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Cascade and Vertical Aeration Systems in Aquaculture: Current Status, Design Hypotheses and Future Needs

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ABSTRACT: Aquaculture being one of the fastest growing food production sectors still possesses a significant challenge for maintaining optimal dissolved oxygen (DO) levels in farmed ponds particularly in intensive culture systems. Many times, the oxygen demand of the cultured organisms is not met by the natural aeration processes. Hence, the artificial aeration comes into play to support health, growth and productivity of the cultured organisms. Aeration methods like stepped cascades, perforated trays and shower systems have been studied for their ability to improve oxygen transfer by increasing air and water interaction. Cascade aerators are noted for their simplicity and low cost, making them ideal for small-scale farmers, however shower aeration systems show better performance than cascade aerators due to geometric optimization of designs. This review primarily discusses about the importance of cascade aerators and vertical aeration systems used in aquaculture practices highlighting the principle, design, efficiency and their further improvements suiting to the aquaculture practices. Though having a brief progress in research, there are still lack of understanding about the design performance, cost-effectiveness and practical feasibility of these systems under different pond aquaculture conditions. Comparative analysis of reported Standard Aeration Efficiency (SAE) (≈1.2-4.98 kg O_2/kWh) and Standard Oxygen Transfer Rate (SOTR) values among different cascade aerators, alongside case studies from wastewater and aquaculture applications, is used to identify factors governing aeration efficiency, scale limitations and field-level constraints. Building on these insights, the study discusses the development and pond-scale testing of AICRP on PEASEM, centre at ICAR-CIFA vertical aeration prototypes: cascade aerators and shower-based towers, that achieved 33-40% increase in pond DO and demonstrated their suitability for aerating 0.12 ha ponds with relatively low capital cost. The review contributes an integrated conceptual framework for next-generation vertical aeration towers that combine cascade and shower principles, enable continuous water recirculation and can be coupled with solar power and sensor-based automation to minimize energy use while maintaining optimal DO. By explicitly addressing the challenges of energy efficiency, design optimization, scalability and real-pond validation, this work outlines a pathway for replacing or complementing conventional mechanical aeration with cost-effective, environmentally sustainable gravity-driven systems in intensive aquaculture.

Keywords: Aerator efficiency, Cascade aerator, Dissolved oxygen, Pond aeration, Shower aeration system, Vertical aeration towers.

INTRODUCTION

Aquaculture is emerging as one of the fastest growing sectors of the global fisheries. Recent advancements in aeration technology have significantly boosted the efficiency of the fish farming practices. Aeration through natural diffusion of oxygen into the water bodies particularly in the intensive aquaculture systems is insufficient to maintain optimal dissolved oxygen (DO) levels for the culture organisms. Following these conditions artificial aeration methods based on the utilization of external devices and processes to enhance water oxygenation resulting in optimal DO concentrations maintained in the system have been studied by various researchers (Kumar *et al*., 2013; Roy *et al*., 2017; Ochoa *et al*., 2022).

Dissolved oxygen (DO) is a critical factor of the aquacultural practices as it influences the health and survival of aquatic organisms. In freshwater aquaculture practices, insufficient DO levels become a major constraint on the aquatic organisms particularly in intensive aquaculture systems. At depleted DO levels in the system reduced fish growth and lesser production rates affects the overall sustainability and yield from culture operations (Sultana *et al*., 2017; Xiao *et al*., 2020; Yadav *et al*., 2021). Oxygen is a fundamental element required for the survival and physiological health of aerobic life forms. Within aquatic ecosystems, it serves as a vital component for respiration, however, its availability is often limited due to its low solubility in water. The concentration of oxygen in these environments is determined by several interacting variables, including atmospheric diffusion, fluctuations in water temperature and the oxygen released by aquatic vegetation during photosynthesis. These factors collectively determine the dissolved oxygen concentration available for the aquatic organisms (fish) for utilization (Burke *et al*., 2022). The DO levels needed to be checked and maintained as reduced levels of dissolved oxygen concentration results in stress, lower feeding response, disease susceptible and greater mortality rates of cultured species (Boyd and Hanson, 2010; Boyd *et al*., 2018). Hence, aeration becomes a necessity as it elevates the dissolved oxygen (DO) concentrations in the systems, ensures better fish productivity and maintaining overall fish health (Boyd and McNevin 2021; Ariadi *et al*., 2023; Ramesh *et al*., 2024). Aerators use in aquatic systems aids in maintaining the DO levels well above 5.0 mg/l, the optimum concentrations for aquacultural practices (Cheng *et al*., 2019).

Aeration of water bodies can be achieved *via*. injecting air directly into the water (Roy *et al*., 2017; Boyd *et al*., 2018; Roy *et al*., 2021a, b, c). The process of aeration increases the concentration of dissolved oxygen in the water bodies. This process is also effective for removal of harmful dissolved gases like CO_2, H_2S, and volatile organic compounds from the water bodies (Du *et al*., 2020). The two major techniques employed for aeration to improve DO levels of aquatic environments are natural aeration and artificial aeration (Tien *et al*., 2019; Nguyen *et al*., 2021). Increase of DO levels through natural aeration can be achieved through photosynthesis by aquatic plants and atmospheric diffusion on the water surface. Natural aeration also possesses a challenge since DO concentrations generally decrease at night, which can adversely impact the respiration and physiological processes of cultured organisms (Boyd 1998; Tanveer *et al*., 2018). With increasing adoption of intensive farming practices, natural aeration is not itself sufficient for maintaining DO levels for increasing aquaculture productivity. To address these issues artificial aerators have become widely used in aquaculture practices to compensate the greater demands of DO (Roy *et al*., 2021a, b, c).

Artificial aeration system enhances the air to water interaction interface area resulting in a greater amount of diffusion of O_2 from the air into the water surface by stirring or agitating it. Artificial aeration systems are generally categorized into splash aerators and gravity aerators. They operate based on three fundamental mechanisms: (1) aeration achieved by projecting water into the air, *i.e.,* paddle wheel aerators, vertical pumps, spiral aerators and pump sprayers; (2) aeration through the injection of air into water, *i.e.,* propeller aspirators and diffuser aeration systems; and (3) aeration caused by water falling from a height, *i.e.,* cascades, weirs and plate setups (Zhang *et al*., 2020; CIFA, 2024; AICRP on PEASEM, 2024, 2025). In aquaculture, aeration represents one of the most energy-intensive operations, contributing significantly to both high overhead costs and a larger ecological footprint (Jamroen, 2022). When aeration systems are poorly optimized, they lead to excessive power consumption and inconsistent oxygen levels throughout the water column. Such inefficiencies can jeopardize fish health, increase mortality rates and ultimately diminish total harvest yields (Bahri *et al*., 2019; Palya and MacPhee, 2023). These challenges highlight the need for more sustainable aeration technologies that optimize energy efficiency while ensuring adequate oxygenation. Therefore, a method for selecting aerators is crucial that are well-designed to provide a consistent and sufficient oxygen supply in intensive aquaculture systems while keeping energy expenditure costs at a minimum (Tien *et al*., 2019).

A vertical aeration system is a mechanical or hydraulic arrangement designed to circulate water vertically above the pond surface. This system ideally set on the principle of mass transfer of atmospheric oxygen into pond surface to maintain adequate DO levels essential for aquatic organisms. Vertical aeration can be implemented as shower, cascade, trickling columns and other gravity-based aeration as it increases DO content, promotes water mixing and removes excess dissolved gases from the water. This process is widely adopted and practiced in both pond culture system and recirculating aquaculture systems. Cascade aerators have been identified as both effective and cost-efficient for most aquaculture practices (Singh, 2010; Roy *et al*., 2020b; AICRP on PEASEM, 2025). In these systems, water flows over a series of steps, breaking into droplets upon impact, which facilitates the entrainment of air from the atmosphere into the water (Roy *et al*., 2022). To enhance the aeration performance of cascade aerators, numerous studies and experiments have been conducted by researchers (Baylar *et al.*, 2006; Baylar *et al.*, 2010; Singh, 2010; Kumar *et al*., 2013; Roy *et al*., 2020a; AICRP on PEASEM, 2025). Shower aerators are designed with horizontally arranged showers fitted into pipelines positioned about 1.0 m above the water surface (AICRP on PEASEM, 2024; CIFA, 2024). A centrifugal pump is used to recirculate water by lifting it to a height and then it is released as fine spray droplets. These fine droplets augment the oxygen uptake from the atmosphere through adsorption. The aeration efficiency largely depends on the droplet surface area exposed to air, which is influenced by the shower nozzle size and the degree of water dispersion (Roshan *et al*., 2022). In both systems the principle of oxygen transfer is based on the dispersion of water droplets into air which is allowed to free-fall from a certain height, efficiently carries oxygen from atmosphere through the process of adsorption, resulting in the aeration of ponds. The flowing water increases its exposure to air as it spreads over a larger surface area that enables it to absorb oxygen before entering the tank (El-Zahaby and El-Gendy 2016).

This study provides a thorough evaluation of vertical aeration technologies, majorly focusing on their energy efficacy and proposing a process that integrates selection of aerator system, automation and the use of renewable sources of energy. It offers an extensive overview featuring practical executions and actual case studies. This work contributes to the creation of economical and environment friendly aeration systems by addressing both technological and operational challenges. The purpose of this review is to assess the energy efficiency of existing vertical and cascade aeration technologies. It presents a comparison based on cost-effectiveness, performance and applicability and identifies important factors that influence their use in aquaculture. The study additionally investigates its possible applications for sustainable aquaculture methods and provides an integrated model framework for future developments in vertical and cascade aeration systems. The implementation of such innovations is expected to possess lower operational and maintenance costs while addressing issues related to low dissolved oxygen levels, high volatile organic compound concentrations, nitrogenous waste accumulation and water stratification simultaneously. These innovations can serve as energy-efficient alternatives to different mechanical aerators for maintaining the optimum DO levels in aquaculture ponds.

Principles of aeration in aquaculture

Increased oxygenation is essential for preserving water quality because it makes it easier to get rid of dangerous gases like carbon dioxide (CO_2) and ammonia (NH_3), which may adversely affect fish survival, growth and health if they build up (Eze and Ajmal 2020; Roy *et al.*, 2020a, 2022). Other benefits of aeration are preventing thermal stratification and maintaining uniform temperature distribution throughout the water column that is conducive for fish growth (Wongkiew, 2018; Silalahi *et al.*, 2022). In ponds where extensive culture is practiced with a lower stocking density (<10 fish/m² of water surface), aerators are generally not required. However, carrying out partial water exchange at advanced stages ranging from about 10-20%, can yield better results (Jescovitch *et al.*, 2017). Even in ponds with relatively higher stocking densities (10–12 fish/m²) and a production target of 2.0-2.5 tons per hectare per year, aerators may still not be essential. In such cases water exchange becomes important aspect initially at 5% and gradually rising up to 50% by harvest (Soderberg, 2017; Roy *et al.*, 2022). When stocking density levels increases then aeration becomes essential for species survivability (around 15 fish/m² or more).

For a typical pond of 4,000–5,000 m², four paddlewheel aerators of 1 kW each are generally required (Boyd, 1998; Boyd and Tucker 2012; Roy *et al.*, 2022). In such systems, daily water exchange of 20–30% is also necessary. At very high densities (approximately 100 fish/m²), a larger number of aerators is needed. For this type of intensive culture, pond sizes are usually smaller, between 500 and 1,000 m², and require two to four aerators depending on factors such as feeding rate, pond size and stocking density (Boyd, 1998). Water exchange demand in these ponds is extremely high, ranging from 50% to 100% based on the stage of culture. Feed requirement is also substantial, typically 40–50 kg per acre per day (Jescovitch *et al.*, 2017).

Dissolved oxygen plays a crucial role in aquaculture by influencing the metabolism, immune response and general health of fish. The amount of available oxygen directly impacts how efficiently fish convert feed, with low dissolved oxygen levels causing stress, slower growth and greater chances of mortality (Espinal and Matulić 2019; Arepalli and Naik 2024a, b, c). Maintaining enough dissolved oxygen levels supports beneficial microbial processes. It also helps breakdown organic matter and preserves water quality (Ion *et al.*, 2022). Therefore, monitoring oxygen levels and controlling aeration effectively are essential for sustainable aquaculture practices.

Theoretical considerations for mass oxygen transfer

The basic principle of aeration is founded on the classical two-film theory introduced by Lewis and Whitman in 1924. This theory states that the rate of gas transfer is governed by a mass transfer coefficient and is directly proportional to the concentration difference between the gas and liquid phases. Consequently, the transfer of oxygen into water can be described using the following differential equation:

$$\frac{dC}{dt} = K_L a\,(Cs - Co) \qquad (1)$$

In this context, C (mg/l) represents the dissolved oxygen concentration at a given time t, C_s (mg/l) denotes the equilibrium oxygen concentration in the liquid phase, and C_o (mg/l) indicates the initial dissolved oxygen concentration. The term K_La (h^{-1}) refers to the overall oxygen transfer coefficient of the aeration system. By integrating Equation (1), Equation (2) is derived, which enables the determination of the overall mass transfer coefficient K_La with respect to the total liquid volume in the system (Al-Ahmady, 2011; Al Ba'ba'a and Amano 2017).

$$ln(Cs - Ci) = K_L a_T \times t \qquad (2)$$

Here, C_i (mg/l) denotes the dissolved oxygen concentration at time t; K_La_T (h^{-1}) represents the overall oxygen transfer coefficient at a given temperature T °C; and t indicates the elapsed time from the start of the experiment. The value of K_La_T is determined from the slope of the regression line obtained by plotting ln $(Cs-Ci)$ against time (t). The coefficient K_La_T is then adjusted to its standard value at 20°C, denoted as K_La_{20}, using the following relationship (Stenstrom and Gilbert 1981; Shelton and Boyd 1983):

$$K_L a_{20} = K_L a_T / \theta^{(T-20)} \qquad (3)$$

In this equation, K_La_{20} (h^{-1}) represents the overall oxygen transfer coefficient standardized to 20°C, while θ is the temperature correction factor, which has a value of 1.024 for clean water.

The Standard Oxygen Transfer Rate (SOTR), which determines the amount of oxygen transferred into water over an established amount of time, and the Standard Aeration Efficiency (SAE), which demonstrates how well oxygen moves from the aerator to the water in relation to the energy used, are the two primary performance indicators that are frequently employed to measure aeration efficiency (Mulyadi and Yunus 2019; Mulyadi *et al.*, 2022).

The SOTR is defined as the total amount of oxygen transferred to a given volume of water by an aeration device within a fixed time under standard conditions. These standard conditions specify the use of clean tap (potable) water with an initial dissolved oxygen concentration of zero, maintained at 20°C and exposed to uniform atmospheric pressure at the water surface (ASCE, 2007). The SOTR can be calculated using the following equation:

$$SOTR = K_L a_{20} \times (Cs_{20} - Co) \times V \qquad (4)$$

In this equation, SOTR represents the standard oxygen transfer rate (kg O_2/h), Cs20 denotes the dissolved oxygen saturation concentration (mg/l) at 20°C, and C0 is the initial dissolved oxygen concentration (mg/l), typically assumed to be zero. V indicates the water volume in the tank or pond (m^3), and the factor 10^{-3} is used to convert g to kg. The Standard Aeration Efficiency (SAE) expresses the amount of oxygen transferred per unit of energy consumed (Laws and Malecha 1981; Lee *et al.*, 2001) and is computed using the following relationship:

$$\text{SAE (kg } O_2\text{/kWh)} = \text{SOTR / P} \qquad (5)$$

where, P is power supplied to the aerator.

Power (kW) supplied to aerator can be calculated by the following equation (Kumar *et al.*, 2013):

$$P = (9.810 \times H \times Q) / \eta \qquad (6)$$

where, H is the total head equal to the total height of the cascade (m),

Q is the discharge (m^3/s) and

η is the efficiency of the submersible pump.

The parameters calculated using different equations should be considered for evaluating the effectiveness of aeration through aerators. Aeration systems with higher Standard Aeration Efficiency (SAE) provide more effective oxygen transfer while consuming less energy (Ramesh *et al.*, 2024). However, overall aeration efficiency depends not only on SAE, but also on the uniformity of oxygen distribution throughout the pond. Systems that maintain consistent dissolved oxygen levels across all depths operate more efficiently than those that create localized zones of elevated oxygen concentration, which can result in unnecessary energy expenditure (Sujatha *et al.*, 2023; Arepalli and Naik, 2024a, b, c).

Gravity aeration: an overview

Using gravity-driven water flow between culture units is an effective way to increase dissolved oxygen in aquaculture systems. It uses the natural slope of the facility, allowing water to move without any energy input. As water flows downward, it traps air and forms bubbles. These bubbles release oxygen into the water, improving dissolved oxygen levels and supporting better fish growth.

Cascade aeration systems are also referred to as gravity aeration systems (Baylar *et al.*, 2009; Rathinakumar *et al.*, 2017; Roy *et al.*, 2021a), have special design features that are ideally suited for use in small-scale commercial aquaculture tanks and provide a number of benefits. The free-fall of the water in these systems results in extremely high levels of turbulence created by the cascading water column between the different levels of the aerator, creating shear zones at the surface of the water where the water meets the air. This action generates air bubbles of various sizes, which helps facilitate the transfer of molecular oxygen (O_2) into the water as the bubbles float freely in the water, ultimately enhancing the efficiency of the aeration process.

Types of cascade aeration system

Cascade aeration systems have become the center of extensive studies with a focus on their operational performance and functional mechanisms. The discussion which follows summarizes observational studies along with empirical results from a number of significant academic databases.

Stepped cascade aerator. Stepped cascades are used to promote air circulation and disperse rapid water streams (Chanson and Toombes 2002). While water flows over multiple stages, the turbulence generates over the water surface that causes the air-water interface to be altered, which helps the transfer of oxygen. Additionally, this technique helps in the removal of a number of undesirable dissolved materials from the water, such as carbon dioxide, hydrogen sulfide, methane and chlorine (Baylar and Emiroglu 2005).

Circular stepped cascade aerator. The main aeration setup comprises a pump and a circular stepped cascade that ensures uniform distribution of water across successive tiers before it reaches the circular basin at the base of the cascade. The pump, fitted with a control valve, is positioned below the circular stepped cascade and regulates the water flow through the system (Singh, 2010). The system is so designed that each tier of the circular stepped cascade includes multiple circular stages, enabling a smooth and evenly distributed downward flow of water across the tiers, while flow regulation is efficiently managed by the pump–valve arrangement beneath the structure.

Pooled circular stepped cascade aerator

An improved circular stepped cascade aerator developed by Kumar *et al.* (2013) is known as the pooled circular stepped cascade (PCSC). Each stage in the PCSC has barriers, and the separation between these barriers is adjusted for improved performance. Over the PCSC, water flows in a zigzag pattern, increasing the amount of dissolved oxygen in the body of water. It is expected that this design would increase aeration efficiency and oxygen transfer rates. Furthermore, Kumar *et al*. (2013) determined the most suitable geometric parameters to use as a standard for forthcoming studies that seek to enhance aerator performance.

Perforated cascade tray aerator

A tray aerator is helpful in wastewater or aquaculture water treatment. It looks like a section of a part, wherein water is pumped by means of a submersible pump *via*. a riser pipe to the highest point of the segment, and water streams falling down due to gravitational force over a progression of tray found one underneath the other. The water is uniformly circulated all over the perforation of each and every tray until reaching the level of the water body. This, in turn, ensures a big contact surface between the air and the water (Eltawil and Elsbaay 2016; Roy *et al*. 2020a). The comparative analysis on performance of different cascade aerators based on aeration efficiency and oxygen transfer rate was tabulated and presented in Table 1.

Table 1: Comparison of aeration efficiency and oxygen transfer characteristics among cascade aerators.

Type of cascade aerators used	Aeration efficiency (kg O_2/kWh)	Oxygen transfer rate (kg O_2/h)	References
Cascade aerator	1.2 – 2.3	0.6 – 2.0	Chesness and Stephens (1971)
Inclined cascade	0.7 – 0.9	0.02 – 0.069	Doley and Kumar (2015)
Circular stepped cascade	2.16 – 2.70	0.123	Singh (2010)
Pooled circular stepped cascade	2.43 – 3.23	0.143	Kumar *et al.* (2013)
Perforated pooled circular stepped cascade	4.564	0.346	Roy *et al*. (2022)
Rectangular Stepped cascade	0.89	0.90	Moulick *et al.* (2010)
Perforated cascade tray	1.45	0.168 – 0.249	Roy *et al*. (2020b)

Current status of application of cascade aerators in aquaculture practices

Cascade aeration has emerged as a widely adopted technique in aquaculture, primarily for improving dissolved oxygen levels and maintaining water quality. The use of cascade aerators in aquaculture has been extensively studied, with researchers focusing on their capacity to enhance oxygen transfer, improve water circulation and support optimal fish growth. Several design modifications and structural innovations have been proposed, leading to variations in efficiency depending on species cultured, pond characteristics and management practices.

This section reviews the current applications and key findings related to cascade aerators in aquaculture. Chesness and Stephens (1971) reported that cascade aerators achieved maximum standard aeration efficiencies (SAE) ranging between 1.2-2.3 kg O_2/kWh. In a case study by Doley and Kumar (2015), an inclined cascade aerator can achieve specific aeration efficiency (SAE) values comparable to those of a rectangular stepped cascade aerator, provided that the recommended number of steps is properly designed to ensure effective air entrainment into the water at the required flow rate.

Kumar *et al.* (2013) developed a floating aeration system known as the pooled circular stepped cascade (PCSC), which operates by using gravity to facilitate water circulation in aquaculture ponds. Their study examined and optimized several key dimensionless geometric parameters influencing the system's efficiency, including the number of steps (N), the ratio of cascade height to bottom radius (H/Rb), the proportion of the step circumference equipped with enclosures (Pe) and the number of enclosures per step (Ne). Aeration experiments were performed across a range of flow rates (Q) to establish predictive models for evaluating PCSC aeration performance under varying operational conditions, using the optimized design (N = 6, H/Rb = 0.25, Pe = 20%, Ne = 9). Based on estimated brake horsepower (BHP), the prototype attained a standard aeration efficiency (SAE) between 2.43 and 3.23 kg O_2/kWh.

Roy *et al*. (2020b) investigated the performance of a perforated tray aerator (PTA) and, using dimensional analysis, identified several key non-dimensional parameters influencing its design. These parameters included the number of trays (n), the ratio of tray width to total aerator height (W/H), the ratio of perforation diameter to aerator height (d/H) and the ratio of tank water volume to the cube of aerator height (V/H^3). The findings revealed that a three-tray configuration provided the highest performance, corresponding to optimized parameters of $W/H = 0.665$, $d/H = 1.85 \times 10^{-4}$ and $V/H^3 = 312.50$. Under these conditions, the maximum standard aeration efficiency (SAE) achieved was 1.45 kg O_2/kWh.

Roy *et al.* (2021a) introduced a novel aeration device known as the perforated pooled circular stepped cascade (PPCSC) aerator, which offers greater efficiency than conventional aerators owing to its reduced power requirements. When evaluated based on the motor's power output, the PPCSC achieved substantially higher standard aeration efficiency (SAE), ranging from 3.36 to 4.98 kg O_2/kWh, compared with traditional aeration systems. The design incorporates multiple chambers that constitute more than half of the structure, enabling application across various aquaculture pond types without maintenance needs, as the system contains no moving components. In contrast, Singh (2010) reported considerably lower SAE values for conventional circular stepped cascade (CSC) aerators, ranging from 2.16 to 2.70 kg O_2/kWh.

The study by Costa *et al*. (2025) evaluated the effectiveness of gravity-based aeration using a cascade aerator installed downstream of constructed wetlands and upstream of a recirculating aquaculture pond. The designed system consisted of seven bucket-shaped stages connected through a network of pipes and hydraulic components, with a vertical drop of 25 cm between successive buckets. Each bucket had a distinct effective volume, averaging around nine liters. The cascade aerator demonstrated a standard oxygen transfer rate (SOTR) of 0.0036 kg O_2/h and standard aeration efficiency (SAE) of 1.19 kg O_2/kWh. These findings suggest that, relative to traditional aeration systems, cascade aerators offer a cost-effective approach for oxygenation in small-scale aquaculture ponds. Roshan *et al*. (2022) evaluated the performance of a shower aeration system (SAS) installed in a tank measuring 2.0 × 4.0 × 1.5 m. The study aimed to identify the optimal radius of curvature (r) of the SAS, which was varied at 0, 5, 10, 15 and 20 mm, while keeping the number of holes (n), water fall height (H), hole diameter (d), aeration volume (V) and flow rate (Q) constant. The results showed that the system with a 10 mm radius of curvature achieved the highest performance. In addition, the study examined the influence of geometric characteristics on aeration efficiency. Optimization of these design parameters led to notable performance gains, with maximum SAE and NDSAE values of 1.4429 kg O_2/kWh and 15.914 $\times 10^6$, respectively.

In a study by Omofumi and Esan (2023), a cascade aerator was developed to enhance water quality by increasing oxygen levels, which in turn boosted fish stock density which was a major challenge faced by low-income fish farmers in Nigeria. It operates through a sequence of steps that water cascades over, resembling the flow of a stream. The main components included a half-horsepower electric motor pump as the driving force and a cascade system (300 × 100 × 50 mm) with eight steps, totalling 1200 mm in length, constructed from stainless steel. This was mounted on a mild steel collector basin and supported by galvanized angle iron. Experimental results showed that the overall oxygen transfer coefficient ranged between 5.15-8.21 hr^{-1}, the SAE was 0.11-0.21 kg O_2/kW/hr, and the standard oxygen transfer rate varied within 0.04-0.08 kg O_2/hr. The design highlights the importance of vertical aeration systems in aquaculture.

Being constructed entirely of static components, it provides notable benefits such as minimized maintenance expenses and reduced energy requirements when compared to conventional aeration systems (Singh, 2010).

Design and development of different types of aerators at ICAR-CIFA

Cascade aerator for fish rearing ponds. A cascade aerator has been designed and developed at ICAR-AICRP on PEASEM, Bhubaneswar centre for use in pond culture system for increasing oxygen content in water (AICRP on PEASEM, 2025). The designed cascade aerator used four round fibre reinforced plastic (FRP) trays of increasing diameter from top to bottom to maximize air–water contact. Top (first) tray was with 0.5 m dia. (60 holes of 8 mm dia.); second tray 1.0 m dia. (120 holes); third tray 1.5 m dia. (180 holes) and the bottom (fourth) tray 2.0 m dia. (240 holes). The gap between the trays was kept 500 mm. Water circulation was provided by a compact submersible pump measuring 40 × 20 × 16 cm, weighing 4 kg, with a discharge capacity of 5000 LPH and a maximum water head of 5 m through a 1.0” outlet.

The structural stability and flotation of the aerator were ensured using 6.0” PVC pipe floats, which collectively generated a buoyant force of approximately 56 kg, sufficient to balance the aerator’s weight and operational load. This configuration provided an efficient and stable setup for enhancing water aeration performance.

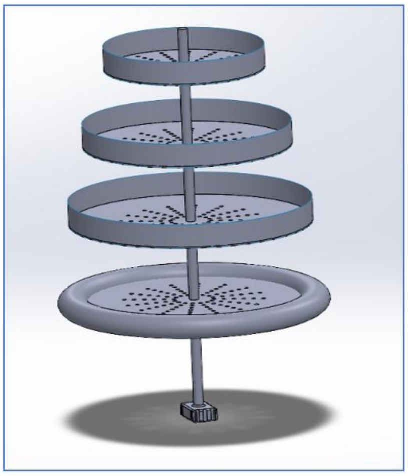

Fig. 1. Schematic diagram of cascade aerator.

It has been tested in pond conditions to improve water quality by increasing dissolved oxygen through splashing and surface contact. The aerator was exactly placed at the middle of the 0.12 ha pond (L 200 ft x B 65 ft) and to measure the effect on aeration in pond, markers (sampling points) were provided at 10 ft intervals on both sides of the aerator. The effect of aeration was measured up to 50 ft on both sides of the aerator against the control (extreme ends of the pond).

The test results highlighted the efficiency of the aerator as the DO concentrations at the sampling points increased with the increase of duration of the aerator operation.

As distance of sampling points increased from the aerator, the DO concentration decreased, but the values were above the control concentrations. From the data analysis, the increase of oxygen content in the water was found up to 40% higher than the control. A single developed aerator is found sufficient for aeration of a 0.12 ha pond. The cost of the aerator was estimated to be Rs 28,000=00 (approx.).

Design and development of vertical aeration tower

A vertical aeration tower of height 3.0 m, having a flow rate of 72.66 l/min with 14 showers was designed and developed at ICAR-AICRP on PEASEM centre at Bhubaneswar (AICRP on PEASEM, 2024).

Calculation of the Flow Rate (Q) of the Pump:

$$Q = \frac{P}{\rho \times g \times H}$$

Where: P is the power in watts (373 watts)

ρ is the density of water (approximately 1000 kg/m³)

g is the acceleration due to gravity (approximately 9.81 m/s²)

H is the head in meters (22 meters)

Plugging the values: $Q = \frac{373}{1000 \times 9.81 \times 22} = 0.00173$

This means the pump delivers about 0.00173 cubic meters per sec.

Converting flow rate to liters per minute (103.8 liters per minute), the efficiency of motor in terms of flow rate at 70% level is 103.8 × 0.7 ≈ 72.66 liters per minute.

Estimation of number of showers:

A typical shower uses between 5 to 10 liters per minute.

For a rough estimate: If each shower uses about 7.5 liters per minute, then:

Number of showers = 103.8/7.5=13.84 ≈ 14

At 70% efficiency, 72.66/7.5 = 9.688 ≈ 10

Therefore, the pump can support 10-14 showers simultaneously, depending on their flow rates and duration.

Total weight of aerator structure was 45.57 kg excluding base frame.

The cost of the aerator was estimated to be Rs 28,500=00 (approx.).

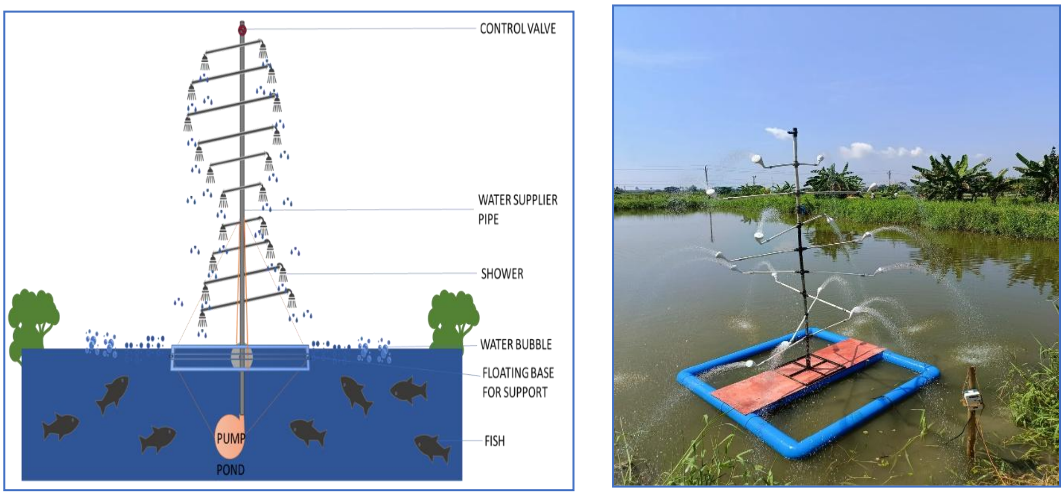

Fig. 2. Schematic diagram of shower aerator and its development for pond.

For testing the vertical aeration tower was placed at the middle of the 0.12 ha (L 200 ft x B 65 ft) pond, which ensured the total aeration of the pond water. The aerator constantly agitated the water surface resulting in the formation of ripples in the pond. Hence, to measure the effect of aeration in pond, markers (sampling points) were provided at 10 ft intervals on both sides of the aerator. The effect of aeration was measured up to 50 ft on both sides of the aerator against the control (extreme ends of the pond). The dissolved oxygen content and temperature of the water were recorded at each sampling points. From the data analysis, the increase of oxygen content in the water was found up to 33% higher than the control. A single developed aerator is found sufficient for aeration of a 0.12 ha pond.

Vertical aeration towers in planning stage at ICAR-CIFA

The other vertical aeration towers conceptualised and to be designed for fish rearing ponds enhancing oxygen transfer efficiency of the aerator is under process. The unit has a maximum diameter of 2.0 m and extends 3.0 m above the water surface, with a central 2.0” diameter pipe connected to multiple 1.0” diameter branch pipes for uniform water distribution. A submersible pump measuring 40 × 20 × 16 cm and weighing 4 kg delivers 5000 LPH at a maximum head of 5 m through a 2.0” outlet, ensuring adequate water lifting and flow. Structural buoyancy and stability are maintained using 6.0” PVC pipe floats, which provide a net buoyant force of 250 kg after accounting for all operational weights.

These configurations are to be designed with a primary objective of ensuring continuous recirculation of pond water, effective gas exchange and improved water quality to support healthy fish growth and pond productivity. By integrating efficient hydraulic design with cascade and shower principles, the hypothesised system ensures enhanced oxygen dissolution, improved water quality and sustainable fish rearing conditions.

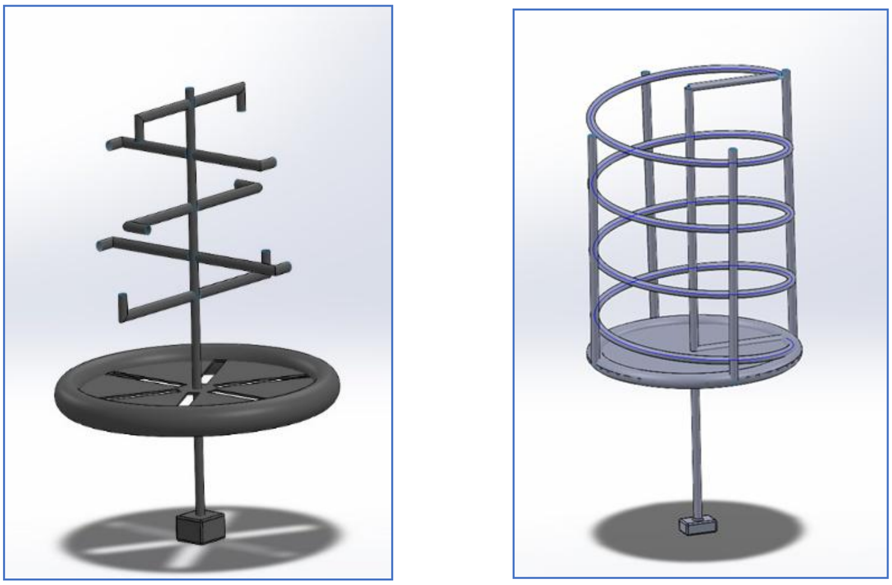

Fig. 3. Schematic representation of vertical aeration towers in planning stage.

CONCLUSION

This review has comprehensively examined the role of artificial aeration systems in aquaculture, emphasizing their importance in maintaining dissolved oxygen levels for sustainable fish farming. By analyzing the principles, design characteristics, and performance of various aeration methods, the study underlines how technological innovations can address challenges related to oxygen depletion, water quality and energy efficiency in intensive aquaculture practices. It also highlights the scope for integrating cost-effective and environmentally sustainable approaches to strengthen aquaculture productivity.

Among the different systems reviewed, cascade aerators stand out for their simplicity, low cost, and reliability in improving water quality, while shower aeration systems demonstrate enhanced performance through design optimization and efficient oxygen transfer. Building upon these, vertical aeration towers integrating both cascade and shower principles are expected to provide superior efficiency by combining the strengths of both systems. Collectively, these advancements indicate that future research and development should focus on optimizing such integrated systems to ensure energy-efficient, sustainable and economically viable solutions for aquaculture ponds.

FUTURE SCOPE

The cascade aerator is a commonly used alternative for the treatment of wastewater in place of conventional method. Used mostly after the initial stages of treatment, as a means of increasing the quantity of dissolved oxygen of the effluent water. Gases that are dissolved in effluent water can be reused (DO) or disposed of (H_2S, CH_4 and CO_2) in a safe manner (Kumar *et al*., 2013). The turbulent movement of water as it descends the cascade steps creates an environment where there is a greater volume of water in contact with the atmosphere; this provides an efficient exchange of air and water, thus improving the oxygen transfer rate and assisting in removing volatile substances from the water, such as methane and chlorine gas, dissolved Fe and Mn, CO_2, H_2S, and volatile oils that may affect the taste and colour of the water (Toombes and Chanson 2005).

Although such aerators are commonly applied in wastewater treatment, their effectiveness in maintaining dissolved oxygen levels under real-world aquaculture conditions has received limited research attention. This study seeks to fill that knowledge gap by examining the properties of cascade aerators, aiming to improve understanding and provide guidance for optimal aeration practices in fish farming operations in practical field conditions. Choosing an appropriate model requires numerous considerations such as the purpose of the pond, characteristics and geometry of the pond, along with the financial costs related to the construction, operation and maintenance of the pond (Roy *et al*., 2020b). According to Roy *et al*. (2021a), gravity-based aerators are cost-effective, simple to operate and maintain, dependable and deliver adequate performance. Those are generally more effective for application in small ponds occupying less than 0.1 hectares.

Hence, the future thrust should be towards innovation of aeration devices mitigating this issue and should be effective for increasing pond sizes. Several noteworthy preliminary studies have already been carried out in this field. There remains potential to introduce new designs, packages, and practices into the existing framework to further strengthen the system and enhance its efficiency. Around three decades ago, a cascade-type bamboo aerator was demonstrated in a pond at ICAR-CIFA, Bhubaneswar.

Some of the schematic diagrams mentioned in this study are currently being tested and evaluated in pond culture practices. At present, there is still scope to incorporate additional cost-effective aeration techniques and where necessary, refine the existing methods to achieve improved aeration in ponds.

The developed cascade aerator significantly improved water quality in fish ponds by enhancing oxygen transfer, achieving an overall transfer coefficient of 5.15–8.21 hr^{-1}, a standard aeration efficiency of 0.11–0.21 kg O_2/kW/hr, and a transfer rate of 0.04–0.08 kg O_2/hr (Kumar *et al*., 2013). This efficient, low-cost system offers a sustainable solution to boost fish stock density for low-income farmers. The shower aeration system (SAS) achieved optimum performance at a 10 mm radius of curvature, yielding (SAE) of 1.4429 kg O_2/kWh and a normalized SAE (NDSAE) of 15.914 × 10^6 (Roshan *et al.*, 2022). Such results highlight the importance of geometric optimization in enhancing system efficiency for effective water aeration. It should be hypothesized that vertical aeration towers, integrating both gravity-driven cascade and shower aeration principles, will achieve superior oxygen transfer efficiency compared to conventional systems. By combining the strengths of cascade and shower aeration, the system is expected to deliver higher SAE values, making it a more effective and sustainable solution for enhancing fish pond productivity.

Integrating innovative aeration technologies with renewable energy sources offers a cost-effective approach to reducing aquaculture's reliance on conventional electricity generation. Among the various renewable options, solar energy is the most widely utilized for pond aeration (Jamroen, 2022). Solar panels can be installed along pond banks or mounted on floating platforms to supply the power required for aeration systems, minimizing dependence on the local electrical grid (Jamroen, 2022; Chudasama *et al.*, 2023; Nugraha, 2025). Sustaining high water quality in aquaculture while enhancing energy efficiency increasingly relies on the integration of sensors and automated control systems within aeration management. Modern aquaculture aeration systems frequently use dissolved oxygen (DO) sensors and other real-time monitoring technologies to track critical water quality parameters and adjust aeration as needed, minimizing energy waste and promoting optimal oxygen levels for cultured species (Uken and Getachew 2023; Flores-Iwasaki *et al*., 2025). By linking these sensors to Internet of Things (IoT)-based automated controls, aerators can be operated only when DO thresholds are not met, reducing unnecessary power consumption and improving overall energy efficiency (Nugraha, 2025). Such sensor-driven automation not only enhances water quality and aquatic health, but also supports environmental sustainability by lowering operational costs and reducing resource use (Uken and Getachew 2023; Flores-Iwasaki *et al*., 2025). Understanding the components of aeration systems including real-time DO sensing, smart controllers, and adaptive feedback loops is essential for selecting strategies that boost both productivity and energy efficiency, positioning the aquaculture industry to address future aeration challenges as sustainable resource management technologies continue to advance.

Future research should emphasize developing methods that make these advancements more accessible and cost-effective for a wider range of users. This study represents a significant step toward enhancing aeration practices in aquaculture and contributes to the sustainable advancement of the aquaculture industry. Henceforth, the current study hypothesizes an optimized cascade aeration can serve as an efficient aerator substituting the mechanical aeration producing higher efficiency than the latter. Testing of the hypothesis through pond-scale trails and simulations will be decisive for the validation of cascade aeration as a scalable solution for the sustainable aquaculture practices.

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