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Original Research Article

Performance Evaluation and Operational Optimization of a Fine-Bubble Porous–Venturi Aeration System

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Abstract

Aeration is the most energy-intensive unit in wastewater treatment systems, particularly in shallow decentralized reactors with limited hydrostatic pressure, which reduces the oxygen transfer efficiency. However, systematic evaluations of integrated porous–Venturi microbubble systems under shallow water conditions are limited. This study aims to address this gap by investigating and optimizing a fine-bubble porous–Venturi microbubble generator (MBG) using laboratory-scale experiments. Clean water experiments were conducted in a 200 L batch reactor with two liquid flow rates (71.6 and 103.8 L/min) and four gas flow rates (0.15–0.60 L/min). Aeration performance was assessed using the volumetric oxygen mass transfer coefficient (KLa(20)), standard oxygen transfer rate (SOTR), and specific aeration efficiency (SAE), supported by one-way ANOVA. The results showed that the gas flow rate influenced KLa(20) and SOTR, whereas the liquid flow rate had a dominant effect on SAE. The optimal operating conditions were identified as Q_L = 71.6 L/min and Q_G = 0.45 L/min, achieving KLa(20) of 2.23 h^{-1} and an SAE exceeding 40 kg O_2/kWh. The findings showed that optimum gas–liquid interaction leads to energy-efficient aeration performance rather than maximum flow rate. It also provides practical design insights for optimizing aeration systems in shallow and decentralized wastewater treatment applications.

Keywords: Fine-bubble aeration, microbubble generator, oxygen transfer, specific aeration efficiency, wastewater treatment.

1. Introduction

Wastewater treatment requires massive amounts of energy to provide good public health and urban sustainability, accounting for 2–4% of global electricity and 1.3% of greenhouse gas emissions (International Energy Agency (IEA), 2018; Gu *et al.*, 2023). In wastewater treatment plants (WWTPs), aeration accounts for approximately 45–75% of the energy, with a maximum of 90%, which affects operating costs (Rosso et al., 2008; Drewnowski et al., 2019). The economic impact is also significant, as aeration energy alone can account for 15–49% of the operational costs of a plant (Guerrini, Romano and Indipendenza, 2017; Skouteris *et al.*, 2020). These challenges are expected to increase the demand for reliable WWTPs, which is parallel to massive urbanization and population growth. Therefore, improving aeration efficiency has become essential for achieving SDG 6 (Clean Water and Sanitation) and SDG 7 (Affordable and Clean Energy) (United Nations Statistics Division (UNSD), 2024).

Fine-bubble aeration is often used to increase oxygen transfer because of its larger surface area-to-volume ratio and longer bubble residence time in WWTPs (Zhao et al., 2021; Puri et al., 2023). Aeration performance can be significantly improved by optimizing the gas–liquid mass transfer efficiency through bubble size reduction and increased interfacial contact area (Ahmadi *et al.*, 2022). Venturi-based aeration systems form microbubbles through induced negative pressure and shear in the throat section and automatically draw in outside air with a simple and compact structural design (Yadav et al., 2021; Ochoa et al., 2022; Mahmud et al., 2024; Sidhi et al., 2024). Optimizing parameters such as throat length and the number of air holes can improve aeration efficiency (Yadav, Kumar and Sarkar, 2021; Lee *et al.*, 2023). Further developments incorporating swirling flow fields and integrating porous media with Venturi channels can form more microbubbles with improved oxygen dissolution performance (Majid *et al.*, 2018; Liew *et al.*, 2020; Wang *et al.*, 2020). Long-term studies on the diffuser type confirmed that material and configuration innovations increased oxygen transfer performance by up to 17% (Behnisch et al., 2020; Mukandi et al., 2021).

Current fine-bubble aeration test lab-scale often overlooks the characteristics of wastewater behavior in real conditions by relying strictly on deep-tank, clean-water protocols, and this leads to a significant result and insight gap for shallow systems in decentralized WWTPs (Stenstrom, Leu and Jiang, 2006; Uby, 2019). Shallow systems such as oxidation ditches (~1.2–1.8 m) and facultative ponds (~1–2 m) suffer from decreasing hydrostatic pressure and shortening bubble residence time, causing less oxygen transfer efficiency (Morling, 2008; U.S. Environmental Protection Agency (EPA) (2011). Although the newest microbubble innovations have demonstrated improvements in mass transfer in controlled settings, there is still a limited understanding of the combination effect in these shallow wastewater systems (Liew *et al.*, 2020). Temesgen and Han (2023) and Mahmud et al. (2024) highlighted the need for optimization of aerator configurations for shallow-water conditions. Although depth and submergence affect oxygen transfer (e.g., increasing depth generally raises KLa/SOTE) (Wagner and Pöpel, 1998; Al-Ahmady, 2006), comparative studies linking aerator design to oxygen transfer indicators (KLa, SOTR) and energy metrics (e.g., SAE) at shallow depths are lacking. Aeration systems operating at depths of less than 2 m are constrained by decreasing hydrostatic pressure, leading to limited bubble residence time and decreasing mass transfer performance, resulting in higher energy demand (Azis et al., 2019; Zhang et al., 2020). This highlights the need for lab-scale experiments on fine-bubble porous–Venturi aeration systems that can maintain higher oxygen transfer and minimize energy demand in shallow wastewater treatment.

This study aimed to evaluate and optimize the performance of a fine-bubble porous–Venturi system under shallow-water conditions for typical small-scale WWTPs. The novelty of this study lies in addressing aeration inefficiencies in shallow systems, where oxygen transfer is usually limited by low hydrostatic pressure and short bubble residence times. The system performance was analyzed by measuring the volumetric mass transfer coefficient (KLa(20)), standard oxygen transfer rate (SOTR), and specific aeration efficiency (SAE) as the main indicators of oxygen transfer efficiency (Uby, 2019; Gu *et al.*, 2023). We used a parametric experimental approach by varying the airflow rate, liquid circulation flow rate, and water depth to determine their individual and combined effects on KLa(20), SOTR, and SAE. Optimization focused on identifying the operational threshold that provides the highest oxygen transfer per unit of energy power consumed. These empirical and statistical results provide a framework and insight to help design energy-efficient aeration technologies in shallow treatment systems and solve the practical trade-off between oxygenation demand and energy constraints.

2. Materials and Methods

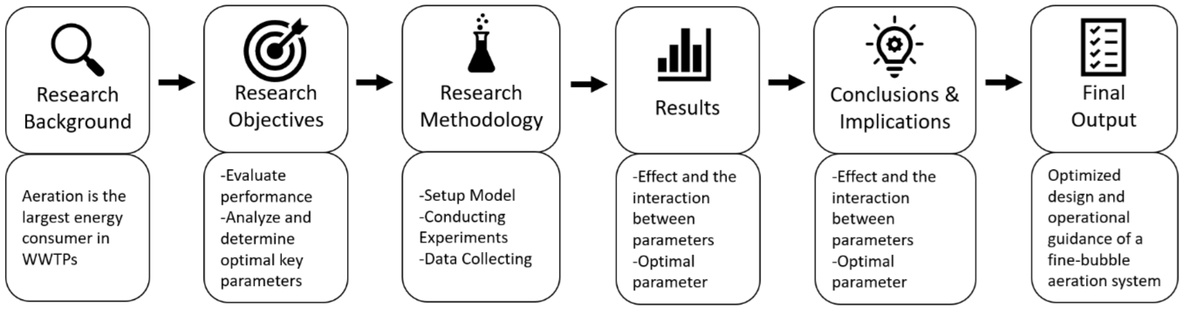


Figure 1. Research flow diagram

Figure 1 presents the Research Flow Diagram outlining the stages of optimizing a fine-bubble porous-venturi aeration system for energy-saving wastewater treatment in shallow systems. The background of the study highlights the need for energy-efficient aeration owing to the high energy consumption in wastewater treatment. The objectives were to evaluate aeration performance, assess the effects of key parameters on oxygen transfer (KLa), standard oxygen transfer rate (SOTR), and specific aeration efficiency (SAE), and identify the optimal parameters for maximum efficiency. A factorial experimental design was used, with varying liquid and gas flow rates, followed by statistical analysis to determine the optimal conditions. The results provide practical design insights for energy-efficient aeration systems in shallow wastewater treatment.

2.1 Experimental Setup

Experiments were conducted in a lab-scale batch aeration reactor, which is a rectangular glass tank (100 × 50 × 50 cm, 4 mm thickness) that holds 200 L of clean tap water to simulate shallow-water conditions typical of small decentralized wastewater treatment units, and uses a porous–Venturi microbubble generator (MBG). The MBG, with a Venturi body featuring a 0.98 cm orifice and 1.88 cm inlet and outlet diameters, used a porous insert and throat-induced pressure drop to entrain gas into the recirculating liquid, generating fine bubbles with high oxygen-transfer efficiency, as shown in Figure 2.

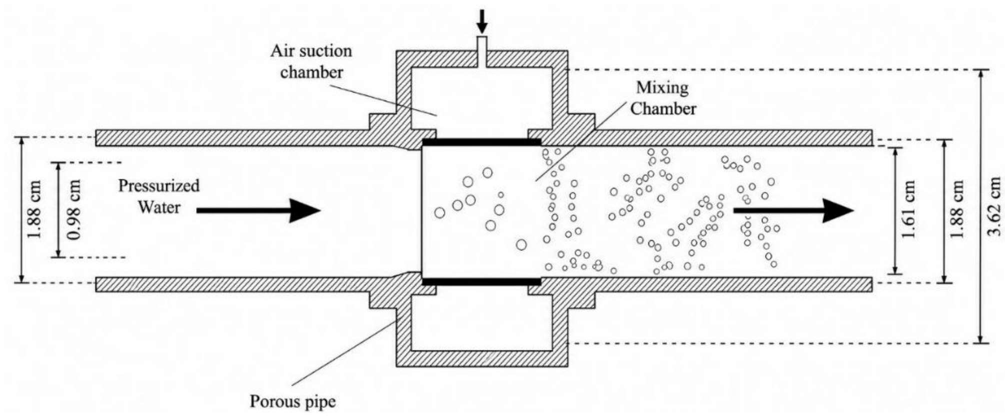
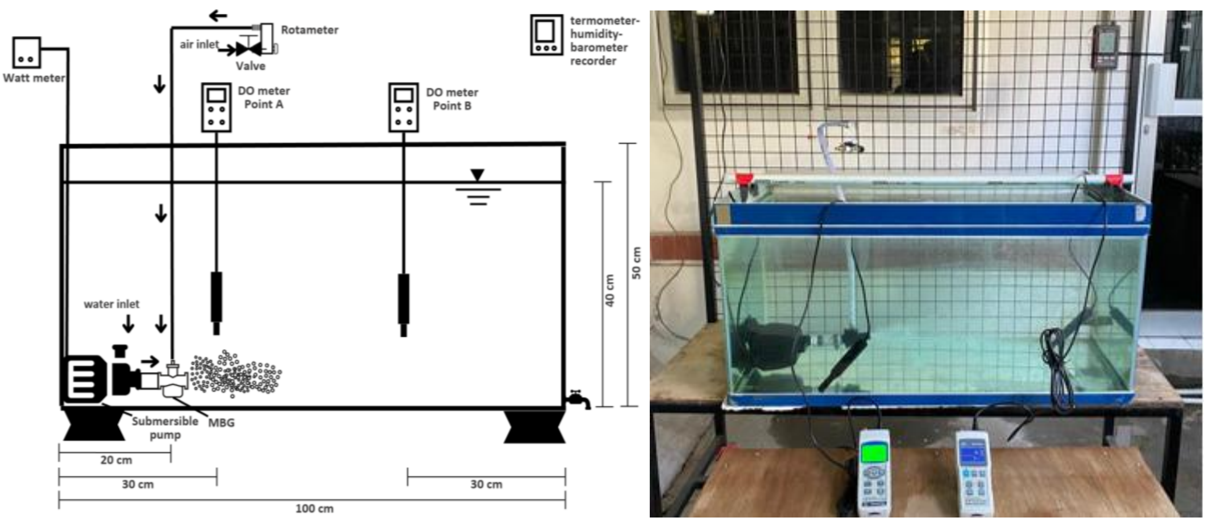


Figure 2. Schematic of the porousVenturi microbubble generator (Majid *et al.*, 2018).

A batch aeration reactor and porous-venturi microbubble generator (MBG) were selected for their proven effectiveness in enhancing oxygen transfer in small-scale wastewater systems (Majid *et al.*, 2018; Mistoro *et al.*, 2023). Porous Venturi MBGs have been shown to outperform conventional aerators in oxygen transfer because the microbubbles generate a greater interfacial area and rise more slowly through the water column, both of which increase the mass transfer coefficients. Liew et al. (2020) reported better results in oxygen dissolution and aeration efficiency by tuning the liquid and gas velocities, and Ochoa et al. (2022) found that the gas-to-liquid flow ratio was key to maximizing the SOTR and SAE.

Two submersible pumps (71.6 L/min and 103.7 L/min) were used to drive the liquid circulation in the tank and were connected to the porous-venturi MBG with flexible hoses to form a closed recirculation loop. The MBG outlet was placed at the bottom of the tank to increase the bubble residence time and obtain a wider aeration distribution. The air supply was arranged using a rotameter paired with a control valve to set the desired gas flow rate, and the DO was monitored at two points (A and B) using probes mounted at the mid-depth of the tank to obtain representative DO across the system. Environmental and process data (water and ambient temperature, humidity, and pressure) were recorded at regular intervals using dataloggers and a thermo-hygro-barometer. The power drawn by the pump was measured using a wattmeter, and the SAE was calculated from the SOTR values. The full experimental setup and instrumentation are shown in Figure 3. The tank, MBG, pump, gas line, and DO measurement point configurations followed the optimization study by Mistoro *et al.* (2023). This setup maintained the microbubble plume, maximized the bubble residence time, and enhanced oxygen transfer. This positioning allowed for effective evaluation of oxygen transfer and DO spatial uniformity and provided representative conditions for monitoring system performance.



(a) (b)

Figure 3. Experimental setup: (a) schematic diagram and (b) photograph of the assembled experimental apparatus.

2.2 Experimental Procedure

2.2.1 Operating Conditions and Parametric Design

The operating conditions of the porous–Venturi aeration system were varied for parametric evaluation and optimization. All tests were conducted using clean tap water at a shallow water depth (working volume ≈ 200 L) to simulate conditions typical of small decentralized WWTPs. Before each experiment, the water temperature and DO concentration were monitored as a baseline, and the initial DO was adjusted to a low value (~0,5-1 mg/L) to ensure consistency across the experimental runs.

Two liquid circulation flow rates, Q_L (71.6 and 103.7 L/min), were selected based on the pump capacities, and four gas flow rates, Q_G (0.15, 0.30, 0.45, and 0.60 L/min), were chosen within the microbubble generator's stable operating range. These values formed a factorial experiment with eight operating conditions (two levels of Q_L × four levels of Q_G) at the chosen shallow-water depth. Triplicate experiments were performed for each sample, and data were collected. Between the runs, the system was reset by repeating the deoxygenation procedure and replacing the tank water to prevent salt accumulation. The parametric optimization aimed to identify the combination of Q_L and Q_G that generated the volumetric mass transfer coefficient (KLa(20)) and standard oxygen transfer rate (SOTR) and obtained the optimum specific aeration efficiency (SAE), considered as the optimal operating window for shallow-depth applications.

The selection of the liquid flow rate (Q_L) and gas flow rate (Q_G) ranges in this study was determined based on the optimization of a previous study conducted by Mistoro et al. (2023), who measured the gas flow rate range that successfully generated microbubbles using the same fine-bubble porous–Venturi aeration system, which was used as the benchmark for setting the experimental apparatus for this study. Khadwilard et al. (2026) also showed that adjusting water and air flow ratesaffectedn oxygen transfer, with optimal combinations resulting in higher KLa(20) and specific aeration efficiency (SAE). These results are consistent with those of earlier studies on fine-bubble aeration, which showed that smaller bubbles improve dissolved oxygen transfer by maximizing the gas-liquid surface area (Lu *et al.*, 2021).

2.2.2 Clean-Water Oxygen Transfer Test

Oxygen transfer was measured using the non-steady-state clean-water test in accordance with the ASCE Standard for the Measurement of Oxygen Transfer in Clean Water (ASCE, 2007), which consisted of a deoxygenation stage followed by a reaeration stage for each operating condition. The DO profiles from each run were used to calculate KLa(20), SOTR, and SAE, as described in Section 2.3. Each condition was tested in triplicates to ensure repeatability and consistency.

Deoxygenation stage: Before the aeration process, the sample water must have a low DO concentration below 0.2 mg/L by adding sodium sulfite (Na_2SO_3), with a cobalt salt catalyst if needed. This stage must ensure uniform deoxygenation and typically lasts 15–20 min, depending on the initial DO concentration.

Reaeration stage: The aeration process began with Q_L and Q_G set to the desired values, and data acquisition began at t=0, with DO probes recording the DO concentration at fixed intervals (every 30–60 s) and temperature. Measurements continued until the DO concentration approached saturation in 50-60 minutes.

2.3 Performance Evaluation

2.3.1 Volumetric Mass Transfer Coefficient KLa(20)

The main indicator for evaluating performance is the volumetric oxygen mass transfer coefficient, KLa(20), which represents the overall rate of oxygen transfer from the gas to the liquid phase per unit volume, and is calculated using the ASCE (2007) Standard for the Measurement of Oxygen Transfer in Clean Water. This method normalizes the transfer coefficient to 20°C, providing a reliable measure of aeration efficiency under standard conditions. In clean water, oxygen transfer during reaeration is described by the classical first-order differential equation in Equation (1):

$$\frac{dC}{dt} = K_L a(C_s - C) \tag{1}$$

C_S is the saturated DO concentration (mg/L), C is the bulk DO concentration at time t, and the term (C_S – C) defines the oxygen deficit. Rearranging and integrating between the initial time t_o and time t gives a linear form, as shown in Equation (2):

$$ln\left(\frac{C_s - C_0}{C_s - C_t}\right) = K_L a(t - t_0) \tag{2}$$

C_o is the DO concentration at t_o. For each experimental run, the measured DO data were converted to oxygen deficit and plotted as $\ln(C_s – C_o)$ versus time. A least-squares linear regression was applied, and the slope of the best-fit line was taken as the overall KLa under the given operating conditions. The saturation DO concentration (C_S) was calculated for each run using the measured water temperature and the local barometric pressure. First, the pure water saturation concentration at standard pressure, C_{tab}, was obtained from an empirical correlation based on the Antoine and Streeter–Phelps formulations. The value was then corrected for the actual barometric pressure according to Equation (3):

$$C_s = C_{tab}\left(\frac{BP-P^{-}}{760-P^{-}}\right) \quad (3)$$

where BP is the measured barometric pressure (mmHg) and P^{-} is the water vapour pressure at the measured temperature. Finally, KLa values were normalized to a reference temperature of 20 °C using a standard temperature correction factor θ, following the ASCE clean-water procedure, and reported as KLa(20).

2.3.2 Standard Oxygen Transfer Rate (SOTR)

Once KLa(20) was determined for each operating condition, the corresponding standard oxygen transfer rate (SOTR) was calculated. SOTR is defined as the hypothetical mass of oxygen transferred per unit time in a given water volume under standard conditions (water temperature of 20 °C and barometric pressure of 1 atm). According to the ASCE (2007), SOTR refers to the oxygenation capacity of the aeration system under controlled conditions, and it is calculated using the oxygen deficit, which is derived from the difference between the saturation concentration (Cs) and the actual DO concentration (C). In this study, the SOTR was obtained by multiplying KLa(20) by the tank volume and standard oxygen deficit. The result was expressed in kg O_2/h, providing a direct measure of the oxygenation capacity of the porous–Venturi system at each combination of gas and liquid flow rates.

2.3.3 Specific Aeration Efficiency (SAE)

To evaluate the energy efficiency, the specific aeration efficiency (SAE) was derived from the SOTR and measured power input. The SAE is defined as the mass of oxygen transferred per unit of electrical energy consumed, as shown in Equation (4):

$$SAE = \frac{SOTR}{P} \quad (4)$$

where *P* is the total power demand of the aeration system (kW), including the recirculation pump and the air supply. SAE is reported in kg O_2/kWh. The instantaneous power draw of the pump was recorded using a plug-in watt meter during each test, and the average value was used as *P*. This measurement followed the ASCE Standard guidelines (ASCE, 2007) to ensure that the SAE calculation was consistent with the best practices for energy efficiency. Combining SAE with SOTR allowed a direct comparison of the energy performance of this porous–Venturi aeration system across all conditions and against typical SAE ranges reported in the literature.

2.4 Statistical Analysis and Identification of Optimal Operating Window

For each operating condition, clean water tests provided time-series data for the DO to calculate KLa(20), SOTR, and SAE (Section 2.3). Each combination of liquid circulation flowrate (Q_L) and gas flowrate (Q_G) was repeated three times, and the mean and standard deviation for each performance indicator were computed. One-way analysis of variance (ANOVA) was used to determine the differences in aeration performance among the operating conditions, with Q_L (71.6 and 103.7 L/min) and Q_G (0.15, 0.30, 0.45, and 0.60 L/min) as factors. The null hypothesis assumed no difference in the mean values across all conditions, with a significance level of α=0.05. Pairwise comparisons were performed when significant differences were detected. Before ANOVA, normality and homogeneity of variance were checked using residual plots, and log-transformed data were used if necessary. The optimal operating window was calculated based on statistical comparisons with conditions that yielded high KLa(20), SOTR, SAE, and DO saturation for shallow-depth applications.

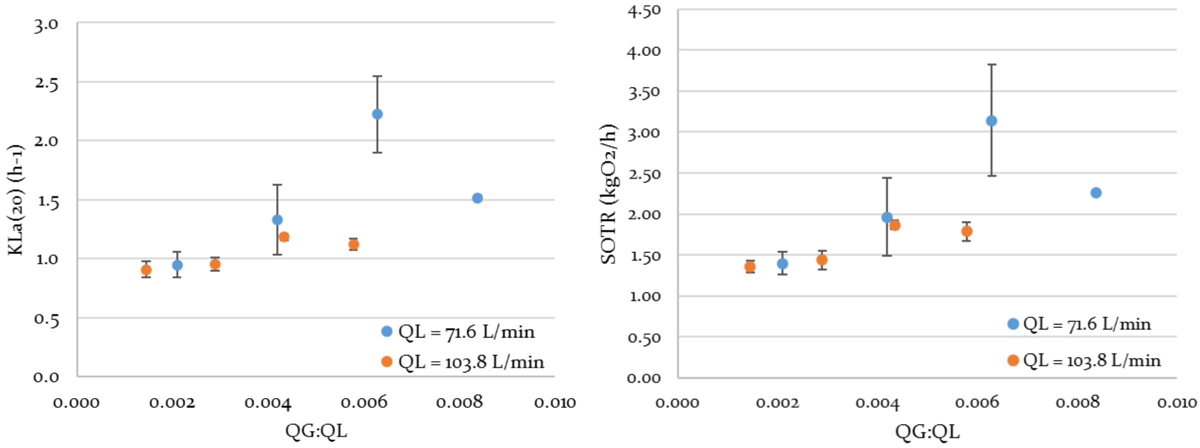
3. Result and Discussion

3.1 Oxygen Transfer Performance under Different Operating Conditions

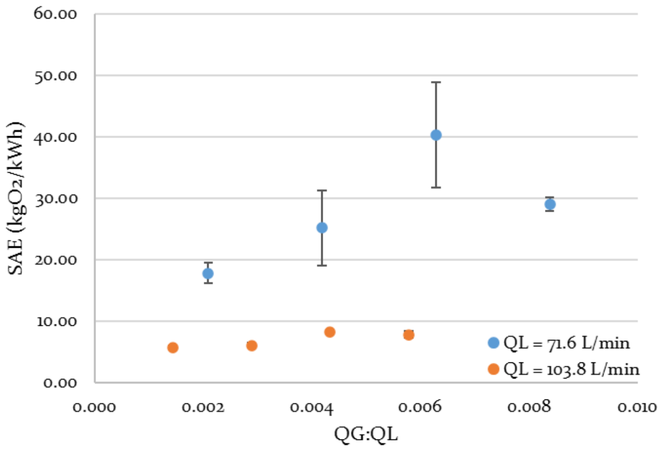
The overall aeration performance of the porous–Venturi system under shallow-water conditions was evaluated using KLa(20), SOTR, and SAE. These parameters represent the oxygen transfer intensity, oxygenation capacity, and energy efficiency. The combined evaluation of these three parameters is essential because the conditions that achieve high oxygen transfer do not always provide high energy efficiency. In this study, the aeration performance was assessed across different liquid circulation flow rates (Q_L) and gas flow rates (Q_G), with each operating condition tested in triplicate. The mean values and standard deviations are presented in Table 1, while the overall trends as a function of the gas-to-liquid flowrate ratio (Q_G:Q_L) are shown in Figure 4.

Table 1. Mean values and standard deviations of the volumetric oxygen mass transfer coefficient KLa(20), standard oxygen transfer rate (SOTR), and specific aeration efficiency (SAE)

Water Flowrate (Q_L) (L/min)	Gas Flowrate (Q_G) (L/min)	Q_G:Q_L	Mean K_La(20)	SD K_La(20)	Mean SOTR	SD SOTR	Mean SAE	SD SAE
71.6	0.15	0.0021	0.95	0.11	1.40	0.14	17.77	1.71
71.6	0.30	0.0042	1.33	0.30	1.96	0.47	25.12	6.05
71.6	0.45	0.0063	2.23	0.33	3.15	0.68	40.30	8.52
71.6	0.60	0.0084	1.52	0.02	2.27	0.02	29.00	1.12
103.8	0.15	0.0014	0.91	0.07	1.36	0.07	5.65	0.30
103.8	0.30	0.0029	0.95	0.06	1.44	0.11	6.06	0.44
103.8	0.45	0.0043	1.18	0.03	1.86	0.05	8.18	0.29
103.8	0.60	0.0058	1.12	0.05	1.79	0.11	7.78	0.52



(a) (b)



(c)

Figure 4. Overall aeration performance as a function of the gas-to-liquid flowrate ratio (Q_G:Q_L): (a) volumetric oxygen mass transfer coefficient KLa(20), (b) standard oxygen transfer rate (SOTR), and (c) specific aeration efficiency (SAE).

The results show that the porous–Venturi system demonstrated a nonlinear response to changes in the gas-to-liquid flowrate ratio. At Q_L = 71.6 L/min, increasing Q_G from 0.15 to 0.45 L/min enhanced the oxygen transfer performance, as indicated by the increase in KLa(20) from 0.95 to 2.23 h and SOTR from 1.40 to 3.15 kg O_2/h. The SAE also increased from 17.77 to 40.30 kg O_2/kWh under the same operating range. Further increasing Q_G to 0.60 L/min reduced KLa(20), SOTR, and SAE to 1.52 h^{-1}, 2.27 kg O_2/h, and 29.00 kg O_2/kWh, respectively. The same pattern was observed at Q_L = 103.8 L/min, although the overall SAE values were lower than those obtained at the lower liquid flow rate. These results indicate that the oxygen transfer performance of the porous–Venturi system was not driven simply by increasing the air supply, but by achieving an effective balance between gas injection, liquid circulation, bubble dispersion, and energy input.

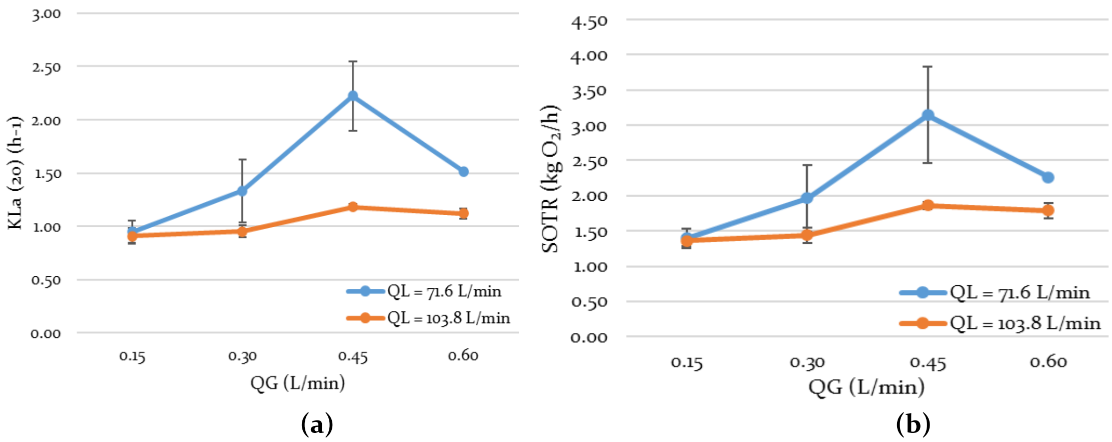
The improvement in KLa(20) and SOTR at low-to-moderate Q_G can be attributed to the increased gas bubbles and larger gas–liquid interfacial area. In a Venturi-based aeration system, the gas supply is promoted by the pressure drop in the throat section, and shear forces contribute to bubble breakup and dispersion. This process enhances oxygen dissolution by increasing the contact area between the air and water. Ochoa et al. (2022)also reported that the water–air flow ratio is a key operating variable controlling KLa(20), SOTR, and SAE in Venturi and Venturi–Vortex microbubble aeration systems. Porous Venturi-orifice microbubble generators increase oxygen dissolution by refining the bubble size and expanding the gas–liquid interface, indicating that bubble size and dispersion are the core drivers of aeration performance.

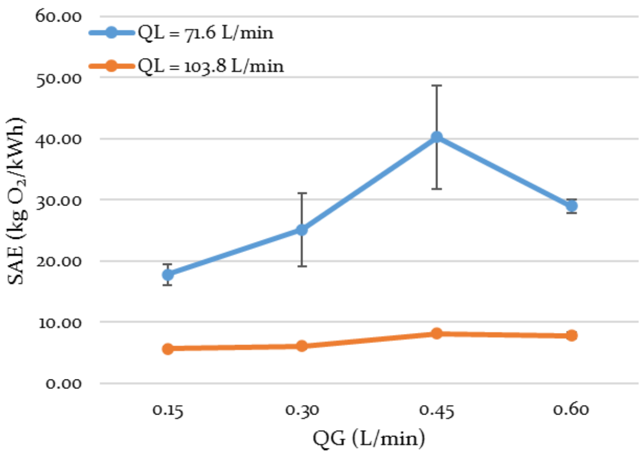
However, the lower performance at the highest QG suggests that excessive gas injection may create an inefficient, two-phase flow regime. When the gas flow rate becomes too high, the number of bubbles in the reactor increases, but the effective interfacial area does not increase. Bubble crowding and coalescence may occur, generating larger bubble sizes, leading to higher rising velocities and shorter residence times. These bubbles also have lower surface areas per unit gas volume and leave the water column more rapidly, thereby reducing the effective contact time for oxygen dissolution. This explanation is consistent with the general principle that bubble size and water depth strongly influence the oxygen transfer efficiency. Wagner and Pöpel (1998) emphasized that diffuser submergence and aeration configuration are important factors affecting oxygen transfer and aeration efficiency, while Al-Ahmady (2006) experimentally showed that water depth significantly affects oxygen transfer capacity, efficiency, and oxygen absorption in subsurface aeration systems. Therefore, shallow-water conditions exacerbate the negative impacts of bubble coalescence and shorten the residence time owing to the small depth.

The SAE trend also confirms the relationship between oxygen transfer performance and energy efficiency; at Q_L = 71.6 L/min, the highest SAE was obtained at Q_G = 0.45 L/min, indicating the optimum operational window for the system. In contrast, although comparable or moderate KLa (20) and SOTR values were maintained, the higher liquid circulation at Q_L = 103.8 L/min resulted in lower SAE across all gas flowrates, indicatings that additional hydraulic energy input did not produce proportional gains in oxygen transfer. Behnisch et al. (2020) highlighted that aeration performance must be evaluated not only based on oxygen transfer capacity but also on operational efficiency. Uby (2019) also stated that the clean-water oxygen transfer test should be interpreted carefully because standard indicators must be linked to practical operating conditions and hydrodynamics. Figure 4 shows that the porous–Venturi system has a distinctive optimum operating range under shallow-water conditions, where the best performance was achieved at Q_L = 71.6 L/min and Q_G = 0.45 L/min, yielding the highest KLa(20), SOTR, and SAE. This suggests that moderate gas injection with lower liquid circulation can generate good bubble dispersion and gas–liquid contact without exceeding the energy demand or bubble coalescence. Therefore, optimization of shallow aeration systems should not focus on maximizing gas or liquid flow rates independently, but on finding a balanced gas–liquid interaction that enhances oxygen transfer while maintaining energy efficiency.

3.2 Effect of Liquid and Gas Flow Rates on Oxygen Transfer Performance

The effects of liquid circulation flowrate (Q_L) and gas flowrate (Q_G) on aeration performance are shown in Figure 5, and the statistical significance of each variable is summarized in Tables 2 and 3. The results showed that both parameters affected the oxygen transfer behavior, but their roles were different. The gas flow rate drives the oxygen transfer intensity by controlling the amount of air and gas–liquid interfacial area. Meanwhile, the liquid circulation flow rate influences the hydraulic conditions in the reactor, affecting turbulence, bubble dispersion, and power consumption. Therefore, the interpretation of KLa(20), SOTR, and SAE should consider not only oxygen transfer enhancement but also the energy penalty from liquid recirculation.





(c)

Figure 5. Effect of liquid flow rate (Q_L) at different gas flow rates (Q_G): (a) KLa(20), (b) SOTR, and (c) SAE. Symbols represent mean values, and error bars indicate standard deviation (n = 3).

At Q_L = 71.6 L/min, increasing Q_G from 0.15 to 0.45 L/min improved the oxygen transfer performance, and KLa(20) increased from 0.95 to 2.23 h^{-1}, while SOTR increased from 1.40 to 3.15 kg O_2/h. The SAE also increased from 17.77 to 40.30 kg O_2/kWh, indicating that the additional gas supply within this range was effectively converted to oxygen transfer. However, when Q_G was increased to 0.60 L/min and KLa(20) decreased to 1.52 h^{-1}, SOTR and SAE decreased to 2.27 kg O_2/h and 29.00 kg O_2/kWh, respectively. This trend indicates the presence of an optimum gas flow rate, beyond which additional air injection no longer improves the oxygen transfer performance. In Venturi-based aeration systems, gas entrainment is induced by a pressure drop in the throat section, and shear forces promote bubble breakup and dispersion. Ochoa et al.(2022) similarly reported that the water–air flow ratio is one of the key variables affecting KLa(20), SOTR, and SAE in Venturi and Venturi–Vortex microbubble aeration systems. Yadav et al. (2021) also concluded that the Venturi aeration performance is affected by hydraulic and geometric parameters that influence air entrainment and oxygen transfer efficiency. Thus, the observed increases in KLa(20) and SOTR up to Q_G = 0.45 L/min can be attributed to improved air entrainment, bubble formation, and gas–liquid contact.

The decline in oxygen transfer performance at Q_G = 0.60 L/min suggests that excessive gas injection may have changed the system toward a less efficient two-phase flow regime. At high gas loadings, bubble crowding and coalescence can occur, leading to the formation of larger bubbles. Larger bubbles have a smaller interfacial area and a higher rising velocity than smaller bubbles, leading to a slower residence time in the liquid phase, making them more efficient under shallow-water conditions. Therefore, the decrease in KLa(20) and SOTR at the highest gas flow rate shows the combined effects of bubble coalescence, reduced effective contact time, and lower oxygen dissolution efficiency. As previously stated, smaller bubbles increase oxygen transfer due to their larger surface-area-to-volume ratio and longer residence time. Agarwal et al. (2011) described microbubble and nanobubble technologies as promising technologies because of their physicochemical behavior and promoted interfacial characteristics, whereas Liew et al. (2020) demonstrated that porous Venturi-orifice microbubble generators can improve oxygen dissolution through effective fine-bubble generation.

The effect of Q_L showed a different pattern; although increasing Q_L from 71.6 to 103.8 L/min could intensify hydraulic mixing, this higher circulation rate did not improve the overall energy performance. At Q_L = 103.8 L/min, KLa(20) values ranged from 0.91 to 1.18 h^{-1}, while SOTR ranged from 1.36 to 1.86 kg O_2/h and SAE remained low, ranging from 5.65 to 8.18 kg O_2/kWh across all Q_G levels. These values were lower than those obtained at Q_L = 71.6 L/mi,n and it can be proved that the additional hydraulic energy introduced by the higher liquid flowrate was not effectively converted into oxygen transfer. In shallow systems, excessive recirculation can increase turbulence and mixing intensity, but also shortens the bubble residence time, disturbs the bubble plume stability, and increases the pump energy demand. Consequently, a higher Q_L can reduce the energy efficiency, even if there is some improvement in mixing.

The statistical analysis in Table 2 supports this interpretation by showing that the liquid flow rate affected all three performance indicators, namely KLa(20) (F = 8.9896, p = 0.0066), SOTR (F = 6.4829, p = 0.0184), and SAE (F = 56.7916, p = 1.6×10^{-7}). The most significant effect was observed for SAE, as indicated by the much higher F-value compared to KLa(20) and SOTR. This result suggests that the liquid circulation rate is the main factor controlling the energy efficiency of the porous–Venturi aeration system. From a hydrodynamic perspective, increasing Q_L may increase the flow velocity, turbulence, and mixing intensity; however, it also increases the pump energy demand. When the additional hydraulic energy does not produce a proportional improvement in oxygen transfer, the SAE decreases substantially. Therefore, the statistical significance of Q_L, particularly for SAE, confirms that hydraulic recirculation is a critical operational parameter in shallow aeration systems.

Table 2. Statistical significance of the liquid flow rate (Q_L) on KLa(20), SOTR, and SAE based on one-way ANOVA (α = 0.05).

Parameter	F-value	p-value	Status
Kla(20)	8.9896	0.0066	Significant
SOTR	6.4829	0.0184	Significant
SAE	56.7916	1.6E−07	Highly significant

Table 3 shows that the gas flow rate had a different statistical effect compared with the liquid flow rate, with Q_G affecting KLa(20) (F = 5.148, p = 0.0084) and SOTR (F = 5.879, p = 0.0048), confirming that air injection directly influenced oxygen transfer capacity. However, Q_G did not affect the SAE (F = 1.037, p = 0.3976). Although increasing the gas flow rate can enhance oxygen availability and interfacial contact up to an optimum point, the resulting changes in oxygen transfer per unit energy were not statistically significant across all operating conditions. In other words, the gas flow rate primarily determines the oxygen transfer rate, whereas the energy efficiency is more strongly controlled by liquid recirculation. The non-significant effect of Q_G on SAE also implies that simply increasing the air supply is not an effective strategy for improving energy efficiency, particularly when the hydraulic power requirement of the recirculation system dominates the total energy input.

Table 3. Statistical significance of gas flow rate (Q_G) on KLa(20), SOTR, and SAE based on one-way ANOVA (α = 0.05).

Parameter	F-value	p-value	Status
Kla(20)	5.148	0.0084	Significant
SOTR	5.879	0.0048	Significant
SAE	1.037	0.3976	Not significant

The ANOVA results clarify the different roles of Q_L and Q_G in the porous–Venturi system, where Q_G acts mainly as an oxygen-transfer driver by increasing air entrainment and gas–liquid interfacial area, whereas Q_L acts as both a mixing enhancer and an energy-consuming variable. This dual role explains why a higher Q_L does not always improve performance and instead reduces the SAE under the tested conditions. Therefore, system optimization should not focus on maximizing the individual flow rate but on finding an operating window where bubble formation, dispersion, residence time, and energy input are balanced.

Overall, the optimum operating condition was obtained at Q_L = 71.6 L/min and Q_G = 0.45 L/min, where the system achieved KLa(20) of 2.23 h^{-1}, SOTR of 3.15 kg O_2/h, and an SAE of 40.30 kg O_2/kWh. This condition showed effective gas–liquid interaction, where the gas supply was sufficient to increase oxygen transfer, while liquid circulation remained low to maintain energy demand. These findings demonstrate that the porous–Venturi aeration system performs efficiently under balanced operating conditions rather than under maximum gas or liquid flow rates.

3.3 Overall Performance and Identification of Optimal Operating Window

The overall performance of the porous–Venturi aeration system was evaluated by integrating the oxygen transfer capacity and energy efficiency, as shown by the relationship between KLa(20) and SAE in Figure 6. This assessment is important because high oxygen transfer does not always indicate efficient operation if it requires excessive energy. Therefore, optimum conditions should be determined not only from the highest KLa(20) or SOTR, but also the system's ability to maintain high SAE under shallow-water conditions. This interpretation is consistent with the clean-water oxygen transfer testing principle, which emphasizes that standard indicators should be related to hydrodynamic and operational conditions (Uby, 2019).

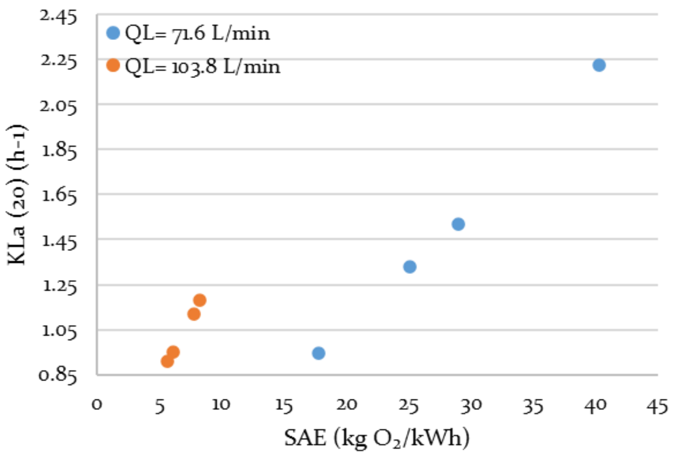


Figure 6. Trade-off between KLa(20) and SAE for all tested liquid and gas flow rate combinations.

Figure 6 shows two distinct performance regions according to the liquid circulation flow rate. The operating points at Q_L = 71.6 L/min were located in the higher-performance region, with higher KLa(20) and SAE values. In contrast, the points at Q_L = 103.8 L/min were in the lower-performance region, showing substantially lower SAE despite moderate oxygen transfer values. This implies that increasing the liquid circulation does not always improve the overall performance. Although a higher QL can increase mixing and turbulence, the additional energy input is not converted proportionally into oxygen transfer, leading to lower energy efficiency. The same statement has been emphasized in a fine-bubble aeration study, where oxygen transfer performance must be assessed together with energy efficiency (Behnisch et al., 2020).

The highest performance was achieved at Q_L = 71.6 L/min and Q_G = 0.45 L/min, with KLa(20), SOTR, and SAE values of 2.23 h^{-1}, 3.15 kg O_2/h, and 40.30 kg O_2/kWh, respectively, indicating the optimum operating window of the porous–Venturi system under shallow-water configuration. It also clarifies that the air supply is sufficient to form fine bubbles and improve gas–liquid contact, and that liquid circulation remains sufficiently low to maintain hydraulic energy demand. Ochoa et al. (2022) similarly reported that Venturi-based microbubble aeration performance depends strongly on the balance between water and air flow conditions rather than on air supply alone.

The lower performance at Q_G = 0.60 L/min confirms the presence of diminishing returns, and at Q_L = 71.6 L/min, increasing Q_G from 0.45 to 0.60 L/min reduced KLa(20) from 2.23 to 1.52 h^{-1}, SOTR from 3.15 to 2.27 kg O_2/h, and SAE from 40.30 to 29.00 kg O_2/kWh. This decrease might be attributed to excessive gas loading, which promotes bubble crowding, coalescence, unstable two-phase flow, and a shortened bubble residence time. These effects are particularly important in shallow-water systems because the limited water depth reduces the available contact time for oxygen to dissolve. The importance of fine bubbles for enhancing gas–liquid mass transfer through a larger specific interfacial area and slower rising velocity has also been reported for porous Venturi-orifice microbubble generators (Liew *et al.*, 2020).

Overall, the KLa–SAE indicates that the porous–venturi aeration system should be operated within a balanced gas–liquid interaction regime rather than at the maximum gas or liquid flowrate. The optimum condition was achieved when the bubble form, dispersion, residence time, and hydraulic energy input were balanced. This finding is relevant for shallow and decentralized wastewater treatment systems with less depth and energy that can provide sufficient oxygen transfer without excessive operational energy demand.

4. Conclusions

This study evaluated the oxygen transfer and energy performance of a fine-bubble porous–venturi aeration system under shallow water conditions. The results showed that the gas flow rate mainly affects the oxygen transfer intensity with significant effects on KLa(20) and SOTR, and the liquid circulation flow rate affects the energy efficiency. The optimum operating condition was obtained at QL = 71.6 L/min and QG = 0.45 L/min, achieving KLa(20) of 2.23 h^{-1}, SOTR of 3.15 kg O_2/h, and SAE of 40.30 kg O_2/kWh. Increasing the gas or liquid flow rate did not improve the overall performance and showed that excessive aeration or recirculation may reduce efficiency through bubble coalescence, shortened residence time, and increased hydraulic energy demand. These findings clarify the balanced gas–liquid interaction for optimizing shallow aeration systems and provide a basis for further validation in real wastewater and pilot-scale systems.

Ethics Statement

This study did not involve human participants, animals, or sensitive data; therefore, no ethical approval was required.

CRediT Author Statement

Niesa Hanum Mistoro: Conceived and Designed the Analysis, Collected Data, Performed Analysis, Wrote the Paper. **Sri Puji Saraswati:** Conceived and Designed the Analysis, Supervised the Research, Contributed to Data Interpretation, Reviewed and Edited the Paper. **Johan Syafri Mahathir Ahmad:** Conceived and Designed the Analysis, Contributed to Methodology Development, Supervised the Research, Reviewed and Edited the Paper. **Henny Sudibyo:** Contributed Analysis Tools, Performed Data Interpretation, Reviewed and Edited the Paper. **Dahlia Anggita Zahra:** Contributed to Literature Review, Reviewed and Edited the Paper.

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