Water and Wastewater, Vol. 35, No. 6, pp:65-79

Integrated OSA, Ultrasonication and Oxidation for Excess Sludge Reduction in a Sequencing Batch Reactor

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https://doi.org/10.22093/wwj.2026.555360.3523 **Original Paper**

Abstract

Among the various methods developed to reduce excess sludge in activated sludge processes, the Oxic-Settling-Anoxic process has attracted considerable attention due to its low cost, operational simplicity, and compatibility with existing wastewater treatment plants. When OSA process is integrated with a Sequencing Batch Reactor system, a portion of the activated sludge from the SBR is passed through an anaerobic side-stream reactor and then returned to the aerobic reactor. This approach promotes endogenous decay and uncouples catabolism from anabolism, resulting in less excess sludge production. In this study, the performance of the OSA process was enhanced by integrating ultrasonication and hydrogen peroxide (H_2O_2) oxidation in a laboratory-scale SBR. A pilot system was operated under different configurations, including a conventional SBR (as control system), OSA, OSA combined with ultrasonication, OSA integrated with H_2O_2 oxidation, and the combined OSA, ultrasonication and H_2O_2 system. The system performance was evaluated using the biomass yield coefficient (Y), sludge reduction efficiency, and COD removal efficiency. The Y for SBR was determined as 0.70 mg MLVSS/mg COD removed. Incorporating the OSA process reduced Y to 0.20 mg MLVSS/mg COD removed, corresponding to approximately 71% sludge reduction. Adding ultrasonication and H_2O_2 oxidation to the system decreased Y to 0.16 and 0.15 mg MLVSS/mg COD removed, representing sludge reductions of approximately 77% and 79%, respectively. The combined OSA, ultrasonication and H_2O_2 system achieved the lowest Y of 0.11 mg MLVSS/mg COD removed, showing an overall sludge reduction of 85%, while COD removal efficiency remains above 85%. The results demonstrate that combining biological (OSA), mechanical (ultrasonication), and chemical (H_2O_2 oxidation) treatments provides a synergistic approach for minimizing excess sludge production while preserving satisfactory treatment performance. This integrated strategy highly reduces the sludge management costs and environmental impacts in activated sludge wastewater treatment systems which is of high importance.

Keywords:
Wastewater Treatment, Biological Sludge Reduction, Oxic-Settling-Anoxic, Sequencing Batch Reactor, Ultrasonication, H_2O_2 Oxidant, Excess Sludge.

Received: Sep. 22, 2024
Revised: Oct. 21, 2024
Accepted: Nov. 16, 2024

To cite this article:
Nazif, S., Mosavary, S., Akbari, Z., Omid Naeeni, S. T., 2025. Integrated OSA, ultrasonication and oxidation for excess sludge reduction in a sequencing batch reactor. *Water and Wastewater*, 35(6), 65-79. https://doi.org/10.22093/wwj.2026.555360.3523.

1. Introduction

Various types of activated sludge processes are used for wastewater treatment purposes, such as conventional activated sludge[1] and Sequencing Batch Reactor[2] (Droste and Gehr, 2018). A common problem with the activated sludge process is the significant generation of sludge because the sludge treatment and management process highly increases the investment and operating costs of wastewater treatment plants[3] (Han et al., 2017; Banisaeid et al., 2024). Furthermore, due to high energy usage in these processes, they drastically increase the environmental impacts of wastewater treatment. As a result, excessive sludge production is a significant concern for WWTPs' management. Therefore, developing effective strategies to reduce sludge production has become an important objective for improving both the economic and the environmental sustainability of wastewater treatment processes. This has ended in developing various techniques to reduce sludge production, as demonstrated in Fig. 1 (Guo et al., 2013; Mohammadi et al., 2011; Nazif et al., 2016; Zuriaga-Agustí et al., 2016).

The technologies developed to reduce excess biological sludge, are classified into biological, chemical, physical (mechanical), and thermal approaches (Fig. 1). Biological methods are mainly based on promoting endogenous metabolism or predation on bacteria. The Oxic-Settling-Anoxic[4] system, biological hydrolysis, and the use of combined biological configurations are some of the biological methods. Chemical methods rely on metabolic uncouplers or advanced oxidation processes. Using oxidants such as ozone, hydrogen peroxide, and chlorine, to promote cell lysis and sludge minimization are among the chemical methods. Mechanical methods mainly employ shear forces generated by ultrasonication or other mechanical disruption techniques to break microbial cells and enhance cryptic growth. Thermal methods disrupt microbial cell structures by exposing sludge to elevated temperatures or repeated freezing and thawing. This helps significantly in sludge degradation.

Among the sludge production reduction procedures, OSA process is one of the most emerging approaches (Takdastan et al., 2025; Semblante et al., 2017; Zhou et al., 2015). According to the recent researches, OSA has already attracted notable attention owing to its low development and operation costs (Romero-Pareja et al., 2017), considerable sludge production reduction (between 20 and 65%), improvement of sludge settleability (Guo et al., 2013), minimum need for maintenance (Semblante et al., 2017), a slight oxidation–reduction potential[5] (Zhou et al., 2015), no need for chemical additives, and great adaptability with available WWTPs (Nazif et al., 2016).

Khursheed et al. (2015) reported the reduction of sludge production from 3% to 51% by recirculating 3.8–9.8 gVSS recycled/gVSS of the aerobic sludge from SBR to an anaerobic side reactor. They compared the proportion of sludge reduction to the specific oxygen uptake rate[6] gradient with and without OSA application in SBR. SOUR increased during the stay in an aeratd condition with abundant substrate and decreased during the stay in an anaerobic side reactor to enhance cell maintenance. Despite the significance of the ORP level in sludge decomposition during the OSA process, controlling ORP through nitrogen purging or chemical dosing can lead to increased costs and operational challenges.

Wang et al's. (2015) experiments showed that modifying the OSA process by using thickened sludge can reduce excess sludge without the need for OPR control. According to the results, the modified OSA can also enhance sludge settling characteristics. Semblante et al. (2016) studied how the sludge retention time[7] affects the performance of the OSA system when combined with SBR. Through increasing SRT from 10 to 20 days, volatile solids decomposition was improved. However, increasing SRT to 40 days did not have significant effect on volatile solids decomposition. At the optimum SRT (20 days) the highest sludge production reduction (>35%) and sludge dewaterability resulted.

Nazif et al. (2016) applied OSA process, thermal treatment, shear stress method, and the combination of them to improve the sludge production reduction in SBR system, which was fed with domestic wastewater. The OSA process decreased sludge production by 24%, while decreasing the COD removal efficiency from 90% to 86%. The thermal treatment and shear stress with OSA process decreased the sludge production up to 46%, even though these methods have limitations from COD removal efficiency side. The highest sludge reduction was achieved by combining the OSA process with thermal (90°C) and shear stress (voltage of 80 V) methods. The main advantage of this combination is that the COD removal efficiency remained at 88%, while the yield coefficient, which measures the sludge production rate, decreased by up to 10%.

The evaluation of respirometric analysis on OSA system by microbial basis for sludge reduction was evaluated by Yağcı et al. (2018). They studied the OSA reactor and SBR reactor as a parallel system, in which the organic substrate was a peptone mixture. In their study, by calibrating a model through oxygen uptake rate

[1] Conventional Activated Sludge (CAS)
[2] Sequencing Batch Reactor (SBR)
[3] Wastewater Treatment Plant (WWTP)
[4] Oxic-Settling-Anoxic (OSA)
[5] Oxidation–Reduction Potential (ORP)
[6] Specific Oxygen Uptake Rate (SOUR)
[7] Sludge Retention Time (SRT)

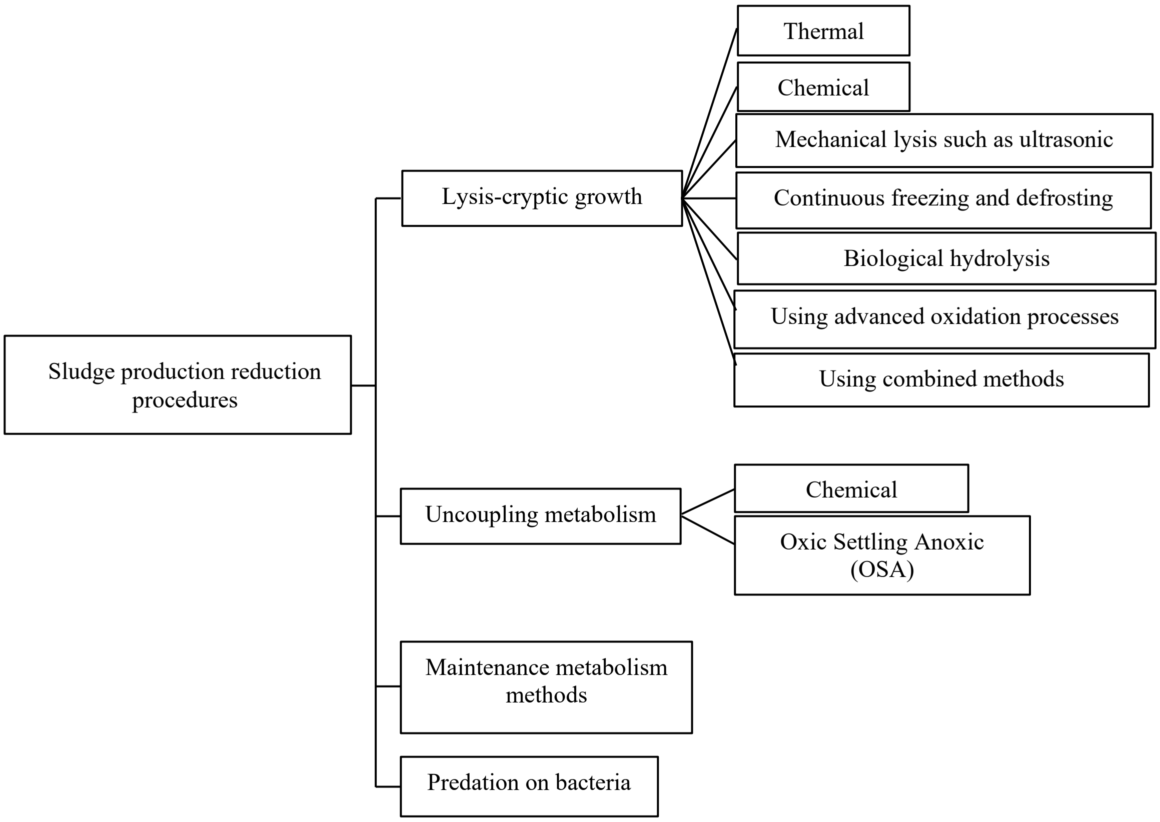

Fig. 1. Sludge production reduction procedures

the experiments follow the evaluation of the different streams condition. The results showed that the exchange stream contained a significant portion of the heterotrophic biomass. Based on the mass balance, the OSA reactor retained a significant amount of active biomass compared to the SBR reactor. The main reason for the reduction of excess sludge in the OSA system was the increase in endogenous decay due to the higher level of active sludge heterotrophic biomass remaining in the OSA reactor.

Takdastan et al. (2018) investigated the application of the OSA process in a SBR system and demonstrated that incorporating an anaerobic side-stream reactor effectively reduced excess biological sludge while maintaining stable treatment performance. The study also reported improved sludge settleability, highlighting the potential of OSA as a practical and economical modification to CAS systems.

Vitanza et al. (2019) operated an OSA process by feeding the pilot plant with real wastewater to reduce excess sludge production due to the recycling of activated sludge through the sludge holding tank. The observed sludge yield (Y_{obs}) was between 0.112 and 0.465 g TSS/g COD, which indicated that the excess sludge obtained between 49.6 ± 20.7% compared to the CAS system. The results of this study were simulated in Martins et al.'s (2022) study.

Martins et al. (2022) evaluated sludge reduction via an OSA system fed with real wastewater by employing a short 12h hydraulic retention time[1] over 100 days. Based on the results, OSA system was a suitable solution for treating real wastewater with 43% of excess sludge reduction, compared to the CAS process, which in CAS configuration the Y_{obs} was 0.33 kg TSS kg^{-1} COD, while in the OSA process the rate dropped to 0.19 kg TSS kg^{-1} COD. These results confirmed that adding an OSA process to the return sludge line reduced the rate of sludge production.

In another research by Sodhi et al. (2020), the mechanism for destroying excess sludge from real tannery wastewater was demonstrated. It has been confirmed that an OSA-CAS configuration can reduce biological sludge by approximately 51%. These results demonstrate the significant impact of utilizing real wastewater, which is more complex, indicating lower sludge reduction compared to studies involving synthetic wastewater. The study by Corsino et al. (2023) examines the use of the OSA process with synthetic wastewater to evaluate the impact on methane productivity of two

[1] Hydraulic Retention Time (HRT)

different configurations: sludge return from an anaerobic side-stream reactor to either the anoxic (scheme "A") or the aerobic (scheme "B") reactor of a pre-denitrification plant. Based on the results, scheme "A" promoted increases in methane productivity and kinetic activity, although significant reduction in the excess sludge production (31%) is observed. In contrast, scheme "B" induces metabolic pathways that significantly reduce methane production, demonstrating the importance of specific sludge reduction mechanisms in maintaining high levels of methane production.

Khursheed et al. (2023) integrated Ozone-Activated Sludge into an Anaerobic-Anoxic-Aerobic process in an SBR pilot. This integration led to a 25% reduction in sludge production and a 3.46-fold increase in phosphorus removal efficiency, reaching up to 6.41gVSSrecycled/gVSS.

Mannina et al. (2024) compared CAS and OSA layouts in a WWTP. The results showed that implementing the OSA configuration reduced sludge production in the OSA by about 17.3% compared to CAS. Additionally, there was a significant increase in the efficiency of PO4-P removal.

The other sludge production reduction procedures such as mechanical lysis-cryptic growth technology and advanced oxidation processes have also been effectively used in recent years. Ultrasonication method is a practical mechanical lysis-cryptic growth technology that applies ultrasound energy with frequencies in the range of 20-31 kHz in order to decompose sludge.

He et al. (2011) studied the impact of ultrasonic lysis–cryptic growth in sludge production reduction in a SBR system used for municipal wastewater treatment. The HRT of SBR was 8 hours, and ultrasound wave (20 kWh/kg TS) was used for sludge lysis. The results showed that sludge sonication proportion was the most important factor affecting energy consumption and energy efficiency. When the sludge sonication proportion was 30%, the sludge reduction efficiency was the maximum (67.6%) and the energy consumption was 0.101 kWh/d.

Mohammadi et al. (2011) developed a laboratory-scale SBR reactor to study how ultrasonic waves affect excess sludge reduction. Results showed that 78% of sludge reduction was achieved at an ultrasonic wave power of 100 W (generated at a frequency of 20 kHz), with a high HRT of 5 hours, and increasing energy supplied to the sludge mass up to 35,000 kJ/kg VSS.

Romero-Pareja et al. (2017) investigated the performance of OSA process in combination with ultrasound treatment. In their experiments, ultrasonic waves (20 Hz) were used to destruct sludge components before entering the anaerobic tank. Thereupon, the performance in reducing sludge production improved. According to this research, combining the OSA process with ultrasound treatment increases the OSA efficiency by up to 20%.

Mohammadi et al. (2019) studied the effect of high-frequency ultrasound (1.8 MHz) at different intensities on activated sludge characteristics in batch conditions. For obtaining optimal condition, sludge settling velocity, supernatant turbidity, and height of sludge under ultrasonic waves at various volumes of samples and mixed liquor suspended solids[1] were surveyed. The optimal condition was found by using ultrasound intensity of 0.4 w/cm^2 and sonication mode of 10s off 10s on at MLSS concentration of 8000 mg/L and sample volume of 3 l. The achieved results indicated that effluent turbidity and the height of sludge were reduced up to 82.2% and 44%, respectively, under high frequency ultrasound; Also, the settling velocity of sludge increased.

Parandoush and Mokhtarani (2022) studied the reduction of sludge production using ultrasonic waves and ozonation in an SBR system through synthetic laboratory-scale experiments. They focused on determining the optimal ozone dose assessing how it integrates with different ultrasound energy levels. The results showed that using an ozone dosage of 11 mg O_3/g MLSS, followed by applying a specific ultrasound energy of 12,000 kJ/kg TS, reduced excess sludge production about 54% in the SBR system.

Using Hydrogen peroxide (H_2O_2) is one of the most promising methods in advanced oxidation processes for minimization of excess sludge by degradation of microorganisms. Scientists have tended to use H_2O_2 as a strong oxidizing agent due to its affordability, accessibility, and environmental friendliness (Kim et al., 2009; Chavoshani et al., 2018; Guan et al., 2018; Rahmani et al., 2019).

Kim et al. (2009) applied H_2O_2 for excess sludge reduction and used alkaline pretreatment method to improve the H_2O_2 oxidation efficiency. By disintegrating sludge particles through H_2O_2 oxidation, the ratio of SCOD to Total Chemical Oxygen Demand[2] of sludge was raised to 57.4%, and 69.1% of the viscosity was diminished for H_2O_2 oxidation and alkaline hydrolysis. The results showed that using a 1.6M H_2O_2 dose and pH of 11, the combination of H_2O_2 oxidation with alkaline pretreatment achieved the best results in reducing excess sludge (almost 49%) and enhancing sludge settleability (66.7%).

Cho et al. (2015) concluded that the pretreatment process by H_2O_2 oxidation and Fe/MgO catalyst reduced the sludge production by about 30%, and TCOD was clearly decreased from 2.1 to 27.4%.

According to the literature, it can be concluded that OSA, ultrasonic waves and H_2O_2 oxidation methods can

[1] Mixed Liquor Suspended Solids (MLSS)

[2] Total Chemical Oxygen Demand (TCOD)

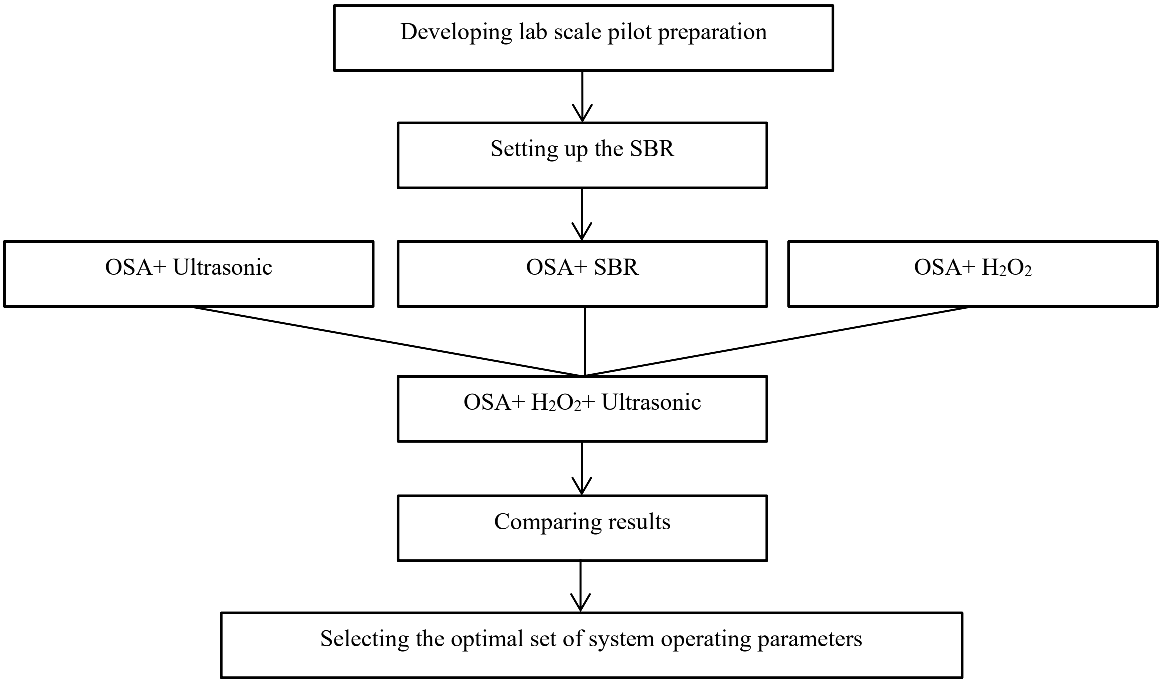

Fig. 2. The proposed methodology for combining OSA, ultrasonic and H_2O_2 oxidation for maximizing the excess sludge reduction

be significantly useful in excess sludge reduction. Therefore, in this paper, for the first time, the effect of using a combination of these three methods on excess sludge reduction is investigated. The main objective of this study is to determine how the combination of these methods could be used to maximize the reduction of excess sludge while maintaining the COD removal efficiency of the system at the desired level. For this purpose, a lab scale pilot is developed, and different tests are performed to determine the appropriate values of the operating parameters of the system.

2. Materials and methods

This research aims to evaluate the efficiency of OSA process in sludge production reduction in SBR systems while combining with two other technologies of ultrasonication and chemical oxidation. The flowchart of the research process is shown in Fig. 2. The detailed description on the methodology steps is given in the following sections.

2.1. The SBR system

The SBR is a fill and draw activated sludge process in which aeration, clarification, and sludge separation are carried out sequentially in a single reactor rather than in separate treatment units. A typical SBR cycle consists of filling, aeration, settling and decanting phases. The system performance is primarily controlled by operating parameters such as HRT, SRT, dissolved oxygen[1], cycle duration, and organic loading rate. Compared with a CAS system, SBR is more flexible in operation, requires less infrastructure, and allows easier control of biological processes. All these features make the SBR system an appropriate option for investigating the OSA process and its integration with the other sludge reduction methods on a pilot scale.

In this study, a SBR system is set up with 5-liter useful volume, which required 14 days for stabilizing. The SBR was operated with a 6 h treatment cycle consisting of 4 h of aeration, 1.5 h of settling, and 0.5 h of effluent discharge. Based on this, there are four complete treatment cycles per day. The pilot SBR was operated entirely manually. Aeration was supplied during the reaction phase using two air pumps, followed by a settling period to allow biomass separation. The treated effluent was manually decanted from the supernatant after settling, and approximately 125 mL of waste sludge was manually withdrawn at the end of each cycle to maintain the desired SRT.

The amount of waste sludge removed from the system was determined based on the SRT (θc). In this study, the SRT was maintained at 10 days, and the required daily waste sludge flow rate was calculated using Equation 1:

$$\theta_c = \frac{V_{reactor}}{Q_w} \tag{1}$$

[1] Dissolved Oxygen (DO)

Where

θ_c= Sludge age (day), $V_{reactor}$= Volume of reactor (ml), Q_w= Flow rate of waste sludge (ml/day). Given a reactor working volume of 5 L (5000 mL), the daily waste sludge flow rate is calculated as 500 mL/day. Since the SBR operated with four treatment cycles per day, 125 mL of sludge was manually wasted at the end of each cycle to maintain the desired SRT.

During the system operation, DO, pH, COD and mixed liquid volatile suspended solids[1] are measured. All analytical measurements, including COD, MLSS and MLVSS were conducted in accordance with the procedures described in Standard Methods for the Examination of Water and Wastewater (APHA, 2012).

2.2. The OSA system

The OSA system consisted of a SBR system attached to an anaerobic tank in the activated sludge return line, which affects sludge yield coefficient of SBR by depending on HRT, influent features and the rate of sludge interchange. The OSA system, as a CAS process modification, is constituted by inserting an anaerobic tank in the activated sludge return line. During this process, the return sludge enters an anaerobic tank with short HRT before entrance to the aeration tank. The OSA system effect on sludge production is described based on the uncoupled energy theory. According to this theory, when the return sludge is in anaerobic reactor the ATP content decreases, and when the sludge enters the aeration reactor the new ATP is generated due to oxygen and substrate availability. Therefore, microorganisms use energy for cell growth instead of new cell synthesis. For circulation of sludge in aerobic and anaerobic conditions, the cyclic changes of ATP content uncouples catabolism and anabolism, thus restricting the available energy for anabolism, which leads to a decrease in sludge production (Foladori et al., 2010).The optimal HRT of anaerobic tank is determined based on COD removal efficiency while considering variations in yield coefficient.

2.3. Ultrasonic waves

The effect of Ultrasonication on further sludge reduction in OSA system was also evaluated. Ultrasound causes sludge reduction through aquatic cavitation and bubble burst by generating high pressure, temperature and excessive shear forces. Besides, hydroxyl radicals ($\dot{O}H$) are produced in this method, which make sludge breakdown by oxidation (Wang et al., 2017). It has been well documented that the ultrasonication method could improve the sludge dewaterability, biodegradability and settleability as well as COD removal efficiency (Guo et al., 2013; Romero-Pareja et al., 2017). It is necessary to mention that the HRT for mechanical sludge reduction systems has been recommended to be between 5 and 30 min considering operation limitations (He and Wei, 2010; Lin et al., 2012; Zhang et al., 2007).

2.4. Chemical oxidation

Applying oxidizers such as chlorine and ozone to reduce sludge production has been studied specifically (Kim et al., 2009; Wang et al., 2017), but this research aims to apply H_2O_2 as the oxidizer and combine it with OSA process for the first time. Hydrogen peroxide has low cost and its oxidation power is higher than chlorine and lower than ozone (Hassani et al., 2011); therefore, it has a good potential to be applied in full scale application. The range of chlorine dosage used in previous studies was 0.023-0.33 g Cl_2/ g MLSS and the range for ozonation is 0.001 to 0.02 g O_3/ g MLSS (Hassani et al., 2011; Wang et al., 2017). Considering the oxidation power of H_2O_2, four different dosages were tested: 0.001, 0.01, 0.02 and 0.03 g H_2O_2/ g MLSS. These values were selected because the oxidation power of H_2O_2 is closer to ozone.

At the end of the sludge retention period in the 200 mL anaerobic reactor, the calculated amount of H_2O_2 was added directly to the sludge. The sludge was maintained in contact with the oxidant for 5 min before being returned to the SBR reactor for continued operation. The H_2O_2 dosage was calculated according to the measured MLSS concentration in the sludge and expressed as g H_2O_2/g MLSS.

2.5 Laboratory pilot set-up

The lab-scale SBR pilot used in this study is a cubic reactor made of Plexiglas. Its dimensions are 20×20×20 cm, which results in a useful volume of 5 L. The schematic of the developed laboratory pilot and treatment flow is shown in Fig. 3. To provide the required oxygen for the system, two aerators with air transmission capacity of 3 and 7 L/min are applied. The reactor used a mixer with a multi-plate blade and a vertical shaft, with an engine speed of 10 rpm, to ensure uniform air distribution, especially at low aeration rates, and to supply the necessary mixing energy (Mohammadi et al., 2011).

The reactor was fed with synthetic wastewater that contained 375 mg/L COD and COD:N:P ratio of 100:5:1. The combination of the synthetic wastewater was determined in a way that the resulted quality was similar to the urban wastewater in the study area. According to Table 1, the synthetic wastewater was synthesized by using glucose (as a COD source), ammonium dihydrogen phosphate (as phosphorus source) and ammonium nitrate (as a nitrogen source) (Pajoum-Shariati et al., 2014).

The anaerobic tank consists of a sealed glass container with a volume of 200 ml. This volume is selected based on Nazif et al., (2016) and is about 10%

[1] Mixed Liquid Volatile Suspended Solids (MLVSS)

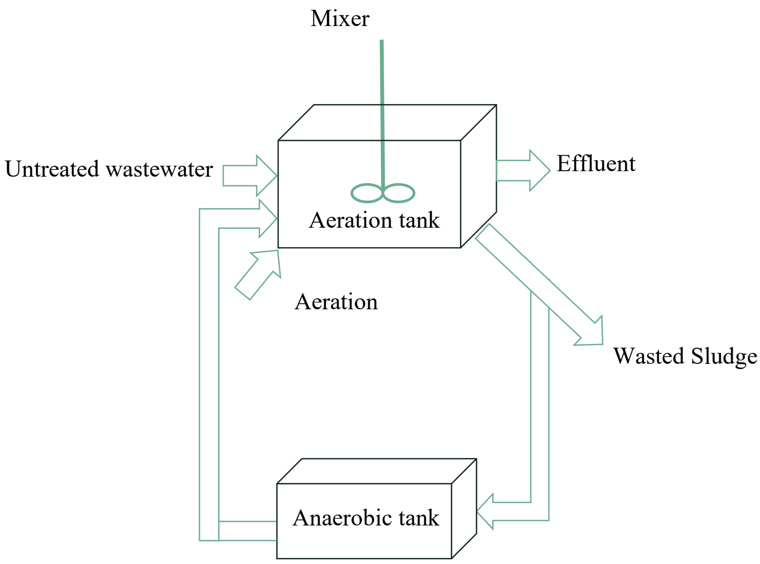

Fig. 3. The schematic of the developed laboratory pilot

Table 1. Synthetic wastewater materials

Materials	Chemical formula	Concentration (mg/L)
Glucose	$C_6H_{12}O_6$	4690
Ammonium dihydrogen phosphate	$NH_4H_2PO_4$	585
Ammonium nitrate	$N_2H_4O_3$	212

of produced sludge. It should be mentioned that this volume is determined considering sludge age and operation costs which will increase by increasing returned sludge volume. The sealing ensures anaerobic condition and the bottle is held inside a dark place to prevent algae reactions with room temperature.

Sludge ultrasonication was performed using an Elmasonic S30H ultrasonic bath (Elma GmbH & Co. KG, Germany) operating at an ultrasonic frequency of 37 kHz with a rated ultrasonic power of 80 W (maximum peak power of 320 W). The sludge-containing anaerobic reactor was placed inside the ultrasonic bath and exposed to continuous ultrasonication for different time intervals while all other operating conditions remained unchanged. During this phase, the return sludge undergoes exposure to ultrasonic waves following its passage through the anaerobic tank and prior to entering the aeration tank.

Four different radiation times of 5, 10, 15 and 25 minutes have been considered in this study, with the fixed temperature of 25 ˚C. These time periods are determined based on the values reported in previous studies.

The experimental tests considered in this study are shown in Table 2. Considering the high costs of tests needed for this study, we attempted to usethe minimum number of tests while still covering the effective range of measured factors. The experiments were conducted stepwise, starting with the conventional SBR as the control system, followed by the OSA configuration, OSA combined with ultrasonication, OSA combined with H_2O_2 oxidation, and finally the combined OSA–ultrasonication–H_2O_2 system. After each operational change, the reactor was operated for approximately 7 days to reach stable conditions before sampling and data collection were performed.

3. Results and discussion

3.1. SBR system

Initially, the SBR system undergoes configuration and is actively managed until its operational efficiency reaches a stable state. The average concentrations of COD and MLSS during the initial six weeks of the pilot startup are presented in Table 3. The results show that the pilot system attains a stable state approximately three weeks (21 days) into the experiment, with the MLVSS concentration stabilizing at around 4000 mg/L by the fourth week.

COD removal efficiency is selected as the main parameter to specify the optimal detention time in aerobic tank. According to the operational standards for SBR systems, it is advised that a cycle of municipal wastewater treatment process lasts from 6 to 14 hours (EPA, 1999).

Table 2. The structure of the experimental tests

Methods	Control parameter	Tests	n
OSA+ SBR	6-7-8 hr.	COD	6×3
		MLSS	6×3
		MLVSS	6×3
OSA+ Ultrasonic	5-10-15-25 min	COD	6×4
		MLSS	6×4
		MLVSS	6×4
OSA+ H_2O_2	0.001, 0.01, 0.02, 0.03 g H_2O_2/ g MLSS	COD	6×4
		MLSS	6×4
		MLVSS	6×4
OSA+ H_2O_2+ Ultrasonic	The optimal control parameters determined from previous steps	COD	6
		MLSS	6
		MLVSS	6

Table 3. The changes of effluent COD and MLSS in the SBR reactor during startup

Week	COD (mg/L)	MLSS (mg/L)
First	350	3005
Second	308	3565
Third	20	3605
Fourth	15	3991
Fifth	10	4026
Sixth	10	4140

3.2. Anaerobic tank of OSA system

This phase involved identifying the ideal HRT in the anaerobic tank of the OSA system, based on the efficiency of COD removal, from the evaluated durations of 6, 7, 8, 9, 10, and 11 hours (Nazif et al., 2016).

The data in Fig. 4 indicates that the peak COD removal efficiency occurred at 6, 7 and 8 hours, leading to their selection for evaluating the impact of the OSA process on sludge reduction production. It is worth mentioning that extending the anaerobic retention time to more than 8 h, results in a gradual decline in COD removal efficiency. This observation is because of the prolonged anaerobic exposure of the return sludge, which promotes endogenous respiration and sludge reduction but also reduces the microbial activity available for subsequent aerobic biodegradation. Similar results have been reported in other OSA studies, where excessively long anaerobic retention times adversely affect the biological activity of the sludge and reduce treatment efficiency (Nazif et al., 2016; Semblante et al., 2016; Wang et al., 2015).

When integrating the OSA system into the SBR system, it is crucial to assess the variations in COD removal and Y coefficient, with findings illustrated in Figs. 5 and 6. According to the statistics, the OSA system has effectively minimized sludge production by as much as 80%. While the quality of the effluent has experienced a slight decrease, it continues to meet the required standards.

The analysis indicated that a 6-hour HRT was the most suitable choice for the anaerobic tank within the OSA system, resulting in the lowest biomass yield and effluent COD concentration.

Due to the influent's characteristics the duration of the treatment cycle was determined as given in Table 4.

Table 4. Duration of different steps in municipal wastewater treatment cycle of the developed SBR system

Process	Time (hr)
Aeration	4
Settling	1.5
Discharge	0.5
Total	6

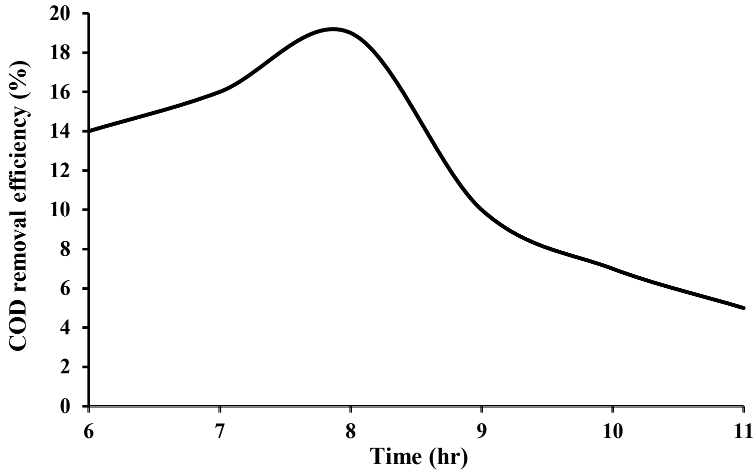

Fig. 4. COD removal efficiency of anaerobic tank in OSA system

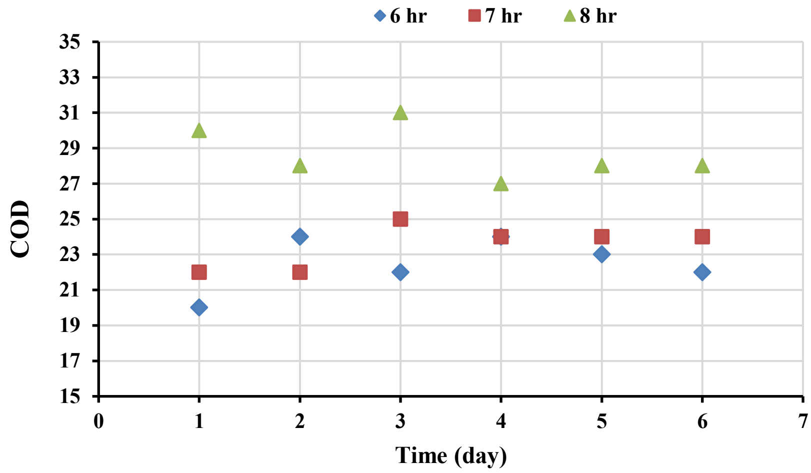

Fig. 5. The variation of COD*out* in response to different HRTs of anareabic tank in OSA system

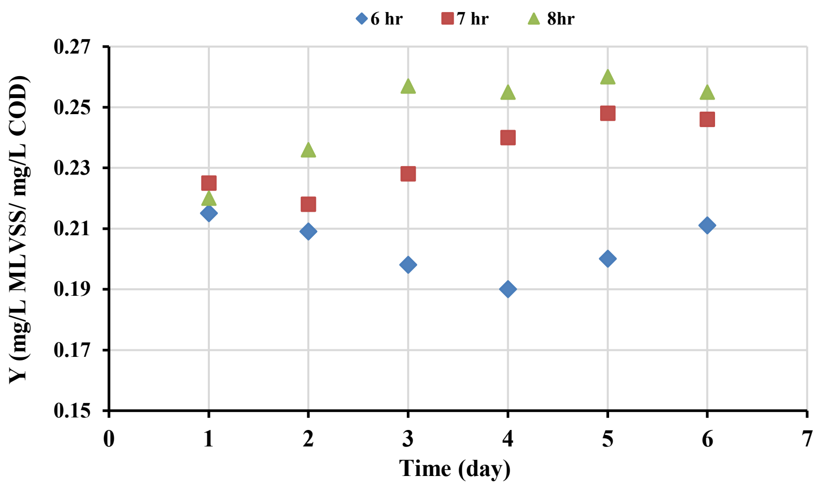

Fig. 6. The changes of Y in OSA system in response to various HRTs of anareobic tank

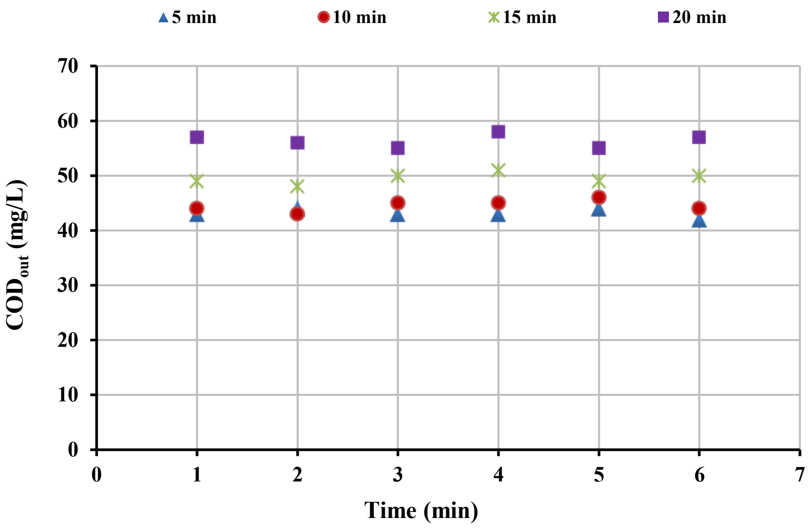

Fig. 7. The variation of COD*out* in response to different HRTs of ultrasonication in combination with OSA system

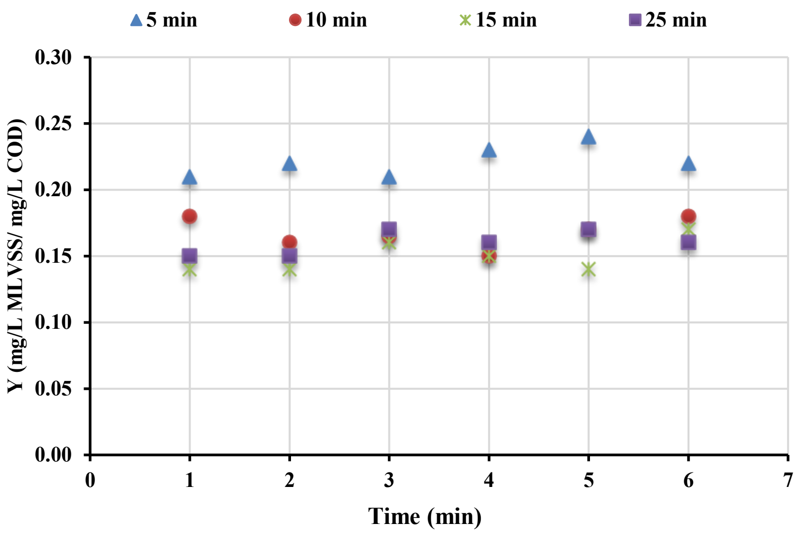

Fig. 8. The changes of Y in response to various HRTs of ultrasonication in combination with OSA system

3.3. Applying ultrasonication in combination with OSA system

Figs. 7 and 8 illustrate that ultrasonication durations of 5 minutes or shorter do not enhance OSA performance, while extending ultrasonication beyond 25 minutes results in a decline in effluent quality. Ultrasonication effectively diminishes the mean diameter of sludge particles while enhancing the SCOD by liberating organic nutrients from the cells of microorganisms, thereby facilitating increased interactions among them (Filibeli et al., 2018; Romero-Pareja et al., 2017; Yang et al., 2015). Consequently, the best sludge production reduction efficiency in combination with ultrasonication with OSA system was achieved, when the sludge exposed to the ultrasonic waves for 10 minutes.

3.4. Addition of H_2O_2 as an oxidant to the OSA system

During this phase, varying amounts of H_2O_2 were introduced to the sludge prior to its entry into the aeration tank. The interaction between hydrogen peroxide and sludge releases heat and produces gas, yet after a duration of five minutes, both the thermal energy and the gas output will diminish.

As Figs. 9 and 10 show the concentration of 0.0001 g H_2O_2/g MLSS has no considerable effect on OSA process improvement. Furthermore, despite the significant sludge reduction in concentration of 0.03 g H_2O_2/g MLSS, it reduces the output wastewater quality severely. Meanwhile two intermediate concentrations have relatively similar responses in effluent quality, but

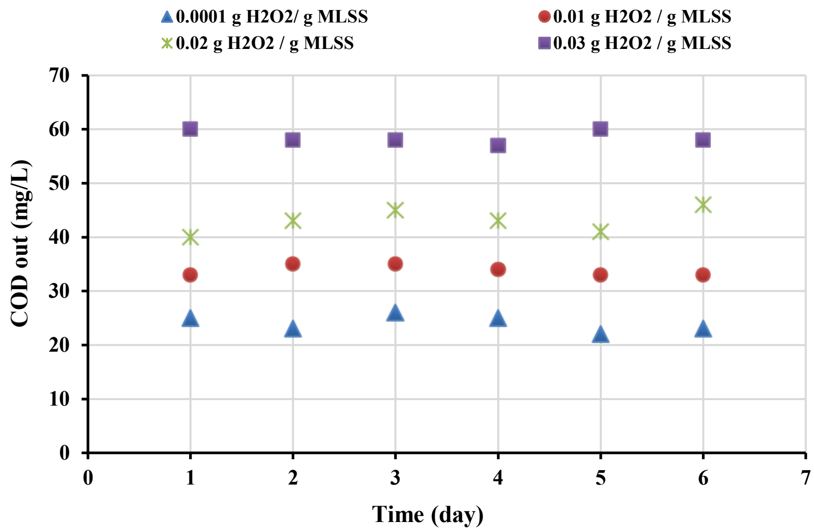

Fig. 9. The variation of COD*out* in response to different H_2O_2 concentrations in combination with OSA system

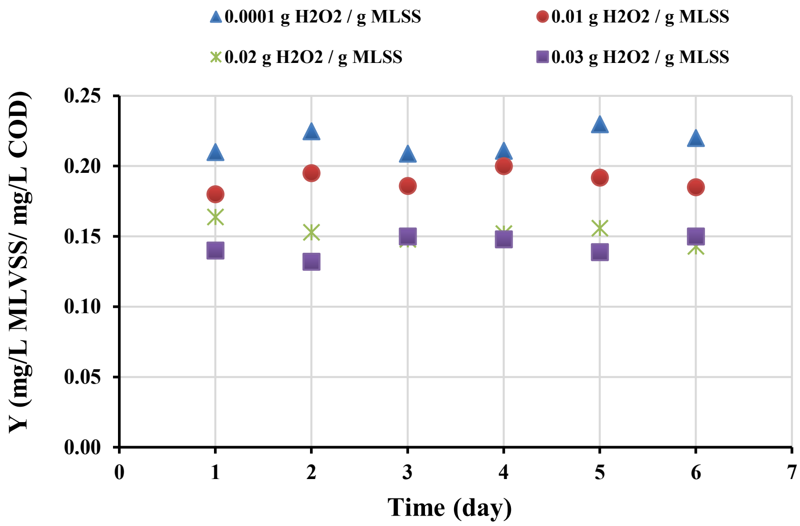

Fig. 10. The changes of Y in response to different H_2O_2 concentration in combination with OSA system

in the concentration of 0.02 g H_2O_2/g MLSS the Y is lower. Therefore, the concentration of 0.02 g H_2O_2/g MLSS has been considered for further analysis.

3.5. Ultrasonication and chemical oxidation in OSA system

In the last step, ultrasonication and chemical oxidation were combined in OSA system according to the optimal parameters determined in the previous steps (Table 5).

Table 6 details how different variables influence the efficiency of COD removal and the associated Y measurements. To enhance the investigation, the findings from different operational days of the system are summarized in this Table.

Table 6 illustrates that integrating these processes has significantly lowered the yield coefficient while maintaining a COD removal efficiency of approximately 85%, which is deemed suitable. Compared to conventional mechanical or chemical oxidation processes, this approach presents key advantages, including a reduction in sludge production of up to 32% and 27%, respectively, alongside a minor rise in the COD of the effluent.

The enhanced sludge reduction observed in the integrated OSA, ultrasonication and H_2O_2 system can be attributed to the complementary mechanisms of the three treatment processes. The OSA process promotes endogenous respiration and uncouples microbial metabolism through alternating aerobic and anaerobic conditions, which results in less net biomass production. Ultrasonication mechanically disrupts microbial flocs and lyses bacterial cells. This releases intracellular organic matter which increases the availability of biodegradable substrates.

Table 5. Optimal conditions in sludge production reduction process

Process	Optimal condition
OSA	HRT=4 hr
Ultrasonication	HRT=10 min
Chemical oxidation	0.02 g H_2O_2/g MLSS

Table 6. The results of ultrasonication and chemical oxidation in OSA system

Combination of ultrasonication and chemical oxidation in OSA system							z Average
Day	1st	2nd	3rd	4th	5th	6th	-
COD_{out} (mg/L)	56	55	58	59	57	56	56.83
COD removal (%)	85.07	85.33	84.53	84.27	84.80	85.07	84.84
Y (mg/L MLVSS/ mg/L COD)	0.124	0.10	0.13	0.115	0.11	0.12	0.11

Finally, the addition of H_2O_2 further oxidises cellular components and extracellular polymeric substances, enhancing sludge disintegration and solubilisation. The produced soluble organic compounds through ultrasonication and chemical oxidation, are biologically degraded after returning the sludge to the SBR, promoting cryptic growth and further reducing excess sludge production.

As a result, the integration of biological, mechanical, and chemical processes produces a synergistic effect which further reduces sludge in comparison with any individual treatment alone, while maintaining satisfactory COD removal efficiency.

The results obtained in this study are well supported by previous studies about sludge reduction technologies. The OSA process alone resulted in an approximately 40% reduction in sludge production, which is comparable to the 24-46% reductions reported by Nazif et al., (2016) for OSA-based systems. The combined application of OSA and ultrasonication represented an approximately 56% reduction in sludge production which is consistent with the findings of Mohammadi et al., (2011), who demonstrated the effectiveness of ultrasonication for sludge minimisation, and Romero-Pareja et al., (2017), who reported sludge reductions of 45.7–78.6% using OSA combined with ultrasonication.

Finally, the integrated OSA–ultrasonication–H_2O_2 system achieved the lowest biomass yield coefficient and an approximately 85% reduction in sludge production while maintaining COD removal efficiencies above 85%. These results indicate that the addition of H_2O_2 to the OSA–ultrasonication process further enhanced sludge disintegration and biodegradation, resulting in superior sludge reduction compared with the individual and dual-treatment systems as well as those reported in previous studies.

4. Conclusion

The primary objective of this research was to advance the functionality of the OSA system by utilizing both ultrasonic and chemical oxidation techniques to curtail sludge formation in sequencing batch reactors. In order to achieve this objective, a laboratory pilot of 5 liters was constructed and utilized for a period of 4 weeks to ensure stability. The yield coefficient, a reliable indicator of sludge production, for the SBR was found to be 0.7. After implementing the OSA to SBR system, the yield coefficient decreased to 0.2. At the next step, we assessed how ultrasonication affected the reduction of sludge.

Five different radiation times were tested, and the most efficient one, with Y equal to 0.16, was selected for the next step. Applying the H_2O_2 resulted in Y=0.15. The minimum value of Y was obtained as 0.11 when ultrasonication and chemical oxidation were combined with the OSA system. It is important to note that throughout all phases, the system evaluated the effectiveness of COD removal, and optimal parameter settings were identified to guarantee that the efficiency remained above 85%.

It should be also mentioned that although the proposed integrated system showed promising performance for sludge reduction, the findings are based on laboratory-scale experiments under specific operating conditions. Future studies should validate the results through replicated experiments and measurements and investigate the long-term performance and practical applicability of the proposed system at pilot and full scales. Further investigation on the proposed system's effects on sludge settleability, nutrient removal, potential oxidation by-products, and microbial community dynamics are also needed to provide a more comprehensive assessment of the process.

From a practical perspective, the proposed integrated system has the potential to reduce the overall operating costs of WWTPs by substantially decreasing excess sludge production and, consequently, the costs associated with sludge thickening, dewatering, transportation, and disposal. Although the combined use of ultrasonication and H_2O_2 introduces additional energy and chemical requirements, these costs may be partially or fully offset by the savings achieved through reduced sludge handling and disposal. A detailed techno-economic assessment is beyond the scope of the present study but should be considered in future research to evaluate the feasibility of full-scale implementation.

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