

Optimizing an Integrated SBR and UV/H₂O₂ System for Detergent-Rich Gray Water Treatment

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Article Info

Article type:

Research Article

Article history:

Received 23 December 2025

Revised 17 June 2026

Accepted 05 July 2026

Published online 22

December 2026

Keywords:

Pollutant Removal Efficiency

UV/H₂O₂ Chemical Oxidation

Gray water treatment

Sequential Batch Reactor

ABSTRACT

Objective: While SBR and hybrid SBR-AOP systems have been investigated for conventional wastewater treatment, their application and optimization for highly detergent-rich gray water presents unique challenges, such as biomass inhibition and low initial biodegradability (BOD₅/COD ratio of 0.25). The distinct novelty of this study lies in the systematic configuration optimization and phase-duration management of an integrated SBR and UV/H₂O₂ system specifically tailored for gray water containing elevated detergent concentrations. Unlike traditional hybrid systems that apply chemical oxidation as a polishing step, this research evaluates and demonstrates the significant advantages of operating the UV/H₂O₂ process as a pre-treatment stage. This specific sequencing effectively breaks down non-biodegradable surfactants and mineralizes complex organic compounds prior to the biological stage, thereby enhancing the overall system efficiency to a COD removal rate of 97%.

Methods: Gray water with initial pollutant concentrations of 600 mg/L COD, 200 mg/L BOD, 4 mg/L TP, and 15 mg/L TKN was treated using an SBR system combined with UV/H₂O₂ chemical oxidation. Additionally, the potential of granular activated carbon (GAC) added during the SBR aeration phase to enhance pollutant removal was evaluated. Different chemical oxidation conditions were evaluated, and the effects of anaerobic pre-treatment and anaerobic phase duration were assessed.

Results: The SBR reduced BOD₅ to 40 mg/L and COD to 162 mg/L, while activated carbon had a limited effect. The optimal chemical oxidation conditions were 12 mg/L H₂O₂ and a reaction time of 3 hours. Under these conditions, the integrated system achieved removal efficiencies of 90.6% for COD, 85% for BOD, 82.5% for TP, and 65% for TKN. Chemical oxidation as a pre-treatment step improved the biodegradability of organic compounds by 6%. In addition, the inclusion of an anaerobic unit before aeration improved phosphorus removal, although extending the anaerobic phase beyond two hours provided no further benefit.

Conclusions: the integrated SBR and UV/H₂O₂ system is an effective method for treating gray water with high detergent concentrations, significantly reducing pollutant levels and improving biodegradability. The use of anaerobic pre-treatment can further enhance phosphorus removal, but longer anaerobic durations are not necessarily advantageous.

Cite this article: Govahi, S., Derikvand, E., Khoshnavaz, S., Solimani Babarsad, M. & Parseh, I. (2026). Optimizing an integrated sbr and uv/h₂o₂ system for detergent-rich gray water treatment. Journal of New Approaches in Water Engineering and Environment, 5(4), 90-110. <https://doi.org/10.22034/nawee.2026.584375.1226>.



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Publisher: Gonbad Kavous University.

DOI: <https://doi.org/10.22034/nawee.2026.584375.1226>

1. Introduction

Gray water, defined as untreated domestic wastewater generated from sinks, showers, kitchens, and laundry basins, typically constitutes 65% to 85% of total household water consumption. Its volumetric generation varies significantly based on geographic location and household plumbing configurations, with daily per capita outputs ranging from 30 to 300 liters (Carden et al., 2007; Tsoumachidou et al., 2019; Tamizi et al., 2026). Despite its substantial potential as an alternative resource for agricultural and landscape irrigation, untreated gray water often harbors elevated levels of alkaline substances, surfactants, total coliforms, and *Escherichia coli*. Consequently, it poses critical risks to public health and environmental quality if left untreated (Eriksson et al., 2010; Pittock et al., 2023; Rodda et al., 2011; Zakerinia and Bagheri, 2026). Driven by rapid population growth and expanding industrial activities, the increasing demand for water reuse necessitates highly effective treatment technologies capable of mitigating pathogens, suspended solids, and emerging contaminants (Bernadet, 2024; Kataki et al., 2021; Chin et al., 2009). This is particularly crucial as conventional wastewater treatment systems often fail to eliminate persistent organic pollutants and pharmaceuticals, leading to their accumulation in aquatic ecosystems and sewage sludge (Pereira et al., 2015; Silva et al., 2023; Ahn et al., 2007). In arid and semi-arid regions where water scarcity is severely exacerbated by climate change, the sustainable management of water resources through efficient recycling has become a global imperative (Gavala and Ahring, 2002; Almendariz et al., 2001; Pittock et al., 2023). Therefore, developing advanced treatment technologies and establishing stringent regulatory frameworks are essential to ensure that recycled gray water is safe for non-potable reuse without triggering environmental degradation (Eriksson et al., 2015; Karthik and Philip, 2021; Nowruzi et al., 2024; Zazouli et al., 2024).

Gray water treatment methodologies are categorized into three primary types: physical, chemical, and biological, followed by a disinfection phase and pretreatment procedures to mitigate clogging before microbiological disinfection (Li et al., 2009). Advanced computational modeling tools, such as Simulink, are employed by researchers to elucidate the interactions among various pathways within gray water treatment units (Marszałek et al., 2016; Kuriqi et al., 2019). Since the 1970s, numerous studies have been conducted on gray water treatment and recycling. Early technologies focused on primary treatments like solid removal or membrane filtration, often integrated with disinfection processes. Between the 1980s and 1990s, biological-based technologies such as Moving Bed Biofilm Reactors (MBBRs), aerated biofilters, and sequencing batch reactors were developed. Concurrently, simple physical separation systems combined with disinfection methods were designed and implemented in individual households. The late 1990s saw reports on the use of advanced technologies such as sophisticated membrane bioreactors (MBRs) alongside simpler systems like reed beds and ponds (Awasthi et al., 2024; Hassanshahi and Karimi-Jashni, 2018). Since the late twentieth century, biological treatment systems have been employed either independently or in conjunction with various physical treatment techniques for gray water treatment. Rotating Biological Contactors (RBCs), Sequencing Batch Reactors (SBRs), and Upflow Anaerobic

Sludge Blankets (UASBs) have all been evaluated by multiple researchers (Eriksson et al., 2015; Hernández-Leal et al., 2011; Georgiou et al., 2002; Mösche and Meyer, 2002).

The SBR operates through five distinct phases: filling, reacting, settling, decanting, and idling. An SBR was utilized to treat gray water from the bathrooms of Tunis's El Manzeh student residence (Lamine et al., 2012). The findings indicated that the SBR effectively removed nutrients and reduced the COD by up to 90%. The process also ensured the biodegradation of organic matter from gray water with effective solid sludge settling properties. Additionally, Hermawan et al. (2019) found that the SBR could reduce the BOD to less than 5 mg/L and was effective in removing five paraben biocides (methyl-, ethyl-, propyl-, butyl-, and iso-butyl-esters of para-hydroxybenzoic acid). Their findings demonstrated that the removal efficiency of the selected biocides varied from 87% to 99%, as the bacterial community utilized paraben as a carbon source for reproduction. Similarly, high-strength gray water was treated in an SBR with a retention period of 11.7 hours and a sludge retention duration of 15 days. The results showed significant reductions in influent concentrations of COD (830 mg/L), Total Phosphorus (TP, 7.7 mg/L), Total Nitrogen (TN, 53.6 mg/L), and ammonia (1.2 mg/L) to effluent concentrations of COD (130 mg/L), TP (6.5 mg/L), TN (34.4 mg/L), and ammonia (0.41 mg/L) (Awasthi et al., 2024). Another SBR was used to treat high-strength gray water, with the sludge retention period extended to 378 days and the hydraulic retention time reduced to 5.9 hours. This system achieved reductions in influent concentrations of COD (827 mg/L), TP (8.5 mg/L), TN (29.9 mg/L), and ammonia (0.8 mg/L) to effluent concentrations of COD (100 mg/L), TP (5.8 mg/L), TN (26.5 mg/L), and ammonia (0.44 mg/L). Organic nitrogen accounted for 90% of the effluents, whereas total nitrogen was 74%, indicating minimal transformation of particulate organic nitrogen to ammonia during the oxidation process (Awasthi et al., 2024). Smetana and Grosser (2024) utilized the SBR to treat brewery (BW) and dairy wastewater (DW). They claimed that BW and DW required effective and eco-friendly treatment due to their high COD, BOD₅, and nutrient levels. Conventional methods like activated sludge are often inefficient, while anaerobic processes present a viable alternative. This review explores anaerobic co-digestion and subsequent effluent post-treatment. Akyürek and Ağdağ (2024) compared constructed wetlands (CsW) and package type sequencing batch reactor (SBR) treatment plants in rural Denizli City, Türkiye. They found that CsWs offer superior stability, efficiency, and lower operational costs compared to SBRs, despite similar initial investment costs. CsWs achieved higher BOD₅ (92%) and SS (88%) removal efficiencies than SBRs (85% and 81%, respectively). Operating costs for CsW were 0.018 USD/m³ versus 0.13 USD/m³ for SBR. CsWs are favored for their low costs, energy efficiency, sustainability, and compliance with discharge standards. Ettaloui et al. (2023) evaluated the efficiency of a sequential batch reactor (SBR) for treating oil washing wastewater. Over 25 days, the SBR demonstrated significant pollutant reduction: COD (81%), BOD (91%), TSS (72%), ammonium (100%), nitrate (52%), and phenol (63%). The study highlights SBR's potential due to its simplicity, low space and energy requirements, and minimal need for specialized personnel. Liu et al. (2023) investigated nitrogen removal from low C/N ratio wastewater using

a step-feed sequence batch reactor with surface-modified carriers. They demonstrated enhanced nitrogen removal ($0.062 \pm 0.010 \text{ kg}/(\text{m}^3 \cdot \text{d})$) without external carbon sources, compared to traditional activated sludge ($0.031 \pm 0.010 \text{ kg}/(\text{m}^3 \cdot \text{d})$) and conventional IFFAS systems ($0.057 \pm 0.014 \text{ kg}/(\text{m}^3 \cdot \text{d})$). The modified carriers facilitated efficient denitrification and promoted beneficial microbial by-product production, presenting a cost-effective and efficient nitrogen removal method for practical applications. Ghaderpoori and Dehghani (2020) highlighted that detergents, particularly linear alkyl benzene sulfonates (LAS), significantly impact microbial processes in wastewater treatment. LAS, which are biologically degradable, have replaced the more resistant non-linear alkyl benzene sulfonates (ABS). Gray water treatment technologies range from basic storage to advanced oxidation processes (AOPs), with limited application of AOPs in gray water treatment, where photo-catalysis is primarily explored. Vohla et al. (2019) investigated phosphorus removal from wastewater, finding that calcium-containing absorbents with pH above 7 were generally effective. Industrial absorbents, like furnace ash, achieved up to 420 grams of phosphorus removal per kilogram, significantly outperforming natural materials (about 40 grams). The study revealed that lime absorption levels correlated with phosphorus removal, while pH had a minor effect. It suggested exploring factors such as hydraulic load, saturation percentage, filter material type, and availability to further enhance absorption efficiency. Dalahmeh (2018) assessed the effectiveness of pine bark, activated charcoal, and sand filters in removing pollutants from wastewater at the laboratory scale. Using general regression models to analyze hydraulic and organic loading rates, activated charcoal outperformed others in removing BOD (83-97%), TKN (50-98%), and TP (64-98%) due to its high specific surface area. Sand filters showed lower BOD removal (67-91%) and minimal nitrogen removal. While tree bark and charcoal were effective for organic compound removal, additional systems are needed for nitrogen and bacterial contaminants to meet Jordanian irrigation water standards. Jefferson et al. (2016) and Günther (2014) discussed how traditional wastewater management combines wastewater with water before treatment, often producing effluent similar to gray water. They proposed that segregating gray water at its source could improve its reuse potential. Research on gray water recycling reveals significant variability in its quantity and quality, even within the same household. Eriksson et al. (2015) reported that gray water parameters include biochemical oxygen demand (5-1460 mg/L), chemical oxygen demand (13-8000 mg/L), pH (8-10), turbidity (15-240 NTU), and suspended solids (17-330 mg/L). Leal et al. (2010) compared aerobic sequential batch reactors, anaerobic UASB systems, and their combination for domestic wastewater treatment, all with a hydraulic residence time of 12-13 hours. Aerobic conditions achieved over 90% COD removal, while anaerobic systems removed about 51%, due to high anionic surfactant concentrations and poor colloidal organic compound removal. The combined aerobic-anaerobic system also achieved over 89% COD removal, similar to aerobic treatment. Methanogen production was 32% for anaerobic and 25% for combined systems, with minimal energy production, indicating that aerobic treatment is preferred over anaerobic pretreatment. Despite the extensive research on sequencing batch reactors (SBR) and advanced oxidation processes (AOPs), a significant knowledge gap remains

regarding the treatment of gray water characterized by exceptionally high detergent concentrations. Previous studies on hybrid SBR-AOP systems have primarily focused on low-strength domestic gray water or have conventionally applied AOPs exclusively as a post-treatment polishing step. This conventional configuration possesses a major limitation: high surfactant and detergent loads in raw gray water exert severe toxic effects on the biological sludge in the SBR, thereby inhibiting microbial activity and resulting in poor nutrient and organic removal efficiencies. Furthermore, how individual SBR phase durations (specifically the anaerobic and aerobic periods) respond to high detergent stress remains under-explored. To bridge these existing gaps, the present work systematically evaluates the integration of SBR and UV/H₂O₂ oxidation by shifting the traditional paradigm and utilizing AOP as a pre-treatment stage. The specific scientific contribution of this study is to provide a clear mechanism of how chemical pre-oxidation overcomes biomass inhibition, enhances the initial biodegradability of surfactant-rich streams, and optimizes inner-cycle operations for simultaneous organic and nutrient removal.

While SBR and hybrid SBR-AOP systems have been investigated for conventional wastewater treatment, their application and optimization for highly detergent-rich gray water presents unique challenges, such as biomass inhibition and low initial biodegradability (BOD₅/COD ratio of 0.25). The distinct novelty of this study lies in the systematic configuration optimization and phase-duration management of an integrated SBR and UV/H₂O₂ system specifically tailored for gray water containing elevated detergent concentrations. Unlike traditional hybrid systems that apply chemical oxidation as a polishing step, this research evaluates and demonstrates the significant advantages of operating the UV/H₂O₂ process as a pre-treatment stage. This specific sequencing effectively breaks down non-biodegradable surfactants and mineralizes complex organic compounds prior to the biological stage, thereby enhancing the overall system efficiency to a COD removal rate of 97%.

2. Materials and Methods

1.1 Experimental setup

A bench-scale hybrid treatment configuration consisting of a biological system and a chemical oxidation unit was employed, as systematically illustrated in Fig. 1 and Fig. 2. The biological reactor utilized an 8-liter polyethylene vessel, which was inoculated up to 60% of its working volume with activated sludge obtained from a full-scale extended aeration wastewater treatment plant. The detailed composition and chemical characteristics of the synthetic greywater are summarized in Tables 1 and 2.

To acclimate the biomass to the greywater matrix, the Sequencing Batch Reactor (SBR) was operated continuously for a one-month stabilization period. During this acclimation phase, the SBR cycle consisted of six sequential phases: filling, anaerobic reaction, aerobic aeration, anoxic reaction, settling, and treated effluent decanting. Continuous aeration was supplied via a laboratory-scale air pump to maintain dissolved oxygen (DO) levels strictly above 5 mg/L. At the end of the startup period, the mixed liquor suspended solids (MLSS) concentration

stabilized at 2800 mg/L, and the sludge volume index (SVI) was 95 mL/g, confirming readiness for experimental runs.

Following the stabilization period, the SBR was operated under systematically varied phase durations to investigate and determine the optimal cyclic configuration for maximum pollutant removal efficiency. Because these operational durations (filling, anaerobic, aerobic, anoxic, and settling times) were the primary independent variables being optimized as part of the experimental outcomes, their detailed evaluation and final optimized values are comprehensively presented and discussed in the Results and Discussion section (Section 3). During the subsequent target experimental runs under these optimized conditions, granular activated carbon (GAC) was introduced into the mixed liquor at various concentrations ranging from 250 to 1250 mg/L to evaluate its synergistic effect.

Two 15-watt low-pressure mercury UV lamps emitting at a wavelength of 254 nm (UV-C spectrum) were installed on the ceiling of a glass enclosure (80 x 20 x 15 cm), lined with aluminum foil to prevent water contact with the radiation source. The lamps were positioned 5 cm above the water surface. Environmental temperatures ranged from 25 to 35°C, and the stirrer speed within the SBR unit was maintained at approximately 50 RPM. To enhance biological treatment efficiency, granular activated carbon (Norit GAC 830) with an effective size of 0.9 mm, uniformity coefficient of 1.7, and surface area of 975 m²/g was employed. Gray water samples were stored at 4°C and analyzed within 48 hours. The hydrogen peroxide (H₂O₂) solution was prepared from a commercial analytical-grade stock solution (30% w/w). To prevent thermal and photochemical decomposition, the stock solution was stored in a dark container at 4°C. The required amount of H₂O₂ was calculated according to the predetermined target concentrations and introduced into the photo-oxidation reactor via a single-pulse injection method at the exact onset of the UV irradiation phase to ensure instantaneous and uniform distribution.



Figure 1. Schematic diagram and component identification of the UV/H₂O₂ photo-oxidation pre-treatment system.



Figure 1- The BR biological treatment

Table 1- Gray water compounds

Compound	Unit in 20 liters of water	Value
laundry detergent	mg	200
Meat extract	mg	600
Cake flour	mg	15
Soap Body	mg	4
Oil	mg	0.01

Table 2- Gray water characterization

Compound	Unit	Value
BOD ₅	Mg/l	270
COD	Mg/l	600
pH	-	9
TSS	Mg/l	25
TDS	Mg/l	800
Cl	Mg/l	26
TKN	Mg/l	15
TP	Mg/l	4

1.2 Analytical Methods and Quality Control

All water quality parameters, including Chemical Oxygen Demand (COD), 5-day Biochemical Oxygen Demand (BOD₅), Total Kjeldahl Nitrogen (TKN), and Total Phosphorus (TP), were measured in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 2012). Specifically, COD was determined using the closed reflux colorimetric method (Method 5220 D), and BOD₅ was measured using the 5-day BOD test (Method 5210 B). Total Phosphorus and TKN were analyzed using persulfate digestion followed by ascorbic acid colorimetry (Method 4500-P E) and the macro-Kjeldahl method (Method 4500-N B), respectively. pH was monitored continuously using a digital pH meter (accurate to 0.1). To ensure data reliability and reproducibility, all experimental runs and analytical measurements were performed in triplicate, and the average values were reported.

To ensure the reproducibility and statistical reliability of the experimental outcomes, all analytical measurements and SBR operational runs were performed in triplicate (n = 3). The experimental data are reported as the mean values, and the calculated standard errors are visually represented as error bars in the respective figures.

The Chemical Oxygen Demand (COD) removal efficiency (R, %) was quantified using the following equation:

$$R (\%) = [(COD_{in} - COD_{out}) / COD_{in}] \times 100$$

Where COD in and COD out represent the influent and effluent COD concentrations (mg/L), respectively.

3. Results and discussion

1.3 COD removal rate with aeration time in the SBR system

The removal rates of COD and BOD₅ from synthetic gray water (initial COD = 600 mg/L and BOD₅=270 mg/L) with a volume of 3 liters over 24 hours in an SBR were examined during the filling, anaerobic, aeration, anoxic, and settling phases. The aerobic and anaerobic stages were maintained for 6 and 12 hours, respectively, to assess system performance and optimize operational parameters, as illustrated in Figure 2. The operational profile revealed a distinct variance between the dynamic fluctuations of dissolved oxygen (DO) and the steady, monotonic depletion of COD and BOD within each SBR cycle. While COD and BOD represent the cumulative mass of organic substrates that decrease progressively as biodegradation and

chemical oxidation proceed, DO operates under a highly sensitive, real-time equilibrium. At the immediate onset of the aerobic phase, the DO concentration experiences a temporary suppression due to the high initial Oxygen Uptake Rate (OUR) as the acclimated biomass rapidly metabolizes the readily biodegradable detergents. As the organic load (BOD/COD) is progressively depleted, the microbial respiration rate diminishes, allowing the constant aeration supply to surpass the oxygen demand, which triggers a sharp, characteristic surge in DO levels toward saturation at the end of the cycle. As depicted in Figure 3, a dramatic drop in DO levels was observed immediately after the 18th hour. This sharp decline is directly attributed to the scheduled termination of the aerobic (aeration) phase and the subsequent transition into the anoxic and settling stages. Upon turning off the aeration blowers at hour 18, the mechanical oxygen supply ceases entirely, while the active biomass rapidly depletes the residual dissolved oxygen through endogenous respiration, causing a rapid decline in DO concentrations. The COD removal efficiencies during the anaerobic, aeration, and total phases were 46%, 34%, and 73%, respectively. The BOD₅ removal efficiencies during the anaerobic, aerobic, and total stages were 65.5%, 52.5%, and 85%, respectively. Post-SBR, the BOD₅ of gray water decreased from 270 mg/L to 40 mg/L, and the COD reduced from 600 mg/L to 162 mg/L. During the initial two and four hours of the anaerobic and aeration phases, the COD and BOD₅ removal rates were highest, with diminishing returns observed thereafter, indicating that extending these phases beyond 2 and 4 hours, respectively, would not enhance pollutant removal. The limited removal efficiency was attributed to the high concentration of detergents and low concentration of biodegradable compounds, resulting in a BOD/COD ratio of 0.25 post-SBR. Consequently, biological treatment alone is insufficient for removing organic compounds from this type of gray water for safe environmental discharge.

The highest removal rates for COD and BOD₅ were observed during the first two and four hours of the anaerobic and aeration phases, respectively. This indicates a rapid initial degradation of organic matter, followed by a plateau in removal efficiency, suggesting that extending these phases beyond the identified optimal durations does not significantly enhance pollutant removal.

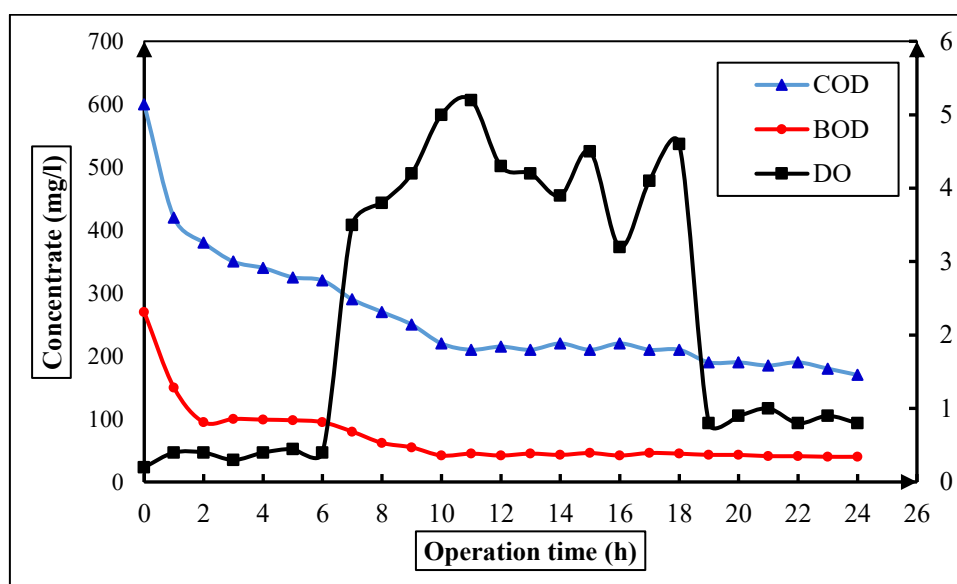


Figure 2- Removal rate of organic compounds in SBR

1.4 Phosphorus and nitrogen removal rates in the SBR system

Gray water containing 4 mg/L of phosphorus and 15.1 mg/L of nitrogen was treated in a sequencing batch reactor (SBR) with a 3-liter volume, following the steps of filling, anaerobic, aeration, anoxic, settling, and discharge. Figure 4 demonstrates that the phosphate concentration increases during the first 2 hours of the anaerobic phase and subsequently plateaus until the 6-hour mark. This trend is highly logical and represents the classic anaerobic phosphorus release mechanism characteristic of Enhanced Biological Phosphorus Removal (EBPR) systems driven by Phosphorus Accumulating Organisms (PAOs). Under anaerobic conditions, PAOs utilize intracellularly stored polyphosphate as an energy source to take up readily biodegradable organic substrates (such as volatile fatty acids derived from greywater), converting them into intracellular storage compounds, namely polyhydroxyalkanoates (PHAs). The cleavage of these high-energy polyphosphate bonds results in the concomitant release of orthophosphate into the bulk liquid, causing the initial rise in soluble phosphorus levels. The plateau observed after 2 hours indicates the complete depletion of the easily assimilable carbon source or the exhaustion of the intracellular polyphosphate reserves available for release, demonstrating that extending the anaerobic duration beyond this optimal 2-hour window yields no additional phosphorus release. After 5 hours of aeration, ammonia nitrogen and phosphate concentrations decreased from 15.1 mg/L and 13.2 mg/L to 5.26 mg/L and 0.7 mg/L, respectively. Extending the aeration period to 12 hours did not significantly enhance ammonia nitrogen removal. Consequently, an anaerobic phase of 2 hours and an aeration phase of 5 hours are deemed sufficient and optimal for achieving 82.5% phosphorus removal and 65% ammonia nitrogen removal.

The results underscore the importance of optimizing phase durations in SBR operations to achieve effective nutrient removal from gray water. The plateau in phosphorus removal beyond 2 hours of anaerobic treatment and the minimal impact of extended aeration on ammonia nitrogen removal highlight the need for targeted phase management to enhance treatment

efficiency. These insights can inform the design and operation of SBR systems for gray water treatment, particularly in scenarios with high nutrient loads.

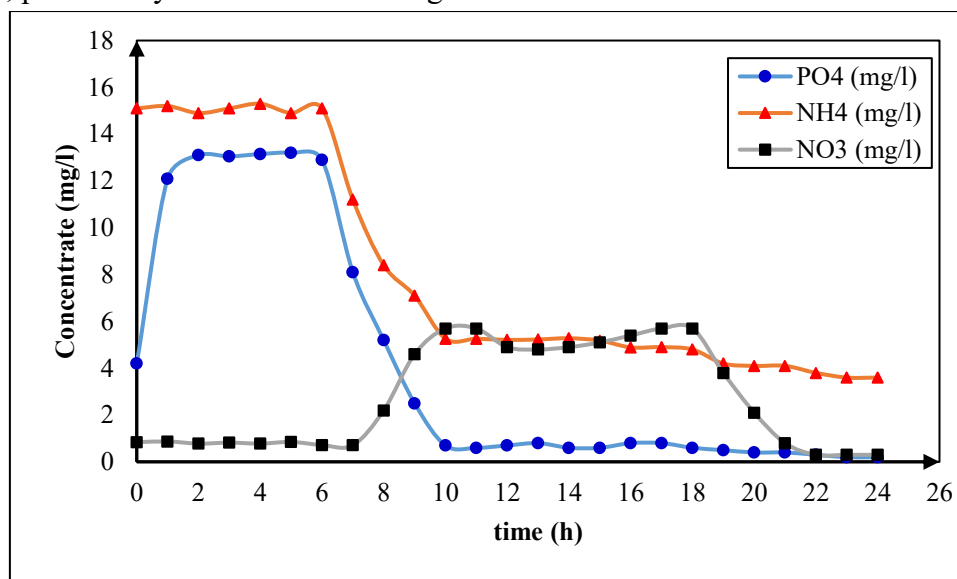


Figure 3- Rate of phosphorus and nitrogen removal in SBR

1.5 The effect of using granular activated carbon on pollutant removal

Building on the optimal conditions identified in previous stages, the durations for filling, anaerobic, aerobic, anoxic, and settling phases were set to 2 minutes, 2 hours, 4 hours, 1 hour, and 30 minutes, respectively. In the SBR, GAC was added in concentrations ranging from 250 to 1250 mg/L during the aeration phase, as recommended by prior studies. Fig. 5 illustrates that the removal efficiencies for COD, NH₄, and PO₄ increase slightly with higher GAC concentrations, although the maximum net improvement was limited to only 1 to 2%, confirming a minor and statistically non-significant impact.

The relatively lower-than-expected adsorption efficiency of Granular Activated Carbon (GAC) within the SBR system can be attributed to several compounding biochemical and physical phenomena. Crucially, in a mixed liquor environment with a high biomass concentration (MLSS of approximately 2800 mg/L), the outer surface of the GAC particles is rapidly colonized by microorganisms, leading to the formation of a dense biological film. This biofilm development, along with the secretion of extracellular polymeric substances (EPS), causes "pore blinding" or clogging of the GAC's microporous and mesoporous structures, thereby severely restricting the intraparticle diffusion of target greywater pollutants (such as detergents) to the inner active adsorption sites. Additionally, competitive adsorption within the complex organic matrix of greywater plays a significant role; readily biodegradable background dissolved organic matter (DOM) competitively occupies the available active sites, reducing the net adsorption capacity for more recalcitrant compounds. Finally, the hydrodynamic shear and fluidization within the aerated SBR limit the mass transfer efficiency of GAC compared to conventional fixed-bed column configurations.

Overall, the introduction of GAC showed only a minor improvement in COD, NH₄, and PO₄ removal efficiencies, indicating that while GAC can aid in adsorbing organic compounds and nutrients, its baseline impact remains limited under the current operating conditions. The optimal phase durations of 2 minutes for filling, 2 hours for anaerobic, 4 hours for aerobic, 1 hour for anoxic, and 30 minutes for settling were reaffirmed as effective for primary nutrient and organic matter mitigation from greywater. However, the minor gains (less than 2%)

obtained from GAC concentrations up to 1250 mg/L suggest that further process optimization or integration with alternative treatment strategies may be required to achieve superior purification performance.

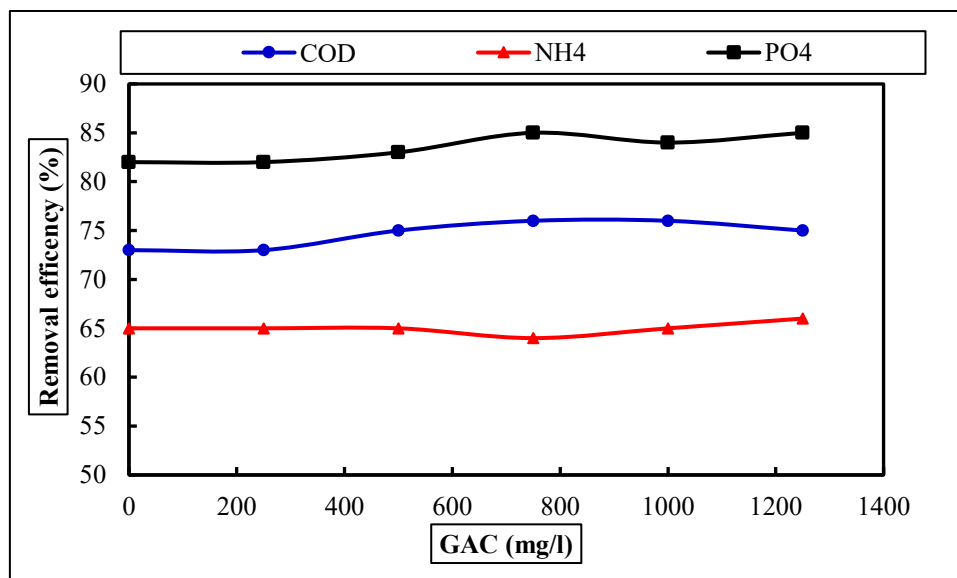


Figure 5- The effect of granular activated carbon (GAC) concentration on the removal efficiencies of contaminants

1.6 The effect of pH and residence time on gray water COD removal in the UV/H₂O₂ process

The next purpose of the present study was to investigate the efficacy of UV/H₂O₂ chemical oxidation in further reducing the COD of biologically treated synthetic gray water. The objective was to determine the optimal pH and residence time for maximizing COD removal efficiency, thereby enhancing the overall treatment process. Synthetic gray water with an initial COD of 170 mg/L, following biological treatment, was subjected to UV/H₂O₂ chemical oxidation. The effects of residence time and pH on COD removal efficiency are depicted in Figure 6. The COD removal efficiency at a fixed contact time of 3 hours and varying pH levels of 2, 4, 6, 8, 10, 12, and 14 was 65%, 71%, 73%, 78%, 81%, 62%, and 49%, respectively (referring to **Error! Reference source not found.**). These results indicate that the removal efficiency of organic compounds increases slightly with pH up to 10, beyond which it decreases. The UV/H₂O₂ chemical oxidation process effectively reduces COD levels in biologically treated synthetic gray water, with the optimal pH identified as 10 for maximum removal efficiency (81%) at a residence time of 3 hours. The study highlights the importance of pH in the oxidation process, suggesting that maintaining an alkaline environment (up to pH 10) is beneficial. However, excessively high pH levels reduce the process's effectiveness, indicating a need for precise pH control. Further research should explore the combined effects of varying residence times and pH levels to fully optimize the UV/H₂O₂ oxidation treatment for gray water.

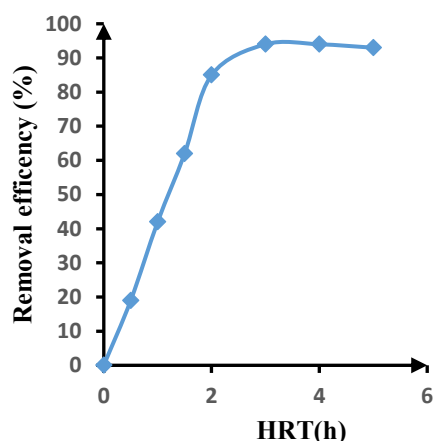


Figure 6a- Effect of hydraulic retention time (HRT) on COD removal efficiency (Operating conditions: initial COD = 170 mg/L).

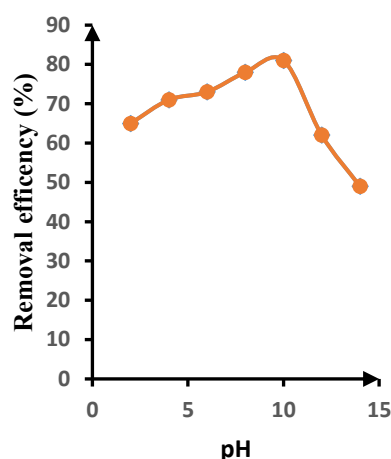


Figure 6b-Effect of pH on COD removal efficiency (Operating conditions: initial COD = 170 mg/L, constant HRT = 3 h).

1.7 Optimal dose of H_2O_2 to remove organic pollution

Gray water discharged from the SBR with an average COD of 170 mg/L was treated using UV/ H_2O_2 chemical oxidation. Based on previous optimization results, the pH was maintained at 10 and the irradiation time was set to 3 hours. **Error! Reference source not found.** illustrates the COD reduction achieved with varying hydrogen peroxide (H_2O_2) dosages of 0, 3.5, 5, 7, 12, 15, and 20 mg/L, resulting in output COD values of 170, 90, 78, 65, 56, 56, and 56 mg/L, respectively. The results indicate that increasing the H_2O_2 dosage up to 12 mg/L improves COD removal efficiency. Beyond 12 mg/L, no further reduction in COD is observed, suggesting a saturation point where additional H_2O_2 does not enhance the oxidation process. The optimal dosage of H_2O_2 for maximum COD removal was identified as 12 mg/L, achieving a final COD of 56 mg/L. Higher dosages did not result in further COD reduction, indicating that 12 mg/L is the most effective concentration for the given treatment conditions. These findings demonstrate that UV/ H_2O_2 oxidation is effective in significantly reducing COD levels in gray water, with an optimal H_2O_2 dosage identified. The plateau in COD reduction beyond 12 mg/L suggests that there is an optimal range for H_2O_2 dosing, beyond which the efficiency does not improve. This highlights the importance of optimizing chemical dosages to achieve cost-effective and efficient water treatment.

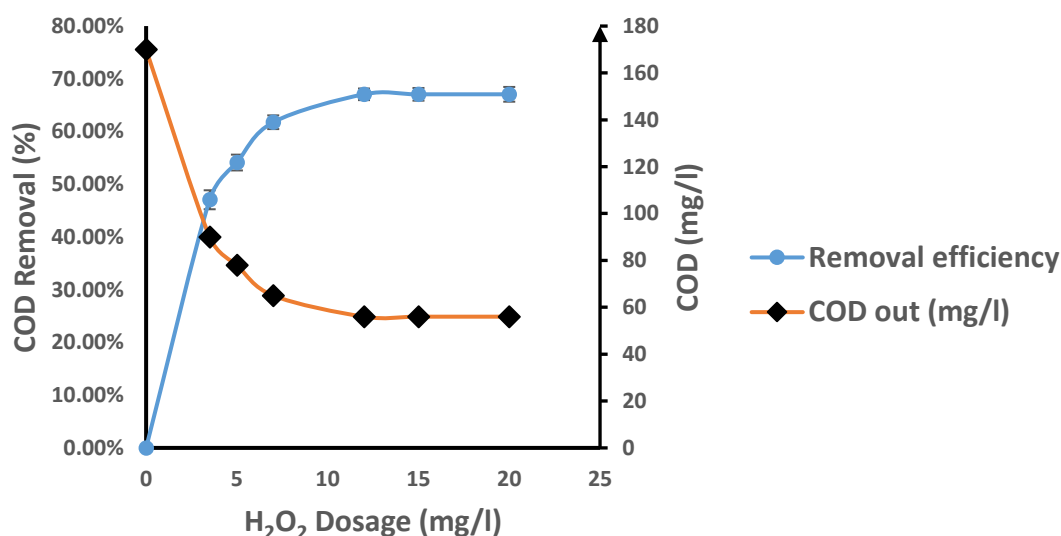


Figure 7- Optimization of H₂O₂ concentration for the removal of organic pollutants (Operating conditions: initial COD = 170 mg/L, pH = 10, and reaction time = 3 hours).

1.8 The effect of chemical oxidation before and after biological treatment

Under the optimal conditions identified for the SBR and UV/H₂O₂ chemical oxidation processes, gray wastewater was first subjected to UV/H₂O₂ chemical oxidation followed by biological treatment in an SBR. The final concentrations of COD, TKN, and TP in the treated water were 18 mg/L, 5.25 mg/L, and 0.72 mg/L, respectively. As depicted in Figure 4, the overall COD removal efficiency reached 97% (final effluent of 18 mg/L, based on the initial raw COD of 170 mg/L) when UV/H₂O₂ chemical oxidation was conducted as a pre-treatment **before** the biological treatment in the SBR, which is higher than the 91% efficiency obtained in the post-treatment configuration. This represents a 6% increase compared to conducting biological treatment before chemical oxidation. The enhanced COD removal can be attributed to the oxidative breakdown of organic compounds by UV/H₂O₂, which pre-treats the wastewater, making it more amenable to subsequent biological degradation. The COD reduced from 170 mg/L to 18 mg/L, achieving a 97% removal efficiency. The previous stages achieved a COD removal efficiency of 91%, indicating a 6% improvement when the sequence was reversed. The concentrations of TKN and TP in the output treated water were 5.25 mg/L and 0.72 mg/L, respectively. The removal efficiencies of nitrogen and phosphorus did not show significant changes with the alteration in process sequence, suggesting that the biological treatment step primarily governs these removals. The findings underscore the importance of sequencing in wastewater treatment processes. Performing UV/H₂O₂ chemical oxidation prior to SBR enhances COD removal, likely due to the preliminary oxidative breakdown of complex organic molecules, facilitating subsequent biological degradation. However, the removal efficiencies for TKN and TP remain governed by the biological treatment step, unaffected by the sequence of chemical oxidation. Conducting UV/H₂O₂ chemical oxidation before biological treatment in an SBR significantly enhances COD removal efficiency, achieving a 97% reduction compared to 91% when the sequence is reversed. This improved sequence does not

affect the removal efficiencies of nitrogen and phosphorus. These insights highlight the potential benefits of optimizing process order in wastewater treatment to maximize pollutant removal efficiencies. Future research could further explore integrating additional advanced oxidation processes to address nutrient removal challenges effectively.

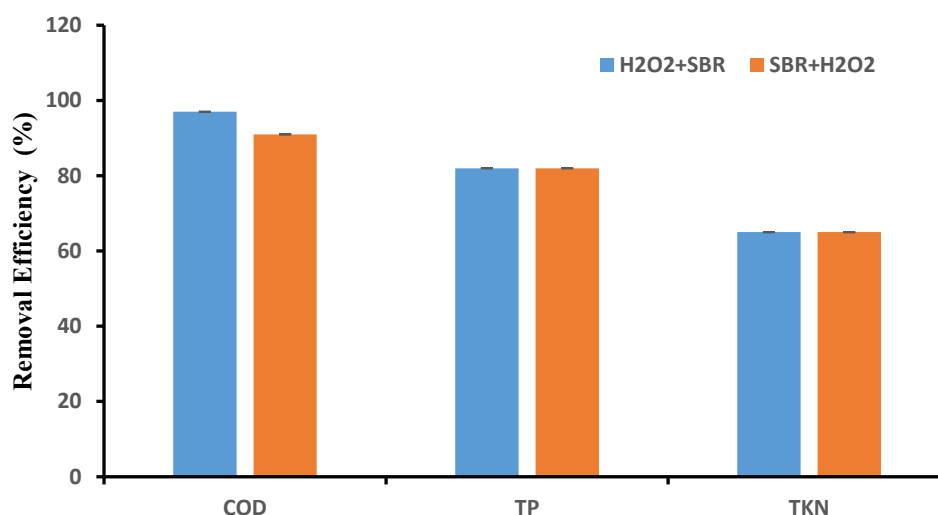


Figure 4- The effect of using chemical oxidation before and after biological treatment

1.9 Study limitations and future perspectives

While the use of formulated synthetic greywater was essential in this study to ensure a highly reproducible influent quality, thereby allowing for the precise, isolated optimization and kinetic evaluation of the integrated SBR and UV/H₂O₂ system, it represents a deliberate simplification of real-world scenarios. In actual domestic environments, greywater exhibits significant qualitative and quantitative diurnal fluctuations, varying organic loads, and a diverse mixture of commercial surfactants and personal care products. Consequently, the generalizability of these bench-scale results to full-scale decentralized applications may be limited. Future research will focus on validating this hybrid configuration using real, fluctuating domestic greywater streams in a continuous pilot-scale operation to assess long-term system resilience.

3. Discussion

1.10 Mechanistic Evaluation of COD Removal Configurations

The sequential integration of biological treatment and advanced oxidation processes (AOPs) demonstrated a significant synergistic effect on organic matter degradation in detergent-rich gray water. However, the positioning of the UV/H₂O₂ stage relative to the SBR played a critical role in determining the overall treatment efficiency. When the UV/H₂O₂ process was employed as a pre-treatment stage (UV/H₂O₂ → SBR), the overall COD removal efficiency reached its maximum at 97%, decreasing the initial COD from 600 mg/L to a final effluent concentration

of 18 mg/L. This superior performance can be attributed to the chemical modification of refractory surfactant molecules and complex organic compounds present in the raw gray water during the photochemical oxidation phase. The hydroxyl radicals ($\bullet\text{OH}$) generated by the UV/H₂O₂ system non-selectively attack large-molecular-weight and recalcitrant contaminants, partially oxidizing them into smaller, oxygenated, and more biodegradable intermediates (such as volatile fatty acids and alcohols). Consequently, this pre-treatment drastically enhances the biodegradability index (BOD₅/COD ratio) of the influx entering the subsequent biological stage. This phenomenon aligns with findings reported by Tuhkanen et al. (1997), who demonstrated that integrating oxidation prior to activated sludge systems effectively breaks down recalcitrant fractions into readily assimilable compounds. The specialized biomass inside the SBR can then easily mineralize these altered fractions, leading to an ultra-low final COD concentration that meets strict discharge standards.

Conversely, the post-treatment configuration (SBR $\rightarrow$ UV/H₂O₂) yielded a lower overall COD removal efficiency of 91% (final effluent of 56 mg/L). In this setup, the SBR initially removed only the easily biodegradable organic matter, leaving behind a highly concentrated fraction of non-biodegradable or refractory COD (170 mg/L) in the SBR effluent due to the poor initial biodegradability of surfactant-laden wastewater (Verma et al., 2021). When this stream entered the subsequent UV/H₂O₂ stage, the chemical oxidation process faced higher kinetic limitations. Because AOPs are highly energy-intensive and chemical consumption depends heavily on the radical-scavenging effects of the background organic and inorganic matrix, treating the residual recalcitrant compounds isolated after biological treatment required longer reaction times or higher oxidant dosages to achieve a comparable effluent quality. This explains why the post-treatment setup could only reduce the COD from 170 mg/L to 56 mg/L, proving less efficient than utilizing chemical oxidation as an initial biodegradability enhancer.

1.11 Nutrient Removal Dynamics (TP and TKN) and Cycling Optimization

Nutrient mitigation showed no variation between the configurations, with both the pre-treatment and post-treatment setups exhibiting identical removal efficiencies of 82.5% for Total Phosphorus (TP) and 65% for Total Kjeldahl Nitrogen (TKN). This identical performance indicates that nutrient removal in the integrated system is predominantly governed by the biological metabolic pathways within the SBR, rather than the chemical oxidation mechanisms of the UV/H₂O₂ process.

The reduction of TKN is primarily driven by biological nitrification (the aerobic conversion of ammonia to nitrate) and subsequent denitrification, alongside standard biomass assimilation for cellular growth. Similarly, TP removal is achieved through the Enhanced Biological Phosphorus Removal (EBPR) metabolic pathway carried out by Phosphorus-Accumulating Organisms (PAOs) during the alternating anaerobic/aerobic cycles in the SBR. Under the initial anaerobic conditions, PAOs hydrolyze their intracellularly stored polyphosphate to generate energy for organic matter uptake, which subsequently releases orthophosphate into the liquid phase. The true elimination of phosphorus from the aqueous matrix takes place during the subsequent aerobic phase, where PAOs exhibit enhanced (luxury) uptake of orthophosphate,

accumulating it as intracellular polyphosphate, which is then definitively removed from the system through biomass growth and subsequent sludge wasting.

The UV/H₂O₂ process, as an advanced oxidation method, is highly efficient at breaking down organic carbon skeletons but lacks the chemical pathway to eliminate absolute gaseous nitrogen or precipitate dissolved phosphorus species from the aqueous phase. While exposure to UV and hydroxyl radicals may alter the speciation of nitrogenous or phosphorus-based compounds—such as converting organic nitrogen to ammonia—the total elemental mass represented by TKN and TP remains conserved until it enters the biological system. This behavior is consistent with the photocatalytic treatment trends of gray water reported by Tsoumachidou et al. (2019), where reductions in major elemental nutrients were strongly dependent on subsequent biological steps. Within the SBR system, the optimal aeration duration was found to be distinct for organic matter and nutrient removal due to the varying metabolic kinetics of the specialized biomass. While a 4-hour aeration period was sufficient for heterotrophic bacteria to fully oxidize and minimize carbonaceous COD and BOD₅ fractions, maximum nutrient mitigation required an extended aeration time of 5 hours. This longer duration is scientifically justified by the slower enzymatic and growth kinetics of autotrophic nitrifying bacteria and PAOs responsible for completing nitrification and luxury orthophosphate uptake, respectively. Consequently, maintaining a 5-hour aeration phase successfully maximizes the concurrent removal of both elemental nutrients and recalcitrant organic matrix from detergent-contaminated gray water.

4. Conclusions

This study investigated the performance optimization of a Sequencing Batch Reactor (SBR) integrated with UV/H₂O₂ chemical oxidation for the treatment of detergent-rich gray water. The experimental results demonstrated that standalone biological treatment via SBR was insufficient for safe environmental discharge, yielding a low effluent BOD₅/COD ratio of 0.25 due to the high toxicity and recalcitrant nature of the detergents. Optimization of the photochemical oxidation process revealed that a hydrogen peroxide dosage of 12 mg/L under an alkaline environment of pH 10 and an irradiation contact time of 3 hours provided the most effective treatment conditions. When integrated sequentially, the pre-treatment configuration (UV/H₂O₂ → SBR) significantly outperformed the post-treatment sequence, boosting the overall COD removal efficiency to 97% with a final effluent of 18 mg/L, compared to a lower efficiency of 91% and a final effluent of 56 mg/L when the operational order was reversed. Conversely, nutrient mitigation was predominantly governed by the biological pathways within the SBR rather than the chemical stage; operating the reactor with a 2-hour anaerobic phase and a 4-to-5-hour aeration phase achieved maximum removal efficiencies of 82.5% for Total Phosphorus (TP) and 65% for Total Kjeldahl Nitrogen (TKN) across both configurations. Ultimately, the sequential UV/H₂O₂ → SBR arrangement is recommended as the highly efficient and optimized configuration for maximizing organic pollutant degradation in gray water streams contaminated with complex detergents.

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