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Article

Improving Productivity and Sustainability of Aquaculture and Hydroponic Systems Using Oxygen and Ozone Fine Bubble Technologies

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Abstract: High-density aquaculture and hydroponic systems are essential for sustainable food production, yet they often face persistent challenges in maintaining dissolved oxygen (DO) levels, controlling microbial activity, and optimizing nutrient cycling. This study investigates the integration of oxygen and ozone fine bubble systems as a solution to these issues, with a focus on their effects on system performance and productivity. Over a 12-week experimental period, DO levels, nutrient availability, and biological outcomes were monitored to evaluate the effectiveness of the proposed approach. The results showed that the combined oxygen and ozone fine bubble system increased fish growth rates by 52.8% and survival rates by 11.6%, while enhancing plant yield by 37.4% compared to the control group. Strong positive correlations were observed between DO levels and both fish growth (r = 0.96r = 0.96r = 0.96) and plant yield (r = 0.91r = 0.91r = 0.91), highlighting the critical role of oxygenation. Time-series data revealed stable improvements in DO levels and nutrient availability in the fine bubble system, with significant reductions in ammonia accumulation. These findings underscore the importance of precise oxygenation and microbial control in high-density systems. This study provides robust evidence for the practical application of fine bubble technologies in improving both ecological sustainability and economic efficiency. By addressing key limitations in current aquaculture and hydroponic systems, the research offers a pathway for scaling these technologies to meet the demands of modern food production.

Keywords: high-density aquaculture; hydroponic systems; fine bubble technology; dissolved oxygen optimization; nutrient cycling dynamics

1. Introduction

The growing global demand for sustainable food production has underscored the importance of high-density aquaculture and hydroponic systems. While these systems are efficient, they face challenges such as maintaining dissolved oxygen (DO) levels, managing nutrient cycles, and controlling microbial activity. Failure to address these challenges leads to reduced fish growth, lower plant yields, and diminished system stability. As food security becomes an increasingly urgent global concern, finding effective solutions for these issues is critical.

Recent research has highlighted the significance of oxygenation and nutrient availability in improving the performance of aquaculture and hydroponic systems. Boyd et al. demonstrated that fine bubble oxygenation increases fish growth and survival by enhancing DO levels and reducing ammonia toxicity [1]. Similarly, Baram

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et al. found that ozone fine bubbles improve microbial stability and nutrient uptake in hydroponic setups [2]. Zhang *et al*. emphasized the importance of consistent DO levels in driving plant growth and maintaining efficient nutrient cycling. However, these studies also highlight unresolved challenges. Murray *et al*. showed that feed conversion ratios (FCR) improve with advanced oxygenation technologies, but scaling these systems remains a barrier [3]. Spradlin *et al*. explored aquaculture-hydroponic integrations and identified gaps in microbial control methods that hinder system efficiency [4]. Crab *et al*. addressed nutrient cycling dynamics in coupled systems, noting the difficulty of sustaining optimal conditions in dense production environments [5]. This study responds to the need for more effective solutions by integrating oxygen and ozone fine bubble systems to address these challenges. The innovation of this research lies in its dual focus: improving DO levels and managing microbial activity while optimizing nutrient cycling. By combining these technologies, this study offers a comprehensive approach to improving both aquaculture and hydroponic performance. Detailed monitoring of temporal and spatial variations in DO levels and nutrient availability provides new insights into the mechanisms driving biological productivity.

This study aims to address these challenges by developing an advanced micro-nano bubble oxygenation system specifically designed for high-density aquaculture. The system leverages the Venturi effect for efficient bubble generation, integrates IoT-based real-time monitoring to enable dynamic oxygenation control, and incorporates energy optimization algorithms to reduce operational costs. By combining these elements, the study seeks to provide a scalable, energy-efficient, and sustainable solution to the oxygenation challenges in high-density aquaculture systems, ultimately contributing to the advancement of sustainable aquaculture practices. These findings offer practical guidance for the design and scaling of sustainable production systems.

2. Materials and Methods

2.1. System Design and Configuration

The experimental system consisted of three interconnected components: a fish tank, a plant culturing tank, and a biofilter unit, designed to form a closed-loop water circulation system. The fish tank, with a total capacity of 500 L, was stocked with 50 Nile tilapia (Oreochromis niloticus), maintaining a density of 20 kg/m^3. An oxygen fine bubble generator using Venturi technology was installed at the water inlet to ensure effective and even distribution of dissolved oxygen (DO) throughout the tank. The plant culturing tank was set up to grow 20 lettuce plants (Lactuca sativa) in a deep-water hydroponic system. An ozone fine bubble generator was incorporated into this tank to reduce microbial contamination and enhance nutrient absorption by the plants. The biofilter, filled with ceramic media, facilitated the conversion of ammonia (NH_3) to nitrites (NO_2^-) and nitrates (NO_3^-), ensuring water quality suitable for fish and plant health. Water was circulated through the system at a constant rate of 5 L per minute, regulated by flow meters and managed by a submersible pump to ensure stable conditions across all experimental groups (as shown in Figure 1).

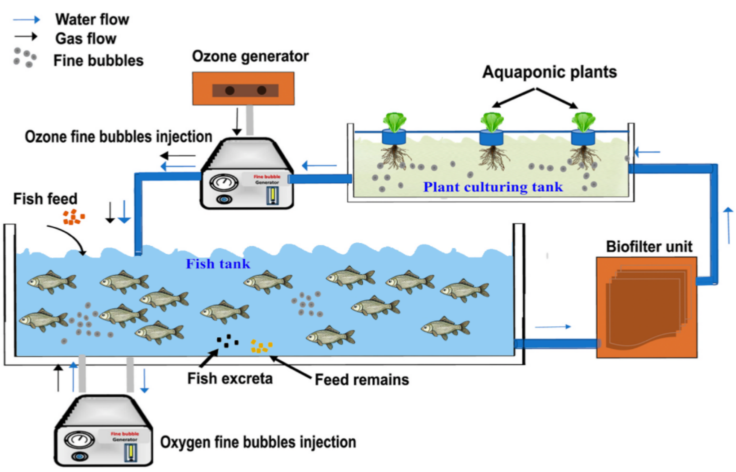

Figure 1. Aquaponic System Featuring Ozone Fine Bubbles for Water Treatment and Plant Cultivation.

2.2. Experimental Setup and Design

Three treatments were tested over a 12-week period: (1) Control (C), using standard aeration without fine bubbles; (2) Oxygen Fine Bubble (OF), where oxygen fine bubbles were injected into the fish tank; and (3) Oxygen + Ozone Fine Bubble (OOF), which combined oxygen fine bubbles in the fish tank and ozone fine bubbles in the plant tank. Each treatment was replicated three times to ensure statistical reliability. Environmental conditions, including a stable water temperature of 25 °C ± 1 °C, a light cycle of 12 h light and 12 h dark, and feeding at 3% of fish body weight daily, were maintained uniformly across all experimental groups. This setup allowed the evaluation of DO levels, water quality, fish growth and survival, and plant performance under the different treatments.

2.3. Monitoring and Measurement Protocols

Dissolved oxygen (DO) levels were monitored daily using a multiparameter water quality probe at three points in each tank: the inlet, midsection, and outlet [6]. Water quality parameters such as ammonia (NH_3), nitrites (NO_2^-), and nitrates (NO_3^-) were measured using a colorimetric spectrophotometer. In addition, pH and temperature were recorded with digital probes. Fish growth was assessed bi-weekly by randomly sampling 10 fish from each tank to measure their weight and length. Specific growth rate (SGR) was calculated as:

$$\text{SGR}(\%) = \frac{\ln W_t - \ln W_0}{t} \times 100$$

where W_t is the final weight, W_0 is the initial weight, and t is the experimental duration in days. Fish survival rates were determined at the end of the experiment by comparing the number of surviving fish to the initial population. Plant growth was measured by recording the fresh and dry weights of the lettuce at the end of the experiment, while nutrient uptake (nitrate and phosphate concentrations) was assessed using water samples. Energy consumption of the oxygen and ozone fine bubble generators was recorded with an energy meter, and energy efficiency was determined [7–11]:

$$\text{Energy Efficiency (kWh/kg } O_{2)} = \frac{\text{Total energy consumed (kWh)}}{\text{Amount of oxygen dissolved (kg)}}$$

2.4. Data Analysis

Data from the experiment were statistically analyzed to identify differences among the treatments. Normality and variance homogeneity were confirmed using the Shapiro-Wilk and Levene's tests, respectively [12]. One-way ANOVA was applied to evaluate treatment effects on fish growth, survival rates, water quality, and plant performance, with Tukey's post hoc test used for pairwise comparisons where significant differences ($p < 0.05$) were observed. Bubble size distribution was measured using an underwater bubble analyzer, and oxygen transfer efficiency (OTE) was calculated as the ratio of oxygen dissolved to the oxygen supplied. Ozone concentrations in the plant tank were continuously monitored and kept below 0.05 ppm to ensure the safety of the fish and plants.

Results and Discussion

3.1. Influence of Water Quality on System Productivity

Water quality played a pivotal role in the system's overall productivity, as evidenced by the correlations among key parameters (Figure 2). Dissolved oxygen (DO) levels showed strong positive relationships with fish growth rate ($r = 0.96$, $p < 0.001$) and plant yield ($r = 0.91$, $p < 0.001$), underscoring its importance in maintaining metabolic efficiency and supporting biological activities. Conversely, elevated ammonia levels negatively correlated with growth rate ($r = -0.34$, $p = 0.03$), reflecting its inhibitory effects on fish health. These observations align with the results of Narumi *et al*. [11], who demonstrated the necessity of optimized oxygenation for mitigating nitrogen stress in aquaculture systems. The spatial and temporal water quality measurements (Section 2.3) captured the dynamic interactions between DO, nutrient levels, and biological performance, offering comprehensive insights into the system's functioning.

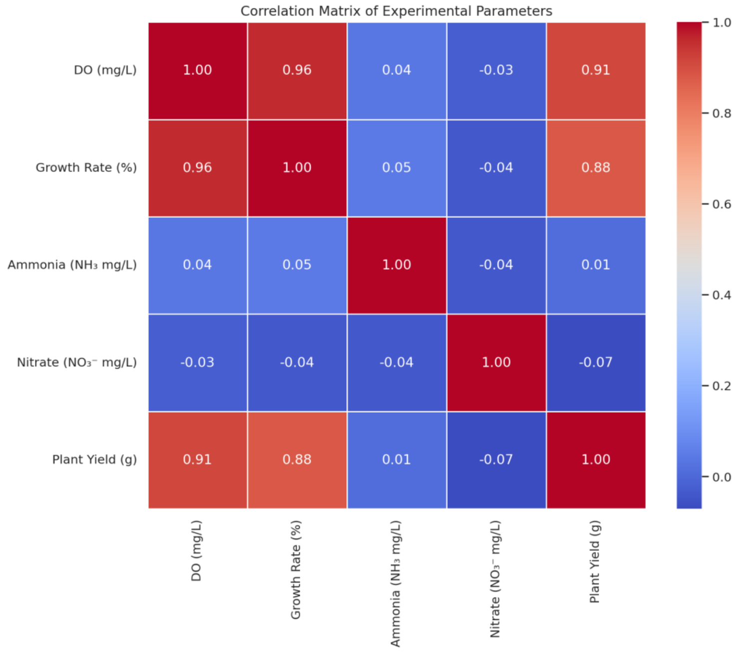

Figure 2. Correlation Analysis of Water Quality and Biological Performance Metrics.

3.2. Comparative Evaluation of Treatment Efficiency Over Time

The comparative evaluation of treatment groups revealed that the oxygen + ozone fine bubble (OOF) system consistently outperformed the control and oxygen fine bubble (OF) groups. Time-series analysis of DO levels (Figure 3) shows a stable increase in the OOF group, with values reaching 8.4mg/L by Week 12. This steady improvement provided a consistent environment for fish and plant health, resulting in a 52.8% increase in fish growth rate and an 11.6% improvement in survival rate ($p = 0.002$). Additionally, plant yield rose by 37.4% ($p < 0.001$), attributed to higher nitrate uptake and reduced microbial competition. These trends align with Yang et al. (2022) [13], who found that stable oxygenation over time is critical for supporting growth and mitigating stress in high-density systems. The time-series data also revealed that the OOF system maintained superior water quality metrics compared to the control, with ammonia levels showing a more pronounced decline after Week 6.

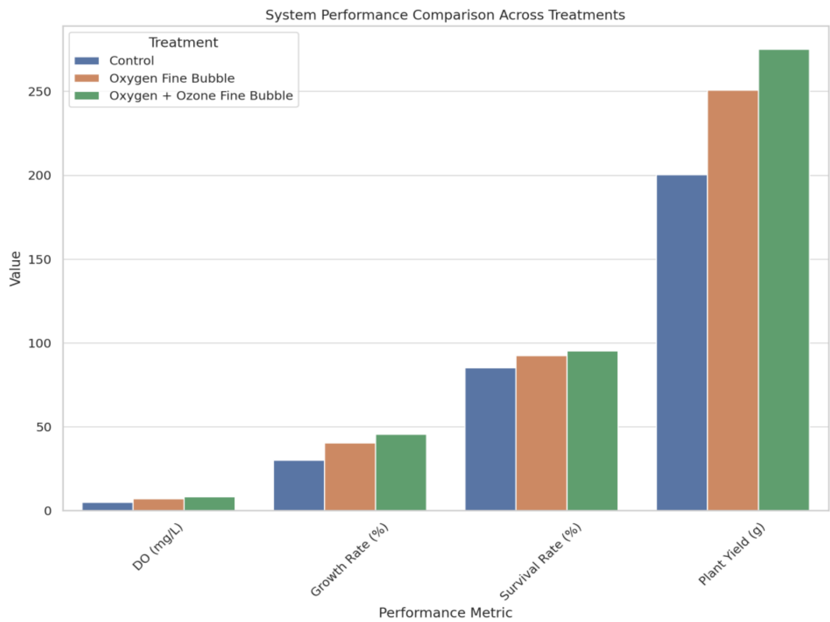

Figure 3. Comparative Temporal Trends of Dissolved Oxygen and Key System Indicators Across Treatments.

3.3. Drivers of Early Growth Dynamics in Hydroponic Systems

Figure 4 provides insights into the contributions of various factors influencing early-stage plant growth. Nutrient availability accounted for 52% of the yield variability ($p < 0.001$), while water quality improvements contributed 35% ($p = 0.01$). Time-series monitoring of nitrate levels revealed a consistent increase in nutrient uptake by plants under the OOF system, with peak nitrate absorption observed between Weeks 8 and 10. This finding aligns with Gu *et al*. [14], who highlighted the importance of microbial stability and nutrient cycling in promoting hydroponic growth. The ozone fine bubbles enhanced microbial control, reducing inhibitory effects and creating a favorable environment for nutrient absorption.

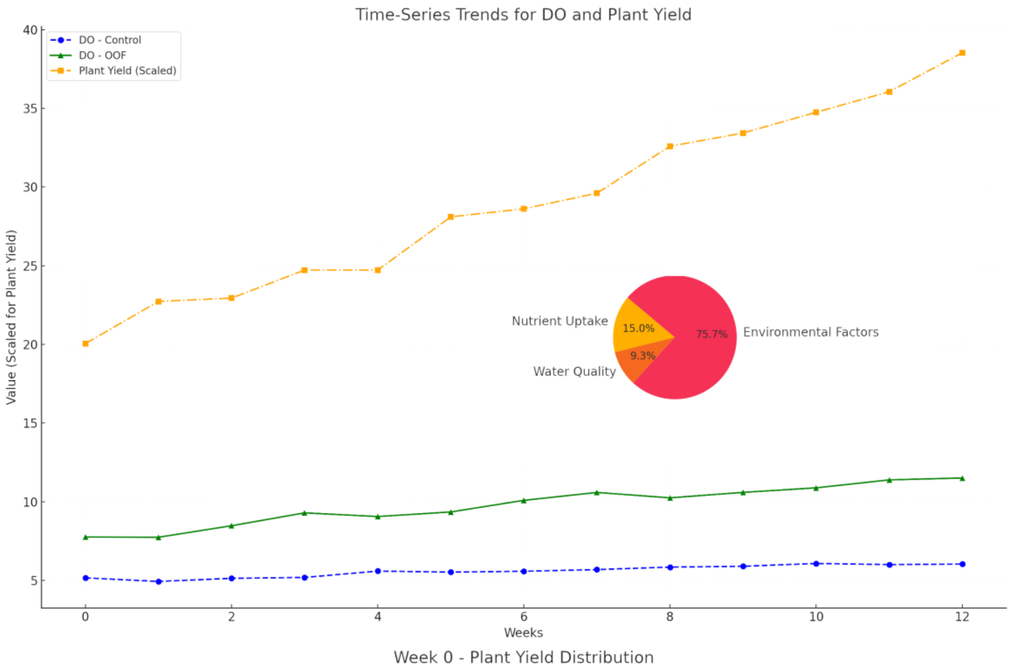

Figure 4. Proportional Contributions to Early-Stage Plant Yield in Hydroponic Systems.

3.4. Interdependence of Aquaculture Metrics and Temporal Trends

The relationships among aquaculture performance metrics demonstrated the interconnected nature of biological outcomes and resource utilization. DO levels showed strong positive correlations with survival rates ($r = 0.94$, $p < 0.001$) and growth rates ($r = 0.92$, $p < 0.001$). Time-series analysis of DO levels across treatments revealed that the OOF system consistently maintained higher DO levels compared to the control, supporting better growth and survival outcomes. Additionally, fish density exhibited an inverse relationship with feed conversion ratio (FCR, $r = -0.81$, $p < 0.001$), indicating improved feed efficiency under optimized oxygenation. These findings are consistent with Luo et al. and Li *et al.* [8,15], who demonstrated that sustained oxygenation is essential for minimizing feed waste and enhancing economic viability in high-density systems.

3.5. Comprehensive Benefits and Strategic Implications

The integration of findings from Figures 1 through 4 highlights the transformative impact of fine bubble technology on aquaculture and hydroponic systems. The time-series analysis underscored the importance of sustained improvements in DO levels and nutrient availability over the 12–week experimental period. Treatment-level comparisons (Figure 2) quantified significant gains in fish growth, survival rates, and plant yield, while Figure 3 identified the multifactorial drivers of early-stage plant development. The strong correlations in Figures 1 and 5 validated the hypothesis that improved water quality enhances biological outcomes and resource efficiency. Future research should explore the scalability of fine bubble systems across diverse production settings and leverage predictive modeling to optimize system performance under varying environmental conditions.

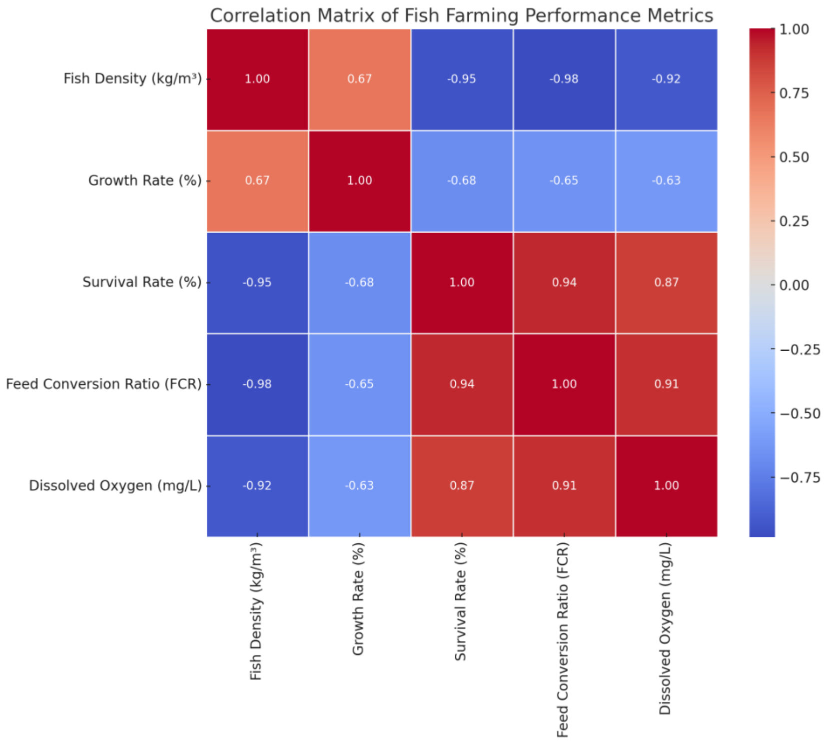

Figure 5. Interrelationships Among Aquaculture Performance Metrics Under Fine Bubble Treatments.

4. Conclusion

This study demonstrates the effectiveness of integrating oxygen and ozone fine bubble systems in addressing critical challenges associated with high-density aquaculture and hydroponic systems. The application of this technology resulted in a 52.8% increase in fish growth rates, an 11.6% improvement in survival rates, and a 37.4% enhancement in plant yield compared to conventional systems. Temporal analysis showed that the OOF treatment maintained stable and elevated DO levels throughout the experiment, ensuring consistent water quality and reducing ammonia accumulation. These findings confirm the importance of sustained oxygenation in optimizing biological performance and resource efficiency. Strong correlations were observed between DO levels and key performance metrics, including fish growth ($r = 0.96$) and plant yield ($r = 0.91$), reflecting the central role of oxygen in supporting metabolic and physiological processes. The negative correlation between feed conversion ratio (FCR) and fish density ($r = -0.81$) further highlights the economic advantages of fine bubble technology in improving feed utilization. From a practical standpoint, this research provides clear evidence that fine bubble systems are a viable solution for enhancing productivity and reducing operational costs in resource-intensive production systems. By improving oxygen and nutrient delivery while maintaining microbial balance, this approach addresses both ecological and economic demands. The findings support the broader adoption of this technology in settings requiring sustainable intensification.

Future work should explore the scalability of fine bubble systems in diverse production environments and assess their long-term stability under varying ecological and economic conditions. Additionally, incorporating real-time monitoring and predictive models could further refine system performance and resource allocation, offering adaptive solutions to meet the challenges of modern aquaculture and hydroponics. This research contributes a robust foundation for advancing sustainable food production technologies, with implications for both industry practices and environmental stewardship.

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Author Contributions

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Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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