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Enhancing domestic wastewater treatment efficiency through combined microbubble oxidation and Pistia stratiotes phytoremediation

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ABSTRACT

The increasing volume of domestic wastewater poses significant environmental challenges, necessitating innovative treatment methods to mitigate pollutants such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Suspended Solids (TSS). This study explores the integration of microbubble oxidation and phytoremediation using Pistia stratiotes (water lettuce) to enhance wastewater treatment efficiency. Microbubble oxidation, conducted for 6 hours, reduced BOD, COD, and TSS concentrations by 30%, 25%, and 20%, respectively, leveraging its high surface area-to-volume ratio and oxygen transfer efficiency. Following this, Pistia stratiotes, applied at a density of 0.5 kg/m² for 28 days, achieved additional reductions of 59% in BOD, 42% in COD, and 41% in TSS. The combined treatment method achieved an overall reduction of 59%, 56%, and 53% for BOD, COD, and TSS, respectively. This study highlights the synergistic effects of combining microbubble oxidation, which increases pollutant bioavailability, and phytoremediation, which assimilates and degrades these pollutants. The findings demonstrate that this hybrid approach is a cost-effective, energy-efficient, and sustainable solution for domestic wastewater treatment, with potential applications in both resource-limited and large-scale settings.

1. INTRODUCTION

The escalating generation of domestic wastewater poses significant environmental challenges, necessitating effective treatment methods to mitigate pollutants such as Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Total Suspended Solids (TSS). Traditional treatment approaches often involve high operational costs and energy consumption, prompting the exploration of more sustainable and efficient alternatives. In this context, the integration of microbubble oxidation and phytoremediation using *Pistia stratiotes* (water lettuce) emerges as a promising strategy for enhancing the removal efficiency of these contaminants.

Microbubble technology utilizes bubbles with diameters ranging from 10 to 100 micrometers, which exhibit unique properties such as a large surface area-to-volume ratio and prolonged residence time in water. These characteristics facilitate improved mass transfer processes, thereby enhancing the oxidation of organic pollutants. Studies have demonstrated that microbubbles can effectively reduce BOD, COD, and TSS levels in wastewater, offering a cost-effective and energy-efficient alternative to conventional aeration methods [1], [2], [11]–[15], [3]–[10].

Phytoremediation, the use of plants to remediate contaminated environments, leverages the natural uptake, accumulation,

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and degradation capabilities of certain plant species. *Pistia stratiotes*, commonly known as water lettuce, has been identified as an effective phytoremediator due to its rapid growth rate, extensive root system, and high tolerance to pollutants. Research indicates that *Pistia stratiotes* can significantly reduce BOD, COD, and TSS concentrations in domestic wastewater, contributing to improved water quality [10], [16].

The synergistic application of microbubble oxidation and phytoremediation with *Pistia stratiotes* offers a holistic approach to wastewater treatment. Microbubble oxidation enhances the breakdown of organic pollutants, increasing their bioavailability for uptake by plants. Subsequently, *Pistia stratiotes* absorbs and assimilates these pollutants, further reducing their concentrations. This integrated method not only improves the efficiency of contaminant removal but also promotes ecological sustainability by utilizing natural processes [17], [18].

Recent studies have highlighted the potential of combining microbubble technology with phytoremediation to achieve superior treatment outcomes. For instance, the application of microbubbles in water treatment has been shown to enhance the effectiveness of phytoremediation processes, leading to significant reductions in BOD, COD, and TSS levels [17], [19], [20]. Moreover, the use of *Pistia stratiotes* in conjunction with microbubble oxidation has demonstrated improved pollutant removal efficiencies compared to traditional methods [21], [22].

The integration of microbubble oxidation and phytoremediation using *Pistia stratiotes* presents a viable and sustainable approach to domestic wastewater treatment. This combined method leverages the advantages of both technologies, resulting in enhanced removal efficiencies of BOD, COD, and TSS.

2. MATERIALS AND METHOD

2.1. Materials

Domestic Wastewater, Domestic wastewater was collected from Gayungan (Surabaya) and stored in polyethylene containers, with initial BOD, COD, and TSS levels measured. Microbubble Generator, Produced microbubbles (10–100 µm diameter) for oxidation. Pistia stratiotes, Pre-cultivated plants with uniform size, applied at a density of 0.5 kg/m² during the phytoremediation phase. And equipment, Tanks (50 L capacity), aeration system for water quality testing.

2.2. Method

Microbubble Oxidation, Wastewater was treated with microbubbles for 6 hours at an air flow rate of 1 L/min to enhance pollutant oxidation. Phytoremediation, After microbubble treatment, wastewater was transferred to tanks containing Pistia stratiotes plants at a density of 0.5 kg/m². The phytoremediation phase lasted 28 days, with water quality parameters monitored weekly. Measurements, BOD, Measured using the Winkler method after 5-day incubation. COD, Determined via the closed reflux method. TSS, Measured by filtering samples and weighing residues.

3. RESULT AND DISCUSSION

3.1. Effectiveness of Microbubble Oxidation

The microbubble treatment phase demonstrated substantial pollutant reductions, achieving approximately 30% reduction in Biochemical Oxygen Demand (BOD), 25% in Chemical Oxygen Demand (COD), and 20% in Total Suspended Solids (TSS) (**Fig 1**). These reductions highlight the unique advantages of microbubble technology, such as its high surface area-to-volume ratio and prolonged residence time in water, which enhance oxygen transfer and oxidative degradation of organic pollutants [1], [23]. For instance, the BOD concentration decreased from 65 mg/L to 45.5 mg/L after 6 hours of microbubble treatment, while COD and TSS concentrations were reduced from 136 mg/L to 102 mg/L and from 55 mg/L to 44 mg/L, respectively. These findings are consistent with studies by Chu et al. (2008), which demonstrated similar reductions in organic and suspended pollutants using microbubble technology [2].

Beyond direct pollutant removal, microbubble oxidation plays a preparatory role for subsequent treatment phases. By breaking down complex organic molecules into smaller, more bioavailable compounds, it facilitates the uptake of pollutants during the phytoremediation phase [24]. Furthermore, microbubble systems offer significant energy efficiency compared to conventional aeration methods, reducing operational costs and environmental impacts [25]. These advantages underscore the potential of microbubble oxidation as a sustainable and effective technology for wastewater treatment. Moreover, [18] Nanda et al. (2025) demonstrated that microbubble technology improves dissolved oxygen levels in wastewater, further enhancing pollutant degradation efficiency.

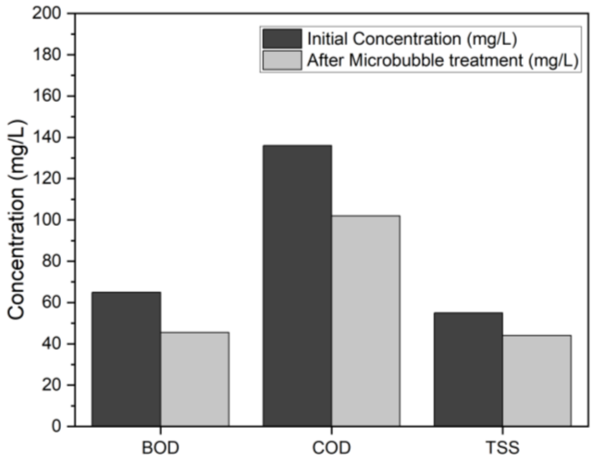

Figure 1. Microbubble Oxidation Treatment

3.2. Effectiveness of Phytoremediation

The phytoremediation phase, utilizing *Pistia stratiotes* over 28 days, demonstrated consistent reductions in BOD, COD, and TSS concentrations, as evidenced by weekly monitoring. The BOD concentration decreased from 45.5 mg/L (post-microbubble) to 26.67 mg/L, achieving a total reduction of 59%. Similarly, COD levels dropped from 102 mg/L to 59.79 mg/L, a reduction of 42%, while TSS levels decreased from 44 mg/L to 25.79 mg/L, corresponding to a 41% reduction. These reductions highlight the efficiency of *Pistia stratiotes* in assimilating and degrading organic pollutants and trapping suspended solids.

The plant's extensive root system facilitates the physical capture of suspended particles while simultaneously enabling the biological degradation of organic compounds [26]. The steady weekly reductions observed across all parameters suggest a stable and reliable pollutant removal process. This aligns with findings by Imron et al. (2023), who emphasized the effectiveness of *Pistia stratiotes* in reducing organic and particulate pollutants over extended treatment durations [27]. Additionally, Ali et al. (2024) reported that the high growth rate and adaptability of *Pistia stratiotes* make it an ideal candidate for phytoremediation in tropical regions [10].

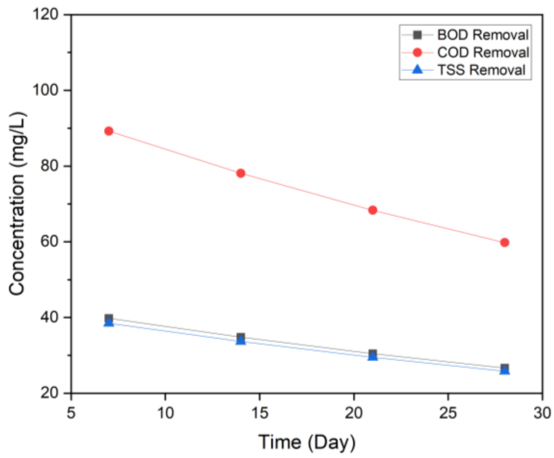

Figure 2. Phytoremediation treatment

The extended 28-day treatment period allowed for sustained pollutant uptake and degradation, ensuring maximal removal efficiency. However, optimizing the treatment duration by increasing plant density or using mixed plant species could reduce the time required for similar results, enhancing the feasibility of phytoremediation for high-throughput systems [18]. Further, the biomass generated by *Pistia stratiotes* can be repurposed as a bioresource, such as biofertilizer or bioenergy feedstock, making this process even more sustainable [25].

3.3. Synergistic Effects of Combined Treatment

The integration of microbubble oxidation and phytoremediation achieved remarkable reductions in pollutant concentrations, surpassing the efficiency of either method applied independently. The combined system reduced BOD levels from 65 mg/L to 26.67 mg/L, representing a 59% reduction. Similarly, COD levels decreased from 136 mg/L to 59.79 mg/L (56% reduction), while TSS levels were reduced from 55 mg/L to 25.79 mg/L (53% reduction). These results underscore the synergistic benefits of combining these two treatment methods (**Fig 1**).

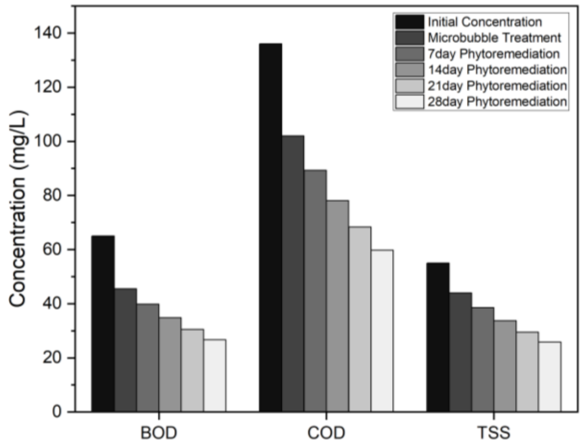

Figure 1. Synergistic Effects of Combined Treatment

Microbubble oxidation enhances pollutant bioavailability by breaking down complex organic molecules into simpler forms, which are then more readily assimilated by *Pistia stratiotes* during phytoremediation[22]. This dual action results in higher overall removal efficiencies compared to standalone methods. Similar findings were reported by Liu (2024), who observed enhanced pollutant removal efficiencies in hybrid systems integrating advanced oxidation and phytoremediation [28].

The versatility of this combined approach is another key advantage. While microbubble technology effectively targets dissolved pollutants, phytoremediation complements this by addressing suspended solids and residual organic matter. This comprehensive treatment capability makes the integrated system suitable for a wide range of wastewater types. Kaushik and Chel (2014) highlighted the adaptability of such hybrid systems for treating diverse wastewater sources, emphasizing their potential for practical applications in resource-limited settings [23]. Additionally, studies by Imron et al. (2023) have shown that hybrid systems significantly reduce treatment times compared to traditional standalone methods [27].

4. CONCLUSION

This study highlights the effectiveness of integrating microbubble oxidation and phytoremediation using Pistia stratiotes for the treatment of domestic wastewater. Microbubble oxidation demonstrated significant reductions in BOD, COD, and TSS concentrations, with reductions of 30%, 25%, and 20%, respectively, within 6 hours of treatment. The microbubble technology not only effectively reduced pollutants but also enhanced their bioavailability for subsequent phytoremediation. The phytoremediation phase, spanning 28 days, further achieved consistent reductions of 59% in BOD, 42% in COD, and 41% in TSS. This highlights the ability of Pistia stratiotes to assimilate organic pollutants and trap suspended solids through its extensive root system.

The combined treatment system achieved remarkable overall reductions, with 59%, 56%, and 53% reductions in BOD, COD, and TSS, respectively. These results underscore the synergistic benefits of integrating microbubble oxidation and phytoremediation, offering a holistic solution for addressing a wide range of pollutants. The dual mechanisms of oxidation and biological uptake provide a comprehensive approach to improving water quality while reducing the environmental and economic costs associated with traditional methods. This study demonstrates the potential of this hybrid treatment system as a sustainable, scalable, and cost-effective alternative for wastewater management.

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