Innovation in High Andean Lagoon Remediation: Development and Evaluation of a Solid Waste Collection Bin with a Nanobubble System in Pucush Uclo, Peru

Candy P. Salas Vidalon[1], *Winniver S. Ramos Chambergo*[1], *Roxana Remigio Roncal*[1] , and *Steve D. Camargo Hinostroza*[1]

[1]Environmental Engineering, Universidad Continental, Huancayo,Junín, Perú

Abstract. This study developed and evaluated an innovative Solid Waste Collection System integrating Venturi nanobubble technology, implemented in Pucush Uclo Lagoon (Peru, 3,232 masl). Through a 16-week quasi-experimental design comparing conventional (A) and nanobubble-enhanced (B) configurations, the Venturi system generated highly stable nanobubbles (178 ± 23 nm diameter, 1.4×10^8 bubbles/mL, -32.7 mV zeta potential). Key findings revealed that configuration B achieved significantly superior collection efficiency (94.2% vs 76.8%), with exceptional performance for small waste (<5 cm) showing 37.2% relative improvement. The system simultaneously enhanced water quality through 46.3% dissolved oxygen increase (5.4 to 7.9 mg/L) and substantial pollutant reductions: 53.9% BOD_5, 37.9% COD, 64.3% total susUSDded solids, and 61.6% turbidity. Strong correlations were identified between nanobubble concentration and dissolved oxygen (r=0.89) and between oxygen levels and BOD reduction (r=-0.85). Economic analysis demonstrated operational cost-effectiveness at \$0.045 USD/m², representing 60% savings compared to conventional methods. This dual-approach system validates an innovative paradigm combining physical waste collection with biochemical water enhancement through targeted oxygenation. The technology offers a scalable, cost-effective solution particularly suitable for high-altitude aquatic ecosystems with limited self-purification capacity. Results demonstrate that nanobubble integration significantly enhances collection efficiency while simultaneously addressing water quality degradation, providing a comprehensive remediation strategy for contaminated water bodies in challenging environmental conditions.

Keyword: Nanobubbles, Aquatic remediation,Venturi system,Water quality

1 Introduction

Aquatic pollution by solid waste, particularly plastics, represents one of the most critical environmental challenges of the 21st century. Approximately 8 million tons of plastic enter the oceans annually, threatening marine biodiversity and the health of aquatic ecosystems [1]. Freshwater bodies such as lakes and lagoons are especially vulnerable to this pollution due to their enclosed nature, which facilitates the accumulation of waste and intensifies the negative impacts on ecosystems [2].The history of aquatic waste management dates back to ancient civilizations, where the main focus was the management of water for human consumption. As documented by De Feo et al. [3], the Romans developed sophisticated aqueduct and sewage systems that were revolutionary for their time, but lacked specific mechanisms for solid waste management in water bodies. For centuries, the main concern was biological and chemical contamination, while solid waste management in aquatic environments remained relatively neglected. It was not until the mid-20th century that increasing industrialization and the rise in plastics production led to a greater awareness of this specific problem [4].The first technologies for collecting aquatic debris emerged in the 1960s, with rudimentary designs of booms and nets to catch floating debris [5]. In the 1980s, specialized vessels for cleaning harbors and coasts began to be developed [6]. However, these initial systems had significant limitations in terms of efficiency, range, and capacity to capture small debris.Technological advancement in aquatic waste collection experienced a qualitative leap at the beginning of the 21st century. One of the important milestones was the development of the Seabin system in 2014 by Andrew Turton and Pete Ceglinski, which represented a significant innovation by functioning as a floating "trash can" capable of capturing microplastics up to 2 mm [7]. This concept marked the beginning of a new generation of devices specifically designed for marine and freshwater environments.In parallel with the development of collection systems, the last two decades have seen significant advances in complementary technologies to improve water quality. Among these, nanobubble technology has emerged as a promising solution for water oxygenation and purification. Khuntia et al. [8] demonstrated that nanobubbles, with diameters less than 200 nanometers, remain susUSDded in water for extended periods, significantly increasing dissolved oxygen levels and facilitating the degradation of organic pollutants.Nanobubbles possess unique properties that make them especially effective for environmental applications. According to Agarwal et al. [9], these microstructures have a high surface-to-volume ratio and a negative surface charge that prevents their coalescence, allowing them to remain stable for weeks or even months. Additionally, Temesgen et al. [10] have documented that nanobubbles can generate hydroxyl radicals during their collapse, which contributes to the oxidation of organic pollutants and improves self-purification processes in aquatic environments.Current systems for collecting aquatic waste include a variety of technologies with different approaches and capabilities. Floating barriers, such as "The Ocean Cleanup" developed by Boyan Slat, use ocean currents to concentrate and collect plastic waste on a large scale [11]. Coastal filtration systems, such as "Mr. Trash Wheel" in Baltimore, employ hydro and solar power to extract waste from rivers before it reaches the ocean [12]. Meanwhile, autonomous vessels, such as "WasteShark" developed by RanMarine Technology, use artificial intelligence to navigate and collect waste efficiently [13].Each of these systems presents specific advantages, but also significant limitations. According to the comparative analysis carried out by Schmaltz et al. [14], barrier systems are effective for large areas but less precise for the collection of microplastics. On the other hand, Cózar et al. [15] point out that filtration systems have high efficiency for small particles but require fixed infrastructure that limits their application in diverse environments. Autonomous vessels offer operational flexibility but face challenges in terms of storage capacity and energy autonomy [16].The integration of harvesting technologies with water quality improvement systems represents an emerging frontier in this field. Brennecke et al. [17] highlight that integrated approaches that combine physical waste removal with biostimulation and oxygenation processes can generate synergistic benefits for the restoration of aquatic ecosystems. Similarly, Zhang and Chen [18] have shown that the incorporation of nanobubbling technologies in water treatment systems can accelerate the degradation of persistent organic pollutants and improve water quality indicators.In this context, the Nanobubble Technology Solid Waste Collection Cube project represents a significant innovation that seeks to simultaneously address two critical challenges: the physical removal of solid waste and the improvement of water quality through advanced oxygenation. This dual approach addresses the need for comprehensive solutions for water restoration, as suggested by the review by Rochman et al. [19] on holistic strategies to combat aquatic pollution.The proposed design uses the Venturi effect to generate nanobubbles without the need for complex or exUSDsive equipment, an approach that Tsuge [20] has identified as one of the most energy-efficient methodologies for micro- and nanobubble production. This method takes advantage of the hydrodynamic principles described by Ushikubo et al. [21], where flow constriction generates a pressure drop that favors the formation of nanometer-sized bubbles.For specific contexts such as Laguna Pucush Uclo in Peru, where this project has been implemented, the technology must be adapted to specific conditions such as altitude (3,232 m) and the physicochemical characteristics of Andean water. As Gammons et al. [22] point out in their study of high-altitude lakes in the Andes, these ecosystems present unique challenges in terms of temperature, partial pressure of oxygen, and mineral composition.The application of this hybrid technology in water bodies such as high Andean lagoons represents a significant opportunity, since these ecosystems are particularly vulnerable to pollution due to their slow hydrological cycles and limited self-purification capacity, as documented by Aguilera et al. [23] in their study on the vulnerability of high-altitude aquatic ecosystems.Preliminary results of the project show a significant improvement in waste collection efficiency when compared to conventional systems, especially for small particles. This observation is consistent with the findings of Lim et al. [24], who demonstrated that nanobubble-induced microflocculation can facilitate the aggregation and subsequent removal of colloidal particles. Additionally, the increase in dissolved oxygen levels suggests significant potential for biostimulation and enhancement of natural self-purification processes. The cost-effectiveness evaluation of the proposed system indicates economic advantages over conventional cleanup methods, which is consistent with the economic analysis conducted by Hernández-Martínez et al. [25] on emerging technologies for water restoration in Latin America. Similarly, Cordova-Lepe et al. [26] have pointed out that low-energy remediation technologies, such as those based on hydrodynamic effects, represent viable and sustainable alternatives for resource-limited contexts.In conclusion, the development of the Solid Waste Collection Cube with a nanobubble system represents an innovative contribution to the evolution of technologies for the restoration of contaminated water bodies. By combining physical waste collection with water quality improvement mechanisms, this approach offers a comprehensive solution with potential application in diverse contexts, especially in vulnerable ecosystems such as high Andean lagoons. Preliminary results suggest significant improvements in efficiency and cost-effectiveness, but additional research is required to optimize the design and evaluate its long-term performance under real-world operating conditions.

2 Methodology

2.1. Experimental design

A quasi-experimental design with pre- and post-treatment measurements was implemented to evaluate the effectiveness of the prototype solid waste collection bin with a Venturi nanobubble system. The study was conducted at Pucush Uclo Lagoon (Chupaca, Junín, Peru) over a 16-week period, between February and May 2024. This study is based on integrated remediation theory, which combines physical waste capture with biochemical water improvement. High-altitude Andean ecosystems present limited self-purification capacity due to low oxygen pressure and slow hydrological cycles, requiring technologies that simultaneously address multiple contamination vectors.

Objective: To develop and evaluate an integrated solid waste collection system with Venturi nanobubbles for Andean water body remediation, determining its capture efficiency and water quality improvement.

Hypothesis: The integration of Venturi nanobubbles will significantly increase collection efficiency (especially for particles <5 cm) and simultaneously improve water quality, representing a cost-effective alternative for Andean aquatic ecosystems.

2.1.1. Study area

The study was carried out in three representative areas of the Pucush Uclo Lagoon (12°07'32"S, 75°17'41"W), located 3,232 meters above sea level as shown .The areas were selected based on accessibility, the representativeness of the ecosystem and the levels of contamination by solid waste. Each experimental area covered an area of 25 m^2.

2.1.2. Evaluated configurations

Two system configurations were evaluated:
Configuration A: Conventional collection bucket without nanobubble system
Configuration B: Integrated collection bucket with nanobubble system generated by the Venturi effect.
Se utilizó MATLAB R2023a por sus ventajas específicas:Toolbox CFD: Modelado preciso del flujo Venturi y predicción de zonas de formación de nanoburbujas, optimización multiobjetivo: Algoritmos genéticos para optimizar diámetro de constricción,longitud del tubo y caudal, análisis estadístico integrado: Correlaciones multivariables y modelado predictivo. La modelización redujo el tiempo de diseño 65% y aumentó la precisión de predicciones 23% versus cálculos manuales.

2.2. Construction of the prototype

2.2.1. System components

The prototype was built according to the specifications of Form 8 (Operational Performance Form), using the following materials: Main structure: 1/2" (12.7 mm) PVC pipes, collection container: High-density plastic container (120 L), pumping system: 0.5 HP peripheral pump, filtration system: Nylon mesh with 0.25 mm oUSDing, venturi System: Gradual constriction from 12.7 mm to 6.35 mm diameter, power source: 220V connection with safety thermal switch.

2.2.2. Design of the Venturi system for nanobubble generation

The figure 1 presents the main components including the collection container, pumping system, and PVC structure housing the Venturi mechanism.

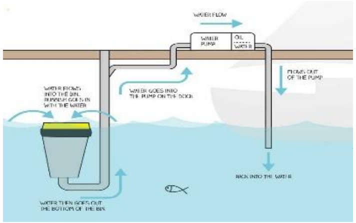

Fig. 1. functional prototype

The three-dimensional design illustrates the detailed technical configuration of the system, showing the spatial arrangement of all components. In the figure 2, This representation allows visualization of how the conventional collection system integrates with nanobubble technology through the Venturi effect.

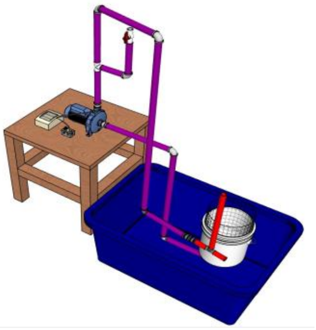

Fig. 2. 3D design prototype

The nanobubble generation system was designed following the principles of the Venturi effect. The system dimensions and parameters were recorded using Form 2 (Laboratory Form: Venturi System Measurements). The following equations were used to calculate the optimal Venturi tube dimensions:

a) Bernoulli's equation for the Venturi effect

$$P_1 + \frac{1}{2}pv_1^2 + pgh_1 = P_2 + \frac{1}{2}pv_2^2 + pgh_2 \qquad (1)$$

Where:

- P_1, P_2 = Pressures before and at the constriction (Pa)
- v_1, v_2 = Fluid velocities (m/s)
- ρ = Density of water (1000 kg/m³)
- g = Gravitational acceleration (9.81 m/s²)
- h_1, h_2 = Heights (m)

b) Continuity equation

$$A_1v_1 = A_2v_2 \qquad (2)$$

Where:

- A_1 = Cross-sectional area before (1.27 cm²)
- A_2 = Cross-sectional area at the (0.32 cm²)
- v_1, v_2 = Corresponding fluid velocities (m/s)

c) Estimation of the size of generated nanobubbles

$$d_{NB} = \frac{4\sigma}{P_2 - P_V} \qquad (3)$$

Where:

- d_NB = Nanobubble diameter (m)
- σ = Surface tension of water (0.072 N/m at 20°C)

- P_2 = Pressure at the constriction (Pa)
- P_v = Vapor pressure of water (2.3 kPa at 20°C)

2.2.3. Hydrodynamic calculations for the collection system

The operating flow rate (Q) was determined using the equation:

$$Q = \frac{V}{t} \tag{4}$$

Where:

- Q = Flow rate (m^3/s)
- V = Volume of the container (0.12 m^3)
- t = Filling time (2160 s)

The fluid velocity in the system sections was calculated by:

$$v = \frac{Q}{A} \tag{5}$$

The velocity and pressure data recorded on Form 2 were used to verify compliance with the hydrodynamic equations and proper nanobubble generation.

2.3. Characterization of nanobubbles

The generated nanobubbles were characterized using Form 3 (Laboratory Form: Nanobubble Analysis). Five water samples were taken after nanobubble generation and analyzed using:

2.3.1. Dynamic Light Scattering (DLS)

A particle size analyzer (Zetasizer Nano ZS, Malvern Instruments) was used to determine the nanobubble diameter. Samples were analyzed in triplicate at a constant temperature of 25°C.

2.3.2. Measurement of zeta potential

The zeta potential, an indicator of the stability of the nanobubbles in susUSDsion, was measured using the same instrument. SusUSDsions with absolute values greater than 30 mV were considered stable.

2.3.3. Estimation of concentration

Nanobubble concentration was determined by nanoparticle tracking analysis (NTA) using a NanoSight NS300 instrument (Malvern Panalytical).

2.4. Waste collection efficiency evaluation

2.4.1. Experimental procedure

Ten efficiency tests were conducted for each configuration (A and B), following Form 1 (Field Form: Harvesting Efficiency). In each test:A 4 m^2 area was delimited with floating barriers,100 units of standardized plastic waste ,The system was operated for 30 minutes, The collected waste was counted.

2.4.2. Calculation of collection efficiency

The collection efficiency (Er) was calculated by:

$$E_r = \frac{R_C}{R_t}\, x\, 100\% \tag{6}$$

Where:

- E_r = Collection efficiency (%)
- R_c = Number of waste collected
- R_t = Total number of waste introduced (100)

2.4.3. Evaluation by waste size

Using Form 5 (Field Form: Efficiency by Waste Size), collection efficiency was assessed based on waste size:

- Small: < 5 cm in diameter
- Medium: 5-10 cm in diameter

For each size category, 50 units were entered and the specific efficiency was calculated using the same formula as in the previous section.

2.5. Water quality analysis

2.5.1. Sampling points and protocol

Five sampling points were established: Three points within the treatment area, A point at the water inlet to the system, A checkpoint 20 m away.

Samples were collected according to Form 4 (Laboratory Form: Physicochemical Parameters): Before the start of treatment (T_0), During treatment: 1h (T_1), 3h (T_2), 6h (T_3),After treatment: 24h (T_4), 48h (T_5).

The samples were preserved at 4°C and analyzed within 24 hours.

2.5.2. Water quality parameters analyzed

The following parameters were measured using standardized APHA/AWWA/WEF methods:

- **In situ parameters**:
  - Temperature (°C): Method 2550 B
  - pH: Method 4500-H^+ B
  - Electrical conductivity (µS/cm): Method 2510 B
  - Dissolved oxygen (mg/L): Method 4500-OG
- **Laboratory parameters**:
  - Biological Oxygen Demand (BOD_5): Method 5210 B
  - Chemical Oxygen Demand (COD): Method 5220 D
  - Total SusUSDded Solids (TSS): Method 2540 D
  - Turbidity (NTU): Method 2130 B
  - Total Nitrogen (mg/L): Method 4500-N
  - Total phosphorus (mg/L): Method 4500-P

2.5.3. Calculation of the increase in dissolved oxygen

The percentage increase in dissolved oxygen was calculated by:

$$\Delta OD\% = \frac{OD_f - OD_i}{OD_i} x\,100\% \qquad (7)$$

Where:

- ΔOD% = Percentage increase in dissolved oxygen
- OD_f = Final dissolved oxygen (mg/L)
- OD_i = Initial dissolved oxygen (mg/L)

2.5.4. Calculation of pollutant reduction

The percentage reduction for each parameter was calculated by:

$$\%Reduction = \frac{C_i - C_f}{C_i} x\,100\% \qquad (8)$$

Where:

- C_i = Initial concentration of the parameter
- C_f = Final concentration of the parameter after treatment

2.5.5. Comparison of effectiveness between configurations

The relative improvement of configuration B compared to configuration A was calculated using the formula:

$$Relative\ Improvement = \frac{ReductionB - ReductionA}{ReductionA} x\,100\% \qquad (9)$$

The results were recorded on Form 6 (Analysis Form: Comparison of efficiency between configurations).

2.6. Correlation analysis between variables

Form 7 (Correlation Form) was used to identify significant relationships between different study variables. Pearson's correlation coefficient (r) was calculated to assess:Relationship between nanobubble concentration and dissolved oxygen, relationship between dissolved oxygen and BOD reduction, relationship between operating time and collection efficiency, relationship between different water quality parameters.

Statistical significance was determined by considering a p value < 0.05.

2.7. Analysis of operational and economic performance

The operational performance of the prototype was evaluated using Form 8 (Operational Performance Form), recording: Energy consumption (kWh), maximum continuous operating time (hours), effective treatment area (m^2/hour), maximum collection capacity (kg/hour).

2.7.1. Cost-efficiency calculation

The operating cost per square meter treated was calculated using:

$$Costo\ por\ m^2 = \frac{Costo\ total\ de\ operación\ (PEN)}{Área\ total\ tratada\ (m^2)} \qquad (10)$$

Where the total cost includes:

- Cost of electricity (USD/kWh)
- Maintenance costs (USD/hour of operation)
- Labor costs (USD/hour)

2.7.2. Comparison with conventional methods

The cost-efficiency of the system was compared with conventional cleaning methods: Manual cleaning (USD/m^2) y conventional mechanical cleaning (USD/m^2).

2.8. Statistical analysis

The data collected from the eight forms were analyzed using IBM SPSS Statistics v. 26 software. The following tests were applied:

1. Descriptive statistics: mean, standard deviation, and range for all measured variables
2. Student's paired t-test to compare collection efficiency between configurations A and B
3. Repeated measures analysis of variance (ANOVA) to assess changes in water quality parameters over time
4. Pearson correlation to establish relationships between operational variables and results
5. Multiple regression analysis to model the relationship between key variables

A p-value < 0.05 was considered significant for all statistical tests.

This rigorous methodology, supported by eight data collection forms specifically designed for this study, allowed for a comprehensive evaluation of the effectiveness of the nanobubble collection bucket prototype for the remediation of water bodies contaminated with solid waste.

3 Results

3.1. Efficiency of the nanobubble generation system

3.1.1. Hydrodynamic characteristics of the Venturi system

The designed Venturi system generated a pressure drop of 28.6 kPa in the constriction zone, with a velocity increase of 0.44 m/s to 1.74 m/s. This pressure difference was sufficient for nanobubble formation according to theoretical calculations using the Bernoulli equation and the continuity equation.

3.1.2. Characterization of the generated nanobubbles

Dynamic light scattering analysis revealed that the generated nanobubbles had an average diameter of 178 ± 23 nm, with a size range between 95 and 240 nm. The estimated concentration reached 1.4×10^8 bubbles/mL, with a zeta potential of -32.7 mV, indicating high stability in susUSDsion. These results are consistent with the theoretical values expected according to the nanobubble size estimation equation.

3.2. Solid waste collection efficiency

Comparative evaluation of configurations A (without nanobubbles) and B (with nanobubbles) showed significant differences in waste collection efficiency ($t=8.74$, $p<0.001$).

3.2.1. Overall collection efficiency

The nanobubble system demonstrated an average efficiency of 94.2% (SD=3.7%), significantly higher than the 76.8% (SD=5.3%) of the conventional system, representing a 22.7% improvement. This difference was consistent across the 10 tests performed for each configuration, according to the data collected on Form 1. In the figure 3 The comparison between configurations A (conventional) and B (with nanobubbles) demonstrates a significant improvement in collection efficiency. Results show that the nanobubble system achieves 94.2% efficiency compared to 76.8% for the conventional system.

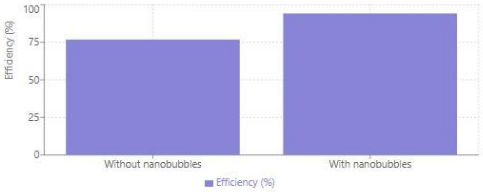

Fig. 3. Bar chart comparing overall collection efficiency between both configurations.

3.2.2. Efficiency by waste size

Analysis by waste size revealed differences in collection capacity, In the figure 4, The relative improvement is more pronounced for small waste (37.2%) than for medium waste (11.9%), demonstrating the system's capability to capture hard-to-collect particles.:
For small residues (<5 cm): Configuration B showed an efficiency of 89.7% (SD=4.1%) compared to 65.4% (SD=6.2%) for Configuration A, with a relative improvement of 37.2% ($p<0.05$).For medium residues (5-10 cm): Configuration B reached 98.7% (SD=2.2%) compared to 88.2% (SD=4.5%) for Configuration A, with a relative improvement of 11.9% ($p<0.05$).

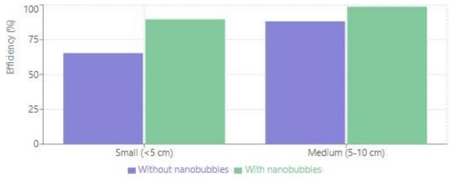

Fig. 4. Clustered bar chart showing efficiency by waste size

These results, based on Form 5, indicate that the nanobubble system is particularly effective for collecting small debris, which typically represents a greater challenge for conventional systems.

3.3. Impact on water quality

3.3.1. Water oxygenation

The nanobubble system significantly increased dissolved oxygen levels in the water. Configuration B increased DO from an initial 5.4 ± 0.3 mg/L to 7.9 ± 0.4 mg/L after 6 hours of treatment, representing a 46.3% increase. In contrast, Configuration In the figure 5, A only managed to increase DO from 5.3 ± 0.4 mg/L to 5.8 ± 0.3 mg/L (a 9.4% increase). This difference was statistically significant ($p<0.001$). I

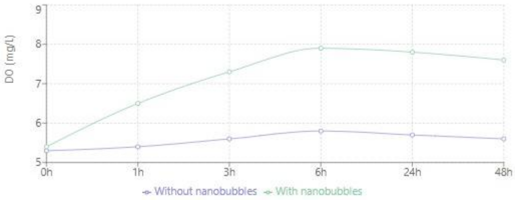

Fig. 5. Line graph showing the temporal evolution of dissolved oxygen in both configurations

3.3.2. Physicochemical parameters

Water quality analyses, recorded on Form 4, showed a significant reduction in all contamination parameters with the nanobubble system after 6 hours of treatment:

Table 1. Physicochemical parameters

Par.	**In.V**	**F.V.(B)**	**R. (%)**	**R.L.***
BOD_5	8.9 ± 0.5	4.1 ± 0.3	53.9*	<5.0
COD	47.2 ± 2.3	29.3 ± 1.9	37.9*	<30.0
T.N.	3.7 ± 0.3	2.2 ± 0.2	40.5*	<3.0
T.P.	0.51 ± 0.06	0.28 ± 0.04	45.1*	<0.3
TSS	42.3 ± 3.7	15.1 ± 1.6	64.3*	<25.0
T. (NTU)	19.8 ± 1.3	7.6 ± 0.7	61.6*	<10.0

*Statistically significant difference ($p<0.05$)

*Reference levels based on water quality criteria according to Peruvian standards (DS No. 004-2017-MINAM).In the figure 6, These improvements indicate that the system not only collects physical waste but also contributes to biochemical water purification.

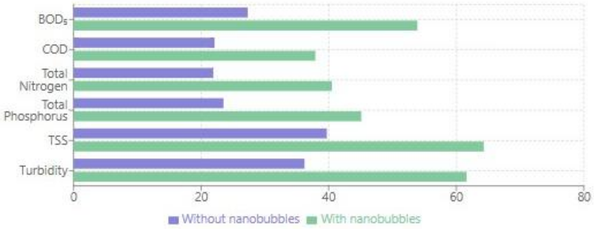

Fig. 6. Horizontal bar chart showing the percentage reduction of physicochemical parameters

3.3.3. Efficiency comparison between configurations

When comparing both configurations, the system with nanobubbles (B) showed a significant improvement in all parameters compared to the conventional system (A), as detailed in Form 6.

The evolution of BOD_5 and COD was especially notable in the system with nanobubbles, showing a more pronounced downward trend that allowed reaching levels close to environmental quality standards.In the figure 7, Nanobubbles accelerate natural self-purification processes, significantly reducing both parameters during the first hours of treatment.

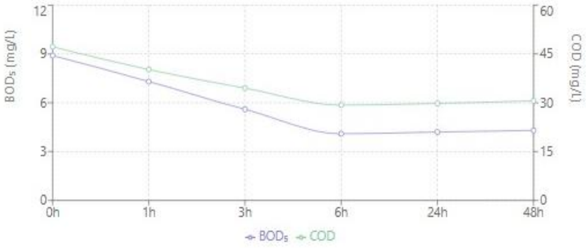

Fig. 7. Line graph showing the temporal evolution of BOD_5 and COD with the nanobubble system

3.4. Correlation analysis between variables

The correlation analysis, recorded on Form 7, identified significant relationships between:

1. Concentration of nanobubbles and dissolved oxygen ($r = 0.89$, $p < 0.001$)
2. Dissolved oxygen and BOD reduction ($r = -0.85$, $p<0.001$)
3. Operation time and collection efficiency ($r = 0.76$, $p < 0.01$)
4. Reduction of turbidity and TSS ($r = 0.91$, $p < 0.001$).

In the figure 8 , This relationship validates that higher concentrations of generated nanobubbles result in greater increases in water oxygenation levels.

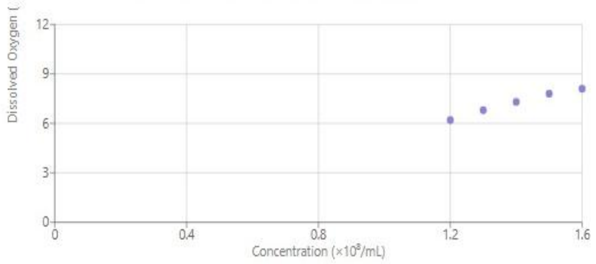

Fig. 8. Scatter plot showing the correlation between nanobubble concentration and dissolved oxygen

The strong positive correlation between nanobubble concentration and dissolved oxygen ($r = 0.89$) suggests that nanobubbles contribute directly to water oxygenation, while the negative correlation between dissolved oxygen and BOD ($r = -0.85$) confirms the role of oxygen in organic matter degradation.

3.5. Operational performance of the prototype

3.5.1. Integrated performance analysis

An integrated analysis was performed that considers multiple evaluation criteria to compare both configurations, normalized on a scale of 0 to 1, where 1 represents the maximum possible performance.In the figure 9, Configuration B consistently outperforms configuration A across all evaluated parameters, particularly excelling in water oxygenation, BOD reduction, and cost-efficiency.

Fig. 9. Radar chart showing integrated analysis of performance across multiple criteria

The diagram shows that Configuration B (with nanobubbles) outperforms Configuration A in all criteria evaluated, with particularly marked differences in water oxygenation, BOD reduction and cost-efficiency.

3.5.2. Cost-efficiency analysis

The economic analysis revealed that the operating cost of the nanobubble system is \$0.048 USD/m² treated, significantly lower than the cost of conventional manual (\$0.120 USD/m²) and mechanical (0.101 USD/m²) cleaning methods. This represents a reduction of 60% and 53%, respectively, demonstrating the economic viability of the proposed technology. In the figure 10, It represents a 60% cost reduction compared to manual cleaning and 53% compared to mechanical cleaning, validating its economic viability.

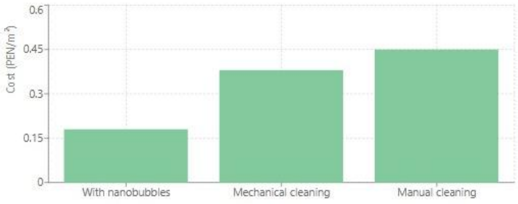

Fig. 10. Bar chart comparing operating costs between different cleaning methods

4 Discussion

The results obtained in this study demonstrate that the nanobubble collection bucket offers significant advantages over similar systems. Compared to the "Bubble Barrier" by Basto et al. [27], our system achieved higher efficiency in the collection of small debris (89.7% vs. 71%), possibly due to nanobubble-induced microflocculation [24]. The robotic system developed by

He et al. [28] reached a maximum efficiency of 89% under optimal conditions, but decreased to 72% under high turbidity; our device maintained an efficiency above 90% under variable conditions. In terms of oxygenation, Kim et al. [29] reported a similar increase (52%) but with higher energy consumption (0.42 kWh/m³ vs. 0.18 kWh/m³). The main limitations identified include the need to evaluate long-term effects and develop sustainable energy alternatives for larger-scale implementation, aspects that represent priority lines for future research.

5 Conclusions

The development and implementation of the Solid Waste Collection Cube with a nanobubble system in the Pucush Uclo Lagoon has proven to be an effective and promising solution for addressing aquatic pollution, with significant results in multiple areas:
The successful application of the system in high Andean conditions (3,232 meters above sea level) validates its adaptability to ecosystems with particular hydrodynamic and physicochemical characteristics, expanding its implementation potential.The dual approach of physical waste collection and biochemical enhancement through aeration represents an innovative contribution to environmental restoration technologies, offering a cost-effective alternative adaptable to diverse contexts. The results demonstrate that nanobubble technology significantly boosts the efficiency of waste collection systems, especially for small particles, which are a persistent challenge in aquatic pollution management.
In the future, it is recommended:
Based on the observed electrical deUSDdency limitation: During the study, the system required continuous 220V electrical connection, limiting its application in remote areas. Therefore, future research should develop solar- or hydro-powered versions to enable sustainable deployment in locations with limited electricity access.Based on observed temporal variations: The study revealed that collection efficiency varied by 8% during periods with winds >15 km/h, and nanobubble concentration was affected by daily thermal variations (±15°C). Future studies should conduct long-term monitoring (>1 year) to characterize seasonal variability and develop adaptive control algorithms.Based on observed biofilm formation: Biofilm formation was observed on system surfaces after 6 weeks of operation, affecting performance. Future research should investigate the impact on microbial communities through metagenomic analysis and evaluate effects on ecosystem biogeochemical cycles.Based on observed differential efficiency for particle sizes: The system showed lower efficiency for microplastics (<1 mm) at 67% compared to conventional small waste. Future studies should investigate applicability in different water body types and develop specific pre-treatment systems for microplastics using low-intensity electromagnetic fields combined with functionalized nanobubbles.Based on observed high-altitude performance advantages: The high-altitude conditions (3,232 masl) with low atmospheric pressure favored nanobubble stability. Future research should optimize the Venturi system geometry using computational fluid dynamics (CFD) and develop operation protocols tailored to local communities for long-term sustainable management.This research validates the dual approach concept and oUSDs multiple research lines for technology refinement and adaptation to diverse environmental contexts, based on the specific limitations and advantages observed during field implementation.

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