JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(11), 353–369
https://doi.org/10.12911/22998993/231025
ISSN 2299–8993, License CC-BY 4.0

Received: 2026.07.02
Accepted: 2026.09.15
Published: 2026.10.01

Optimizing conventional activated sludge and sequencing batch reactors through chemical analyses in domestic wastewater treatment

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ABSTRACT

This study evaluated the seasonal performance of a conventional activated sludge (CAS), a sequencing batch reactor (SBR), and a combined treatment configuration (S2 + S3) for domestic wastewater treatment using physicochemical analyses. Monthly monitoring was conducted over a 12-month period to determine pH, temperature, dissolved oxygen (DO), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), and turbidity. The influent wastewater showed considerable seasonal variability, with COD ranging from 293 to 1050 mg/L and a mean BOD_5/COD ratio of 0.41, indicating generally good biodegradability. All treatment systems achieved high removal efficiencies for organic pollutants, exceeding 98% for BOD_5, 94% for COD, and 96% for TSS, while complying with the discharge limits of Council Directive 91/271/EEC for these parameters. The SBR system showed lower average effluent concentrations of TN (27.68 mg/L) and TP (0.78 mg/L), corresponding to removal efficiencies of 79.75% and 94.05%, respectively, whereas CAS showed lower nutrient removal performance. The findings demonstrate that all investigated biological systems effectively removed organic pollutants, while SBR showed improved performance for nutrient removal under the investigated operating conditions.

Keywords: sludge tank CAS, SBR, wastewater, optimization.

INTRODUCTION

The wastewater originating from domestic sources is rich in nitrogen and phosphorus compounds, in addition to a variety of suspended and dissolved pollutants. Industrial, medical, and other anthropogenic activities contribute to the more complex mixture of contaminants in wastewater streams, such as pathogenic microorganisms, pharmaceutical residues, hazardous chemicals, biological materials, and environmental toxins. These diverse and potentially harmful components highlight the critical importance of effective wastewater treatment technologies [1]. The growing interest in improving water treatment technologies has led to extensive research on the efficiency of various reactors for treating polluted waters. Their performance factors include treatment time, space requirements, reagent consumption, easy operation, cost, control, and maintenance. One of the most effective approaches to enhance treatment efficiency is the optimization of operational parameters based on chemical pollution analysis. These parameters include chemical oxygen demand (COD), ammonium compounds (AC), phosphorus compounds (PC), dissolved oxygen (DO), suspended solids (SS), etc. Among the most commonly used systems in wastewater treatment is the conventional activated sludge (CAS), which operates through three main stages: preliminary (as part of primary), secondary, and tertiary treatment. In the primary treatment, wastewater initially passes through screens and a grit removal chamber – collectively known as the preliminary treatment before entering a settling tank, where suspended solids are removed. The secondary treatment relies on biological processes, where microorganisms metabolize and decompose organic matter under either aerobic or anaerobic conditions. These biological processes are essential for the removal of organic pollutants. The tertiary stage, applied as a finishing step, focuses on the removal of residual nutrients and pathogens, enhancing the final effluent quality [2-5]. Tertiary treatment is focused on removing non-biodegradable pollutants that are not effectively eliminated by the primary and secondary treatment stages. This tertiary treatment stage often involves methods such as chlorination, ultraviolet (UV) irradiation, membrane filtration, constructed wetlands, microalgae cultivation, ozonation, and other processes aimed at cleaning effluents by ensuring compliance with environmental discharge standards. Each of the methods used in the tertiary treatment has its own advantages and limitations, and their effectiveness largely depends on the characteristics of the wastewater being treated. For instance, the chlorination process is more effective in eliminating bacteria and viruses due to its strong oxidizing properties. However, chlorine can react with organic matter in water by forming harmful substances known as chlorinated by-products (CBPs), such as trihalomethanes and halo acetic acids. These compounds pose significant risks to both the environment and human health [6]. Unlike CAS, the sequencing batch reactor (SBR) operates in a time-sequenced manner through distinct phases, including filling, reaction, settling, sludge withdrawal, and effluent discharge. Each phase is carried out in the same tank but at different times, allowing for flexible operation and efficient wastewater treatment [7]. The chemical and biological processes occurring in SBR are largely similar to those in conventional systems, with key differences such as the elimination of the return sludge phase, shorter processing times, and the absence of a need for a secondary sedimentation basin. In addition, the SBR system offers several advantages, including energy optimization through controlled microbial and metabolic activity, reduced spatial requirements, efficient removal of nitrogen and phosphorus compounds, as well as the ability to suppress the growth of filamentous sludge-bulking microorganisms. These benefits make the SBR a highly effective and flexible alternative for wastewater treatment [8–12]. In general, both reactors have demonstrated high efficiency in treating domestic and industrial wastewater. However, optimizing operational parameters, such as temperature, and the effectiveness range for the removal of COD, ammonia, phosphorus, and other contaminants, is crucial for maximizing performance. Studies indicated that the efficiency of nitrogen compound removal can increase significantly, from 68.5% to 87.5%, when the operating temperature is elevated from 25 °C to 35 °C [13–15]. In addition, other studies have evaluated the impact of temperature on sludge flocculation and settling capacity. These studies revealed a significant deterioration in the sludge settling performance at elevated temperatures. Specifically, increasing the temperature from 15 °C to 35 °C was found to cause a substantial rise in suspended solids concentration, from 40 to 130 mL/g, indicating reduced sludge compactness and stability [16–18]. In general, there cannot be a clear dividing line between SBR and CAS in terms of overall treatment effectiveness, although each reactor possesses specific advantages depending on the application. Their performance and suitability largely depend on the composition and pollutant load of the wastewater. For instance, urban wastewater typically contains high concentrations of nitrogen, phosphorus, and carbon compounds, primarily from organic matter, for which both reactors have demonstrated good treatment efficiency. The biological processes developed within SBR enable the realization of the three main stages of wastewater treatment, including the physical separation of the liquid phase from the solid phase without the need for separate sedimentation units. This technological approach eliminates the need for the use of recycling pumps, as the sedimentation and separation processes occur within the same reactor, making the system more compact and efficient. Nitrification can only begin when the residence time of the solids in the system (known as sludge age) is sufficient to allow the growth and development of nitrifying microorganisms [19, 20]. This process is also dependent on the temperature of the wastewater, which should be above 12–15 °C to ensure optimal biological activity. The system is designed to allow partial nitrification and denitrification, as long as favorable thermal conditions exist and there is no presence of inhibitors or toxic substances that could hinder microbial activity. However, both the CAS and SBR systems present distinct sets of advantages as well as disadvantages in their operational performance and applications (Table 1). While CAS systems are known for their simplicity, reliability, and effectiveness in treating large volumes of municipal wastewater, they often require substantial space, generate significant sludge, and may reduce efficiency when dealing with fluctuating influent loads. On the other hand, SBR systems offer greater operational flexibility, improved control over treatment cycles, and enhanced nutrient removal, making them suitable for smaller facilities. However, when treating more complex effluents, such as those originating from hospitals or various industrial sectors, system modifications are required for achieving optimal performance. Observations of the impact of wastewater treatment in small communities have raised interest in studying the optimization of reactor parameters through physicochemical analyses. As a developing country, the Republic of Kosovo has an urgent need for broader implementation of wastewater treatment technologies. Although wastewater treatment plants (WWTPs) are operational in major urban centers, expanding such infrastructure to smaller settlements remains essential for ensuring environmental and public health protection. This study was conducted at the KFOR Base, located in the village of Maxhunaj, an area characterized by a limited number of residents and wastewater loads, primarily originating from human activity. The analysis focused on wastewater samples taken at multiple points: at the inflow of both the SBR and CAS treatment plants, after the treatment process, at the outflow, and within the disinfection tank. The measured parameters from both reactors were compared to assess and draw conclusions about their respective efficiencies in treating wastewater. The aim of this study was to evaluate which reactor performed more effectively under identical conditions and to identify the strengths and weaknesses of each system throughout the treatment process. The findings of this study provided valuable insights into the potential for optimizing reactor operations and wastewater treatment practices in accordance with relevant wastewater directives.

MATERIALS AND METHODS

Description of the wastewater treatment plants

The study was conducted at two small-scale wastewater treatment plants located at the KFOR military base in the village of Maxhunaj, Vushtrria Municipality, Kosovo (42°47’02.4”N, 21°01’52.5”E). The investigated biological treatment systems consisted of a CAS process and an SBR Reactor. The CAS system was designed to treat the wastewater generated by approximately 1,000 population equivalents (PE), whereas the SBR system had a design capacity of approximately 500 PE (Table 2). Both treatment systems received the same municipal wastewater generated within the KFOR military base. Prior to biological treatment, the influent passed through preliminary screening using a coarse screen (5-mm openings) to remove large suspended solids. The screened wastewater was subsequently collected in an equalization chamber, where it was homogenized before being equally distributed to the CAS and SBR systems (Figure 1). This configuration ensured comparable influent characteristics for evaluating the treatment performance of the two biological processes under identical operating conditions. The wastewater collection network consists of approximately 5 km of plastic pipelines with diameters ranging from 32 to 200 mm. An emergency overflow was incorporated into the collection chamber to accommodate hydraulic loads exceeding the treatment capacity of the biological reactors. The activated sludge used in both treatment systems originated from the wastewater treatment facilities operating within the KFOR military base in Maxhunaj. The monitoring program was conducted over a one-year period, from September 2023 to August 2024, allowing the assessment of seasonal variations in treatment performance. Wastewater samples were collected from four sampling points: (S1) the influent wastewater before biological treatment, (S2) the effluent of the CAS system, (S3) the effluent of SBR, and (S4) the final mixed effluent obtained after combining the treated wastewater from both systems. The combined sample (S4), referred to throughout this study as the combined system (S2+S3), represents the overall treatment performance achieved through the simultaneous operation of the CAS and SBR systems.

Four to five wastewater samples were collected monthly from each sampling point throughout the one-year monitoring period. For each monitored parameter, the analytical results were averaged to obtain a single representative monthly value, thereby minimizing the influence of short-term fluctuations in wastewater characteristics and ensuring that the dataset reflected

Table 1. Advantages and disadvantages of conventional activated sludge and sequencing batch reactor

Activated sludge tank reactor		Sequencing batch reactor tank	
Advantages	Disadvantages	Advantages	Disadvantages
Low-cost installation	Poor performance due to changes in the composition of wastewater	Small space and low energy consumption.	Requires automatic control of time cycles – requires PLC system and accurate sensors
Small land area	Relatively high operating cost	Produced fast and easily assembled	Interruptions in the cycle can affect the final water quality
High performance in wastewater quality	Sensitive to certain types of industrial waste	Easily operated, practically no problems	Many mechanical components in operation – increased need for maintenance
Effective in removing organic compounds (BOD, COD)	High sludge production requires increased treatment and management	Does not require a separate tank for settling	Not always suitable for large industrial flows
Easy adaptation to advanced processes such as nitrification and denitrification.	Requires constant monitoring of parameters such as dissolved oxygen	Suitable for operating conditions can be connected with PLC	Foam formation and heavy odors in cases of inefficient management of the aerobic phase

Table 2. Design characteristics of conventional activated sludge (CAS) and sequencing batch reactor (SBR) systems for small municipal wastewater treatment plants

Parameter	Unit	Design criterion	500 PE	1000 PE	Reference / Basis
Population equivalent (PE)	PE	-	500	1000	EN 12255
Average daily wastewater flow (Qavg)	m³/day	150 L/PE·day	75	150	Design assumption
Specific BOD_5 load	g BOD_5/PE·day	60	30 kg/day	60 kg/day	EN 12255
Specific COD load	g COD/PE·day	120	60 kg/day	120 kg/day	EN 12255
Specific TSS load	g TSS/PE·day	70	35 kg/day	70 kg/day	EN 12255
Organic loading rate (CAS)	kg BOD_5/m³·day	0.40–0.60	–	–	Design guidelines
Organic loading rate (SBR)	kg BOD_5/m³·day	0.30–0.50	–	–	Design guidelines
Hydraulic retention time (CAS)	h	6–8	–	–	Typical design practice
Hydraulic retention time (SBR)	h	8–12	–	–	Typical design practice
Biological reactor volume (CAS)	m³	BOD_5/OLR	50–75	100–150	Calculated
Biological reactor volume (SBR)	m³	BOD_5/OLR	60–100	120–200	Calculated

Note: PE – population equivalent; Qavg – average daily flow rate; BOD_5 – five-day biochemical oxygen demand; COD – chemical oxygen demand; TSS – total suspended solids; OLR – organic loading rate; HRT – hydraulic retention time; CAS – conventional activated sludge; SBR – sequencing batch reactor. The calculations are based on a specific organic load of 60 g BOD_5/PE·day and an average domestic wastewater generation of 150 L/PE·day, in accordance with EN 12255 and commonly adopted wastewater treatment design practices. The reactor volumes were estimated using typical design ranges of the organic loading rate (OLR) for small municipal wastewater treatment plants

the overall operational performance of the treatment systems. The average OLR applied to the CAS system ranged from 0.3 to 0.8 kg BOD_5 m³/day, whereas the SBR system operated at an average OLR ranging from 0.3 to 0.5 kg BOD_5 m³/day. Wastewater temperature was monitored continuously throughout the study period, and the recorded values are presented in Table 4. To ensure a representative evaluation of treatment performance, all analytical data were subjected to statistical analysis using Jamovi software (version 2.3. 37). Descriptive statistical parameters were calculated for all monitored variables, and comparative statistical analyses were performed to evaluate the differences in pollutant removal efficiencies among the CAS, SBR, and hybrid treatment systems. The statistical analysis was used to provide an objective assessment of the observed variations and to support comparisons between the investigated treatment configurations.

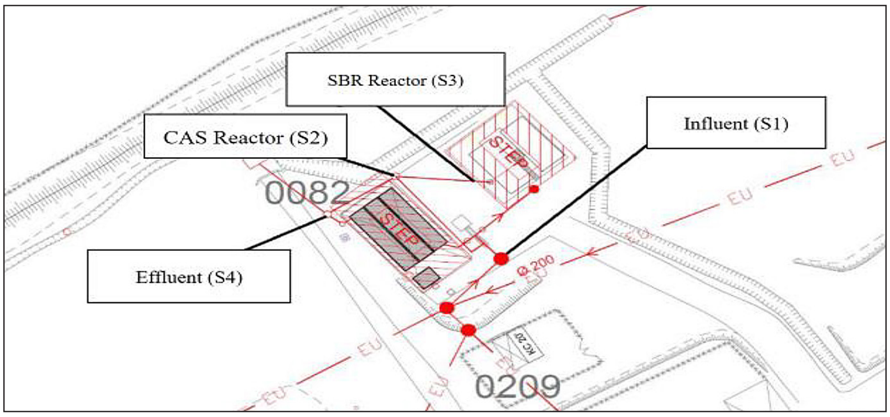

Figure 1. Schematic representation of sampling sites

Conventional activated sludge reactor

The CAS reactor consisted of two interconnected biological treatment units, each designed to treat the wastewater generated by approximately 500 population equivalents (PE), providing a total treatment capacity of 1.000 PE (Figure 2). The modular configuration allows flexible operation while maintaining stable treatment performance under varying hydraulic loads. The treatment process comprised preliminary, primary, secondary, and tertiary treatment stages. Following preliminary screening and flow equalization, wastewater entered the biological aeration tanks, where activated sludge was maintained under aerobic conditions. Continuous aeration and mixing promoted the biodegradation of organic matter and the biological transformation of nitrogen compounds. The mixed liquor subsequently flowed to the secondary clarifier, where biomass settled by gravity. A portion of the settled sludge was recirculated to the aeration tank as RAS to maintain the microbial population, while excess sludge was periodically removed from the system. During the monitoring period, the CAS reactor operated at an average OLR ranging from 0.3 to 0.8 kg BOD_5 m^3/day (Table 3). Wastewater temperature was continuously monitored throughout the study, as temperature is an important operational parameter influencing biological treatment processes. The recorded values are presented in Table 4. During the winter period, when wastewater temperatures decreased below 15 °C, commercially available microbial products (Novozymes Toler-X 5100 and Novozymes BioRemove 5825) were applied as part of the routine operational management of the treatment plant, following the manufacturer's recommendations. Their application was intended to support the biological treatment process under low-temperature conditions. The performance of these products was not evaluated separately in this study and therefore was not considered as an experimental factor in the comparative assessment of the AS and SBR treatment systems.

Sequencing batch reactors

The SBR system used in this study was designed to treat wastewater generated by approximately 500 population equivalents (PE) (Figure 3). In contrast to the continuous-flow activated sludge (AS) system, all biological treatment processes in the SBR were performed sequentially within a single reactor. The treatment cycle consisted of five operational phases: filling, aeration (reaction), settling, decanting, and idle/refilling. During the aeration phase, oxygen was supplied to maintain aerobic conditions for the biodegradation of organic matter and the biological oxidation of nitrogen compounds. After aeration, mixing was stopped to allow biomass to settle by gravity. The clarified supernatant was then discharged through a decanting system, while the settled sludge remained in the reactor to serve as the active biomass for the subsequent treatment cycle. This operational configuration eliminated the need for a separate secondary clarifier and return activated sludge pumping. During the monitoring period, the SBR system operated at an average organic loading rate (OLR) ranging from 0.3 to 0.5 kg BOD_5 m^3/day (Table 3). Wastewater temperature was continuously monitored throughout the study (Table 4), as it represents an important operational parameter influencing biological treatment processes. The SBR and CAS systems were operated under the same influent wastewater conditions throughout the one-year monitoring period to enable a direct comparison

Figure 2. Conventional activated sludge tank reactor

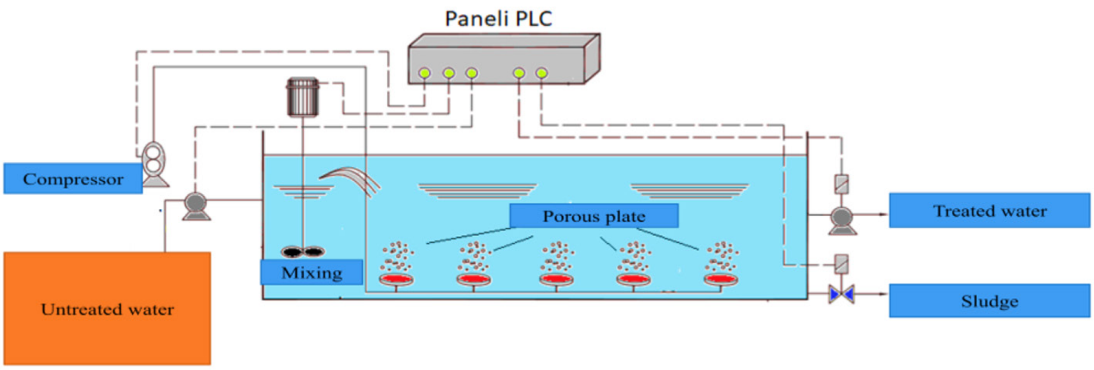

Figure 3. Schematic representation of the sequencing batch reactor tank

of their treatment performance. The hybrid system (S4) represents the combined treated effluent obtained after mixing the final effluents from the SBR and AS treatment systems and was evaluated as an integrated treatment configuration.

Sample collection methodology

Wastewater samples were collected from four designated sampling points within the treatment system (Figure 4): (S1) influent wastewater before biological treatment, (S2) the effluent of the CAS system, (S3) the effluent of SBR, and (S4) the final mixed effluent obtained after combining the treated effluents from both systems (S2+S3). The monitoring program was carried out over a one-year period, from September 2023 to August 2024. Four to five samples were collected monthly from each sampling point, resulting in a representative dataset covering seasonal variations in wastewater characteristics and treatment performance. To minimize the influence of short-term fluctuations, the analytical results obtained during each month were averaged and reported as a single representative monthly value for each monitored parameter. The samples were collected at weekly intervals, transported to the laboratory under refrigerated conditions, and analyzed on the day of collection.

Separate polyethylene and glass containers were used for physicochemical analyses, whereas microbiological samples were collected in sterile, hermetically sealed containers following standard sampling procedures. All sampling, preservation, and analytical procedures were performed according to Standard Methods for the Examination of Water and Wastewater and the corresponding HACH analytical protocols [21–24]. The monitored physicochemical parameters included: temperature, pH, DO, BOD_5, COD, TSS, TN, TP, and free chlorine. Temperature, pH, DO, and free chlorine were measured in situ using a HACH HQ40D multiparameter instrument. COD, TN, and TP were determined spectrophotometrically using HACH DR3900/DR3800 instruments and the corresponding HACH reagent kits, while TSS was determined gravimetrically by vacuum filtration. BOD_5 was determined using the standard five-day dilution method. Microbiological quality was assessed in the final treated effluent after

Figure 4. Wastewater collection and distribution room in wastewater treatment plants

Table 3. Operating conditions of CAS and SBR reactors

Operating conditions of CAS and SBR reactors			
CAS parameter	Value	SBR parameter	Value
Population equivalent (PE)	1000 PE	Population equivalent (PE)	500 PE
Average influent flow rate	150 m³/day (6.25 m³/h)	Average influent flow rate	75 m³/day (3.125 m³/h)
Total plug flow aeration tank reactor volume	60 m³	Number of SBR tanks	2
Hydraulic retention time (HRT) of aeration tank	7.68 hr	Total SBR tank volume	50 m³
Return sludge flow rate	37.5 m³/day	SBR tank volume	25 m³
Return sludge ratio	25%	SBR tank depth	5.0 m
Waste sludge flow rate	3.0 m³/day	Area of SBR tank	5.0 m²
Mixed liquor suspended solids (MLSS)	2910 mg/L	Total cycle time	360 min (4 cycles/d)
Solid retention time (SRT)	6.24 m³/day	Total fill time	90 min (45 min mixed fill + 45 min aerated fill)
Circular settling tank area	10 m²	Aeration time	135 min
Settling tank depth	4.0 m	Settling time	55 min
Settling tank volume	40 m³	Decant time	60 min
Overflow rate (OFR) of settling tank	18.75 m³/m²/day	Waste sludge time	20 min
Hydraulic retention time (HRT) of settling tank	6.4 hr	Influent wastewater volume	18.75 m³/cycle
Total plant reactor + settling volume	100 m³	Decant flow rate	18.0 m³/cycle
		Waste sludge flow rate	0.75 m³/cycle
		Volumetric exchange ratio of SBR (VER)	37.50%

the disinfection stage by determining fecal coliforms using the IDEXX Colilert-18 Most Probable Number (MPN) method [25]. Water samples were incubated for 18 h at 45.5 °C and analyzed using the IDEXX Quanti-Tray Sealer PLUS system according to the manufacturer's protocol. Descriptive statistics were used to summarize the main characteristics and variability of the monitored parameters. Additional statistical analyses, including correlation analysis, regression analysis, and PCA, were applied to evaluate relationships among variables and differences in treatment performance between the CAS, SBR, and combined (S4) systems.

STATISTICAL ANALYSIS

Statistical analysis was performed using Jamovi statistical software (Version 2.7.37). Descriptive statistics were calculated for all monitored wastewater quality parameters, including mean values, standard deviation, median, minimum, and maximum values, in order to characterize the variability of the dataset and the treatment performance of the investigated systems. The removal efficiency (%) of each pollutant parameter was calculated for CAS, SBR, and combined (S4) treatment configurations. The statistical significance of differences among the investigated treatment systems was evaluated using appropriate comparative tests according to data distribution. Correlation analysis was performed to evaluate relationships between operational parameters (e.g., temperature, dissolved oxygen, and organic loading rate) and wastewater quality indicators (BOD_5, COD, TN, TP, and TSS). Linear regression analysis was applied to investigate the influence of selected operational variables on pollutant removal efficiency. The combination of descriptive, inferential, and multivariate statistical analyses was used to provide a comprehensive evaluation of treatment performance and to support the interpretation of observed differences between the investigated configurations.

RESULTS AND DISCUSSION

The influent wastewater characteristics showed noticeable seasonal variability during the monitoring period, reflecting the influence of temperature fluctuations and variations in organic loading conditions. The influent pH remained relatively stable throughout the study period, ranging from 8.15 to 8.80, with an average value of 8.53 ± 0.25, indicating slightly alkaline wastewater conditions. Such stability suggests that pH was not a limiting factor for biological treatment processes, since the observed values remained within the acceptable range for activated sludge microorganisms [26, 27]. The wastewater temperature varied considerably, from 8.15 °C in February to 27.8 °C in August, with an average value of 16.43 ± 6.23 °C. This seasonal variation is relevant for biological wastewater treatment because microbial growth and substrate utilization rates are strongly temperature dependent. Lower temperatures during winter months may reduce biological activity, whereas higher temperatures during summer generally enhance biodegradation kinetics. Similar temperature-dependent behavior has been reported for biological wastewater treatment systems, where reduced microbial activity at low temperatures may affect organic matter removal efficiency [28, 29]. The influent organic load showed substantial seasonal fluctuations. COD concentrations varied between 293 and 1050 mg/L, with an average value of 682.75 ± 210.11 mg/L, while BOD_5 ranged from 180 to 420 mg/L (270.67 ± 83.65 mg/L). The highest organic concentrations were observed during the summer

Table 4. Seasonal variation and statistical analysis of physicochemical parameters and biodegradability index of wastewater influent (S1) during the monitoring period

Month	pH (-)	Temperature (°C)	DO (mg/L)	COD (mg/L)	BOD_5 (mg/L)	TSS (mg/L)	BOD_5/COD
September	8.60	22.5	2.20	588	220	354	0.37
October	8.45	19.6	2.15	720	380	330	0.53
November	8.54	17.5	3.20	590	390	310	0.66
December	8.70	12.2	3.40	582	240	290	0.41
January	8.22	10.5	4.15	480	190	250	0.40
February	8.18	8.15	4.20	293	180	240	0.61
March	8.15	9.10	5.10	650	185	330	0.28
April	8.65	11.5	5.10	720	193	285	0.27
May	8.21	15.2	3.50	690	250	345	0.36
June	8.69	18.5	2.10	870	265	315	0.30
July	8.75	24.6	1.90	950	345	295	0.36
August	8.80	27.8	1.03	1050	420	290	0.40
Minimum	8.15	8.15	1.03	293	180	240	0.27
Maximum	8.80	27.8	5.10	1050	420	354	0.66
Average (Mean)	8.53	16.43	3.18	682.75	270.67	302.83	0.41
Standard deviation (SD)	0.25	6.23	1.35	210.11	83.65	37.05	0.13

Note: The BOD_5/COD ratio was calculated as an indicator of wastewater biodegradability. Values above 0.4 generally indicate good biodegradability and suitability for biological treatment processes, while lower values may indicate the presence of slowly biodegradable or non-biodegradable organic compounds. Statistical parameters were calculated from 12 monthly measurements.

period (July–August), indicating increased organic loading entering the treatment systems. The biodegradability index (BOD_5/COD) ranged from 0.27 to 0.66, with an average value of 0.41 ± 0.13 (Table 4). According to commonly reported criteria, the BOD_5/COD ratios above approximately 0.4 indicate good biodegradability of wastewater, whereas lower values suggest a higher fraction of slowly biodegradable or non-biodegradable organic compounds [30]. Therefore, although the influent wastewater was generally suitable for biological treatment, the lower ratios observed during March–April and June indicate periods with reduced biodegradability. The influent TSS concentration showed moderate seasonal variation, ranging from 240 to 354 mg/L, with an average value of 302.83 ± 37.05 mg/L. Compared with COD and BOD_5, the relatively lower variability of suspended solids indicates a more stable particulate load entering the biological systems.

The Pearson correlation matrix revealed the relationships among the main physicochemical parameters of wastewater. COD and BOD_5 showed a strong positive correlation, indicating their common association with organic pollution load. Temperature showed a negative relationship with dissolved oxygen, reflecting the reduced oxygen solubility at higher temperatures. These correlations highlight the influence of seasonal variations on wastewater characteristics (Figure 5). The CAS reactor demonstrated stable physicochemical performance during the monitoring period. The effluent pH remained close to neutrality, varying between 6.90 and 7.54 (average 7.29 ± 0.22), confirming the buffering capacity of the biological process and the absence of significant acidification or alkalization effects. The dissolved oxygen concentration remained within an aerobic range, with values between 2.50 and 5.30 mg/L (average 4.37 ± 0.91 mg/L). These values indicate adequate aeration conditions for heterotrophic oxidation of organic matter. However, a gradual reduction of DO was observed during the warmer summer months, particularly in August, which may be related to increased oxygen consumption caused by higher organic loading and reduced oxygen solubility at elevated temperatures. The CAS system achieved efficient organic matter removal, reducing COD concentrations from an influent average of 682.75 mg/L to an effluent average of 31.20 ± 5.30 mg/L. This corresponds to an average COD removal efficiency of approximately 95.4%. Similarly, BOD_5 concentrations were reduced to 3.07 ± 0.54 mg/L, representing an average removal efficiency above 98%. These results indicate effective biodegradation of readily biodegradable organic compounds. Seasonal variations in CAS performance were mainly observed for COD removal during the periods of increased influent loading. The highest effluent COD concentration (41.84 mg/L) occurred in June, coinciding with elevated influent COD levels and higher temperatures (Table 5). This suggests that increased organic loading may

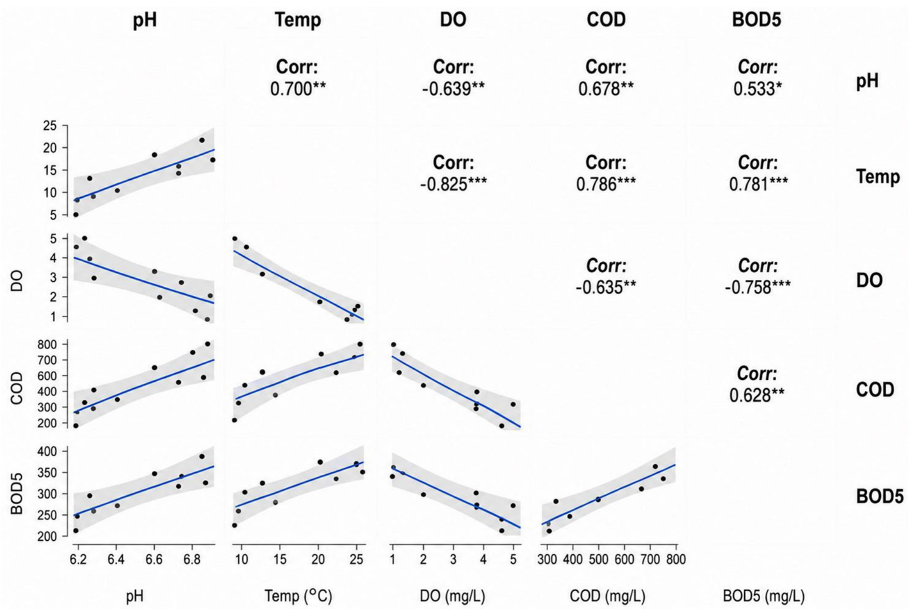

Figure 5. Pearson correlation matrix plots between physicochemical parameters of domestic wastewater. Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

influence the treatment capacity of the system, although the process maintained relatively stable performance [31]. The TSS concentration in the CAS effluent ranged from 3.27 to 13.68 mg/L, with an average value of 8.09 ± 2.99 mg/L. The higher variability compared with COD and BOD_5 indicates that solids separation processes may represent a more sensitive operational parameter than biological oxidation alone.

The SBR system also maintained stable treatment conditions, with effluent pH values ranging from 7.10 to 7.90 (average 7.51 ± 0.28). The slightly higher average pH compared with CAS may be associated with the intermittent operational mode of SBR, where alternating aerobic and settling phases can influence biochemical reactions [32]. The average DO concentration in the SBR effluent was 3.85 ± 0.88 mg/L, with values between 2.40 and 5.10 mg/L. The observed seasonal decrease in DO during summer months corresponds with increased influent organic loading and higher microbial oxygen demand. The COD concentrations in the SBR effluent varied between 25.12 and 46.14 mg/L, with an average value of 34.47 ± 7.77 mg/L (Table 6). Although SBR achieved high organic removal efficiency (approximately 95%), the variability was slightly higher than that observed in CAS. The highest COD values occurred during May–August, corresponding to the period with maximum influent COD concentrations. This indicates that SBR performance was influenced by seasonal loading variations. BOD_5 removal remained consistently high, with effluent concentrations ranging from 2.04 to 3.99 mg/L (average 3.11 ± 0.74 mg/L). The similarity between CAS and SBR results indicates that both systems (S4) provided effective removal of biodegradable organic matter. However, higher TSS concentrations were observed in the SBR effluent compared with CAS, reaching a maximum of 18.75 mg/L and an average value of 10.32 ± 5.64 mg/L. The greater variability may be related to the cyclic operation of SBR and sensitivity of biomass settling characteristics to operational conditions.

The combined system showed intermediate behavior between CAS and SBR for most evaluated parameters. The effluent pH remained stable (7.05–7.67), with an average value of 7.39 ± 0.22, indicating suitable biological conditions throughout operation. The average COD concentration in the combined system effluent was 32.01 ± 5.95 mg/L, corresponding to approximately 95.3% removal efficiency. The observed COD values were comparable with those obtained from individual CAS and SBR reactors, suggesting that the combined configuration maintained effective organic matter degradation. The BOD_5 concentration remained low, ranging from 2.10 to 3.89 mg/L (average 3.06 ± 0.61 mg/L). The similarity between the combined system and individual

Table 5. Seasonal variation of physicochemical characteristics and statistical summary of the treated effluent from the conventional activated sludge reactor (S2) during the monitoring period

Month	pH (-)	Temperature (°C)	DO (mg/L)	COD (mg/L)	BOD_5 (mg/L)	TSS (mg/L)
September	7.20	21.40	5.25	34.32	2.15	3.62
October	6.90	14.68	4.49	28.85	2.39	3.27
November	7.20	12.47	3.50	25.05	2.55	8.22
December	7.54	10.59	4.45	28.96	2.89	7.27
January	7.04	8.81	5.20	31.52	2.69	7.75
February	7.25	11.16	4.90	23.13	3.28	6.93
March	7.40	10.26	5.30	29.78	3.31	12.77
April	7.08	11.70	5.25	26.46	3.27	6.77
May	7.53	18.45	4.50	32.37	3.79	13.68
June	7.47	20.98	3.90	41.84	3.99	8.11
July	7.50	24.60	3.20	34.16	3.20	8.50
August	7.38	26.95	2.50	37.90	3.30	9.20
Minimum	6.90	8.81	2.50	23.13	2.15	3.27
Maximum	7.54	26.95	5.30	41.84	3.99	13.68
Average (Mean)	7.29	16.00	4.37	31.20	3.07	8.09
Standard deviation (SD)	0.22	6.08	0.91	5.30	0.54	2.99

Table 6. Seasonal variation of physicochemical characteristics and statistical summary of the treated effluent from the SBR (S3) during the monitoring period

Month	pH (-)	Temperature (°C)	DO (mg/L)	COD (mg/L)	BOD_5 (mg/L)	TSS (mg/L)
September	7.15	22.50	3.37	28.26	2.10	2.37
October	7.20	15.80	3.46	26.21	2.04	3.44
November	7.10	14.20	3.40	36.02	2.21	4.87
December	7.80	12.00	4.45	34.51	3.66	4.30
January	7.15	10.00	4.60	25.12	2.65	6.18
February	7.80	12.20	4.50	28.25	3.75	12.31
March	7.90	12.50	5.10	28.71	3.86	15.72
April	7.50	13.20	4.90	29.71	3.39	10.27
May	7.60	20.20	4.10	40.73	3.99	18.75
June	7.85	23.50	3.40	44.72	3.61	16.94
July	7.45	25.40	2.50	46.14	3.08	14.20
August	7.60	27.50	2.40	45.20	3.00	14.50
Minimum	7.10	10.00	2.40	25.12	2.04	2.37
Maximum	7.90	27.50	5.10	46.14	3.99	18.75
Average (Mean)	7.51	17.42	3.85	34.47	3.11	10.32
Standard deviation (SD)	0.28	5.92	0.88	7.77	0.74	5.64

biological processes indicates that the additional operational configuration did not produce a substantial improvement in biodegradable organic matter removal. The TSS concentration averaged 9.59 ± 4.36 mg/L, lower than SBR but slightly higher than CAS (Table 7). This suggests that the combined system may provide improved solids control compared with SBR alone; however, the observed differences should be interpreted cautiously without statistical confirmation.

The seasonal variation of total nitrogen (TN), total phosphorus (TP), and turbidity (Tur) parameters in the effluents of the CAS and SBR systems is presented in Table 8. The results indicate differences in the removal behavior of both treatment configurations, particularly for nutrient-related parameters, while both systems maintained relatively stable effluent quality throughout the monitoring period. The TN concentration in the CAS effluent ranged from 30.85 to 49.80 mg/L, with an average value of 40.53 ± 6.88 mg/L. The highest TN concentration was observed in November (49.80 mg/L), followed by June (48.50 mg/L), whereas the lowest value occurred in January (30.85 mg/L). The relatively high average TN concentration and seasonal variability (SD = 6.88 mg/L) suggest that nitrogen removal in the CAS system was influenced by operational conditions and seasonal changes. The increased TN concentrations during the autumn and summer months may be associated with higher nitrogen loading and variations in microbial activity under changing temperature conditions.

In comparison, the SBR system showed consistently lower TN concentrations, ranging from 18.65 to 39.26 mg/L, with an average value of 27.68 ± 6.74 mg/L. The lowest TN concentration was recorded in February (18.65 mg/L), while the highest was observed in June (39.26 mg/L). The lower mean TN concentration in SBR than in CAS indicates higher observed nitrogen removal performance under the investigated operating conditions. This behavior may be related to the intermittent operation of SBR, which provides alternating aerobic and anoxic conditions that can favor nitrification and denitrification processes. However, further evaluation using nitrogen loading rates and statistical significance testing would be required to confirm the magnitude of this difference.

A more pronounced difference between the two systems was observed for TP. The CAS effluent showed TP concentrations between 3.62 and 8.56 mg/L, with an average value of 5.60 ± 1.64 mg/L. The relatively high TP variability indicates that phosphorus removal in the CAS system was limited and sensitive to operational conditions [33, 34]. The SBR system demonstrated substantially lower TP concentrations, ranging from 0.48 to 1.27 mg/L, with an average value of 0.78 ± 0.24 mg/L. Compared with CAS, the lower mean TP

Table 7. Seasonal variation of physicochemical characteristics and statistical summary of the treated effluent from the combined system (S4) during the monitoring period

Month	pH (-)	Temperature (°C)	DO (mg/L)	COD (mg/L)	BOD_5 (mg/L)	TSS (mg/L)
September	7.15	22.50	4.31	31.45	2.10	2.98
October	7.05	16.00	3.97	27.53	2.21	3.55
November	7.15	14.00	3.45	30.53	2.38	6.54
December	7.67	11.50	4.50	31.73	3.27	5.78
January	7.09	11.00	4.90	28.32	2.60	6.96
February	7.50	12.00	4.70	25.69	3.51	9.62
March	7.65	13.50	5.20	29.24	3.33	14.24
April	7.29	13.50	5.07	28.08	3.39	8.52
May	7.55	20.50	4.30	36.55	3.89	16.21
June	7.60	22.10	3.65	43.28	3.80	12.52
July	7.50	24.80	2.85	40.15	3.14	11.30
August	7.50	26.90	2.45	41.55	3.15	11.85
Minimum	7.05	11.00	2.45	25.69	2.10	2.98
Maximum	7.67	26.90	5.20	43.28	3.89	16.21
Average (Mean)	7.39	17.19	4.11	32.01	3.06	9.59
Standard deviation (SD)	0.22	5.69	0.91	5.95	0.61	4.36

concentration and reduced variability (lower SD) indicate more consistent phosphorus removal in the SBR configuration. This difference may be attributed to the cyclic operation of SBR, where alternating reaction phases can enhance biological phosphorus transformation mechanisms [35, 36]. Turbidity values also showed differences between the two treatment systems. In the CAS effluent, turbidity ranged from 1.59 to 10.20 NTU, with an average value of 5.35 ± 2.74 NTU. The relatively high standard deviation indicates greater variability in suspended particulate removal during the monitoring period, which may reflect fluctuations in the sludge settling characteristics.

The SBR effluent presented turbidity values between 2.59 and 6.80 NTU, with an average of 4.13 ± 1.42 NTU. Although the minimum turbidity value in CAS was lower than in SBR, the SBR system showed lower average turbidity and reduced variability. This suggests a more stable effluent quality regarding particulate matter removal during the investigated period. The lower variability may be associated with the settling phase incorporated into SBR operation, which promotes improved solid–liquid separation.

Table 9 compares the average effluent quality obtained from the CAS, SBR, and the combined system (S4) with the discharge requirements established by Directive 91/271/EEC. All three treatment configurations achieved excellent removal of biodegradable organic matter, with concentrations of 3.07, 3.11, and 3.06 mg/L, respectively, which were substantially below the regulatory limit of 25 mg/L. Similarly, the average COD concentrations (31.2–34.5 mg/L) and TSS concentrations (8.09–10.32 mg/L) remained well below the Directive limits of 125 mg/L and 35 mg/L, respectively, demonstrating effective removal of organic matter and suspended solids.

In contrast, nutrient removal was less effective. The average of TN concentrations ranged from 27.68 to 40.53 mg/L, exceeding the Directive limit of 10–15 mg/L in all treatment configurations. Although the SBR system showed the lowest average TN concentration (27.68 mg/L), none of the evaluated systems achieved the required discharge standard. This limited nitrogen removal may be related to insufficient nitrification/denitrification conditions, inadequate hydraulic or solids retention time, limited availability of readily biodegradable carbon during denitrification, or operational conditions that were primarily optimized for carbon removal rather than biological nitrogen removal [37–38]. In addition, seasonal temperature fluctuations may have affected nitrifying bacterial activity, particularly during colder periods, contributing to lower nitrogen removal efficiency. A similar trend was observed for TP. The SBR system achieved an average concentration of 0.78 mg/L, complying with the Directive limit of 1–2 mg/L, whereas

Table 8. Seasonal variation of total nitrogen (TN), total phosphorus (TP) and turbidity (Tur) parameters in the CAS and SBR effluents during the monitoring period

Month	CAS			SBR		
	TN (mg/L)	TP (mg/L)	Tur (NTU)	TN (mg/L)	TP (mg/L)	Tur (NTU)
September	32.90	8.25	1.59	30.70	1.27	3.25
October	34.50	7.25	2.10	26.35	1.00	2.59
November	49.80	8.56	4.60	27.03	0.59	3.58
December	43.80	6.20	4.80	32.27	0.65	2.61
January	30.85	4.45	3.50	19.90	0.55	4.19
February	35.55	4.31	4.30	18.65	0.61	4.25
March	31.90	5.28	7.20	19.58	0.71	6.50
April	39.50	4.53	3.90	21.12	0.48	3.16
May	41.00	5.03	10.20	29.80	0.72	6.80
June	48.50	5.41	8.40	39.26	0.77	3.70
July	43.90	3.62	7.20	31.84	1.04	4.53
August	44.20	4.25	6.50	35.61	0.98	4.40
Minimum	30.85	3.62	1.59	18.65	0.48	2.59
Maximum	49.80	8.56	10.20	39.26	1.27	6.80
Average (Mean)	40.53	5.60	5.35	27.68	0.78	4.13
Standard Deviation (SD)	6.88	1.64	2.74	6.74	0.24	1.42

the CAS (5.60 mg/L) and combined system (3.19 mg/L) exceeded the recommended values. The improved phosphorus removal observed in SBR may be associated with the cyclic operation of the reactor, which provides alternating anaerobic and aerobic conditions that favor enhanced biological phosphorus removal (EBPR) [39–40]. In contrast, the relatively higher phosphorus concentrations in CAS and combined systems may indicate that the operational conditions were not sufficient to promote efficient biological phosphorus uptake or that chemical phosphorus precipitation was not applied. Regarding turbidity, the average values ranged from 4.13 to 5.35 NTU. The SBR effluent exhibited the lowest turbidity, while CAS and the combined system produced slightly higher average values. Nevertheless, all systems generated relatively low turbidity, indicating satisfactory clarification and solids separation [41].

The results (Table 10) indicate that all three treatment configurations achieved high removal efficiencies for biodegradable organic matter and suspended solids. The removal of BOD_5 exceeded 98.8% in all systems, while COD removal ranged from 94.95% to 95.43% and TSS removal ranged from 96.59% to 97.33%. The minimal differences observed among the three configurations suggest that all systems provided comparable performance for the removal of organic pollutants under the investigated operating conditions (Figure 6). More pronounced differences were observed for nutrient removal. The SBR system achieved

Table 9. Comparison of wastewater parameters treated by CAS (S2) and SBR (S3) reactors and combined system (S4) with European Directive 91/271/EEC

Comparison of wastewater values of CAS (S2), SRB (S3) and combined (S4) reactors by urban wastewater directive				
Parameters	S2	S3	S4	Directive 91/271/EEC
BOD_5 mg/L	3.07	3.11	3.06	≤ 25
COD mg/L	31.2	34.5	32.1	≤ 125
TSS mg/L	8.09	10.32	9.59	≤ 35
N tot mg/L	40.53	27.68	34.10	≤ 10- 15 *
Ptot mg/L	5.60	0.78	3.19	≤ 1-2
$Trub_{NTU}$	5.35	4.13	4.74	< 2-5

Note: * Depending on water temperature.

Table 10. Effectiveness of CAS (S2) and SBR (S3) reactors separately and combined (S4) in removing pollutants from wastewater

Parameter	Influent (Mean)	CAS effluent	CAS removal (%)	SBR effluent	SBR removal (%)	Combined effluent	Combined removal (%)
BOD_5 (mg/L)	270.67	3.07	98.87	3.11	98.85	3.06	98.87
COD (mg/L)	682.75	31.20	95.43	34.47	94.95	32.01	95.31
TSS (mg/L)	302.83	8.09	97.33	10.32	96.59	9.59	96.83
Total nitrogen (mg/L)	136.70	40.53	70.35	27.68	79.75	34.10	75.06
Total phosphorus (mg/L)	13.10	5.60	57.25	0.78	94.05	3.19	75.65
Turbidity (NTU)	12.70	5.35	57.87	4.13	67.48	4.74	62.68

the highest removal efficiencies for both total nitrogen (79.75%) and total phosphorus (94.05%), whereas the CAS system showed lower removal efficiencies of 70.35% and 57.25%, respectively. The combined system (S4) showed intermediate performance, with average removal efficiencies of 75.06% for TN and 75.65% for TP.

The contribution biplot showed a clear separation between the wastewater treatment systems, with Dimension 1 explaining 97.3% of the total variation. The influent was strongly associated with BOD_5, COD, and TSS, indicating the high organic and suspended solids load of untreated wastewater. The CAS system was mainly associated with

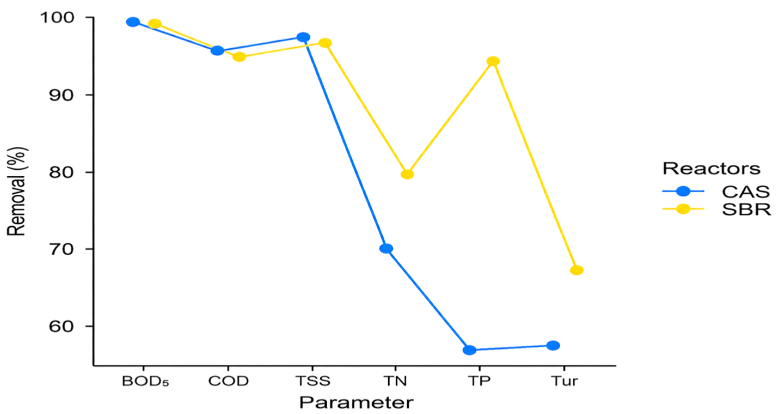

Figure 6. Comparison of removal efficiency (%) of wastewater quality parameters between CAS and SBR systems

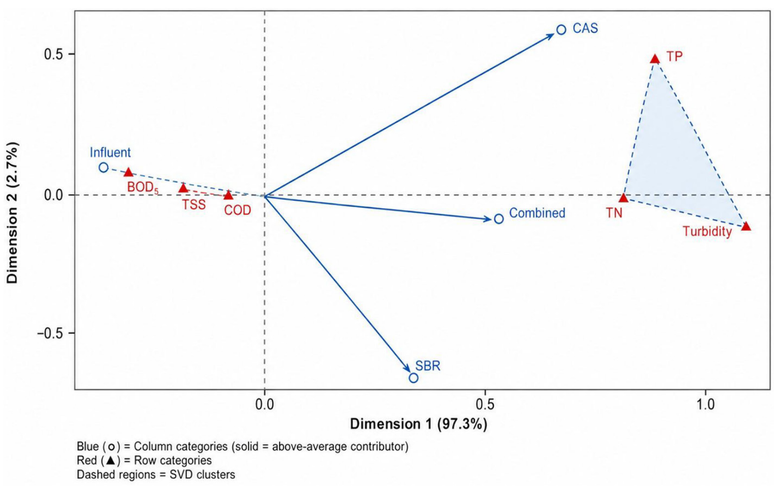

Figure 7. The relationship between treatment systems (CAS, SBR, and combined S4) and wastewater quality parameters shown by the contribution biplot

TP, reflecting its lower phosphorus removal performance compared with the other systems. In contrast, the SBR system showed a distinct position, indicating a different treatment behavior and improved removal of nutrient-related parameters, particularly TN and TP. The Combined system (S4) showed an intermediate position between CAS and SBR, suggesting a combined treatment effect (Figure 7). The improved nutrient removal observed in the SBR system may be related to its cyclic operational mode, which provides alternating aerobic and anoxic conditions that are more favorable for biological nitrogen and phosphorus removal processes [42–49]. However, this interpretation should be considered with caution because operational parameters, such as sludge retention time, internal recirculation, and dissolved oxygen distribution, were not specifically evaluated. For turbidity, the SBR system also achieved the highest average removal efficiency (67.48%), followed by the combined system (62.68%) and CAS (57.87%). This may indicate improved settling and solid–liquid separation under batch operating conditions [50, 51]. Despite the observed differences in nutrient and turbidity removal, all systems demonstrated consistently high efficiency in removing organic matter, confirming the suitability of biological treatment for reducing the organic pollution load of municipal wastewater [52].

CONCLUSIONS

The results demonstrated that all investigated systems provided stable and efficient removal of biodegradable organic matter throughout the monitoring period despite seasonal variations in influent characteristics. The influent wastewater exhibited considerable fluctuations in organic loading, with COD ranging from 293 to 1050 mg/L, BOD_5 from 180 to 420 mg/L, and a mean biodegradability index (BOD_5/COD) of 0.41, indicating that the wastewater was generally suitable for biological treatment. Seasonal temperature variations influenced the influent characteristics but did not substantially affect the overall treatment performance. All treatment configurations achieved high removal efficiencies for organic pollutants. The average removal efficiencies exceeded 98% for BOD_5, 94% for COD, and 96% for TSS, demonstrating the effectiveness and operational stability of biological treatment under varying loading conditions. The differences among the three systems for these parameters were relatively small, indicating comparable performance in organic matter removal. Greater differences were observed in nutrient removal. The SBR reactor achieved the highest average removal efficiencies for TN (79.75%) and TP (94.05%), whereas the combined system showed intermediate performance and the CAS system showed the lowest nutrient removal efficiencies. These results suggest that the cyclic operational characteristics of SBR may provide more favorable conditions for biological nutrient removal.

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