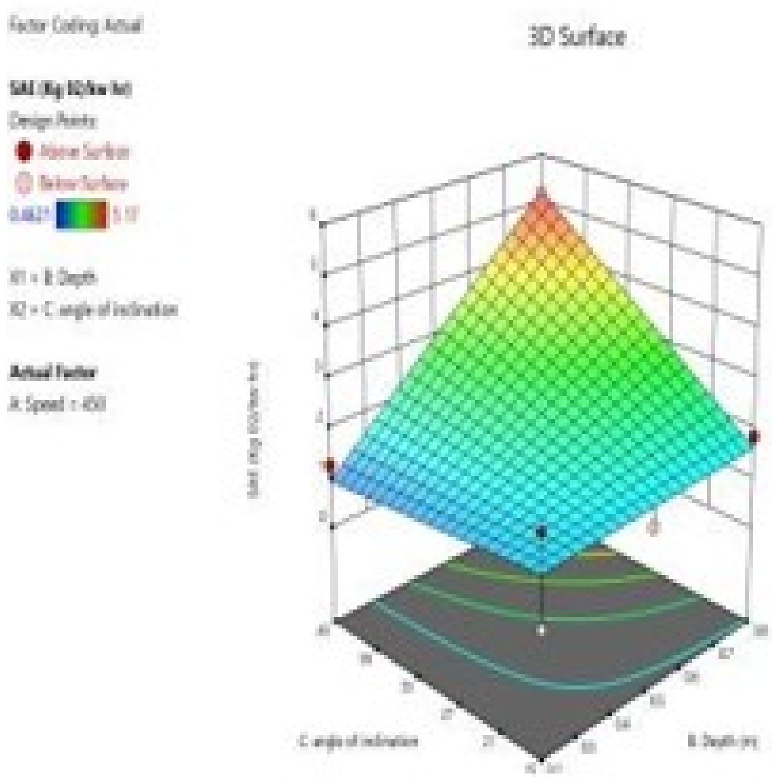

Figure 3: The 3D surface plot in shows the effect of speed (450rpm) on standard aerator efficiency

CONCLUSION

This study presents a design modification and performance evaluation of a locally fabricated mechanical paddle wheel aerator intended for use in fish pond systems. Through a structured evaluation of critical design parameters (rotational speed, paddle submersion depth, and blade inclination angle) the study identified an optimal configuration that simultaneously enhanced oxygen transfer efficiency and minimized energy consumption. The highest Standard Aeration Efficiency (5.856 kg O/kWh) was observed at 450 rpm, 0.2 m depth, and a 45° blade angle, while the peak Standard Oxygen Transfer Rate (5.656 kg O/h) occurred at 600 rpm under the same depth and angle. These findings confirm that strategic modification of paddle wheel design significantly improves aeration performance. The outcomes of this research contribute to the understanding of aeration dynamics in aquaculture and offer actionable guidance for farmers and designers aiming to enhance water quality in pond-based systems. The proposed modifications can serve as a template for developing efficient, low-cost aeration solutions adaptable to small- and medium-scale aquaculture operations. Future studies should focus on scaling the system for commercial application, evaluating long-term durability, and integrating renewable energy sources to further enhance sustainability.

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