The impact of microbubble generator technology on vannamei shrimp growth and water quality

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Abstract. The rapid growth of shrimp farming has raised concerns regarding sustainability, with challenges such as water quality management, feed efficiency, and disease outbreaks threatening the industry's future. Innovative technologies are essential for enhancing productivity while ensuring ecological sustainability. This study aimed to evaluate the effectiveness of micro-bubble generator (MBG) technology, explicitly comparing ball nozzles and a combination of ball and pore nozzles, in optimizing dissolved oxygen levels, water quality, and growth performance of *Litopenaeus vannamei* shrimp. The research was conducted in a collaborative shrimp pond in Purworejo Regency and utilized an experimental design with two MBG configurations. Shrimp were cultured for 90 days, and various environmental parameters, including dissolved oxygen, pH, temperature, and nutrient levels, were monitored biweekly. Growth metrics were recorded at regular intervals, and statistical analyses were performed to assess differences in growth and water quality between the treatments. The findings indicated that shrimp cultivated with the MBG using ball nozzles exhibited superior growth in both weight and length, alongside lower size variance compared to those with combined nozzles. Water quality measurements showed that dissolved oxygen levels were higher in ponds with ball nozzles, while nitrate and phosphate concentrations remained comparable across treatments. The study concluded that MBG technology, particularly with ball nozzles, significantly enhances the growth and sustainability of vannamei shrimp farming by improving oxygenation and water quality, ultimately supporting the long-term viability of the aquaculture sector in Indonesia.

Key Words: aquaculture, management, pond, quality, technology.

Introduction. Indonesia is known as one of the world's leading shrimp producers and exporters, with an impressive production volume exceeding 530,000 tons in 2023 and a consistent annual growth rate of 4–7% in shrimp exports (Cheng et al 2023). Vannamei shrimp, a species popular for aquaculture, are widely cultivated in various regions, including Java, Sumatra, Kalimantan, and Sulawesi. Specifically, the southern coastal areas of Java have seen a surge in vannamei shrimp farming on marginal sandy lands, particularly in the Special Region of Yogyakarta, Central Java, and West Java. This high-value commodity has significantly contributed to the fisheries sector, generating substantial foreign exchange for the Indonesian economy.

The cultivation of vannamei shrimp has experienced rapid growth since the early 2000s, driven by the need to meet the increasing domestic and international demand for shrimp products (Liao & Chien 2011). Shrimp from aquaculture and capture fisheries offer a variety of sizes, qualities, and types, which meet the diverse preferences of the global market. This diversity, combined with the superior quality and competitive prices of Indonesian shrimp, has contributed to its strong reputation in the international market. The continuous evolution of aquaculture practices and the adoption of increasingly sophisticated technology have played a crucial role in maintaining the competitiveness of Indonesian shrimp. The fisheries sector, particularly shrimp farming, plays an important role in the country's economy, contributing a significant portion of non-oil and gas export revenue. About 80-85% of shrimp exports come from aquaculture, while the remaining

15-20% come from capture fisheries. Indonesian shrimp exports are targeted at various international markets, including the United States, Japan, Europe, and other Asian countries (Portley 2016).

The vannamei shrimp farming industry has experienced rapid growth in recent decades to meet the continuously increasing demand of the global market. However, this rapid expansion has also posed several challenges that threaten the long-term sustainability of the shrimp farming sector. Water quality management, feed efficiency, and disease outbreaks are just a few of the main issues shrimp farmers must face. Poor water quality can cause stress and disease in shrimp, while inefficient feed utilization increases production costs and wastes resources. Disease outbreaks can decimate entire shrimp populations and disrupt market supply, whether caused by viruses, bacteria, or parasites. Therefore, developing and adopting innovative technologies that simultaneously enhance productivity and maintain the ecological sustainability of shrimp aquaculture has become increasingly important. These technological solutions must address various challenges faced by the shrimp farming industry, ranging from improved monitoring and processing of water quality to enhanced feed formulations and delivery systems to implementing early warning systems for disease prevention and control. By developing this sustainable shrimp farming technology, the vannamei shrimp aquaculture sector can continue to meet the increasing global demand while ensuring the long-term sustainability of this important economic activity.

One of the promising solutions is the use of a micro-bubble generator (MBG). The MBG technology can produce tiny bubbles with a much larger surface area than regular bubbles, resulting in higher gas solubility and transfer efficiency. The presence of microbubbles in shrimp ponds can substantially increase the dissolved oxygen levels in the water, thereby improving the cultivated shrimp's overall living environment. This increase in oxygenation can result in better feed utilization and growth performance, as the shrimp will have access to more dissolved oxygen to support their metabolic processes. Furthermore, the microbubble generator can potentially reduce disease risk by directly supporting the shrimp's immune system function and decreasing the prevalence of pathogenic microorganisms in the pond environment. By implementing MBG technology, shrimp farmers can increase productivity and enhance the sustainability of shrimp farming operations.

This study aimed to identify more efficient and environmentally friendly solutions to improve the performance of whiteleg shrimp aquaculture. The study investigates the effectiveness of MBG with ball nozzles and a combination of ball and pore nozzles, evaluating their potential to optimize dissolved oxygen levels, water quality, and overall shrimp growth. This study provides valuable insights and recommendations to advance the productivity and environmental responsibility of whiteleg shrimp aquaculture in Indonesia.

Material and Method

Description of the study sites. We conducted vannamei shrimp cultivation for 3 months, from October to December 2024, in a mulch-lined sand pond, in a collaborative pond between the Department of Fisheries and the Purworejo Regency Government in Keburuhan Village.This research was conducted in a collaborative shrimp pond between the Department of Fisheries at Universitas Gadjah Mada and the local government of Purworejo Regency, located in Keburuhan Village, Ngombol District. The collaborative shrimp pond was equipped with adequate facilities, enabling in-depth research on applying micro-bubble generator technology in cultivating *Litopenaeus vannamei* (white shrimp). The shrimp cultivation in the collaborative pond can be done on sandy land covered with mulch, which provides a suitable environment for white shrimp farming. The water requirement for the shrimp pond is fulfilled by shallow wells ranging from 20 to 40 meters in depth, ensuring a reliable water supply for the cultivation activities.

Research design. This study uses an experimental method to culture a vaname in ponds with MBG applications installed with ball nozzles and combination ball and pores nozzles. The goal is to see how the shrimp grow, and the water quality changes while the two MBG models are being used for cultivation. The study involved the aquaculture of whiteleg shrimp in a 12.5 m^{-2} square pond with a 1.0 m water depth and a concave bottom topography. The results of this study will provide valuable insights into the effectiveness of MBG applications in improving vannamei shrimp growth and pond water quality in the center for drainage (Mohanty 2018).

In each pond, a 1 HP MBG unit with six nozzles at the end was placed, with varying versions (Figure 1). The experiment comprised maintaining vannamei shrimp with an MBG equipped with a ball nozzle model and a combination of ball and pore nozzles. Figure 1 shows the MBG and nozzle designs. Each pond was filled with PL10-15 larvae at a density of 100 individuals m^2. They were kept for 90 days using the recommended cultivation and feeding practices. Temperature, dissolved oxygen, pH, and ammonia levels were regularly checked during the experiment to provide the best circumstances for shrimp growth. The study found that employing both ball and pore nozzles in the MBG unit resulted in higher shrimp survival and growth rates than using solely ball nozzles, according to guidelines.

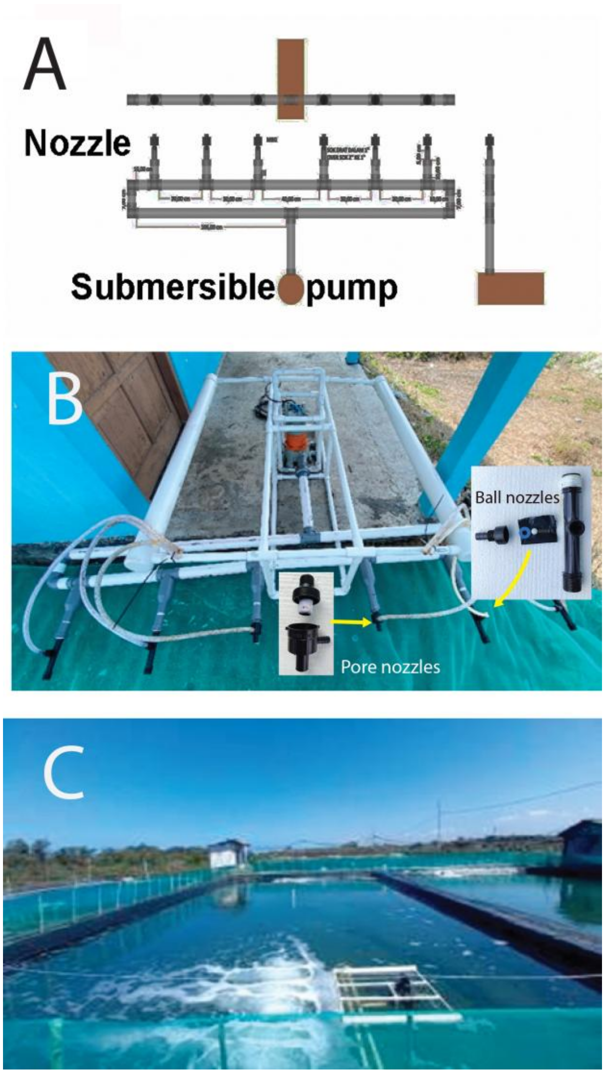

Figure 1. MBG design (panel A), MBG construction with 6 combined ball and pore nozzles (panel B), and MBG installation in shrimp farming pond (panel C).

Data collection

Shrimp growth. Shrimp growth was recorded 30 days after the culture period, and measurements were taken every two weeks. The data collected included the total length and weight of individual shrimp. The number of shrimp samples measured was 20-30 individuals. The length of the shrimp was measured using a metal ruler with a scale accuracy of 0.1 mm, while the weight of the shrimp was measured using an electric scale with a scale accuracy of 0.1 g.

Environmental parameters. The measured environmental parameters included DO, pH, temperature, salinity, and conductivity. The physical parameters of water quality were measured from the beginning of shrimp larvae distribution until the end of the culture. Water quality sampling was carried out every 2 weeks. Water quality measurements were carried out in the morning before sunrise, around 04:00-05:00 AM, and in the afternoon, around 10:00-11:00 AM. Important physical parameters that affect environmental conditions in shrimp ponds, such as dissolved oxygen, pH, temperature, salinity, and conductivity, were measured using the YSI 556 water quality tester. Water quality instruments were standardized according to the guidelines before use. Water samples were taken from each cardinal direction and the pond's center using a bucket, then transferred to a measuring cup, and the YSI sensor was immersed in the sample water. The measured water quality data were recorded and then transferred to a spreadsheet.

Nitrate and phosphate levels. The environmental health laboratory measured total nitrate and phosphate concentrations. Water samples were taken from four stations according to the cardinal directions, plus in the middle of the pond, using bottles. Furthermore, the bottles containing the samples were put in a refrigerated box and taken to the laboratory to measure nitrate and phosphate levels.

Statistical analysis. Statistical tests were conducted to determine the differences in growth between MBG treatments using ball nozzles and a combination of ball nozzles and pores and oxygen concentrations in each research pond. Statistical tests were conducted on growth data (length and weight) and environmental (dissolved oxygen) parameters with a significant level of 5%.

Results. The average development in length and weight of white legs shrimp cultivated in MBG presented in Figure 2. The increase in length and weight under the MBG treatment with both the ball nozzle and the ball+porous nozzle often exhibits comparable outcomes ($P<0.05$). Nonetheless, MBG with the ball nozzle exhibits reduced size variance and improved average weight and length.

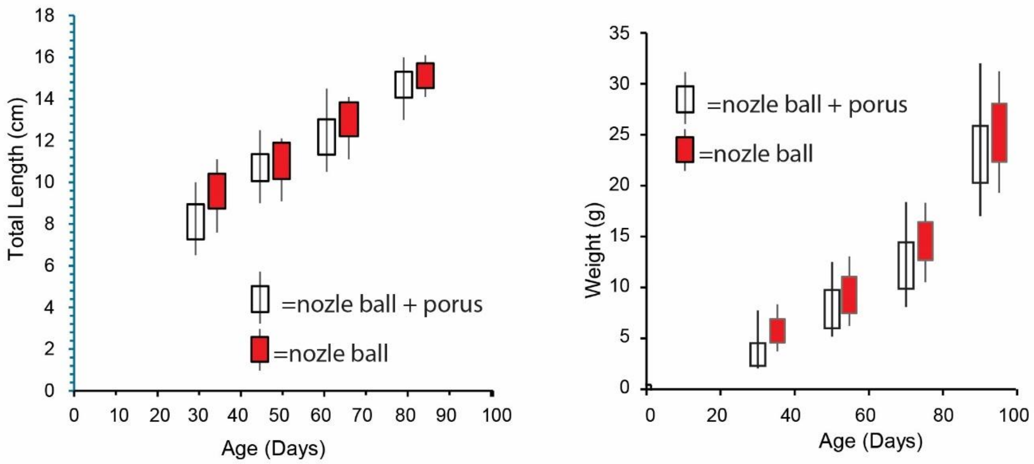

Figure 2. Length (left panel) and weight (right panel) of shrimp at ages 37, 52, 65, and 82 days of rearing, with a sample size of 20 to 30 individuals per sampling.

The comparison of shrimp length and weight during rearing is presented in Table 1. Shrimp rearing used mulched ponds, and aeration used MBG, a combination of ball nozzles + porous nozzles with ball nozzles alone. Then, observations of growth in length and weight were conducted at 37, 52, 65, and 82 days of rearing. The number of shrimp samples for measuring length and weight in each pond ranged from 20 to 30 individuals. The presented data includes the number of individuals (n), average length (cm), standard deviation (std), t-value, significance (sig), and Cohen's effect size (d).

Table 1
Comparison of length (cm) and weight (g) of shrimp at ages 37, 52, 65, and 82 days of cultivation, with a sample size of 20 to 30 individuals per sampling

Age (days)	*Trt*	*N (ind)*	*Length (cm)*	*std*	*t*	*sig*	*d*	*Weight (g)*	*Std*	*t*	*sig*	*d*
37	nbp	30	8.1	0.84	-6.36	0.000	1.51	3.27	0.75	-8.16	0.000	2.07
	nb	30	9.5	0.84				5.25	1.07			
52	nbp	21	10.5	0.80	-1.47	0.149	0.42	7.87	1.87	-1.78	0.084	0.74
	nb	21	10.9	0.87				8.88	1.82			
65	nbp	26	12.2	0.85	-3.26	0.002	0.82	12.15	2.28	-3.55	0.001	1.43
	nb	26	12.9	0.81				14.22	1.89			
82	nbp	30	14.7	0.62	-2.12	0.038	0.42	22.71	1.80	-9.10	0.227	1.15
	nb	30	15.0	0.59				24.57	3.41			
Overall	nbp	107	11.4	2.65	-2.17	0.031	0.47	8.86	5.83	-1.92	0.056	0.72
	nb	107	12.2	2.32				10.61	5.90			

Trt-treatment; d-Cohen’s d value; nbp-nozzle ball and porus; nb-nozzle ball.

The shrimp length and weight growth pattern showed variations depending on treatment and age. The length and weight of shrimp from the beginning of rearing to 37 days of age and at 65 days of age showed significant differences ($P<0.05$), while 52 and 82 days of age showed no significant differences ($p>0.05$). The length of shrimp at the end of rearing showed no significant difference, but the weight of shrimp in the ball nozzle treatment showed more weight ($p<0.05$). Differences in length, weight, and diversity can be caused by the conversion of feed given during rearing. Cohen's d value for shrimp weight shows a larger number than the length, so the treatment has a stronger influence on shrimp weight growth and has a stronger correlation.

Table 2 presents the findings of physical water quality measurements, including oxygen content, pH, salinity, and turbidity. Due to equipment damage, some temperature, pH, and salinity data were not measured (na). The pond water temperature at the onset of the aquaculture period, aligning with the shift from the dry to the rainy season, was comparatively lower than during the harvest period, corresponding with the peak of the rainy season. The early morning temperature was approximately 31-32°C, increasing to 32-33°C throughout the day. The pond water temperature varied marginally due to weather, seasons, and precipitation alterations. During the cultivation period, the weather frequently included heavy rainfall, resulting in a decline of around 1°C in the pond water temperature following extended periods of intense precipitation.

Table 2
Environmental quality measurements (mean±std) at 04.00 and 10.00 AM every 2 weeks

Morning (04.00-05.00 AM)	*Temperature (°C)*	*Dissolved oxygen (mg L^{-1})*	*pH*	*Salinity (g L^{-1})*	*Conductivity (μmhos cm^{-1})*
Age (days)	MBG with a combined nozzle ball and porus				
2	30.5±0.02	5.3±0.43	9.1±0.04	12.1±0.1	35.1±0.79
17	32.63±0.12	5.75±0.37	NA	23.4±0.59	24.2±0.55
37	31.47±0.17	5.74±0.59	8.06±0.02	21.5±0.89	38.9±1.45
52	32.56±0.47	3.59±0.57	7.12±0.03	28.44±1.06	56.33±1.27
65	31.6±0.39	3.70±0.24	7.1±0.2	37.1±0.95	66.7±0.90
82	28.91±0.6	2.97±0.2	7.42±0.3	17.41±1.70	29.9±2.7
	MBG with nozzle ball				
2	30.10±0.52	4.70±0.63	9.2±0.15	12.5±0.3	42.0±0.47
17	32.81±0.17	4.52±2.05	NA	24.4±0.7	25.2±0.56

Morning (04.00-05.00 AM)	Temperature (°C)	Dissolved oxygen (mg L-1)	pH	Salinity (g L-1)	Conductivity (μmhos cm-1)
37	32.04±0.68	5.64±0.89	7.86±0.5	24.24±1.0	44.04±1.77
52	32.24±0.21	3.66±0.53	7.57±0.31	28.37±1.26	55.47±0.79
65	32.41±0.3	3.63±0.26	7.04±0.03	37.0±2.97	67.04±0.03
82	29.11±0.44	4.30±0.25	7.31±0.10	15.95±2.32	28.83±3.2
Daylight (10.00-11.00 AM)		MBG with a combined nozzle ball and porus			
2	31.1±0.3	6.30±0.75	9.2±0.34	12.2±0.05	57.7±0.34
17	33.7±0.42	6.46±0.40	NA	NA	NA
37	33.0±0.37	6.21±0.71	8.13±0.03	35.77±0.45	62.7±1.35
52	33.53±0.15	4.67±0.63	7.36±0.25	32.57±0.70	58.19±2.14
65	33.3±0.31	3.9±0.25	7.2±0.04	36.8±1.15	64.8±2.12
82	32.56±0.47	5.79±0.33	7.22±0.03	NA	58.93±13.8
Daylight (10.00-11.00 AM)		MBG with ball nozzle			
2	31.2±0.30	6.6±0.55	9.2±0.09	12.5±0.02	41.3±0.51
17	34.29±0.16	8.07±0.58	NA	NA	NA
37	33.39±0.27	5.40±0.43	7.89±0.04	37.7±0.42	67.76±1.21
52	33.13±0.14	6.76±0.55	7.83±0.27	31.7±0.98	56.61±1.98
65	33.3±1.6	4.8±0.3	7.20±0.4	35.7±1.9	64.3±4.2
82	28.2±0.21	4.2±0.3	6.7±0.04	NA	38.1±18.9

NA-not available.

The dissolved oxygen content at the beginning of shrimp cultivation reached six ppm but decreased with age due to increasing shrimp biomass and organic matter concentration in the pond. The increased biomass and organic matter resulting from residual feed and feces necessitated using oxygen for respiration and breakdown. At the end of shrimp culture, dissolved oxygen levels in ponds with MBG ball nozzles were greater (>4ppm) than in ponds with mixed MBG nozzles.

During the day, the dissolved oxygen concentration increased by around one ppm due to phytoplankton photosynthesis and air agitation with the pond surface. During the day, phytoplankton photosynthetic activity drives an increase in dissolved oxygen concentration, as does aeration induced by air interaction with the pond surface. Water acidity at the beginning of the culture phase showed a tendency towards alkaline conditions that persisted until the end of the culture period. Water pH remained relatively constant between ponds and throughout the aquaculture period. Water alkalinity remained consistently high throughout shrimp aquaculture, with consistent pH levels observed at various sampling intervals and across the study ponds.

The concentration of dissolved oxygen in the morning and afternoon measurements is presented in Table 3.

Table 3

Comparison of average O_2 levels (ppm) by treatment type and age group (days)

Age (days)	Treatment	Sample (n)	Mean O_2 (mg L-1)	Std	t	sig	d	Mean O_2 (g L-1)	std	t	sig	d
				Morning					Daylight			
37	nbp	7	4.69	0.63	-2.03	0.065	0.80	6.27	0.75	-0.99	0.342	0.43
	nb	7	5.27	0.43				6.61	0.53			
52	nbp	7	5.19	0.50	-2.34	0.037	0.84	6.46	0.40	-6.07	0.000	2.31
	nb	7	5.75	0.37				8.07	0.58			
65	nbp	7	5.64	0.89	-0.25	0.809	0.12	6.21	0.71	2.59	0.024	1.08
	nb	7	5.74	0.59				5.40	0.43			
82	nbp	7	3.66	0.53	0.24	0.812	0.10	3.66	0.53	-10.60	0.000	4.21
	nb	7	3.59	0.57				6.76	0.55			
Overall	nbp	35	5.32	1.33	1.33	0.188	0.36	5.39	1.29	-3.41	0.001	0.91
	nb	35	4.90	1.31				6.40	1.19			

d-Cohen's d value; nbp-nozzle ball and porus; nb-nozzle ball.

This table presents the average oxygen levels (in ppm) in ponds using MBG with a combination of ball and porous nozzles and ball nozzle treatments, with observations made at various age categories (37, 52, 65, and 82 days). Each research pond was sampled at 7 points. Data are presented as average oxygen levels, standard deviations, t-values, significance levels (sig), and Cohen's d effect sizes.

The average oxygen content in ponds with a combination of ball nozzle + porous and ball nozzle treatments from the beginning of cultivation until the age of 65 days in the morning measurements reached more than 5.5 ppm, while at the age of 82 days the dissolved oxygen concentration was around 3.6 ppm. Oxygen levels during daytime observations reached more than 6.5 ppm. Aeration using a microbubble generator combination of a ball nozzle + porous and a ball alone was able to meet the oxygen needs of shrimp and the needs of microbes for the decomposition of organic matter. At the age of 37 days of cultivation, the porous ball nozzle treatment had an average O_2 content of 4.69 ppm, while the ball nozzle group had a higher average of 5.27 ppm. The concentration of dissolved oxygen levels in each pond and at the ages of 37, 65, and 82 days showed the same concentration levels ($p>0.05$) so that there was no strong evidence of differences between treatments and cultivation ages.

Salinity. The water salinity was around 12.0 parts per thousand (ppt) at the start of sowing and subsequently increased to 21.0-23.0 ppt by the 30^{th} day of the culture period. This increase in salinity persisted until the 60th day of aquaculture, when it reached 32.0-37.0 ppt and remained high until the end of farming. The increase in salinity is mainly caused by the evaporation of water from the cultivation ponds, resulting in a concentration effect. During bright sunlight and strong gusts, salt levels were relatively high, accelerating evaporation. On the other hand, salinity levels decline slightly when there is a lot of rain, demonstrating that precipitation impacts salinity dynamics. These salinity oscillations occurred throughout the culture period and substantially impacted many components of the aquaculture system, including the growth and survival of the cultured organisms.

Conductivity. Water conductivity, or the ability to conduct electrical current from the total ions in the water, remains relatively consistent during the cultivation period, ranging from 35-70 µmhos cm^{-1}. The conductivity levels in the cultivation ponds show that the ions come from shallow groundwater in the agricultural area. This constant conductivity was recorded from the start of stockings to the end of harvest. The relatively constant conductivity readings show that the water quality and ionic composition were well-maintained and regulated throughout the aquaculture process, resulting in a favorable farming environment for shrimp.

Nitrate and phosphorus. The aquaculture pond with the mixed MBG system had a nitrate concentration of 0.39±0.01 ppm, whereas the pond with the ball nozzle MBG system had a nitrate concentration of 0.38±0.03 ppm. These findings suggest that the various MBG systems deployed had a minor impact on the nitrate levels in the aquaculture pond. The minor difference in nitrate content between the two pond systems demonstrates that the mixed MBG technology and the ball nozzle can maintain comparable nitrate levels, a crucial water quality indicator for the health and growth of cultivated organisms. The uniformity of nitrate levels across multiple MBG systems illustrates the technology's efficiency in managing the aquaculture water environment and boosting overall aquaculture productivity.

Phosphate levels in MBG ponds with mixed nozzles were 0.45±0.05 ppm, while ball nozzles exhibited a slightly higher concentration of 0.52±0.09 ppm. The differences in phosphate content between the two MBG systems can be traced to the various processes used to generate and disperse microbubbles in the pond environment. The mixed nozzle MBG system may have enabled more efficient phosphate use or removal by aquatic species and biogeochemical processes, reducing the pond's overall phosphate level. In contrast, the ball nozzle MBG system may have resulted in less optimal dispersion or interaction of microbubbles with the pond water column, allowing for more phosphate accumulation. The observed difference in phosphate levels across different MBG systems emphasizes the need to select and optimize technology.

Discussion. The results indicate that both systems yield comparable shrimp length and weight increases, but the ball nozzle system demonstrates less size variance and superior average growth metrics. Environmental conditions were monitored throughout the aquaculture period, revealing fluctuations in water temperature, dissolved oxygen, pH, salinity, and conductivity. Notably, dissolved oxygen levels decreased with shrimp biomass growth, although ponds with ball nozzles maintained higher oxygen levels towards the end of the culture (Kumar & Engle 2016). Salinity increased significantly due to evaporation, while conductivity remained stable, indicating consistent water quality. Nutrient levels, including nitrate and phosphate, were also assessed. MBG systems maintained similar nitrate concentrations, suggesting effective water quality management (Krastanova et al 2022). However, phosphate levels were slightly higher in the ball nozzle system, indicating potential differences in nutrient dynamics influenced by the microbubble dispersion methods (Mawarni et al 2023).

The study of whiteleg shrimp cultivation using different microbubble generator aeration systems reveals significant insights into the impact of nozzle design on shrimp growth performance and water quality parameters. The findings indicate that both the ball nozzle and the combined ball+porous nozzle treatments yield comparable growth outcomes regarding shrimp length and weight. However, the ball nozzle system demonstrates a notable advantage in terms of reduced size variance and enhanced average weight and length of the shrimp, suggesting that nozzle configuration is critical in optimizing the oxygen dynamics and overall water quality within the aquaculture ponds (Mustafa et al 2023).

Further data analysis reveals that the ball nozzle system maintained higher dissolved oxygen levels than the mixed nozzle configuration. However, the overall variation in oxygen dynamics was not statistically significant. This observation suggests that while both aeration systems are effective, the choice of nozzle configuration can influence the oxygen availability and fluctuations within the aquaculture ponds, which is a critical factor in successful shrimp cultivation (Priyono 2019). The subtle differences in oxygen dynamics between the nozzle treatments highlight the importance of optimizing aeration system design to maintain favorable water quality conditions and support the shrimp population's growth and uniform development (Nguyen et al 2024).

In contrast to previous studies that have emphasized the importance of water quality parameters like dissolved oxygen and salinity in determining shrimp growth (Rahman et al 2015), this research highlights a more direct correlation between nozzle design and the consistency of shrimp size. While earlier work by Ariadi et al (2019) demonstrated that variations in dissolved oxygen levels significantly impacted shrimp growth, the current study indicates that the ball nozzle aeration system maintained higher dissolved oxygen concentrations than the mixed MBG nozzle configuration. However, the overall differences in oxygen dynamics were not statistically significant across the treatments. It suggests that while dissolved oxygen remains a crucial factor, the specific method of aeration employed may also play an important role in influencing the growth and uniformity of the cultured shrimp population (Roy et al 2021). To fully capitalize on these benefits, farmers should conduct further research to understand the underlying mechanisms by which nozzle design influences shrimp growth and size distribution. It could involve detailed analyses of water quality parameters, shrimp behavior and feeding patterns, and other factors contributing to the observed differences between the aeration system treatments (Lara et al 2017). By gaining a deeper understanding of these relationships, farmers can make more informed decisions when designing and managing their aquaculture systems, ultimately enhancing their shrimp farming operations' productivity, profitability, and sustainability (Joffre et al 2018).

The environmental conditions monitored throughout the aquaculture period, including temperature, pH, salinity, and turbidity, closely aligned with the key findings from previous comprehensive studies on the culture of *L. vannamei*, the Pacific white shrimp (Naser et al 2022). For instance, the consistent increase in salinity due to evaporation, as noted in this study, corroborates the detailed observations of Zhang et al (2022), who reported similar salinity dynamics that can significantly affect these shrimp's health, growth, and survival rates. The results indicate that salinity levels rose from an optimal starting point of 12 ppt to a concerning range of 32-37 ppt by the 60^{th} day, which is consistent with the critical findings of Zink et al (2017). Such substantial salinity fluctuations can have a profound and detrimental impact on overall shrimp survival rates. These empirical findings collectively underscore the critical importance of close monitoring and rigorously managing key water quality parameters, such as salinity, to ensure the cultivation of optimal conditions required for successful and sustainable vannamei shrimp aquaculture systems. Moreover, the study's findings on nitrate and phosphate levels provide a nuanced understanding of nutrient dynamics in aquaculture systems. The slight differences in nitrate concentrations between the two MBG systems (0.39±0.01 ppm for mixed nozzles vs. 0.38±0.03 ppm for ball nozzles) suggest that both systems are effective in maintaining similar nitrate levels, a crucial indicator of water quality. This aligns with the work of Emerenciano et al (2022), who emphasized the importance of managing nutrient levels to ensure optimal growth conditions for shrimp. However, the observed higher phosphate levels in the ball nozzle system (0.52±0.09 ppm) compared to the mixed system (0.45±0.05 ppm) raises questions about the efficiency of nutrient utilization and removal processes in different MBG configurations.

Vannamei shrimp can thrive and reach their maximum growth potential by maintaining optimal water conditions and sufficient oxygen levels (Araujo et al 2019). The efficient distribution of dissolved oxygen throughout the pond, facilitated by microbubble generators, ensures that shrimp have access to the resources needed for respiration and metabolism. It supports their health, reduces disease risk, and promotes consistent growth rates (Chen et al 2013). In addition, better water quality can lead to more effective feed utilization, as shrimp can convert the nutrients provided into biomass more efficiently. This efficiency results in cost savings and increased profitability for aquaculture operations (Yaparatne et al 2024). Furthermore, careful monitoring and proper control of environmental conditions play a key role in maximizing Indonesia's productivity and sustainability of vannamei shrimp farming.

The findings of this study offer valuable insights for shrimp farmers looking to optimize their aquaculture operations. By carefully selecting and configuring aeration systems, farmers can increase overall shrimp pond productivity and achieve a more uniform size distribution among harvested shrimp (Sivaraman et al 2019). This uniform size can impact product quality, processing efficiency, and marketability. For example, a more uniform shrimp size can allow for more efficient packaging and distribution and may be more appealing to consumers who prefer standardized products. Additionally, uniform shrimp size can simplify processing and cooking procedures, resulting in more consistent and predictable results.

The strategic deployment of microbubble generators with ball+porous nozzles is a crucial component in establishing and sustaining an optimal pond environment for shrimp farming. These aeration systems play a vital role in enhancing water quality, promoting efficient oxygen distribution, and facilitating effective water circulation throughout the aquaculture ponds. By incorporating this advanced technology, aquaculture operators can develop a more sustainable shrimp farming system that maximizes productivity, economic viability, and environmental stewardship (Boyd et al 2020). Through the optimization of key factors such as dissolved oxygen levels, water movement, and overall water quality, aquaculture operators can create an environment that supports the health and growth of their shrimp populations, ultimately leading to increased yields and profitability while maintaining the ecological balance of the farming ecosystem.

Conclusions. The study highlights the significant potential of microbubble generator (MBG) technology, particularly with ball nozzles, in enhancing the growth and sustainability of *L. vannamei* shrimp farming in Indonesia. The findings indicate that using MBG with ball nozzles leads to improved shrimp growth rates, better feed efficiency, and enhanced water quality management compared to other nozzle configurations. This technology optimizes dissolved oxygen levels and promotes a healthier pond environment, thereby reducing disease risks and supporting the long-term viability of shrimp aquaculture. To further advance the shrimp farming sector in Indonesia, it is recommended that aquaculture operators adopt MBG technology with ball nozzles as a standard practice. Additionally, ongoing research should focus on optimizing MBG designs and exploring their integration with other innovative aquaculture practices. Training programs for shrimp farmers on the effective use of this technology and regular monitoring of water quality parameters should also be implemented to ensure the sustainability and profitability of shrimp farming operations. By embracing these recommendations, the Indonesian shrimp industry can improve, in its effort to meet the growing global demand for high-quality shrimp products.

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