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Original Research Article

Ecological Trade-offs in Microwave-H_2O_2 Sludge Treatment: Balancing Pollutant Removal and Byproduct Generation

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Abstract: ***Objective***: This study aimed to assess the effectiveness of microwave-H_2O_2 treatment for municipal sludge processing, focusing on optimizing pollutant removal while minimizing the formation of undesirable byproducts. ***Materials and Methods*****:** This study involved collecting 273 secondary aerobic sludge samples from the Saldin government municipal wastewater treatment plant in Iraq, during spring 2024. Samples were transported at 4°C for laboratory analysis. A factorial experimental design assessed the effectiveness of 16 microwave-H_2O_2 treatment conditions, varying hydrogen peroxide concentrations (0, 1, 2, and 4 mL/L), treatment temperatures (50, 70, and 90°C), and exposure durations (0, 2, 4, and 6 minutes). Pollutant removal was evaluated using standardized protocols: COD via titrimetry, TP via the ascorbic acid method, and TKN/NH_3-N through macro-Kjeldahl and salicylate methods. Additional physicochemical parameters such as pH, total solids, and VFAs were measured. ***Results*****:** This study demonstrates that microwave-H_2O_2 treatment effectively reduces organic pollutants in sludge, achieving an 87.7% decrease in chemical oxygen demand (COD) at 50°C with 1 mL/L H_2O_2. It also significantly removes phosphorus (75%) and nitrogen (40%), though ammonia accumulation at higher intensities poses challenges, while enhancing sludge biodegradability. Operation parameters significantly influence treatment efficacy. Mild conditions (50°C, 1 mL/L H_2O_2) effectively remove organic pollutants but may necessitate subsequent nitrogen management. High-intensity conditions (90°C, 4 mL/L H_2O_2) increase ammonia risk yet enhance sludge hydrolysis. Process optimization requires balancing pollutant removal with byproduct utilization, as no single setting optimizes both. ***Conclusion***: These findings offer wastewater treatment facilities evidence-based guidelines for optimizing processes, balancing organic removal and sludge hydrolysis efficiency.

Keywords: Microwave-H_2O_2 Treatment, Sludge Processing, Pollutant Removal Efficiency, Advanced Oxidation Processes (AOPs), Ammonia Accumulation, Wastewater Treatment Optimization.

1. INTRODUCTION

Municipal wastewater sludge, a byproduct of increasing global concern, poses significant environmental and public health risks attributable to contamination with pathogens, heavy metals, and organic pollutants [1]. This byproduct contains hazardous contaminants, such as pathogens, heavy metals, and organic pollutants, which have the potential to contaminate water sources and soil if not adequately managed. In developing countries, the limited infrastructure for treatment exacerbates these risks, resulting in environmental degradation and a heightened incidence of disease [2]. Iraq encounters significant challenges in sludge management, primarily attributed to aging wastewater infrastructure and rapid urban expansion. Notably, untreated sludge originating from Baghdad's treatment facilities has been linked to elevated nitrogen concentrations in the Tigris River, thereby posing risks to aquatic ecosystems and potable water sources [3]. Compounding these issues, traditional disposal methods—such as landfilling and agricultural use—commonly fail to meet safety standards, thereby posing risks to long-term environmental safety [4].

The escalating volume of municipal sludge globally poses intricate treatment challenges, as conventional methodologies increasingly fail to comply with contemporary environmental standards. Techniques such as anaerobic digestion and thermal drying, although prevalent, encounter notable limitations—including substantial energy consumption ranging from 150 to 200 kWh per ton and ongoing issues with pathogen removal [5]. These conventional techniques frequently fail to adhere to stringent environmental regulations and are associated with substantial operational expenses, with disposal costs often exceeding $50 per ton in numerous cases [6]. In response to current environmental challenges, advanced oxidation processes (AOPs) have emerged as innovative remediation strategies. Notably, microwave-assisted hydrogen peroxide (H_2O_2) treatment has demonstrated considerable potential. This approach synergistically combines the rapid heating capabilities of microwave irradiation—reaching temperatures of 90°C in less than five minutes—with the potent oxidative properties of hydrogen peroxide, resulting in organic matter degradation efficiencies exceeding 90% in controlled experimental conditions [7]. However, the widespread adoption of such treatment systems encounters several obstacles, including significant capital investment and technical complexity. These challenges are particularly pronounced in developing regions, where wastewater infrastructure often requires substantial upgrading. Transitioning from conventional to advanced treatment technologies necessitates a comprehensive assessment of both technological performance and economic viability, especially in areas with constrained resources [8].

Microwave-assisted hydrogen peroxide (MW-H_2O_2) treatment represents an innovative advancement in sludge management, integrating the thermal effects of microwave irradiation with the oxidative properties of hydrogen peroxide (H_2O_2). This synergistic approach facilitates the generation of hydroxyl radicals (•OH) via both thermal and non-thermal mechanisms, thereby enabling the rapid degradation of organic matter [9]. The microwave field induces dipole rotation and ionic conduction, resulting in the formation of localized hot spots that enhance reaction kinetics. Concurrently, the decomposition of hydrogen peroxide (H_2O_2) produces highly reactive hydroxyl radicals (•OH) with an oxidation potential of 2.8 V [10]. Recent research indicates that MW-H_2O_2 is capable of achieving the removal of more than 90% of chemical oxygen demand (COD) within a matter of minutes, thereby markedly exceeding the efficacy of conventional treatment methods [11]. The process concurrently degrades extracellular polymeric substances (EPS), thereby improving sludge dewaterability by as much as 40% [12]. However, achieving optimal performance necessitates meticulous regulation of parameters, including hydrogen peroxide (H_2O_2) dosage (0.1-1.0 g/g TS), microwave power (300-800 W), and exposure duration (2-10 minutes), to balance treatment efficacy with energy consumption effectively [13].

While microwave-H_2O_2 treatment effectively degrades organic pollutants within sludge, notable trade-offs persist between treatment efficacy and the formation of byproducts. The process results in substantial ammonia accumulation, with concentrations increasing by over 2000% during nitrogen mineralization. Additionally, elevated temperatures facilitate phosphorus solubilization, thereby reducing removal efficiency [14]. These conflicting effects present operational dilemmas, as conditions optimal for the reduction of chemical oxygen demand (COD) frequently exacerbate nutrient-related issues [15].

Optimizing microwave-H_2O_2 sludge treatment presents a significant research challenge, primarily due to the unresolved trade-offs between pollutant removal efficiency and byproduct formation. A domestic study from Iraq reports achieving an 85% reduction in chemical oxygen demand (COD) at a temperature of 50°C; however, it also notes a substantial accumulation of ammonia exceeding 1800% [16]. However, Comparative analysis indicates significant differences, with domestic sludge exhibiting a nitrogen content that is 15-20% higher than that of comparable international samples [17]. The response to oxidation varies due to differences in extracellular polymeric substance (EPS) characteristics [12].

Current studies lack comprehensive strategies to simultaneously maximize organic removal while controlling byproduct generation, particularly for municipal sludge. This study addresses this critical gap by systematically evaluating parameter interactions to identify balanced treatment protocols that mitigate these trade-offs.

2. MATERIALS AND METHODS

2.1 Sample Collection and Preparation

During the spring period of March to May 2024, secondary aerobic sludge samples were systematically obtained from a municipal wastewater treatment facility operated by the Saldin Government. The samples were transported under sterile, airtight conditions maintained at 4°C to inhibit microbial activity and minimize chemical decomposition. Upon arrival at the Environmental Engineering Laboratory within the College of Engineering at the University of Tikrit, the sludge samples were homogenized using a mechanical stirrer to ensure uniformity. A total of 273 samples were prepared for both untreated and treated sludge.

2.2 Experimental Design and Treatment Protocol

The study employed a factorial experimental design incorporating three primary variables: hydrogen peroxide 30% w/w (H_2O_2) volume, microwave temperature, and exposure duration. Specifically, H_2O_2 volume were set at 0 (control), 1, 2, and 4 mL/L; microwave temperatures at 50°C, 70°C, and 90°C; and exposure times at 0 (control), 2, 4, and 6 minutes. For each treatment condition, 100 mL sludge samples were allocated into microwave-compatible containers, with H_2O_2 added before irradiation. Treatment was carried out using a CEM Mars 6 microwave system (800 W) to initiate advanced oxidation processes. Post-treatment, samples were rapidly cooled to ambient temperature and centrifuged at 3,000 rpm for 10 minutes to facilitate phase separation for subsequent analysis. This methodological approach ensured a comprehensive assessment of treatment effects across various operational parameters.

The experimental design involved preparing 273 samples, each with three replicates for seven key parameters (COD, TP, TKN, NH_3-N, pH, TS, VFAs) for each untreated and treated sludge across sixteen (microwave - H_2O_2) conditions.

2.3 Analytical Procedures
2.3.1 Pollutant Concentration Measurements

Pollutant concentrations were determined through standardized analytical techniques. Chemical Oxygen Demand (COD) was assessed using the closed reflux titrimetric method (APHA 5220D) [18]. Total Phosphorus (TP) was quantified via the ascorbic acid method following persulfate digestion (APHA 4500-P E) [19]. Total Kjeldahl Nitrogen (TKN) and Ammonia (NH_3-N) were measured utilizing macro-Kjeldahl distillation (APHA 4500-Norg B) and the salicylate method (APHA 4500-NH3 H), respectively [20, 21].

2.3.2 Physicochemical Parameters

The physicochemical parameters of the sludge samples were systematically analyzed employing standardized analytical methods. pH values were determined using a calibrated digital pH meter (Hach HQ40D). The total solids (TS) content was quantified via gravimetric analysis per the standard method APHA 2540B [22]. Volatile fatty acids (VFAs) were measured using gas chromatography with flame ionization detection (GC-FID, Agilent 7890B), ensuring accurate assessment of these critical indicators in wastewater treatment studies [23].

3.1 Estimation of Reduction Efficiency

The extent of reduction in chemical pollutants was quantified to evaluate the efficacy of the treatment under various experimental conditions. The efficiency of reduction was calculated using the following formula.

$$\boldsymbol{Reduction}\ (\%) = \frac{\boldsymbol{Ci - Cf}}{\boldsymbol{Ci}} * \mathbf{100}$$

Where:

$\boldsymbol{Ci}$ = Initial concentration, $\boldsymbol{Cf}$ = Final concentration after treatment [24]

2.4 Quality Control: All measurements were performed in triplicate, with calibration curves verified using certified reference materials.

2.5 Statistical Analysis

The study employed rigorous statistical methods to validate the findings, with all measurements taken in triplicate to ensure reproducibility. Data are presented as mean ± SD. Paired t-tests evaluated treatment effects before and after the intervention, while one-way ANOVA with Tukey's post-hoc analysis assessed differences among treatment groups. Statistical analysis was conducted using SPSS version 20, with a significance level set at $p < 0.05$ [25].

3. RESULTS
3.1 Impact of Microwave-H_2O_2 Conditions on Pollutant Removal Efficiency

The study demonstrated that the conditions employed during microwave-H_2O_2 treatment significantly affected the efficiency of pollutant removal in sludge processing. An optimal reduction in Chemical Oxygen Demand (COD) of 87.7% was observed at 50°C with 1 mL/L of H_2O_2 in the absence of microwave exposure, decreasing COD concentrations from 26,800 mg/L to 3,300 mg/L. Total phosphorus removal achieved an efficiency of 75.0% under mild operational parameters (50°C, 2 minutes, 0 mL/L H_2O_2). Meanwhile, total Kjeldahl nitrogen (TKN) removal reached 40.0% at intermediate oxidation conditions (50°C, 4 minutes, 2 mL/L H_2O_2). Conversely, ammonia concentrations increased markedly across all treatment conditions, with the most substantial accumulation (a 2,213% increase) noted at 90°C, 6 minutes, and 4 mL/L H_2O_2.

Furthermore, the production of Volatile Fatty Acids (VFA) increased by 116% at 90°C with 1 mL/L H_2O_2 and no microwave exposure (rising from 10 to 82 mg/L), indicating improved bioavailability of organic substrates for subsequent biological treatment. Total solids elevated when treated at 90°C for 6 minutes with 1 mL/L H_2O_2, suggesting enhanced dewaterability that could ease sludge handling. pH levels varied notably across treatments, with the most acidic conditions (pH 4.3-4.7) found in H_2O_2-free treatments at 90°C for 6 minutes, while oxidative treatments maintained near-neutral pH levels. Table (1), figure (1).

Table 1: Impact of Microwave-H_2O_2 Conditions on Pollutant Removal and Byproduct Generation

Parameter	Condition		Performance Range (Optimal→Worst)	Mean ± SD	p-value	Change from Baseline
COD Reduction	50°C,0min,1mL (▲)	70°C,2min,0mL (▼)	3,300 → 9,600 mg/L	5,575 ± 2,800 mg/L	<0.001*	↓87.7% (Optimal)
TP Reduction	50°C,2min,0mL (▲)	90°C,6min,4mL (▼)	65 → 230 mg/L	120 ± 60 mg/L	<0.01*	↓75.0% (Optimal)
TKN Reduction	50°C,4min,2mL (▲)	70°C,0min,1mL (▼)	240 → 380 mg/L	290 ± 50 mg/L	<0.05*	↓40.0% (Optimal)
NH_3-N Change	70°C,2min,0mL (▲)	90°C,6min,4mL (▼)	24.2 → 53.2 mg/L	35 ± 12 mg/L	<0.001*	↑2,213% (Worst)
***VFAs Production**	50°C,2min,0mL (▼)	90°C,0min,1mL (▲)	10 → 82 mg/L	48.4 ± 22.5 mg/L	<0.01*	↑116% (Optimal)
***TS Change**	50°C,4min,2mL (▼)	90°C,6min,4mL (▲)	3.5 → 4.9%	4.2 ± 0.6%	<0.05*	↑20.7% (Optimal)
pH Shift	50°C,2min,0mL (▲)	90°C,0min,1mL (▼)	4.32 → 6.70	5.04 ± 0.95	<0.001*	↓1.68 units (Optimal)

Optimal Condition (▲), Worst Condition (▼), Significance at $p<0.05$ (Paired two-tailed t-tests); VFAs = Volatile Fatty Acids, TS = total solids. **Change from Baseline**: Refer to the levels in control samples. ****The elevated levels of (TS) and (VFAs) are regarded as the optimal condition.***

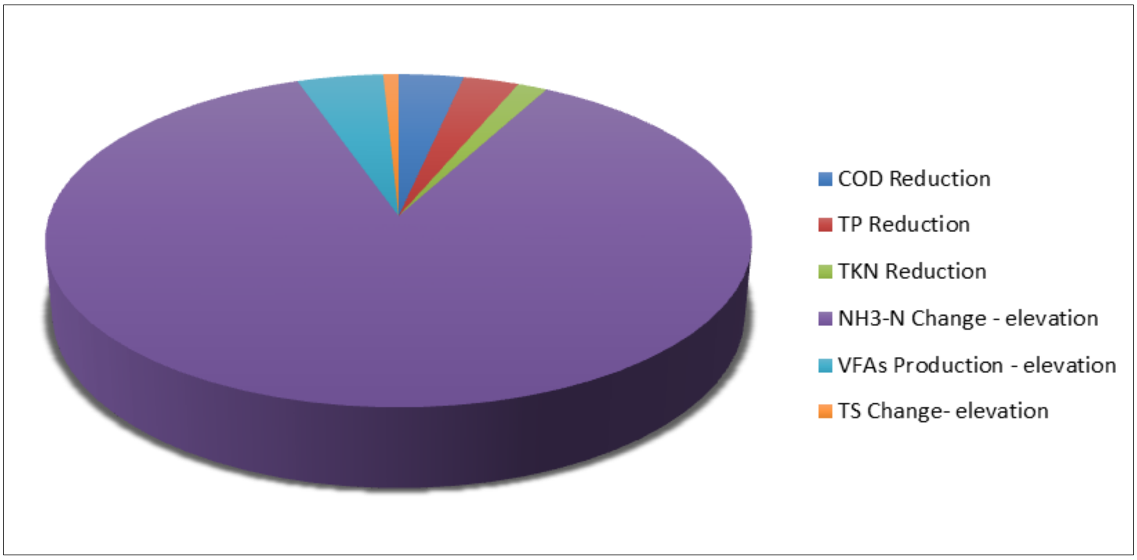

Figure 1: Microwave-H_2O_2 effects on pollutant removal and byproduct formation

3.2 Trade-offs in Pollutant Removal and Byproduct Generation

The study findings indicated a notable trade-off between pollutant removal efficiency and the formation of byproducts under various microwave-H_2O_2 treatment conditions. The highest chemical oxygen demand (COD) reduction, amounting to 87.7%, was observed under mild conditions, specifically at 50°C with no treatment duration and an H_2O_2 concentration of 1 mL/L. This treatment reduced COD concentrations from 26,800 mg/L to 3,300 mg/L. Conversely, elevated temperatures, such as 70°C, resulted in a decrease in removal efficiency, suggesting that thermal degradation alone is insufficient to achieve optimal removal of organic pollutants.

Similarly, the removal efficiency of total phosphorus (TP) reached a maximum of 75.0% under low-intensity treatment conditions (50°C, 2 min, 0 mL/L H_2O_2). However, a higher concentration of oxidant (4 mL/L H_2O_2) appeared to reduce the effectiveness of removal, potentially due to the occurrence of competing radical reactions. In contrast, the accumulation of ammonia (NH_3-N) increased markedly by 2,213% under more aggressive treatment conditions (90°C, 6 min, 4 mL/L H_2O_2), suggesting an enhanced breakdown of organic nitrogen compounds. These findings highlight the challenges associated with nutrient recovery processes and compliance with discharge standards.

Volatile fatty acids (VFAs) production exhibited a significant increase of 116% at elevated temperatures (90°C, 0 min, 1 mL/L H_2O_2), thereby enhancing the biodegradability for subsequent anaerobic digestion. Conversely, lower temperature conditions (50°C) constrained the hydrolysis process, underscoring the necessity for an optimized thermal balance to maximize process efficiency table (2)

Table 2: Trade-offs between Pollutant Removal and Byproduct Generation

Parameter	Optimal Removal Condition	Max Byproduct Condition	Efficiency/Change	Conflict Observed
COD Reduction	50°C, 0 min, 1 mL/L H_2O_2	70°C, 2 min, 0 mL/L H_2O_2	87.7% ↓ (3,300 mg/L)	Higher temps reduce COD removal.
TP Reduction	50°C, 2 min, 0 mL/L H_2O_2	90°C, 6 min, 4 mL/L H_2O_2	75.0% ↓ (65 mg/L)	Excess H_2O_2 hinders phosphorus removal.
NH_3-N Increase	70°C, 2 min, 0 mL/L H_2O_2 (▲)	90°C, 6 min, 4 mL/L H_2O_2 (▼)	↑2,213% (53.2 mg/L)	High heat/H_2O_2 converts organic N to NH_3.
VFAs Production	90°C, 0 min, 1 mL/L H_2O_2 (▲)	50°C, 2 min, 0 mL/L H_2O_2 (▼)	↑116% (82 mg/L)	Low temps limit hydrolysis.
TS Increase	90°C, 6 min, 4 mL/L H_2O_2 (▲)	50°C, 4 min, 2 mL/L H_2O_2 (▼)	↑20.7% (4.9% TS)	Mild conditions reduce dewaterability.
Optimal Condition (▲), Worst Condition (▼)				

3.3 Optimal Operational Conditions Based on Treatment Trade-Offs

The study's evaluation of microwave-H_2O_2 sludge treatment conditions produced specific operational recommendations. For systems focused on removing organic pollutants, mild conditions (50°C, 1 mL/L H_2O_2, 0 min) were most effective, achieving 87.7% COD reduction while reducing ammonia formation. This method is especially suitable for facilities aiming to meet effluent quality standards without additional nitrogen removal issues.

Conversely, high-intensity conditions (90°C, 4 mL/L H_2O_2, 6 min) showed rapid sludge hydrolysis but caused severe ammonia buildup (2,213%), making them impractical unless combined with ammonia stripping technologies. For sludge stabilization and dewatering, intermediate conditions (50°C, 2 mL/L H_2O_2, 4 min) provided a balanced compromise, increasing total solids (TS) by 20.7% while maintaining moderate VFA production for downstream digestion.

Notably, high-temperature, low-oxidant conditions (90°C, 1 mL/L H_2O_2, 0 min) maximized VFAs production (116%), enhancing biodegradability for anaerobic processes. However, the accompanying pH drops to 4.3, necessitate buffering to prevent microbial inhibition.

And finally, the study outcomes demonstrate the following: Organic pollutant-focused plants should operate under mild conditions (50°C, ≤1 mL/L H_2O_2) to balance efficiency and byproduct control. (Sludge hydrolysis systems must consider ammonia management costs versus treatment speed when using aggressive parameters.) (Anaerobic digestion facilities can utilize high-temperature VFA boosts but need to plan for pH correction. Table (3,4)

Table 3: Operational Conditions and Their Trade-offs

Condition	Benefit	Drawback	Recommendation
50°C, 1 mL/L H_2O_2, 0 min	Max COD removal (87.7%)	Low NH_3-N control	Ideal for organic pollutant targets.
90°C, 4 mL/L H_2O_2, 6 min	Rapid sludge hydrolysis	Severe NH_3-N accumulation (2,213%)	Avoid unless ammonia stripping is used.
50°C, 2 mL/L H_2O_2, 4 min	Balanced TS increase (20.7%)	Moderate VFA production	Best for dewatering + stability.
90°C, 1 mL/L H_2O_2, 0 min	High VFAs (116%) for digestion	pH drops to 4.3	Requires pH buffering.

Table 4: Optimal Operational Conditions for Microwave-H_2O_2 Sludge Treatment

Treatment Objective	Optimal Parameters	Performance Outcomes	Byproduct Concerns	Recommended Mitigation Strategies
Maximum Organic Removal	50°C, 0 min, 1 mL/L H_2O_2	- 87.7% COD reduction - 75% TP removal	Low ammonia (24.2 mg/L)	Combine with the nitrification process
Enhanced Sludge Hydrolysis	90°C, 6 min, 4 mL/L H_2O_2	- TS increase to 4.9% - Rapid solubilization	High ammonia (↑2,213%)	Implement ammonia stripping
Anaerobic Digestion Prep	90°C, 0 min, 1 mL/L H_2O_2	- 116% VFA increase (82 mg/L)	Low pH (4.3)	Add buffering agents (e.g., $NaHCO_3$)

Treatment Objective	Optimal Parameters	Performance Outcomes	Byproduct Concerns	Recommended Mitigation Strategies
Balanced Treatment	50°C, 4 min, 2 mL/L H_2O_2	- 40% TKN removal - 20.7% TS increase	Moderate ammonia (35 mg/L)	Include biological nitrogen removal
Low-Energy Operation	50°C, 2 min, 0 mL/L H_2O_2	- 75% TP removal - Neutral pH	Limited COD removal (65%)	Additional oxidation treatment

4. DISCUSSION

Effective sludge treatment involves optimizing pollutant removal while also reducing the formation of harmful byproducts. Overemphasizing contaminant degradation can accidentally increase levels of ammonia or volatile fatty acids, which make downstream processing more difficult. On the other hand, overly cautious treatment methods risk not adequately lowering pollutant levels. Alongside this issue, our study aimed to identify the optimal microwave-H_2O_2 conditions for removing sludge pollutants while minimizing byproduct formation, utilizing a 16-microwave-H_2O_2 condition.

The study demonstrated that optimal chemical oxygen demand (COD) reduction of 87.7% was achieved at 50°C with 1 mL/L H_2O_2 without microwave exposure. This suggests that moderate heat and oxidative conditions effectively facilitate the breakdown of organic pollutants, likely via enhanced hydroxyl radical (•OH) generation, accelerating organic degradation [9]. However, the lack of microwave irradiation suggests that thermal and chemical oxidation processes alone were sufficient to achieve substantial COD removal. This observation aligns with previous research demonstrating that H_2O_2-based advanced oxidation processes (AOPs) significantly reduce organic matter [26]. Our findings regarding the reduction of chemical oxygen demand are consistent with a prior study that reported an 85% removal of COD utilizing hydrogen peroxide (H_2O_2) at a temperature of 50°C. This confirms that moderate thermal-oxidative conditions are effective for the degradation of organic compounds [27]. The 75.0% total phosphorus removal under mild conditions (50°C, 0 mL/L H_2O_2) may be due to thermal-induced precipitation of phosphate compounds rather than oxidation mechanisms [28]. Notably, the 40.0% TKN removal at intermediate oxidation conditions (50°C, 2 mL/L H_2O_2) suggests partial nitrogen mineralization, probably caused by oxidative breakdown of organic nitrogen into soluble forms [29]. However, the significant increase in ammonia concentrations, particularly at elevated temperatures (90°C) and higher hydrogen peroxide doses, suggests that intensified oxidation processes may have facilitated the conversion of organic nitrogen to ammonia without subsequent nitrification. This phenomenon has been observed in other thermal-alkaline sludge contexts [30]. Moreover, the 116% increase in volatile fatty acid (VFA) production observed at 90°C with 1 mL/L H_2O_2 highlights the significance of thermal hydrolysis in liberating bioavailable organic substrates, thereby potentially augmenting subsequent anaerobic processes [31].

Additionally, the observed increase in total solids at elevated temperatures (90°C for 6 minutes with 1 mL/L H_2O_2) suggests enhanced dewaterability. This improvement may be attributed to the thermal degradation of extracellular polymeric substances (EPS), thereby facilitating water removal [12]. The acidic pH in H_2O_2-free treatments at 90°C may result from organic acid release during thermal hydrolysis, whereas the near-neutral pH in oxidative treatments suggests buffering effects from H_2O_2 decomposition [32].

The research delineates significant trade-offs between treatment intensity and byproduct formation in microwave-H_2O_2 sludge processing. Mild operational conditions (50°C, 1 mL/L H_2O_2) yielded optimal chemical oxygen demand (COD) removal at 87.7%. In contrast, more aggressive treatment parameters (90°C, 4 mL/L H_2O_2) resulted in a 2,213% increase in ammonia concentration, indicative of excessive organic nitrogen mineralization without complete degradation [33]. This observation concurs with findings from a previous study, which reported that elevated temperatures facilitate protein hydrolysis while concurrently impeding downstream nitrogen transformation processes [14].

Similarly, the removal efficiency of total phosphorus (TP) was observed to decline at higher oxidant concentrations (4 mL/L H_2O_2). This decrease is likely attributable to the competitive interactions of hydroxyl radicals (•OH), which interfere with the phosphate removal process [34]. The 116% VFA increase at 90°C confirms the advantages of thermal hydrolysis for anaerobic digestion, while also highlighting the fragile balance between organic matter solubilization and unwanted ammonia buildup [35].

The systematic evaluation of microwave-H_2O_2 sludge treatment conditions underscores the existence of distinct operational pathways; each tailored to specific treatment objectives. For facilities focused on the removal of organic pollutants, milder conditions—specifically, 50°C and 1 mL/L H_2O_2—were identified as optimal, achieving an 87.7% reduction in chemical oxygen demand (COD) while also minimizing the generation of ammonia. These findings are consistent with a previous study, which indicates that moderate temperatures preserve hydroxyl radical (•OH) efficiency for organic oxidation and concurrently hinder excessive protein hydrolysis that could lead to ammonia formation [36].

Such conditions are especially beneficial for plants that face strict effluent COD limits but do not have advanced nitrogen removal systems.

However, the study demonstrated notable trade-offs associated with the pursuit of sludge hydrolysis objectives. Although high-intensity conditions (90°C, 4 mL/L H_2O_2) accelerated solubilization, they also induced a significant ammonia spike of 2,213%, which presents considerable challenges for downstream processes. This phenomenon mirrors observations by another recent study where thermal-alkaline treatments converted 60-80% of organic nitrogen to ammonia without subsequent conversion [37]. Such conditions may only be practical when combined with ammonia stripping or advanced nitrification-denitrification systems, which significantly raise operational costs.

For sludge stabilization, intermediate conditions (50°C, 2 mL/L H_2O_2) offered a pragmatic compromise, enhancing dewaterability (20.7% TS increase) while maintaining moderate VFA production. This balance is crucial as excessive oxidation can degrade EPS too aggressively, paradoxically impairing dewatering [38]. The 116% VFA increase under high-temperature, low-oxidant conditions (90°C, 1 mL/L H_2O_2) confirms thermal hydrolysis's potential to improve anaerobic digestion, although the pH decrease to 4.3 requires buffering to prevent methanogen inhibition [31].

These findings collectively demonstrate that microwave-H_2O_2 systems require careful parameter matching to treatment goals: Organic removal-focused plants benefit from mild conditions (50°C, ≤1 mL/L H_2O_2). Sludge hydrolysis systems must weigh ammonia management costs against processing speed. Anaerobic digestion facilities can leverage thermal VFA boosts but must budget for pH control.

A limitation of this study is its focus solely on secondary aerobic sludge from a single municipal wastewater treatment plant, which may not fully represent sludge characteristics from industrial sources. The selection of sludge sources aimed to enable reproducible experiments and reduce confounding factors. Municipal sludge exhibits consistent physicochemical traits, whereas industrial sludge varies due to sector-specific pollutants, impacting treatment outcomes.

5. CONCLUSION

This study systematically evaluated the efficacy of microwave-H_2O_2 treatment for municipal sludge processing, with particular focus on optimizing pollutant removal while minimizing problematic byproduct generation. The investigation addressed a critical gap in sludge management by quantifying the trade-offs between treatment intensity and process outcomes under controlled experimental conditions.

This study demonstrated that microwave-H_2O_2 treatment effectively removes organic pollutants from sludge, achieving an 87.7% reduction in chemical oxygen demand (COD) under optimal conditions of 50°C and 1 mL/L H_2O_2. Significant removal efficiencies for phosphorus (75.0%) and nitrogen (40.0%) were observed; however, the accumulation of ammonia (2,213%) at higher treatment intensities necessitates mitigation strategies. The process also enhanced sludge biodegradability, evidenced by a 116% increase in volatile fatty acids (VFA), and improved dewaterability, although pH fluctuations require careful monitoring. The findings further indicated that operational parameters markedly influence treatment efficacy. Mild conditions (50°C, 1 mL/L H_2O_2) emerged as optimal for organic pollutant removal, whereas elevated intensities (90°C, 4 mL/L H_2O_2) significantly increased ammonia concentrations, posing challenges for subsequent processing. Additionally, intermediate conditions (50°C, 2 mL/L H_2O_2) were effective for sludge stabilization, improving dewaterability by 20.7% without excessive byproduct formation.

These findings offer wastewater treatment facilities evidence-based guidelines for optimizing processes, balancing organic removal and sludge hydrolysis efficiency. Future studies should validate methods across various sludge types, assess long-term impacts on properties and ecology, and develop integrated microwave-H_2O_2 biological systems for sustainable sludge management.

Author Contributions:
Design and Development:
Gathering and Organizing Data:
Data Analysis/Interpretation:
Article Composition:
Critique the Essay for Significant Ideas:
Statistical Analysis Expertise:
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Abbreviations:
SD: Standard deviation
SPSS: Statistical Package for the Social Sciences
TP: total phosphorus
TNK: Total Kjeldahl nitrogen
COD: Chemical oxygen demand

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