Check for updates

Aquaculture, Fish and Fisheries

WILEY

AQUACULTURE, FISH and FISHERIES Open Access

ORIGINAL ARTICLE OPEN ACCESS

Combined Surface-Bottom Aeration: A Pathway to Improved Water Quality and Productivity in Pond-Based Tilapia Farming

Mithun Roy[1] | Md. Asaduzzaman[1] | Debasish Saha[2] | Md Rakeb-Ul Islam[2] | David C. Little[3] | Richard Newton[3] | Abu Tweb Abu Ahmed[4] | Faruk-Ul Islam[5] | Md. Asadujjaman[6] | Muhammad Tanvir Hossain Chowdhury[6] | Abdullah-Al Mamun[2]

[1]Department of Marine Bio-resource Science, Chattogram Veterinary and Animal Sciences University, Chittagong, Bangladesh | [2]Department of Fisheries and Marine Science, Noakhali Science and Technology University, Noakhali, Bangladesh | [3]Institute of Aquaculture, University of Stirling, Stirling, UK | [4]Bangladesh Academy of Sciences (BAS), Dhaka, Bangladesh | [5]WorldFish, Dhaka, Bangladesh | [6]Department of Fisheries, Ministry of Fisheries & Livestock, Dhaka, Bangladesh

Correspondence: Abdullah-Al Mamun (mamun@nstu.edu.bd)

Received: 16 June 2026 | **Revised:** 15 August 2026 | **Accepted:** 20 August 2026

Keywords: aeration systems | dissolved oxygen | economic analysis | growth performance | *Oreochromis niloticus* | pond aquaculture

ABSTRACT

Pond-based aquaculture demands effective management of dissolved oxygen (DO) for sustainable intensification to improve productivity. This study evaluated surface aeration (SA), bottom aeration (BA) and combined surface-bottom aeration (SBA) against a non-aerated control during a 120-day monoculture of Nile tilapia (*Oreochromis niloticus*) stocked at 400 fish/decimal. Water quality and DO dynamics were monitored throughout the culture period, and aeration was initiated on Day 59 when biomass reached 0.58 ± 0.05 kg/m^2 and morning DO declined below 4 mg/L. Aerated ponds maintained more stable DO regimes than the NA control, whereas SBA achieved comparatively improved DO concentrations across water depths. SBA exhibited significantly ($p < 0.05$) higher total production (16.47 ± 0.195 MT/ha), faster specific growth (4.39% ± 0.035%), higher survival (96.88% ± 0.22%) and a lower feed conversion ratio (1.41 ± 0.017), whereas treatment NA showed the lowest performance across growth and feed efficiency parameters. Economic analysis aligned with these results, whereas SBA showed favourable cost–benefit ratios (1.14 ± 0.02) and return on investment (13.60% ± 1.36%). However, because SBA involved a higher installed power input than single-mode aeration systems, the observed benefits reflect the performance of the combined aeration configuration under the applied operational conditions rather than a strictly energy-normalized comparison. By simultaneously evaluating spatial oxygen distribution, operational aeration thresholds, biological performance and economic outcomes, this study provides practical evidence supporting integrated SBA as an effective strategy for sustainable intensification of pond-based Nile tilapia farming.

1 | Introduction

Aquaculture has emerged as the fastest growing food production sector, now contributing 51% of global aquatic animal output, thereby surpassing capture fisheries for the first time in 2022 (FAO 2024). In addition, the aquaculture industry supports around 36% of all fisheries- and aquaculture-related employment worldwide as of 2022 (FAO 2024), underscoring its critical role in global food security and rural livelihoods. This trend reflects a major transition from capture-based fisheries, which face stagnation due to overexploitation and environmental change, towards culture-based systems capable of meeting the increasing

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2026 The Author(s). *Aquaculture, Fish and Fisheries* published by John Wiley & Sons Ltd.

demand for aquatic protein. Within this context, tilapia has become one of the world's most widely farmed fish species being cultured across four continents. Annual production surpassed 6 million tonnes in 2018, making tilapia second only to carps in global aquaculture output (Abwao et al. 2023; FAO 2020), and production is forecasted to reach 7.3 million tonnes by 2030 (FAO 2020). Among tilapia species, Nile tilapia (*Oreochromis niloticus*) stands out for its exceptional aquaculture potential. It grows rapidly in different culture systems and tolerates diverse environmental conditions (Samaddar et al. 2024), exhibits strong tolerance to stress and diseases (Munguti et al. 2022), efficiently utilizes low-trophic feeds and readily accepts formulated diets immediately after yolk-sac absorption is complete (Ng and Romano 2013). Beyond its biological advantages, Nile tilapia offers significant socio-economic value. It is a cost-effective source of high-quality animal protein (Arumugam et al. 2023) and contributes substantially to improving household nutrition and income generation in many developing countries (Djanuandra et al. 2023). These combined attributes make Nile tilapia not only a cornerstone species for aquaculture intensification but also a vital component of sustainable food systems, particularly in regions where food demand, population growth and resource constraints continue to rise.

Intensification in aquaculture generally refers to the practice of increasing stocking density to maximize production. Although this approach enhances production per unit area, it also accelerates the accumulation of dissolved metabolites, including ammonia (NH_3) and organic matter derived primarily from uneaten feed and fish faces. These materials subsequently elevate the biological oxygen demand (BOD) required for their decomposition and conversion into less harmful substances (Klanjšček et al. 2012). As fish biomass rises, these processes become more pronounced, leading to progressive deterioration of water quality and a marked reduction in dissolved oxygen (DO) concentrations (Nadiro et al. 2023). Phytoplankton photosynthesis serves as the primary natural source of DO in pond ecosystems (Boyd et al. 2018). At the same time, phytoplankton biomass also represents a major oxygen sink, both through their own respiration and by generating organic detritus that fuels bacterial decomposition processes (Boyd 1973; Dupree and Huner 1984). DO levels typically reach their lowest point during the night because photosynthetic activity ceases whereas respiratory demand continues (Boyd et al. 2018). In contrast, mechanical aeration increases oxygen supply by enlarging the air–water interface and promoting water movement that disrupts thermal stratification (Boyd and Martinson 1984). Consequently, aerators are commonly used to prevent night-time DO concentrations from dropping below critical thresholds necessary for fish survival and optimal pond metabolism (Boyd et al. 2018).

Tilapia culture often occurs in fertilized semi-intensive systems in earthen ponds where nutrition is partially obtained from the natural productivity of the pond system. DO depletion is particularly pronounced, where limited water exchange and stratification exacerbate oxygen decline, especially during dawn hours when respiration exceeds photosynthesis of the high levels of phytoplankton in the pond (d'Avanzo and Kremer 1994). For Nile tilapia, which are often reared at high densities, poor water quality and low DO levels create unfavourable culture conditions, imposing physiological stress and negatively affecting growth performance, feed utilization and economic losses (Durigon et al. 2023). Moreover, chronic exposure to suboptimal water quality and oxygen concentrations compromises fish immunity, making them more vulnerable to opportunistic pathogens and further threatening the success of the farm business. To counter these challenges, the introduction of aeration technologies has become an indispensable management practice; this incorporation of atmospheric oxygen into water through aeration is required to improve water quality leading to better fish growth, feed efficiency and overall survival, making them critical tools for supporting sustainable intensification of tilapia farming (Sultana et al. 2017).

The fundamental principle of an aerator is to enhance the transfer of oxygen from the atmosphere into pond water, either by agitating surface water or injecting air bubbles within the water column (air diffusion), to increase the surface area of contact between air and water and facilitate greater oxygen absorption (Shah and Zain 2013). Owing to their strong mixing capacity, surface aerators, such as paddlewheels and propeller aspirator pumps, are particularly effective in large ponds, where they improve circulation, raise DO concentrations and stabilize water quality (Mohan et al. 2022; Deka et al. 2022). Conversely, diffuser disks or tubes use blowers to release macro air bubbles (0.8–1.9 mm) from the pond bottom, which rise through the water column and dissolve oxygen as they ascend, thereby transferring oxygen directly and generating vertical mixing currents that remove stratification and distribute oxygen evenly throughout the pond (Yamada et al. 2005; Boyd 1995). These observations align with broader findings that bubble aerators generally perform best in smaller water bodies, whereas mechanical mixers are more effective in larger systems, and combined approaches can further strengthen de-stratification performance (Thant et al. 2025). More recently, advanced approaches, such as Nano-bubble technology, have demonstrated promise in aquaculture farming, with applications in wastewater treatment, disease management and yield improvement (Yaparatne et al. 2024). Given that surface aerators primarily promote horizontal circulation and air diffusers enhance vertical oxygenation, combining these approaches offers a more comprehensive and efficient strategy for maintaining optimal and uniform DO distribution, improving overall pond water quality.

In Bangladesh, pond-based Nile tilapia farming has expanded rapidly due to increasing local demand and the species' adaptability to diverse farming environment. The pursuit for higher production requires higher stocking densities and greater use of formulated feed. The organic matter in uneaten feed and faeces is decomposed to CO_2, whereas fish respiration and the nitrification of ammonia waste further consume DO (Boyd et al. 2018). To address this increasing oxygen demand, farmers commonly use farm-made emergency aerators, typically water pumps fitted with short delivery pipes, to alleviate low DO conditions during the early morning. Bottom aeration (BA) systems composed of perforated plastic pipes driven by air pumps or blowers are also widely used. In addition, commercial paddlewheel and vertical pump aerators are operated during dawn and cloudy weather to prevent critical oxygen depletion (Rajts and Shelley 2020). Although both surface aeration (SA) and BA have been used

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

individually in pond aquaculture, information on their combined application under intensive earthen pond conditions remains limited. Previous studies have mainly focused on improving DO concentrations, whereas comparatively little attention has been given to how different aeration strategies influence oxygen distribution throughout the water column together with water quality, fish growth, feed utilization and economic performance. In addition, little practical information is available on the fish biomass at which supplemental aeration becomes necessary under commercial production conditions. Addressing these gaps is important for developing aeration strategies that improve productivity while remaining economically feasible.

To address these knowledge gaps, this study investigated whether combining surface and BA could improve water quality, fish performance and economic return compared with individual aeration systems or no supplemental aeration in intensive monosex Nile tilapia culture. We hypothesized that the combined surface-bottom aeration (SBA) system would provide a more uniform DO distribution throughout the water column, leading to improved water quality, growth performance, feed utilization and economic return. Accordingly, the objectives were to (1) compare fish growth performance and feed utilization among SA, BA and SBA; (2) evaluate DO dynamics and associated water-quality responses under different aeration systems; and (3) assess the economic performance of each aeration strategy. The findings provide practical information to support the selection of aeration systems for sustainable intensification of pond-based Nile tilapia farming in Bangladesh.

2 | Materials and Methods

2.1 | Location and Experimental Design

The experiment was carried out in 12 earthen ponds located within the pond complex of the 'AQUALENS' Laboratory at Noakhali Science and Technology University (NSTU), Bangladesh. Experimental ponds had 1.2:1 sloping sides, and the bottom and surface dimensions are presented in Figure 1A. The water depth was maintained at 1.56 ± 0.04 m throughout the 120-day culture period (July–November 2023). On the basis of these dimensions, the estimated water-holding capacity of each pond was 77.2 ± 1.9 m^3, calculated using the frustum volume equation (Butuner 2015). A submersible water pump was used to supply water from a local pond known as 'Dighi'. Although the ponds were interconnected by pipes and had inlet/outlet facilities, these were sealed for the duration of the culture period to prevent the mixing of water. Four treatments were tested: NA (no aeration), SA, BA and SBA (Figure 1). Each treatment was replicated three times, and ponds were assigned to treatments using a randomized complete block design (RCBD) to ensure even distribution and minimize spatial bias. Fish species, stocking density and initial size (see Section 2.3), together with pond preparation, aeration power input (see Section 2.2), data-collection schedule and measurement methods (see Sections 2.4 and 2.5), were standardized across all treatments to ensure experimental consistency. The experimental design was developed to simulate intensive pond culture conditions commonly encountered in commercial Nile tilapia farming in Bangladesh, where increasing biomass progressively elevates oxygen demand during the grow-out period. Rather than applying continuous aeration throughout the culture cycle, aeration was introduced only after DO approached the predefined operational threshold (4 mg/L), thereby reproducing practical farm management where supplemental aeration is initiated in response to increasing biomass and oxygen limitation. This approach enabled direct comparison of the effectiveness of different aeration configurations under equivalent operational conditions while minimizing confounding effects associated with unnecessary aeration during the early production stage.

2.2 | Pond Preparation and Aeration Set-Up

All ponds were prepared uniformly by applying quicklime (CaO) at a rate of 247 kg/ha, dissolved in water and evenly spread after cooling. Then water was gradually added over 7 days, followed by a second liming at 123.5 kg/ha (Rashid and Mithun 2020). To enhance natural productivity, di-ammonium phosphate (DAP: 18:46:0) was applied at 0.74 kg/ha. The entire preparation process was completed within 15 days, ensuring optimal water quality before stocking. Aeration systems were installed before fish release (Figure 1B). In the SA treatment, a 1.5 kW floating pump aerator (FB-1500 model; Taizhou Dumile Mechanical & Electrical Co. Ltd., China) was used, with a manufacturer-reported oxygen transfer capacity of approximately 1 kg O_2/h. For BA, a 1.5 kW vortex ring blower connected to two 10-in. fine-bubble diffuser disks (DISC-250; Trundean Machinery, Taiwan) per pond was employed. According to the manufacturer, each diffuser disk had a recommended airflow range of 20–150 L/min and a standard oxygen transfer efficiency (SOTE) of ≥38% at 6 m submergence. An average airflow value of 85 L/min was used to estimate oxygen transfer, which was approximately 0.54 kg O_2/h per disk or 1.08 kg O_2/h per pond with two disks. The SBA treatment combined both systems and therefore operated with a higher installed power input (3.0 kW). However, higher installed power does not necessarily result in proportionally higher oxygenation in ponds because oxygen transfer also depends on aerator type, mixing characteristics and pond conditions. Therefore, SBA was considered as a combined aeration approach intended to improve both surface mixing and bottom oxygen delivery under the applied culture conditions.

2.3 | Stocking and Feeding

Each experimental pond was stocked with all-male Nile tilapia (*O. niloticus*) at a density of 800 individuals per pond (equivalent to 400 fish/decimal; approximately 10 fish/m^2), with an initial mean weight of 0.89 ± 0.02 g. This stocking density is commonly used in intensive pond culture systems reported for Nile tilapia in Bangladesh and is consistent with previous studies conducted under similar production conditions (Rahman et al. 2022; Sultana et al. 2017; Abou Zied 2013). The selected density represents commercially relevant production conditions in which DO demand progressively increases as fish biomass accumulates, thereby providing an appropriate framework for evaluating different mechanical aeration strategies. Before stocking, fish were treated with potassium permanganate ($KMnO_4$)

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

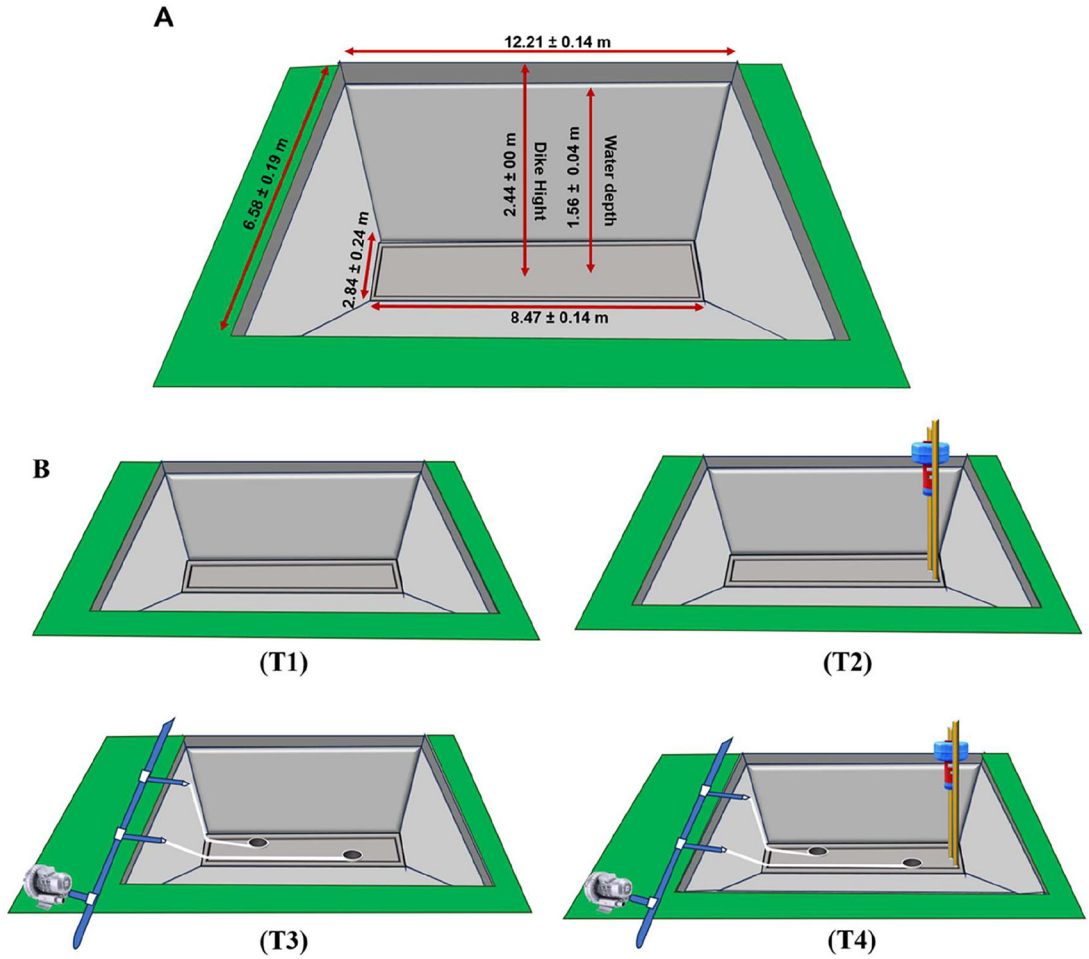


FIGURE 1 | Experimental layout and aeration configurations used during the 120-day culture of mono-sex Nile tilapia (*Oreochromis niloticus*). (A) Geometry of the experimental earthen ponds showing pond dimensions, side slopes and maintained water depth. (B) Schematic representation of the four experimental treatments: no aeration (NA), surface aeration (SA), bottom aeration (BA) and combined surface-bottom aeration (SBA). The combined system integrated surface water circulation with bottom air diffusion to improve oxygen distribution throughout the water column.

at 2 mg/L in the oxygenated carrying bags and subsequently acclimatized for 30 min (Lazur 1996). Fish were fed to 67% of satiation (Bolivar et al. 2013), and feed ration was adjusted at 15-day intervals on the basis of biomass. On the basis of the daily feed consumption, feed intake corresponded to approximately 18% of body weight during the early culture stage and gradually decreased to about 1% as fish grew. A commercially available floating tilapia feed was used, with protein content gradually reduced from 40% to 28% in accordance with fish growth stages. Fry weighing up to 7.76 g were fed a 40% protein diet; those between 7.77 and 20.55 g received 37% protein; fish from 20.56 to 50.45 g were given 36% protein; those between 50.46 and 71.55 g received 35% protein; individuals weighing 71.56–96.15 g were fed 32% protein; and fish above 96.15 g received 28% protein (Stickney et al. 1996). This stepwise adjustment ensured that dietary protein levels matched the nutritional requirements of the fish at each growth stage, optimizing feed utilization and growth performance. Feeding management and feed quality were maintained consistently across treatments throughout the experiment, whereas total feed consumption varied according to biomass development and feeding response under different culture conditions.

2.4 | Monitoring Water-Quality Parameters

DO was measured daily throughout the culture period using a sensor-based digital DO meter (Model: Lutron DO-5509) and cross-verified with a sensor-based multiparameter meter (Model: Hanna HI98192). DO measurements were taken from a fixed sampling location positioned at the farthest practical point from the SA system in order to monitor oxygen conditions under comparatively lower mixing influence, with samples collected at three depths (20, 78 and 136 cm) and at three times of day: 6:00 AM and subsequently at 8-h intervals (Figure 2A). The multiparameter was also used to record water temperature (°C), pH, salinity (mg/L) and total dissolved solids (TDS) (mg/L), which were measured daily at mid-day throughout the culture period. Ammonia nitrogen (NH_3-N), nitrite (NO_2-N), phosphate (PO_4^{3-}), alkalinity and total hardness were measured fortnightly using Hanna Checkers (Models: HI700, HI708, HI717, HI775 and HI735, respectively). In Nile tilapia culture, a DO level of approximately 1.9 ± 0.5 mg/L is considered critical (Ridwanudin et al. 2018), whereas levels below 3 mg/L adversely affect growth, feed utilization, physiology and immunity (Abdel-Tawwab et al. 2014). To maintain a safety margin above the harmful DO

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

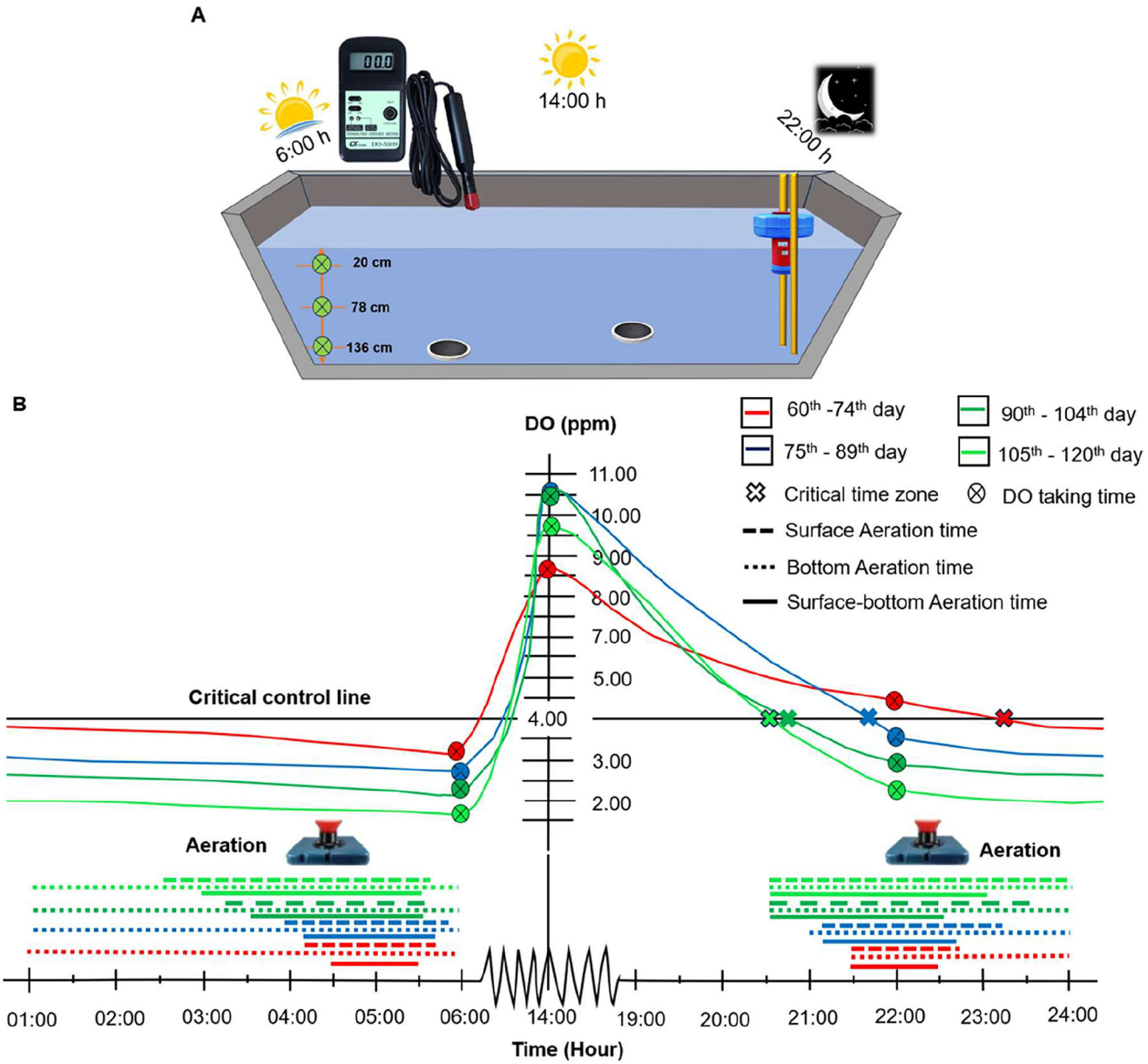


FIGURE 2 | Dissolved oxygen monitoring strategy and operational aeration schedule. (A) Location of dissolved oxygen sampling points at three water depths and three daily observation times. (B) Schematic illustration of the adaptive aeration schedule used to maintain dissolved oxygen (DO) concentrations above the operational threshold (4 mg/L) as fish biomass increased during the culture period.

threshold, a concentration of 4 mg/L was set as the critical level for initiating aeration. Aeration duration was adjusted on the basis of the observed rate of DO increase during aeration and DO decline after aeration ceased. Measurements were taken under routine pond operating conditions rather than controlled steady-state conditions. Under the applied operating conditions, the SBA treatment reached the target DO level more rapidly than the BA system, whereas BA showed comparatively limited DO improvement at the distal monitoring location. Therefore, a common aeration schedule based on the minimum effective duration required by SBA was applied across aerated treatments to maintain operational consistency. A biomass threshold corresponding to a critical DO level (4 mg/L) was identified at Day 59 of culture, estimated assuming a constant %SGR derived from the 60th day sampling, with an average biomass of 0.58 ± 0.05 kg/m^2, corresponding to an average individual weight of 62.62 ± 5.31 g and length of 13.64 ± 0.29 cm. On the basis of this threshold, aeration was scheduled from 21:30 to 22:30 during the first aeration phase, and again from 4:30 to 5:30 h at dawn, keeping DO above the critical limit. As biomass increased, the critical DO level was reached earlier, requiring adjustments to aeration timing as shown in Figure 2B. This study evaluated different aeration strategies under operationally relevant oxygen-limited conditions rather than continuous aeration throughout the production cycle. Supplemental aeration was initiated only after DO reached the predefined operational threshold of 4 mg/L, reflecting the point at which increasing fish biomass creates a practical need for aeration in intensive pond culture. This approach mirrors commercial pond management, where aeration is applied in response to oxygen demand rather than operated continuously

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/aff2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

from stocking. Consequently, all aeration treatments were evaluated from the same operational threshold, allowing comparison of their performance under comparable production conditions while avoiding unnecessary aeration during the early culture stage.

2.5 | Growth and Feed Efficiency Parameters

Fish length and weight were measured fortnightly using a centimetre scale and a dry-cell digital balance (TANITA Model: KJ-111M), respectively, from thirty randomly selected fish from each treatment. Growth and production parameters, including daily weight gain (g/day), total production (MT/ha), survival rate (%), specific growth rate (SGR; % per day), feed conversion ratio (FCR) and condition factor (K_n) were calculated using standard formulae (Alemayehu and Getahun 2017; Jongjaraunsuk and Taparhudee 2022). To assess the relationship between aeration and biomass production, the amount of oxygen supplied per kilogram of biomass gain was estimated for each aeration treatment relative to the control. Oxygen input was calculated from aerator operating time and manufacturer-reported oxygen transfer capacity, whereas biomass gain was derived from the difference in harvested biomass between aerated treatments and the non-aerated control. These calculations were intended to provide a comparative indicator of aeration performance under the applied culture conditions rather than a direct measurement of in-pond oxygen transfer efficiency.

2.6 | Financial Analysis

Economic analysis was conducted separately for each treatment using treatment-specific capital expenditure (CAPEX), operating expenditure (OPEX) and income data. Capital costs (CAPEX) included pond preparation, procurement of aeration equipment (fountain aerator and/or air blower with diffuser units), pipe fittings and associated electrical installation works. Operating costs (OPEX) included the cost of tilapia fry, fertilizers and chemicals, feed, electricity, maintenance, labour and depreciation of aeration equipment. Gross income was estimated using harvested fish biomass and prevailing local market prices during the study period. Depreciation costs for capital items were calculated on the basis of expected lifespan and salvage value (Magna et al. 2023). The electricity costs for aeration were calculated according to the official tariff schedule of the Ministry of Power, Energy and Mineral Resources of Bangladesh (Rahman 2023) considering slab-based unit consumption rates. The costs of lime, salt, tilapia fry, electricity for water management and labour wages were maintained consistently across treatments. The benefit-cost ratio (BCR) and return on investment (ROI) (Magna et al. 2023) were subsequently calculated to see if different aeration strategies would work in pond-based aquaculture. Moreover, economic indicators, such as operating costs, feed costs, electricity cost, profit and capital expenditure, were expressed on a per-unit-production basis (kg fish). This enabled comparisons of production and economic efficiency among treatments. Because SBA required higher installed aeration power, its economic performance was interpreted in the context of both increased fish production and higher energy consumption.

2.7 | Data Processing and Analysis

All recorded data were imported into Microsoft Excel 2016 and organized prior to statistical analysis. Growth, feed efficiency and financial data were analysed using one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) test in SPSS (Statistical Package for the Social Sciences, Version 26.0). Normality and homogeneity of variance were verified before analysis. DO data were processed; figures were generated in R (Version 4.5) with the ggplot2 package. Principal component analysis (PCA) was performed using the prcomp function, with visualization supported by the ggplot2, factoextra and ggrepel packages. Adobe Illustrator (Version 29.0) was used to prepare the schematic illustration. The experimental pond was considered the experimental unit ($n = 3$ per treatment), and statistical significance was accepted at $p < 0.05$.

3 | Result

3.1 | Growth Performance and Feed Efficiency of Fish Biomass

During the pre-aeration period (Days 0–59), fish in all treatments exhibited comparable growth trajectories, indicating that pond preparation, stocking conditions and initial culture management were consistent among treatments (Figure 3A). Following the initiation of aeration on Day 60, clear treatment-specific differences became evident. The SBA treatment consistently achieved the highest individual weight throughout the remaining culture period, followed by SA, BA and NA. By harvest, fish reared under SBA reached a final mean weight of 172.07 ± 2.28 g, representing increases of 53.4%, 29.1% and 6.9% compared with NA, BA and SA, respectively (Table 1). Similar trends were observed for specific growth rate, survival, FCR and total production. SBA produced the highest yield (16.47 ± 0.20 MT/ha), significantly exceeding NA by 61.17%, whereas SA and BA increased production by 47.96% and 17.06%, respectively (Figure 3B; Table 1). The SBA treatment also recorded the highest survival (96.88% ± 0.22%), whereas NA showed lower survival (92.25% ± 1.52%). Feed utilization also improved with aeration, with SBA recording the lowest FCR (1.41 ± 0.02), whereas NA showed the poorest feed efficiency (1.94 ± 0.03). The condition factor (K_n) ranged from 2.22 ± 0.04 to 2.32 ± 0.07 and remained statistically similar among treatments.

3.2 | Effects of Different Aeration System on Culture Environment

3.2.1 | DO Dynamics Over Time

During the initial culture period (Days 0–59), DO concentrations remained above the operational threshold (4 mg/L) in all treatments (Figure 4). As fish biomass increased, morning DO progressively declined and reached the predefined threshold on Day 59, at which time supplemental aeration was initiated. Thereafter, distinct treatment-specific patterns emerged. The SBA treatment consistently maintained the highest DO concentrations throughout the diel cycle, followed by SA and BA, whereas the NA treatment exhibited a continuous decline in DO, particularly during the early morning period. Although BA improved DO

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

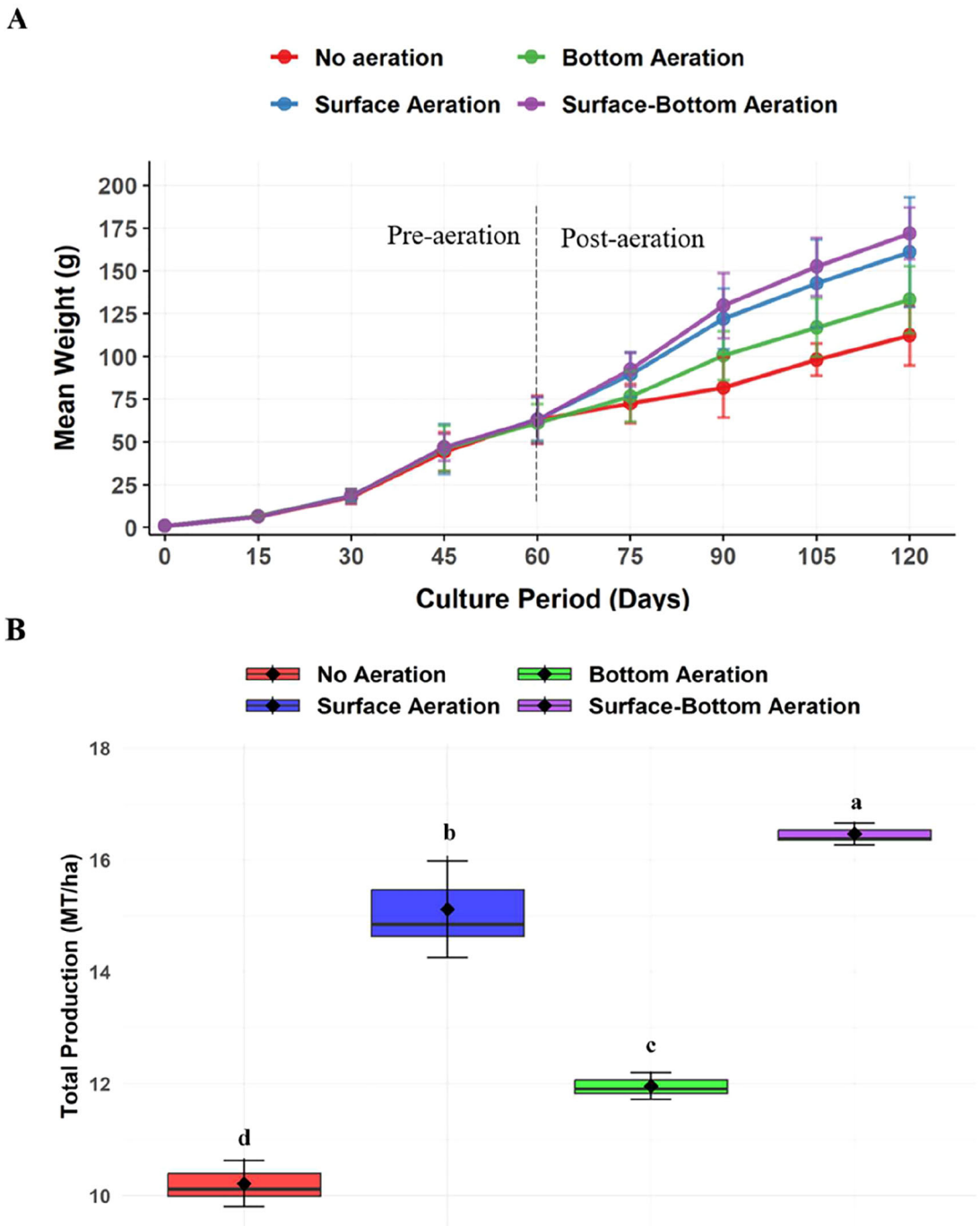


FIGURE 3 | Growth performance of mono-sex Nile tilapia cultured under different aeration systems. (A) Temporal changes in mean individual body weight during the 120-day culture period. The vertical dashed line indicates the initiation of supplemental aeration. (B) Final fish production under each aeration treatment. Bars represent mean ± SD ($n = 3$), and different lowercase letters indicate statistically significant differences among treatments (Tukey's HSD, $p < 0.05$).

relative to the non-aerated control, it occasionally remained below the target threshold during dawn observations, whereas DO concentrations in all aerated treatments remained comparatively stable during the night. Overall, SBA provided the most effective maintenance of DO throughout the culture period under the applied culture conditions.

Depth-wise variation in DO was evident among treatments. SA maintained consistently higher DO concentrations near the water surface (5.03 ± 0.76 mg/L) but comparatively lower concentrations near the pond bottom (4.01 ± 0.74 mg/L). In contrast, BA produced relatively greater oxygenation at depth (3.74 ± 0.99 mg/L) while maintaining 4.72 ± 1.03 mg/L near the surface during the principal aeration period (22:00 to 06:00 h). The SBA treatment maintained the most balanced vertical oxygen profile, with DO concentrations of 5.29 ± 0.77 mg/L near the surface and 4.23 ± 0.65 mg/L near the bottom, indicating improved oxygen distribution throughout the water column.

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 1 | Growth performance and feed utilization of mono-sex Nile tilapia (*Oreochromis niloticus*) cultured under different aeration systems for 120 days.

Parameters	No aeration	Surface aeration	Bottom aeration	Surface-bottom aeration
Initial individual weight (g)	0.89 ± 0.024^{a}	0.89 ± 0.016^{a}	0.89 ± 0.023^{a}	0.89 ± 0.026^{a}
Final individual weight (g)	112.17 ± 6.137^{a}	161.03 ± 10.626^{a}	133.30 ± 3.305^{b}	172.07 ± 2.275^{a}
Specific growth rate (%)	4.03 ± 0.066^{a}	4.33 ± 0.045^{a}	4.18 ± 0.019^{b}	4.39 ± 0.035^{a}
Survival rate (%)	92.25 ± 1.515^{b}	95.04 ± 0.830^{a}	90.83 ± 0.629^{b}	96.88 ± 0.219^{a}
Production (MT/ha)	10.22 ± 0.414^{d}	15.12 ± 0.862^{b}	11.96 ± 0.239^{a}	16.47 ± 0.195^{a}
Feed conversion ratio (FCR)	1.94 ± 0.032^{d}	1.51 ± 0.050^{b}	1.76 ± 0.026^{a}	1.41 ± 0.017^{a}

Note: Values are presented as mean ± standard deviation. Different superscript letters (a–d) within the same row indicate significant differences among treatment groups as determined by one-way ANOVA followed by Tukey's HSD post hoc test ($p < 0.05$).

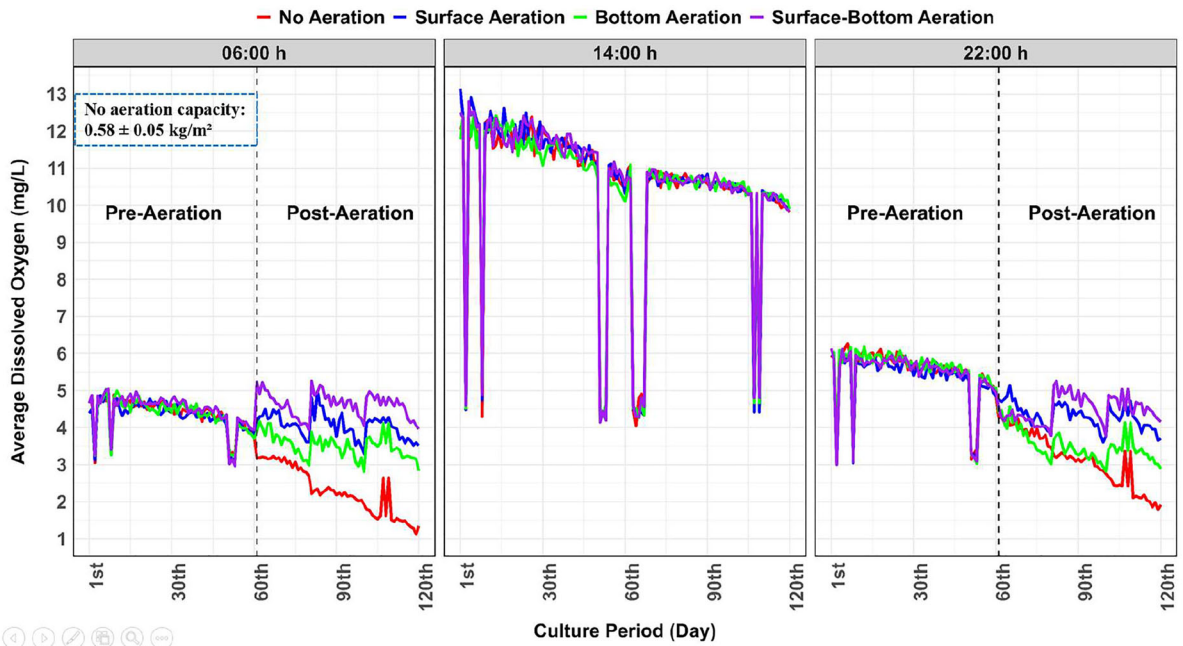


FIGURE 4 | Temporal variation in dissolved oxygen concentrations under different aeration treatments throughout the culture period. Mean dissolved oxygen was recorded at 06:00, 14:00 and 22:00 h. The figure illustrates the transition from the pre-aeration phase to the operational aeration period and demonstrates differences in oxygen dynamics among treatments.

3.2.2 | Physico-Chemical Parameters of the Water

In all treatments, the average mid-day temperature at 78 cm depth decreased over the 120-day culture period, from 36.95°C at the beginning to 23.24°C at the end (Figure 5A), with an overall mean of 30.62°C ± 2.26°C. The pH values were relatively stable during the culture period at mid-day, with an average of 7.97 ± 0.32. The TDS values ranged from 268 to 1382 mg/L with the overall average of 713.53 ± 261.59 mg/L recorded at mid-day. During the seasonal rainfall in August–September the TDS value reduced but increased during the following winter. NH_3-N and NO_2-N showed a concurrent increase across treatments during the culture period (Figure 5B). The SBA treatment consistently showed lower concentrations of both NH_3-N and NO_2-N compared to other treatments, with the mean concentrations of 0.58 and 1.33 mg/L, respectively. In contrast, BA displayed relatively lower NH_3-N but higher NO_2-N concentrations, which may indicate comparatively greater nitrification activity under the applied conditions. The no-aeration and SA treatments showed intermediate levels of NH_3-N and NO_2-N throughout the culture period. Following aeration, SBA also maintained a lower average TDS concentration (652.58 ± 313.07 mg/L) than NA (718.74 ± 137.89 mg/L). PO_4^{3-} levels progressively increased across all treatments before aeration was applied, followed by fluctuating levels until the end of the culture period (Figure 5B). The average PO_4^{3-} throughout the culture period was found to be 0.33 ± 0.13 mg/L. BA occasionally recorded higher phosphate concentrations, reaching up to 1.10 mg/L, whereas SBA maintained comparatively stable levels. Alkalinity levels gradually increased over time in all treatments, with comparatively higher values observed in SBA and lower values in NA. The NA treatment exhibited an average alkalinity of 146.15 ± 23.38 mg/L during the culture period. Across

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

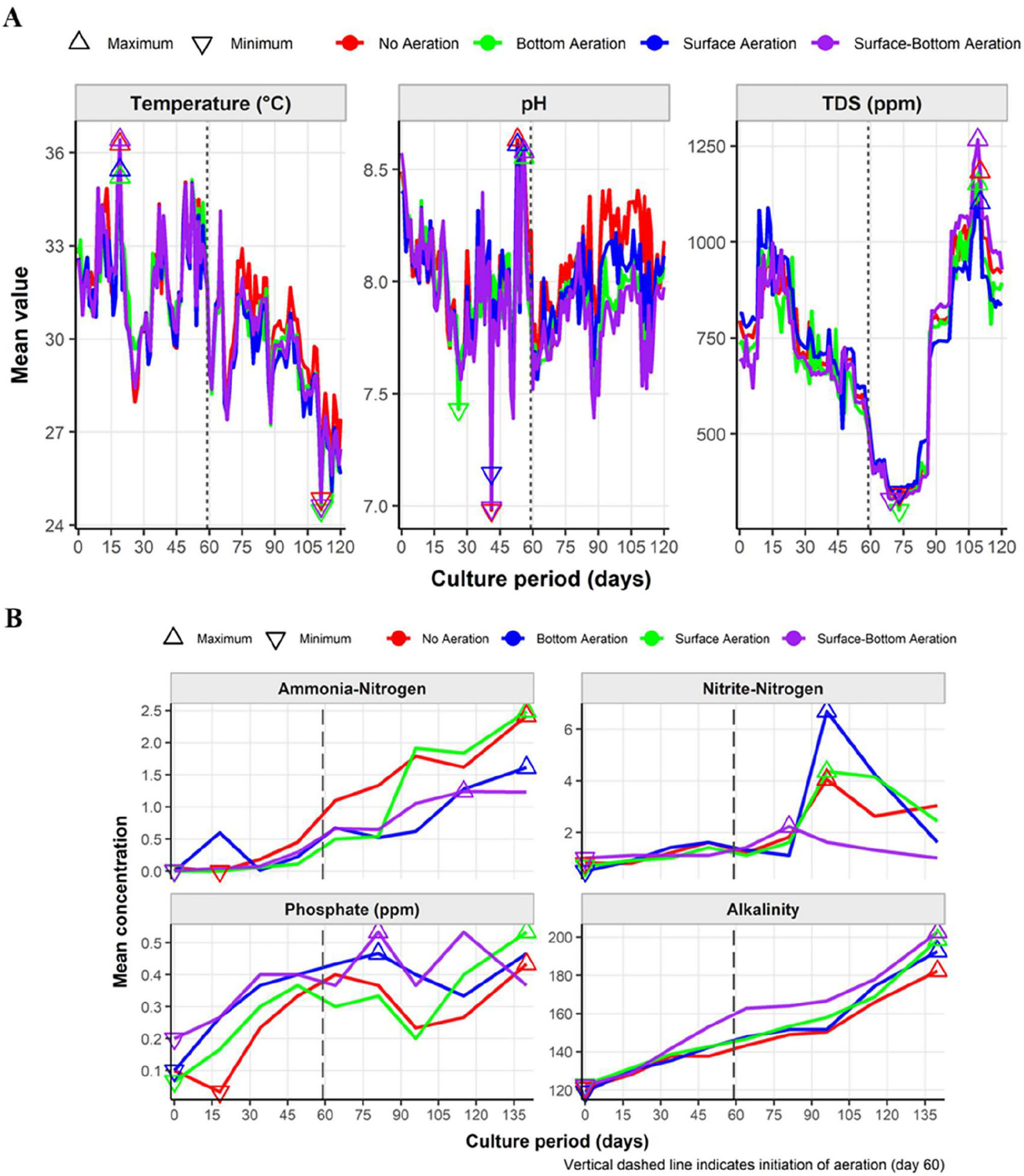


FIGURE 5 | Temporal variation in key water-quality parameters during the 120-day culture period. (A) Daily measurements of temperature, pH and total dissolved solids (TDS). (B) Fortnightly measurements of ammonia-nitrogen (NH3-N), nitrite-nitrogen (NO_2-N), phosphate (PO_4^{3-}) and alkalinity under the four aeration treatments.

the entire culture period, the average alkalinity was 157.74 ± 25.39, 151.19 ± 24.95 and 149.44 ± 24.72 mg/L in SBA, SA and BA, respectively. Following the initiation of aeration, SBA showed a further increase in alkalinity, reaching a post-aeration average of 174.80 ± 18.88 mg/L.

3.2.3 | Water Quality to Production Relationships

PCA illustrated the multivariate relationship between water-quality variables and aeration treatments, where PC1 (34.5%) and PC2 (29%) accounted for 63.5% of the total variance in water quality (Figure 6). In the PC1 axis, DO, phosphate (PO_4^{3-}), TDS

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

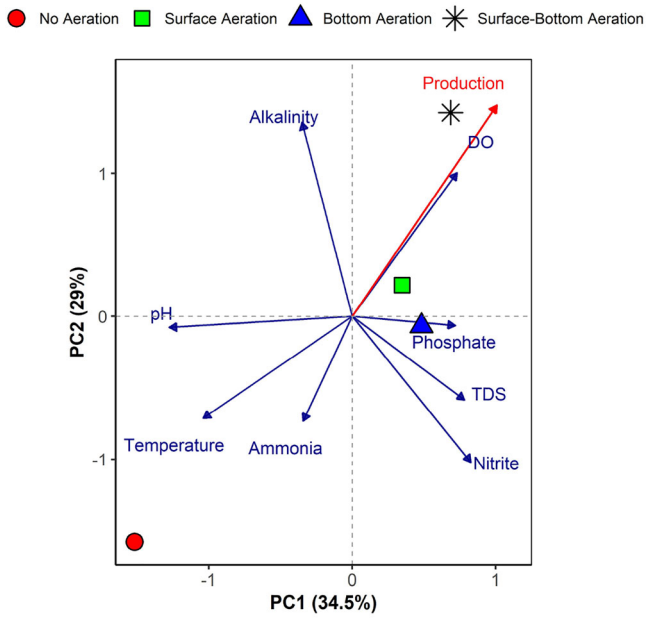


FIGURE 6 | Principal component analysis (PCA) illustrating the ordination of water-quality parameters and treatment centroids in monosex Nile tilapia (*Oreochromis niloticus*) culture under different aeration systems. The PCA was based on mean values of key water-quality variables from Days 75 to 120 of the culture period. Arrows represent variable loadings, coloured symbols indicate treatment centroids, and the red vector represents production which was included as a supplementary variable to illustrate its association with the multivariate water-quality gradients. DO, dissolved oxygen; TDS, total dissolved solids.

and nitrite (NO_2^-) were more closely associated with aerated treatments; on the other hand, temperature, ammonia (NH_3-N) and pH were negatively correlated. Along the PC2 axis, DO and alkalinity remained strongly in the positive direction, whereas temperature and pH were in a more negative direction. The NA treatment clustered on the negative side of PC1 and was associated with comparatively higher ammonia concentrations and temperature, whereas SBA was positioned on the positive side of PC1 and PC2, indicating an association with comparatively improved water-quality conditions. SA and BA occupied intermediate positions between these two extremes. Although production was not significantly correlated with PC1 ($r = 0.44$, $p = 0.1543$), its close proximity to the SBA centroid in the PCA ordination was consistent with the higher production observed under the combined aeration treatment. Overall, the PCA distinguished the non-aerated and aerated treatments based on their multivariate water-quality characteristics and complemented the univariate analyses presented above.

3.2.4 | Oxygen Utilization Efficiency and Feed Performance Across Aeration Systems

Figure 7A indicates that the SBA had the lowest FCR (1.41 ± 0.02) and a moderate oxygen supply ratio (OSR) (9.13 ± 0.34). SA showed intermediate FCR (1.51 ± 0.05) and the lowest OSR (5.53 ± 1.12), whereas BA had higher OSR (13.62 ± 1.96) and comparatively poorer FCR (1.76 ± 0.03), which may indicate comparatively lower oxygen distribution efficiency within the pond environment. The control without aeration (NA) showed the highest FCR (1.94 ± 0.03). This indicates the essential role of oxygen management in aquaculture productivity. The relation between supplied oxygen and the Oxygen Supplied to Biomass Gain Ratio (OSR) provides a comparative indication of oxygen input relative to biomass gain under different aeration systems. SA indicated comparatively efficient oxygen utilization, and the supplied oxygen trend remained relatively close to the OSR trend between Days 75 and 90 (Figure 7B). By Day 120, the OSR in SA reached 5.53 with a cumulative estimated oxygen input of 210 kg O_2, suggesting comparatively balanced oxygen input relative to biomass gain under the applied culture conditions. However, in the SBA system, the substantially larger separation between the oxygen supply and OSR trends (Figure 7B) reflects the higher cumulative oxygen input (436.8 kg O_2) associated with the combined aeration system and its greater biomass production performance. On the other hand, BA consistently maintained higher OSR relative to SA and SBA, and the OSR line remained above the O_2 supply line (Figure 7B), indicating comparatively higher oxygen input relative to biomass gain, potentially associated with less effective oxygen distribution throughout the pond water column.

3.3 | Financial Analysis

SA and BA resulted in additional expenses for equipment and energy use. Due to the combination of both systems, SBA had the highest costs, but it also generated the largest profit and sales revenue. In SBA, higher feed input was required to support increased biomass production; therefore, the total feed cost was highest, despite improved feed conversion efficiency. However, when expressed per unit production (Table 2B), SBA exhibited the lowest feed cost per kg fish, reflecting superior feed utilization efficiency. The depreciation of aeration equipment, especially in BA and SBA, was high due to the principal expenses connected with the installation of the BA system. With the lowest absolute costs and the lowest returns, the no-aeration treatment (NA) resulted in a financial deficit with a cost–benefit ratio (CBR) of 0.90 ± 0.01. On the other hand, SBA produced the highest economic return, with the highest CBR of 1.14 ± 0.015 and ROI of 13.60% ± 1.36% (Table 2A). Overall, the results consistently demonstrated that integrating surface and BA produced the most favourable combination of water quality, fish performance and economic return under the applied intensive culture conditions. These findings are interpreted within the context of previous research in the following discussion.

4 | Discussion

This study evaluated an integrated SBA strategy under intensive pond culture conditions to determine whether combining complementary surface mixing and bottom air diffusion could improve pond performance beyond that achieved by individual aeration systems. Unlike previous studies that primarily evaluated surface or BA independently, the present study simultaneously assessed DO dynamics, vertical oxygen distribution, water quality, fish growth, feed utilization and economic performance within a single experimental framework. The results demonstrate that the combined aeration strategy improved oxygen distribution

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

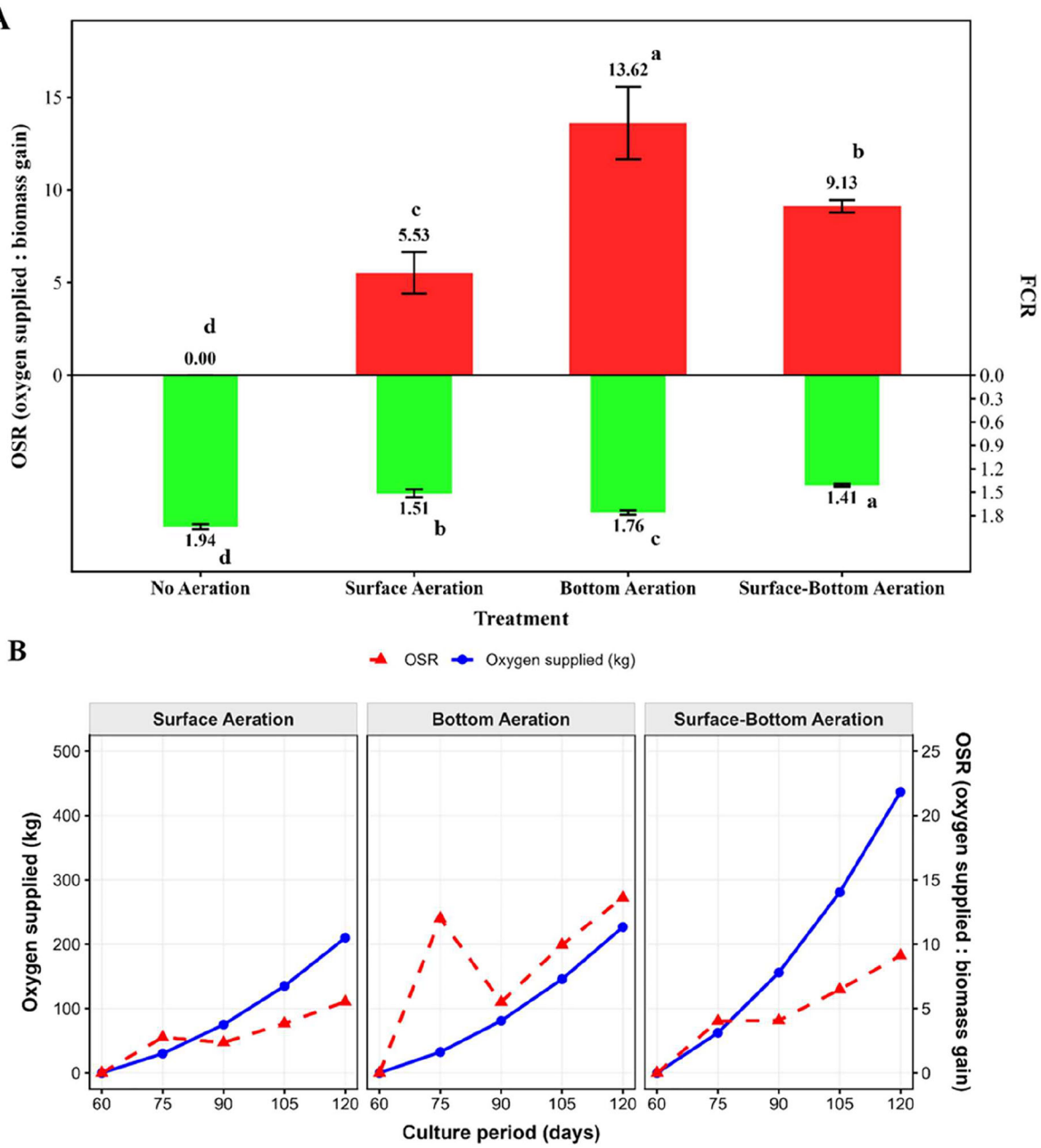


FIGURE 7 | Oxygen utilization efficiency under different aeration systems. (A) Comparison of oxygen supply ratio (OSR) and feed conversion ratio (FCR). Bars represent mean ± SD ($n = 3$), and different lowercase letters indicate significant differences among treatments (Tukey's HSD, $p < 0.05$). (B) Changes in cumulative oxygen supplied and oxygen supply ratio during the post-aeration period, illustrating differences in oxygen utilization efficiency among aeration systems.

throughout the water column and was associated with enhanced fish performance and economic returns under the applied culture conditions. Collectively, these findings provide practical evidence for optimizing aeration management under intensive pond culture conditions. The following discussion interprets these findings in relation to stocking density, DO management, water-quality responses and the economic implications of aeration under intensive pond culture conditions. Previous studies highlight that net income in tilapia farming increases when high stocking density is combined with careful feed and water-quality management (Azab et al. 2018; Mramba and Kahindi 2023). However, the relationship between density and DO is critical: Fish performance is significantly impaired when DO drops below 3 mg/L, particularly under high-density conditions (Abdel-Tawwab et al. 2014). Classic benchmarks indicate that a minimum DO of 3 mg/L is required (Boyd et al. 2018). Aeration was triggered when morning DO fell below 4 mg/L, a threshold aligned with earlier recommendations for safe tilapia culture. The positive influence of oxygen on growth and feed conversion is well established (Mallya 2007). Studies on rainbow trout demonstrated significant declines in growth and survival as DO decreases (Welker et al. 2019), and tilapia culture systems with aeration consistently yield higher survival and production than no-aeration controls (Vijayan and Varghese 1986). Stocking

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 2 | Comparative financial analysis of mono-sex Nile tilapia (*Oreochromis niloticus*) culture under different aeration systems.

(A) Cost components and returns (per pond basis)

Financial analysis

Cost category	Cost particulars	No aeration	Surface aeration	Bottom aeration	Surface-bottom aeration
Capital cost (CAPEX)	Pond preparation	18.49	18.49	18.49	18.49
	Fountain aerator	0.00	144.34	0.00	144.34
	Air blower and diffuser	0.00	0.00	83.00	83.00
	Pipe fittings	0.00	0.00	44.41	44.41
	Electrical equipment	0.00	13.62	13.62	13.62
	Total CAPEX	18.49	176.45	159.52	303.86
Operating cost (OPEX)	Cost of depreciation	4.63	17.59	7.66	20.59
	Tilapia fry	10.83	10.83	10.83	10.83
	Fertilizers and chemicals	0.87	0.87	0.87	0.87
	Feed	99.87 ± 5.77	114.47 ± 10.27	105.77 ± 3.46	116.19 ± 1.19
	Electricity cost	0.56	20.42	2.74	23.72
	Maintenance and worker	3.76	4.96	7.82	7.82
	Total OPEX	120.52 ± 5.77	169.14 ± 10.27	135.69 ± 3.46	180.02 ± 1.19
Sales proceeds		108.23 ± 4.39	176.66 ± 10.07	131.07 ± 2.63	204.51 ± 2.40
Net profit/loss (±)		−12.29 ± 1.50	7.53 ± 1.39	−4.62 ± 1.41	24.49 ± 2.41
Return on investment (ROI, %)		−10.17 ± 0.792^{d}	4.47 ± 0.952^{b}	−3.39 ± 0.992^{a}	13.60 ± 1.360^{a}
Cost–benefit ratio (BCR)		0.90 ± 0.010^{d}	1.04 ± 0.006^{b}	0.97 ± 0.010^{a}	1.14 ± 0.015^{a}

(B) Financial efficiency indicators (per unit production)

Indicator	No aeration	Surface aeration	Bottom aeration	Surface-bottom aeration
Cost per kg fish	1.68 ± 0.01	2.83 ± 0.08	3.05 ± 0.03	3.63 ± 0.05
Feed cost per kg fish	1.21 ± 0.02	0.93 ± 0.03	1.09 ± 0.02	0.87 ± 0.02
Profit per kg fish	−0.15 ± 0.01	0.06 ± 0.01	−0.05 ± 0.02	0.19 ± 0.02
CAPEX per kg fish	0.22 ± 0.01	1.45 ± 0.08	1.65 ± 0.04	2.28 ± 0.03

Note: (A) Values are presented as mean ± standard deviation. Different superscript letters (a–d) within the same row indicate significant differences among treatment groups as determined by one-way ANOVA followed by Tukey's HSD post hoc test ($p < 0.05$). ($1 = 110.85 BDT). (B) Values are expressed as mean ± standard deviation ($n = 3$). Per unit production indicators were calculated on the basis of replicate-level data for each treatment. ($1 = 110.85 BDT).

density is one of the primary factors governing oxygen demand, fish growth and overall pond productivity in Nile tilapia culture. Previous studies conducted under Bangladeshi farming conditions have shown that increasing stocking density generally increases total production but may reduce individual growth performance unless culture management, particularly supplemental aeration, is improved. For example, a stocking with 200 fish/decimal produced the highest growth and economic return, whereas the highest production was achieved at 600 fish/decimal (Majumder et al. 2018). Similarly, supplemental aeration supported high production at a stocking density of 300 fish/decimal (Sultana et al. 2017), whereas optimum production at a stocking density of 450 fish/decimal was achieved using turbine aeration (Abou Zied 2013). Collectively, these previous studies indicate that stocking densities between 300 and 600 fish/decimal are commonly adopted under intensive pond culture, particularly when supplemental aeration and appropriate management practices are applied. The present study used 400 fish/decimal to represent an intensive production condition in which oxygen demand progressively increases with biomass accumulation. The similar growth trajectories observed among treatments before aeration indicate that the initial culture conditions were comparable, whereas the divergence in performance following aeration initiation suggests that oxygen availability became increasingly important as biomass increased. FCRs are a useful indicator of utilization efficiency, is influenced by feed quality and culture management. In Bangladeshi pond systems, FCR typically ranges between 1.5 and 2.5 (Rana and Hassan 2013), with values below 2 are generally considered indicative of efficient production (Craig et al. 2017). Our findings show significant improvements in feed efficiency with aeration, with the combined aeration approach produced the most favourable feed conversion performance and was associated with higher survival and production. This indicates that the combined aera-

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

tion approach was associated with improved feed efficiency and biomass gain, supporting earlier reports that oxygen concentration is positively associated with growth performance (Policar et al. 2024). In addition, condition factor (K_n) remained above one throughout the experiment, indicating that aeration primarily influenced growth efficiency and productivity rather than body condition (Ayoade 2011; Ighwela et al. 2011). The absence of significant treatment differences in K_n further indicates that the effects of aeration were primarily expressed through growth efficiency and biomass production rather than changes in overall body condition. The role of aeration becomes even clearer when diel DO fluctuations are considered. Pond DO concentrations typically fluctuate between dusk and dawn due to photosynthesis and respiration dynamics, with sharp overnight declines (Madenjian et al. 1988). In tilapia ponds, the lowest DO values often occur between midnight and dawn (Shoko et al. 2014; Simon et al. 2011). In our study, morning DO progressively declined as biomass increased, reaching the operational threshold for supplemental aeration by Day 59 when biomass had increased sufficiently to elevate oxygen demand. This pattern highlights the increasing oxygen requirements associated with intensive stocking.Low DO conditions can occur at high stocking densities (Nadiro et al. 2023), and the pronounced decline in morning DO in the non-aerated ponds towards the end of the culture period was accompanied by poorer growth, survival and overall production. These observations emphasize the importance of timely supplemental aeration as biomass and associated oxygen demand increase during intensive pond culture. It is important to emphasize that the objective of the present study was not to compare continuous aeration throughout the production cycle but to evaluate the relative effectiveness of different aeration systems after supplemental aeration became necessary under intensive culture conditions. Because DO remained above the operational threshold during the early culture phase, continuous aeration during this period would not have reflected routine commercial management and would have introduced unnecessary energy consumption. Therefore, the experimental design intentionally focused on the biologically and operationally relevant period when oxygen availability became limiting to fish production.

Performance varied markedly between aeration systems. During the principal aeration time from 22:00 to 6:00 h, SA improved oxygen availability near the surface but left the bottom layers comparatively undersupplied, indicating vertical stratification within the water column and the formation of localized 'discomfort zones' (areas of suboptimal DO concentration). In contrast, BA improved oxygen at depth but resulted in relatively higher DO near the surface, suggesting uneven vertical distribution. Although the absolute differences in DO between surface and bottom layers were relatively small (~1 mg/L), these gradients indicate incomplete mixing within the water column. The integrated SBA system helped reduce both limitations, providing improved DO distribution across depths (Figure 8). This comparatively balanced DO profile may have contributed to the improved growth, survival and FCR performance observed in SBA. Although SBA operated with a higher installed power than the individual aeration systems, increased motor power does not necessarily result in proportionally higher oxygenation in ponds, because oxygen transfer also depends on aerator type, mixing pattern, bubble characteristics and pond conditions. Therefore, the improved performance observed under SBA should be interpreted as the combined effect of surface mixing and BA under the applied operational conditions.

Beyond improving DO availability, aeration also influenced several water-quality variables associated with pond productivity. Throughout the 120-day culture period, water temperature remained within the suitable range for Nile tilapia, indicating that seasonal conditions rather than aeration primarily governed thermal variation. Nevertheless, enhanced water circulation generated by aeration may have minimized thermal stratification and promoted a more homogeneous water column (Akinwole et al. 2014; Ramesh et al. 2024), whereas the recorded temperatures remained within the optimum range for Nile tilapia culture (FAO 2025). Nitrogenous compounds increased progressively with biomass accumulation in all treatments; however, SBA maintained comparatively lower ammonia and nitrite concentrations than the other treatments, suggesting improved nitrification and nitrogen transformation under the applied culture conditions. Similarly, the lower TDS observed in SBA than in the non-aerated treatment, indicating reduced accumulation of dissolved wastes. Pond pH remained within the acceptable range for Nile tilapia culture, showing greater stability, whereas alkalinity remained above the minimum recommended level of 50 mg/L (Boyd 2007) and within the effective range reported for productive aquaculture ponds (Mustapha 2017). The higher alkalinity observed under SBA during the post-aeration period suggests improved buffering capacity and greater resistance to pH fluctuations under the applied culture condition. Phosphate concentrations also remained within the acceptable range for productive aquaculture and below the recommended upper limit of 0.5 mg/L (Boyd 2001; Xu et al. 2023). Although BA occasionally recorded elevated phosphate concentrations (up to 1.10 mg/L), likely due to increased sediment resuspension, SBA maintained comparatively stable phosphate levels, suggesting that integrated SBA improved nutrient redistribution without promoting excessive phosphorus release from pond sediments. Collectively, these findings indicate that the combined SBA strategy contributed to a more stable and balanced pond environment through improved nutrient transformation, buffering capacity and nutrient cycling. These observations are consistent with previous studies demonstrating that enhanced water circulation and oxygen availability can promote nitrification, reduce nitrogenous waste accumulation, stabilize water chemistry and improve overall pond environmental quality (ZhongWen et al. 2010; Ehiagbonare and Ogunrinde 2010; Siwiec et al. 2016; Zhu et al. 2020; Wurts and Durborow 1992).

From an economic perspective, aeration involves both costs and benefits. Farm profitability is influenced by production scale and intensification, although small- and medium-scale farms can also remain economically viable (Burad-Méndez et al. 2023; Gonzaga dos Santos-Filho et al. 2017; L. Castilho-Barros et al. 2020). Previous studies have shown that profitability in tilapia farming varies with culture system, production scale, input intensity and market conditions (Ferdoushi et al. 2019; Toma et al. 2015; Phiri and Yuan 2018). In the present study, SBA provided the highest economic return among the evaluated treatments. Although SBA incurred higher equipment and operational costs, its superior FCR reduced feed expenses—one of the largest production costs, and, together with higher yields, resulted in greater overall profitability compared with the other systems

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

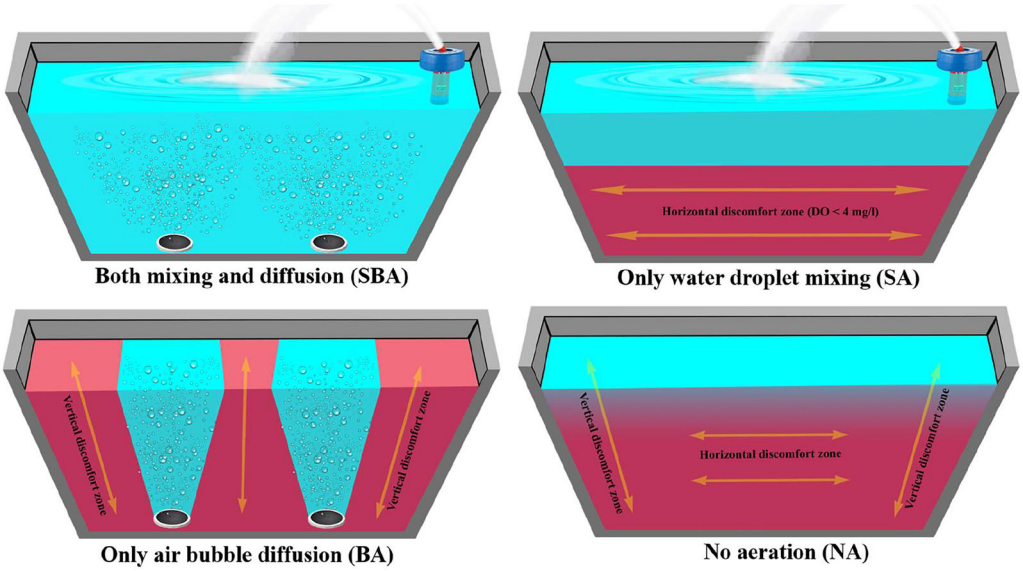


FIGURE 8 | Schematic diagram of discomfort zone (DO < 4 mg/L) created by surface and bottom aeration system along with homogeneous oxygenation by combination of both aeration systems. DO, dissolved oxygen.

(Table 2A). The SA treatment performed moderately, aligning closely with SBA, suggesting its potential as a viable intermediate option. However, SBA showed greater potential to support higher inputs and further intensification, resulting in greater economic returns despite similar baseline costs associated with land use, depreciation, fertilizers and labour.

Overall, the findings indicate that supplemental aeration can improve the economic performance of intensive tilapia pond production when the additional costs of aeration are offset by improvements in feed utilization and fish production. The integrated SBA system not only provided more balanced oxygen distribution within the water column but also stabilized temperature, pH, alkalinity and nutrient cycling. This combined aeration approach was associated with improved growth, feed efficiency and profitability. By maintaining balanced water quality and productivity, SBA may provide a practical and potentially sustainable approach for improving pond-based Nile tilapia production under similar intensive culture conditions.

5 | Conclusion

This study demonstrated that supplemental aeration substantially improved water quality, fish growth, feed utilization and economic performance in the intensive pond culture of monosex Nile tilapia. Among the evaluated systems, the combined SBA treatment maintained the most balanced DO distribution throughout the water column and consistently achieved the highest production, feed efficiency, survival and economic return under the present experimental conditions. These findings suggest that integrating surface mixing with BA can provide a practical management strategy for improving oxygen availability and supporting sustainable intensification of pond-based tilapia farming in Bangladesh and similar production environments. The findings are particularly applicable to intensive pond production systems where biomass accumulation progressively increases oxygen demand during the grow-out period.

The present study was conducted under a single stocking density, one culture season and a specific pond configuration. Consequently, the findings should be interpreted within these experimental conditions, and caution should be exercised when extrapolating the results to other production systems, climatic regions or culture intensities. Future studies should evaluate the combined aeration system under different stocking densities, pond sizes, seasonal conditions and energy optimization scenarios to further assess its long-term technical and economic performance.

Author Contributions

Mithun Roy: conceptualization, methodology, investigation, data curation, formal analysis, visualization, writing – original draft. **Md. Asaduzzaman**: methodology, writing – review and editing, supervision. **Debasish Saha**: data curation, formal analysis, writing – review and editing, supervision. **Md Rakeb-Ul Islam**: data curation, validation, supervision. **David C. Little**: conceptualization, writing – review and editing. **Richard Newton**: writing – review and editing. **Abu Tweb Abu Ahmed**: methodology, validation. **Faruk-Ul Islam**: conceptualization, validation. **Md. Asadujjaman**: conceptualization. **Muhammad Tanvir Hossain Chowdhury**: validation. **Abdullah-Al Mamun**: conceptualization, methodology, data curation, formal analysis, validation, writing – review and editing, supervision, project administration, funding acquisition.

Acknowledgements

The authors gratefully acknowledge the financial support provided by the Bangladesh Academy of Sciences (BAS) under the BAS-USDA Endowment Programme (5th Phase), titled 'Development of a model of intensive fish production through mechanization'. The authors sincerely thank AQUALENS Lab, Noakhali Science and Technology University (NSTU), Bangladesh, for providing pond facilities and technical support

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

for conducting the experimental work. The authors further thank all individuals who contributed to field assistance, data collection and technical support during the study.

Funding

This work was supported by the Bangladesh Academy of Sciences (BAS) under the BAS-USDA Endowment Programme (BUEP), 5th Phase, through the project Development of a model of intensive fish production through mechanization (Grant No. FI-4).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Abdel-Tawwab, M., A. E. Hagras, H. A. Elbaghdady, and M. N. Monier. 2014. "Dissolved Oxygen Level and Stocking Density Effects on Growth, Feed Utilization, Physiology, and Innate Immunity of Nile Tilapia, *Oreochromis niloticus*." *Journal of Applied Aquaculture* 26: 340–355. https://doi.org/10.1080/10454438.2014.959830.

Abou Zied, R. M. 2013. "Effect of Aeration Systems and Stocking Density on Growth Performance, Pond Yield and Economic Impacts of Nile Tilapia (*Oreochromis niloticus*) Reared in Earthen Ponds." *Abbassa International Journal for Aquaculture* 6, no. 1: 213–228. https://www.semanticscholar.org/paper/EFFECT-OF-AERATION-SYSTEMS-ANDSTOCKING-DENSITY-ON-Zied/e58797bcdecb135582300b72b0296682c4f2c3f0.

Abwao, J., J. Jung'a, J. E. Barasa, et al. 2023. "Selective Breeding of Nile Tilapia, *Oreochromis niloticus*: A Strategy for Increased Genetic Diversity and Sustainable Development of Aquaculture in Kenya." *Journal of Applied Aquaculture* 35: 237–256. https://doi.org/10.1080/10454438.2021.1958728.

Akinwole, A. O., A. B. Dauda, and T. Oredein. 2014. "Effect of Aeration on Selected Water Quality Parameters in Freshwater Fish Culture." *International Journal of Biological and Chemical Sciences* 8, no. 6: 2858–2865. https://doi.org/10.4314/IJBCS.V8I6.42.

Alemayehu, T. A., and A. Getahun. 2017. "Effect of Feeding Frequency on Growth Performance and Survival of Nile Tilapia (*Oreochromis niloticus* L. 1758) in a Cage Culture System in Lake Hora-Arsedi, Ethiopia." *Journal of Aquaculture Research & Development* 8: 479. https://doi.org/10.4172/2155-9546.1000479.

Arumugam, M., S. Jayaraman, A. Sridhar, et al. 2023. "Recent Advances in Tilapia Production for Sustainable Developments in Indian Aquaculture and Its Economic Benefits." *Fishes* 8, no. 4: 176. https://doi.org/10.3390/fishes8040176.

Ayoade, A. A. 2011. "Length-Weight Relationship and Diet of African Carp *Labeo ogunensis* (Boulenger, 1910) in Asejire Lake Southwestern Nigeria." *Journal of Fisheries and Aquatic Science* 6, no. 4: 472–478. https://doi.org/10.3923/jfas.2011.472.478.

Azab, A. M., H. M. Khalaf-Allah, A. E. Khattaby, A. S. Sadek, and M. O. Abdel-Ghany. 2018. "Effect of Stocking Density and Feeding Rate on Growth Performance and Total Production of Nile Tilapia, *Oreochromis niloticus* Reared in Earthen Ponds." *Egyptian Journal for Aquaculture* 8, no. 3: 33–54. https://doi.org/10.21608/eja.2018.31481.

Bolivar, R. B., E. B. T. Jimenez, R. M. V. Sayco, and R. J. Borski. 2013. "Supplemental Feeding of Nile Tilapia (*Oreochromis niloticus* L.) in Fertilized Ponds Using Combined Feed Reduction Strategies." In Better Science, Better Fish, Better Life. Proceedings of the Ninth International Symposium on Tilapia in Aquaculture, Shanghai, China, 22–24 April 2011, edited by L. Liping and K. Fitzsimmons, 268–274. Aquafish Collaborative Research Support Program. https://www.cabidigitallibrary.org/doi/full/10.5555/20133318803.

Boyd, C. E. 1973. "The Chemical Oxygen Demand of Waters and Biological Materials From Ponds." *Transactions of the American Fisheries Society* 102: 606–611. https://doi.org/10.1577/1548-8659(1973)102⟨606:TCODOW⟩2.0.CO;2.

Boyd, C. E. 1982. *Water Quality Management for Pond Fish Culture*. Elsevier. https://www.cabidigitallibrary.org/doi/full/10.5555/19821428342.

Boyd, C. E. 1995. "Deep Water Installation of a Diffused-Air Aeration System in a Shallow Pond." *Journal of Applied Aquaculture* 5, no. 1: 1–9. https://doi.org/10.1300/J028V05N01_01.

Boyd, C. E. 2001. *Water Quality Standards: Total Phosphorus*. Responsible Seafood Advocate, Global Seafood Alliance. https://www.globalseafood.org/advocate/water-quality-standards-total-phosphorus/.

Boyd, C. E. 2007. *Total Alkalinity and Total Hardness*. Responsible Seafood Advocate. Global Seafood Alliance. https://www.globalseafood.org/advocate/total-alkalinity-and-total-hardness/.

Boyd, C. E., and S. I. Martinson. 1984. "Evaluation of Propeller-Aspirator-Pump Aerators." *Aquaculture* 36, no. 3: 283–292. https://doi.org/10.1016/0044-8486(84)90243-6.

Boyd, C. E., E. L. Torrans, and C. S. Tucker. 2018. "Dissolved Oxygen and Aeration in Ictalurid Catfish Aquaculture." *Journal of the World Aquaculture Society* 49, no. 1: 7–70. https://doi.org/10.1111/jwas.12469.

Burad-Méndez, A., R. Domínguez-May, M. A. Olvera-Novoa, D. Robledo, and S. Salas. 2023. "Economic Analysis of Nile Tilapia (*Oreochromis niloticus*) Production Based on Farm Size and Number of Rearing Tanks." *Latin American Journal of Aquatic Research* 51, no. 5: 747–759. https://doi.org/10.3856/vol51-issue5-fulltext-3071.

Butuner, S. O. 2015. "Using History of Mathematics to Teach Volume Formula of Frustum Pyramids: Dissection Method." *Universal Journal of Educational Research* 3, no. 12: 1034–1048. https://eric.ed.gov/?id=EJ1083242.

Castilho-Barros, L., M. S. Owatari, J. L. P. Mouriño, B. C. Silva, and W. Q. Seiffert. 2020. "Economic Feasibility of Tilapia Culture in Southern Brazil: A Small-Scale Farm Model." *Aquaculture* 515: 734551. https://doi.org/10.1016/j.aquaculture.2019.734551.

Craig, S., L. Helfrich, D. D. Kuhn, and M. H. Schwarz. 2017. *Understanding Fish Nutrition, Feeds, and Feeding*. Virginia Cooperative Extension. http://hdl.handle.net/10919/80712.

d'Avanzo, C., and J. N. Kremer. 1994. "Diel Oxygen Dynamics and Anoxic Events in an Eutrophic Estuary of Waquoit Bay, Massachusetts." *Estuaries* 17: 131–139. https://doi.org/10.2307/1352562.

Deka, K., D. Bordoloi, A. J. Khound, M. J. Bharali, and R. Chelleng. 2022. "A Review on Aeration Process and Different Types of Aerators Used in Various Aquaculture Systems." *International Journal of Current Microbiology and Applied Sciences* 11: 353–358. https://doi.org/10.20546/ijcmas.2022.1106.039.

Djanuandra, A., T. I. Noor, and I. Nurahman. 2023. "Analysis of Tilapia Cultivation." *Jurnal Ilmiah Mahasiswa Agroinfo Galuh* 10, no. 1: 342. https://doi.org/10.25157/jimag.v10i1.8937.

Dupree, H.K., and Huner J.V., eds. 1984. *Third Report to the Fish Farmers: The Status of Warmwater Fish Farming and Progress in Fish Farming Research*. U.S. Fish and Wildlife Service. https://pubs.usgs.gov/publication/70007004.

Durigon, E. G., T. L. S. Schneider, S. Marasca, et al. 2023. "Compensatory Gain and Oxidative Response of Tilapia Rearing at High Densities in a Biofloc System and Transferred to Clear Water System." *Aquaculture* 577: 739984. https://doi.org/10.1016/j.aquaculture.2023.739984.

Ehiagbonare, J. E., and Y. O. Ogunrinde. 2010. "Physico-Chemical Analysis of Fish Pond Water in Okada and Its Environs, Nigeria." *African Journal of Biotechnology* 9, no. 36: 5922–5928. https://www.ajol.info/index.php/ajb/article/view/93002.

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

FAO. 2020. *The State of World Fisheries and Aquaculture 2020: Sustainability in Action*. FAO. https://doi.org/10.4060/ca9229en.

FAO. 2024. *In Brief to the State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*. FAO. https://doi.org/10.4060/cd0690en.

FAO. 2025. *Oreochromis niloticus. Cultured Aquatic Species Information Programme*. Fisheries and Aquaculture Division. https://www.fao.org/fishery/en/culturedspecies/oreochromis_niloticus.

Ferdoushi, Z., Z. P. Patwary, Y. Ara, and M. Rana. 2019. "Economic Analysis of Tilapia Farming in Some Selected Area of Dinajpur District: A Comparison Between Monoculture and Polyculture." *Journal of The Bangladesh Agricultural University* 17, no. 1: 117–121. https://doi.org/10.3329/JBAU.V17I1.40673.

Gonzaga dos Santos-Filho, L., S. Gil Alves Vieira-Santos, C. E. Lira dos Santos Silva, and R. C. Alves Vieira da Silva. 2017. "Utilização de Indicadores de Viabilidade Econômica na Produção de Tilápia (*Oreochromis niloticus*) em Sistema de Recirculação: Estudo de Caso de uma Piscicultura de Pequena Escala em parnaíba-pi." *Organizações Rurais e Agroindustriais* 18, no. 4: 304–314. https://doi.org/10.22004/ag.econ.265521.

Ighwela, K. A., A. B. Ahmed, and A. B. Abol-Munafi. 2011. "Condition Factor as an Indicator of Growth and Feeding Intensity of Nile Tilapia Fingerlings (*Oreochromis niloticus*) Fed on Different Levels of Maltose." *American-Eurasian Journal of Agricultural and Environmental Science* 11, no. 4: 559–563. https://www.idosi.org/aejaes/jaes11(4)11/17.pdf.

Jongjaraunsuk, R., and W. Taparhudee. 2022. "Weight Estimation Model for Red Tilapia (*Oreochromis niloticus* Linn.) From Images." *Agriculture and Natural Resources* 56, no. 1: 215–224. https://li01.tci-thaijo.org/index.php/anres/article/view/254018.

Klanjšček, J., S. Geček, and T. Legović. 2012. "Influence of Fish Feed Composition on Oxygen Utilization During Decomposition of Aquaculture Effluents." *Aquaculture Research* 43, no. 12: 1845–1860. https://doi.org/10.1111/J.1365-2109.2011.02994.X.

Lazur, A. M. 1996. *The Use of Potassium Permanganate in Fish Ponds*. University of Florida Cooperative Extension Service, Institute of Food and Agriculture Sciences (EDIS). https://ufdcimages.uflib.ufl.edu/IR/00/00/32/76/00001/FA03200.pdf.

Madenjian, C. M., G. L. Rogers, and A. W. Fast. 1988. "Predicting Nighttime Dissolved Oxygen Loss in Aquaculture Ponds." *Canadian Journal of Fisheries and Aquatic Sciences* 45, no. 10: 1842–1847. https://doi.org/10.1139/f88-216.

Magna, E. K., E. T. D. Mensah, F. N. Mabe, M. Johnson-Ashun, L. O. Konadu, and E. K. Appiah. 2023. "Profitability Analysis of Small-Scale Cage Aquaculture Farms in the Volta Lake of Ghana." *Aquaculture Research* 2023: 1–10. https://doi.org/10.1155/2023/1314660.

Majumder, T., P. Chowdhury, M. Shahjahan, and M. Rahman. 2018. "Effects of Population Density on Growth and Production of Tilapia in Monoculture." *International Journal of Agricultural Research, Innovation and Technology* 7: 49–56. https://doi.org/10.3329/ijarit.v7i2.35322.

Mallya, Y. J. 2007. *The Effects of Dissolved Oxygen on Fish Growth in Aquaculture*. United Nations University Fisheries Training Programme (UNU-FTP). https://www.grocentre.is/static/gro/publication/58/document/yovita07prf.pdf.

Mohan, M., B. P. Ch, G. S. Prasad, et al. 2022. "Application and Importance of Aeration System in Aquaculture Pond: A Review." *Asian Journal of Microbiology, Biotechnology and Environmental Sciences* 24: 370–376. https://doi.org/10.53550/ajmbes.2022.v24i02.027.

Mramba, R. P., and E. J. Kahindi. 2023. "Pond Water Quality and Its Relation to Fish Yield and Disease Occurrence in Small-Scale Aquaculture in Arid Areas." *Heliyon* 9, no. 6: e16753. https://doi.org/10.1016/j.heliyon.2023.e16753.

Munguti, J. M., R. Nairuti, J. O. Iteba, et al. 2022. "Nile Tilapia (*Oreochromis niloticus* Linnaeus, 1758) Culture in Kenya: Emerging Production Technologies and Socio-Economic Impacts on Local Livelihoods." *Aquaculture, Fish and Fisheries* 2, no. 4: 265–276. https://doi.org/10.1002/aff2.58.

Mustapha, M. K. 2017. "Comparative Assessment of the Water Quality of Four Types of Aquaculture Ponds Under Different Culture Systems." *Advanced Research in Life Sciences* 1, no. 1: 104–110. https://doi.org/10.1515/arls-2017-0017.

Nadiro, V. N., S. Andayani, M. S. Widodo, and N. Nurhalisa. 2023. "Different Stocking Density on Water Quality of Red Tilapia (*Oreochormis* sp) in Budikdamber System." *Jurnal Penelitian Pendidikan IPA* 9, no. 4: 2030–2035. https://doi.org/10.29303/jppipa.v9i4.3236.

Ng, W. K., and N. Romano. 2013. "A Review of the Nutrition and Feeding Management of Farmed Tilapia Throughout the Culture Cycle." *Reviews in Aquaculture* 5, no. 4: 220–254. https://doi.org/10.1111/raq.12014.

Phiri, F., and X. Yuan. 2018. "Economic Profitability of Tilapia Production in Malawi and China." *Journal of Aquaculture Research & Development* 9, no. 5: 1–6. https://doi.org/10.4172/2155-9546.1000535.

Policar, T., J. Křišťan, H. T. Thorarensen, et al. 2024. "Effects of Oxygen Levels and Temperature on Growth and Physiology of Pikeperch Juveniles Cultured in a Recirculating Aquaculture System." *Animal* 18, no. 11: 101347. https://doi.org/10.1016/j.animal.2024.101347.

Rahman, M. A. 2023. "Govt Raises Bulk, Retail Tariffs of Power Again." The Financial Express, February 1. https://epaper.thefinancialexpress.com.bd/?archiev=yes&arch_date=01-02-2023#.

Rahman, M. H., M. A. Alam, and Flura. 2022. "Assessment of the Comparative Growth Performance of Tilapia (*Oreochromis niloticus*) at Different Stocking Densities." *International Journal of Biological Innovations* 4, no. 1: 171–179. https://doi.org/10.46505/IJBI.2022.4119.

Rajts, F., and C. C. Shelley. 2020. *Guidelines for Managing Aeration and Water Quality in Fishponds in Bangladesh*. WorldFish. https://doi.org/10.13140/RG.2.2.25023.94885.

Ramesh, P., A. Jasmin, M. Tanveer, et al. 2024. "Optimizing Aeration Efficiency and Forecasting Dissolved Oxygen in Brackish Water Aquaculture: Insights From Paddle Wheel Aerator." *Journal of the Taiwan Institute of Chemical Engineers* 156: 105353. https://doi.org/10.1016/j.jtice.2024.105353.

Rana, K. J., and M. R. Hassan. 2013. "On-Farm Feeding and Feed Management Practices for Sustainable Aquaculture Production: An Analysis of Case Studies From Selected Asian and African Countries." In *On-Farm Feeding and Feed Management in Aquaculture*. FAO Fisheries and Aquaculture Technical Paper No. 583, edited by M. R. Hasan and M. B. New, 21–67. FAO. https://www.fao.org/4/i3481e/i3481e.pdf.

Rashid, I., and M. H. Mithun. 2020. "Guidelines for Freshwater Pond Management in Bangladesh." *Bangladesh Journal of Multidisciplinary Scientific Research* 2, no. 2: 1–9. https://doi.org/10.46281/bjmsr.v2i2.645.

Ridwanudin, A., V. Fahmi, and I. S. Pratama. 2018. "Growth of Spiny Lobster *Panulirus homarus* Fed With Moist Diet." *Oseanologi dan Limnologi di Indonesia* 3, no. 2: 95. https://doi.org/10.14203/oldi.2018.v3i2.165.

Samaddar, A., T. Ghosh, and D. K. Verma. 2024. "Global Diversification of Tilapia Production Techniques: Recent Overview—Part 1." *Journal of Advances in Biology & Biotechnology* 27, no. 7: 745–760. https://doi.org/10.9734/jabb/2024/v27i71034.

Shah, M. A. M., and B. A. M. Zain. 2013. "Novelty of Mechanical Surface Aerator Using Flexible Beam to Generate Dissolved Oxygen in Water." In *Advancements in Marine and Freshwater Sciences*. UMTAS. https://www.semanticscholar.org/paper/Novelty-of-Mechanical-Surface-Aerator-Using-Beam-to-Shah-Zain/683744cf9a11155f9bd859850454051e65d39295.

Shoko, A. P., S. M. Limbu, H. D. Mrosso, and Y. D. Mgaya. 2014. "A Comparison of Diurnal Dynamics of Water Quality Parameters in Nile Tilapia (*Oreochromis niloticus*, Linnaeus, 1758) Monoculture and Polyculture With African Sharp Tooth Catfish (*Clarias gariepinus*, Burchell, 1822) in Earthen Ponds." *International Aquatic Research* 6, no. 1: 56. https://doi.org/10.1007/s40071-014-0056-8.

Simon, T. P., S. L. Worden, and R. Morehouse. 2011. "Diel Patterns of Dissolved Oxygen and Selected Chemical Parameters in Three Lakes

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/aff2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Within Hoosier National Forest That Have Experienced Recent Fish Kill." *Proceedings of the Indiana Academy of Science* 120, no. 1/2: 45–51. https://journals.indianapolis.iu.edu/index.php/ias/article/view/21021.

Siwiec, T., M. M. Michel, L. Reczek, and P. Nowak. 2016. "The Influence of Aeration on the Change in Corrosiveness and Aggressiveness of Groundwater." *Water Science and Technology: Water Supply* 16, no. 2: 445–452. https://doi.org/10.2166/ws.2015.155.

Stickney, R. R., R. W. Hardy, K. Koch, R. Harrold, D. Seawright, and K. C. Massee. 1996. "The Effects of Substituting Selected Oilseed Protein Concentrates for Fish Meal in Rainbow Trout *Oncorhynchus mykiss* Diets." *Journal of the World Aquaculture Society* 27, no. 1: 57–63. https://doi.org/10.1111/j.1749-7345.1996.tb00594.x.

Sultana, T., M. M. Haque, M. A. Salam, and M. M. Alam. 2017. "Effect of Aeration on Growth and Production of Fish in Intensive Aquaculture System in Earthen Ponds." *Journal of the Bangladesh Agricultural University* 15, no. 1: 113–122. https://doi.org/10.3329/JBAU.V15I1.33536.

Thant, K. J. W., P. Thew, J. Pera, L. J. Baumgartner, and L. Seneviratha. 2025. "A Critical Review of Artificial Destratification Systems for Mitigating Water Stratification." *Environmental Advances* 21: 100649. https://doi.org/10.1016/j.envadv.2025.100649.

Toma, N. I., M. Mohiuddin, M. S. Alam, and M. M. Suravi. 2015. "An Economic Study of Small-Scale Tilapia Fish Farming in Mymensingh District of Bangladesh." *Journal of Agricultural Economics and Rural Development* 2, no. 3: 50–53. https://www.slideshare.net/slideshow/an-economic-study-of-smallscale-tilapia-fish-farming-in-mymensingh-district-of-bangladesh/54679084.

Vijayan, M. M., and T. J. Varghese. 1986. "Effect of Artificial Aeration on the Growth and Survival of Indian Major Carps." *Proceedings: Animal Sciences* 95: 371–378. https://doi.org/10.1007/BF03179371.

Welker, T. L., K. Overturf, and J. Abernathy. 2019. "Effect of Aeration and Oxygenation on Growth and Survival of Rainbow Trout in a Commercial Serial-Pass, Flow-Through Raceway System." *Aquaculture Reports* 14: 100194. https://doi.org/10.1016/j.aqrep.2019.100194.

Wurts, W. A., and R. M. Durborow. 1992. *Interactions of pH, Carbon Dioxide, Alkalinity and Hardness in Fish Ponds*. Southern Regional Aquaculture Center (SRAC). https://lee-phillips.org/Backyard/cache/464fs.pdf.

Xu, J., J. Wang, S. Lin, et al. 2023. "The Effect of Novel Aquaculture Mode on Phosphorus Sorption-Release in Pond Sediment." *Science of the Total Environment* 905: 167019. https://doi.org/10.1016/j.scitotenv.2023.167019.

Yamada, S., T. Amano, and H. Minagawa. 2005. "A Study for Distribution of Microbubbles and Effects of Oxygen Supplying Into Water." *Nippon Kikai Gakkai Ronbunshu B Hen (Transactions of the Japan Society of Mechanical Engineers, Part B)* 71, no. 5: 1301–1306. https://doi.org/10.1299/kikaib.71.1301.

Yaparatne, S., J. Morón-López, D. Bouchard, S. Garcia-Segura, and O. G. Apul. 2024. "Nanobubble Applications in Aquaculture Industry for Improving Harvest Yield, Wastewater Treatment, and Disease Control." *Science of The Total Environment* 931: 172687. https://doi.org/10.1016/j.scitotenv.2024.172687.

ZhongWen, J., Z. ZhongMing, W. SongJie, Y. ErMao, and H. AnKuan. 2010. "Preliminary Study on Improvement of Pond Water Quality by Bottom Aeration." *South China Fisheries Science* 6, no. 6: 20–25. https://doi.org/10.3969/j.issn.1673-2227.2010.06.004.

Zhu, D., X. Cheng, D. J. Sample, and M. N. Yazdi. 2020. "Effect of Intermittent Aeration Mode on Nitrogen Concentration in the Water Column and Sediment Pore Water of Aquaculture Ponds." *Journal of Environmental Sciences* 90: 331–342. https://doi.org/10.1016/J.JES.2019.11.022.

26938847, 2026, 5, Downloaded from https://onlinelibrary.wiley.com/doi/10.1002/af2.70322 by University Of Stirling, Wiley Online Library on [10/11/2026]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License