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Lab-scale sequencing batch reactor online monitoring and control for biological treatment of synthetic wastewater

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ABSTRACT

One of the major environmental issues facing the world today is water pollution, and there is a growing need to create practical and reasonably priced remediation techniques. As a potentially successful biological wastewater treatment method, the Sequencing Batch Reactor (SBR) is one of the most commonly used procedures to eliminate a variety of contaminants from industrial wastewater. Using suspended biomass and operating in an aerobic environment, the effectiveness of the SBR in treating complex chemical effluents was examined. In this study, two distinct Hydraulic Retention Times (HRT), 24 and 8 h, were adopted to evaluate the performance of the SBR system to remove specific pollutants, such as chemical oxygen demand (COD), ammonium-nitrogen (NH_3-N), nitrate (NO_3-N), and nitrite (NO_2-N). The crucial parameters of oxidation-reduction potential (ORP), dissolved oxygen (DO), and pH were all monitored online during this investigation. The results showed that the highest percentage removals of COD, NH_3-N, NO_3-N, and NO_2-N were found to be 86.74, 95.64, 64.16, and 80, respectively, at 8 h of HRT. Operating the system at 8 h HRT enhanced the activity and growth of suspended biomass, as evidenced by pH, dissolved oxygen (DO), and oxidation-reduction potential (ORP) profiles. Based on these findings, the sequencing batch reactor (SBR) demonstrates potential as an effective method for treating industrial wastewater.

1. Introduction

Water contaminated by various industrial activities and manufacturing processes is known as industrial wastewater. Depending on the industry, such as manufacturing, chemical plants, unit operations, factories, mining, agriculture, or food processing plants, industrial wastewater can contain a variety of pollutants, including chemicals, heavy metals, oils, organic compounds, and suspended solids [1–3]. For now, many industrial operations worldwide still use fresh water to flush out waste products containing extremely hazardous components and dispose of them into rivers, lakes, and oceans, even though some recent trends have prohibited such behaviors or recycling these waste products within the production process. Nevertheless, many industries remained dependent on processes that produce wastewater in this manner. If left untreated, this could have disastrous and negative impacts on aquatic ecosystems and human health [4,5]. The treatment process consists of

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the methods and techniques adopted to clean water contaminated by man-made industrial operations before being released into the environment or used again. They can be recognized by their high levels of chemical and biochemical oxygen demand (BOD, COD), as well as by their color [6]. Additionally, certain harmful substances found in wastewater, such as bacteria and parasites, can result in illnesses like dysentery, cholera, and typhoid [7,8]. Therefore, wastewater treatment is required to remove pollutants, dangerous compounds, big particles, diseases, and increase the water purity so that it can be reused or released back into the environment [9,10]. Different treatment strategies have been implemented using physical, chemical, biological, and sludge treatment methods. However, as a rule of thumb, the wastewater treatment system features are determined by the type of industrial waste, the nature of domestic wastewater transferred by sewers, and the treatment level required to improve water quality [11].

Most currently available wastewater treatment technologies are expensive and difficult to control, particularly in developing countries where funds and expertise to operate the treatment units are essential requirements. For instance, constructing and operating centralized wastewater treatment facilities is costly in low-population areas. Moreover, building low-cost and efficient wastewater treatment units in cities or rural areas is still challenging in many parts of the world [12]. One of the most popular methods for treating residential and commercial wastewater is biological treatment, which involves oxidizing and breaking down organic components, as well as eliminating inorganic ones like ammonia [13,14]. Furthermore, the biological treatment system is the most effective and eco-friendly option among the existing treatment systems, with lower operational costs and capital investment compared to the chemical oxidation processes [15,16]. COD concentrations in industrial wastewater can be successfully removed or reduced through biological treatment. The amount of oxygen needed to chemically oxidize the organic and inorganic matters in wastewater is measured by COD, an important indicator of water quality. As a result, eliminating them is a crucial step in reducing water pollution. The primary process for the elimination of COD is thought to be the breakdown of organic materials, which are typically carried out by microbes. In other words, this method lowers the COD concentrations in wastewater because aerobic bacteria break down organic matter during the aeration phase and transform it into carbon dioxide, water, and new cell biomass.

It is essential to highlight that ammonium, nitrate, and nitrogenous compounds from many sources are discharged into the aquatic environment. Ammonium and nitrate can be dissolved in water from diverse industrial processes, and the nitrogenous components can adversely affect receiving water bodies [17]. Moreover, wastewater treatment facilities suffer from high levels of ammonia that come from many industrial sources and activities [18]. Therefore, it is expected to find ammonia in industrial waste products. Nevertheless, some types of bacteria, such as Nitrosomonas, Nitrobacter, and Nitrospira, which are chemoautotrophic, contribute to removing nitrite and ammonia from wastewater [19–21]. Noteworthy, microbial reactions influence the pH value in a biological treatment system; variations in pH can sometimes give a more unambiguous indication of the biological reactions occurring during an operating cycle [22]. For example, a rise in pH can indicate a denitrification process, while a decrease in pH can indicate a nitrification process [23].

Nowadays, the strategy of industrial wastewater treatment is a crucial criterion in maintaining the environmental sustainability of diverse manufacturing and production processes. A typical wastewater treatment facility may have a sequence of individual unit processes; the unit process has output water (effluent) and input water (influent). Within the unit process, the effluent of one becomes the influent of the other. Usually, the first treatment stage is the physical removal, which readily eliminates the removable pollutants (e.g., floatable and settleable solids), while the remaining pollutants can then be treated with more advanced biological or chemical processes [24]. In this regard, SBR is one of the prominent approaches for treating industrial wastewater. It is an activated sludge process used for biological wastewater treatment that operates under non-steady state conditions with aeration and sludge settlement occurring in the same tank [25,26]. Many advantages are linked to using the SBR treatment process, including its compact size, which combines clarifiers and aeration basins into one reactor basin, flexibility in handling various organic influent volumes and flow rates, reliability in treatment accuracy, cost-effectiveness, potential ability to remove nutrients, such as nitrogen and phosphorus, and the possibility to produce high-quality effluent [27–29]. Besides, the footprint required for SBR is less than that of other treatment processes, such as conventional activated sludge process (ASP) due to its capability to consolidate many treatment stages inside a single basin [30]. For instance, as in the work of Mohan et al. [31], SBR treatment was reported to have a better performance than ASP for the treatment of complex water chemicals, particularly in the removal of COD and BOD, with less HRT (66.4 % removal of COD and 92 % removal of BOD at HRT of 1 day for SBR versus 55 % removal of COD and 67 % removal of BOD at HRT of 5 days for ASP). In addition, the low operational costs and the ability to adapt to various outlet and inlet requirements have made the SBR treatment system one of the promising alternative wastewater treatment methods [32].

The successful and efficient treatment of industrial wastewater using sequencing batch reactors (SBRs) depends on the effective control of operational phases and optimization of their durations. This study investigates the relationship between hydraulic retention time (HRT) and biomass activity by monitoring key real-time indicators: pH, dissolved oxygen (DO), and oxidation-reduction potential (ORP). It evaluates the simultaneous removal of chemical oxygen demand (COD), ammonium-nitrogen (NH_3-N), nitrate (NO_3^-), and nitrite (NO_2^-) from synthetic wastewater. To the best of the authors' knowledge, there is limited comprehensive research on the real-time integration of pH, DO, and ORP in SBR systems, particularly in conjunction with the adjustment of organic loading rates (OLR) and HRT for performance optimization. Therefore, the main objective of this study is to advance process understanding by providing an in-depth evaluation of SBR performance under controlled conditions, using online monitoring of key operational parameters.

2. Materials and methods

2.1. Synthetic wastewater and batch replacement procedures

The synthetic wastewater was prepared inside our laboratory and contained a complex of chemicals presented in Table 1, which were all provided by EMSURE® Merck KGaA, Germany. The synthetic wastewater composition included organic carbon, ammonia, nutrients, and minerals to replicate the characteristics of raw domestic wastewater, as previously investigated. The concentrations of COD and total nitrogen in the feed water were approximately 250 mg/L and 25 mg N/L, respectively [33]. The bacteria were stimulated and increased their activities when aeration and chemicals were available as input sources for the

Table 1
Concentrations and chemical compositions of the synthetic wastewater.

Chemical	Concentrations of stock solution (g/L)	Composition of synthetic wastewater (mg/L)
Glucose	50.0	500
Ammonium chloride	20.0	25
Magnesium II sulfate heptahydrate	8.0	53
Manganese II chloride tetrahydrate	1.0	0.3
Iron III sulfate pentahydrate	0.04	0.3
Potassium dihydrogen phosphate	0.3	4
Sodium bicarbonate	50	500

bacterial growth. The treatment system of the SBR consisted of two reactors, where one reactor (R1) was used for biomass growth only. In contrast, the other reactor (R2) was employed for the water treatment and analysis procedures. The effluent of reactor (R2) was replaced after completion of each HRT experiment of the 24-hour and 8-hour cycles, and the chemicals were added to the new batch following the concentrations given in Table 1. Notably, the HRT represents the average time during which wastewater remains in the reactor during the treatment process, and it determines the contact time between the microorganisms and pollutants in the reactor. In other words, many water treatment cycles were conducted using the reactor (R2), each operating with 24 h of HRT and repeated after completing one cycle. Also, different cycles were accomplished with 8 h of HRT to compare the SBR performance during these two HRT and to find the best removal rates of the contaminants. For the new cycle, only the effluent of reactor (R2) was discharged after achieving one treatment cycle, regardless of the cycle time, and the synthetic wastewater was added again since most of the chemicals were consumed by bacterial activities during the previous treatment cycle. It is essential to highlight that the reactor (R2) was typically drained to a specific sink connected to the lab's sewer before refilling and preparing it for the new cycle.

2.2. Mixed liquor suspended solids (MLSS) analysis

The growth of bacteria during the biological treatment of the SBR was assessed using the MLSS method. A mixed culture of sewage-activated sludge supplied by Indah Water Konsortium SDN BHD, Putrajaya, Malaysia, served as the bacteria (biomass). The SBR treatment reactor's aeration must be stopped first, and then wastewater and biomass must be adequately mixed in the reactor. After that, a 50 mL volume of the mixture was taken out and employed for the MLSS analysis. The 50 mL of the mixture was filtered using a 0.45 μm membrane filter. The filter paper was weighed before the filtration to get the value X, which refers to the weight of the filter paper before the filtration. Upon completion of the filtration step, the filter paper was dried in an oven for two hours at 150 ℃. Once the oven's drying procedure is finished, placing the filter paper in a desiccator is recommended to remove any remaining moisture. The filter paper was weighed again to get the value Y, which refers to the weight of the filter paper after filtration and drying. Finally, the MLSS can be computed to assess the bacterium growth using Eq. (1) with the reactor's working volume in the equation's denominator. The standard unit of measurement for MLSS concentration is (mg/L) [34].

$$\mathbf{MLSS}\left(\frac{\mathbf{mg}}{\mathbf{L}}\right) = \frac{\boldsymbol{Y - X}}{\boldsymbol{working\ volume\ of\ reactor}} \tag{1}$$

2.3. Experimental set-up

Figs. 1 and 2 illustrate the laboratory sequencing batch reactor (SBR, Control EZ Technology SDN BHD/S15007-U, Malaysia) at the Environmental Lab (Faculty of Engineering and Built Environment, UKM) that served as the primary experimental setup for this study. As explained earlier, reactors (R1) and (R2) are the two main reactors comprising the SBR system, each with a 12-liter capacity. The treatment reactor (R2) was equipped with three electronic sensors to detect the parameters of dissolved oxygen (DO), oxidation-reduction potential (ORP), and pH. Thus, the system has three online meters (Swan Analytical Instruments), and the digital meters of pH, DO, and ORP are connected to a computer by cable (32-pin) to transfer the data automatically. The digital meters are also connected to sensors in the treatment reactor (R2), where the pH sensor is Model PD1R1 PHD-PH (Differential sensor 0803430290); the ORP sensor is Model PD1R5 PHD-ORP (Differential sensor 0803430880); and the DO sensor is Model PD1R3 PHD-DO (Differential sensor 0803460960). The data was processed and saved to the computer through the Microsoft Visual Basic® version 6 software, designed by Control EZ Technology SDN BHD. Moreover, air pump (Hygger HG-958 model, China) with flow rate approximately 10 L/min.

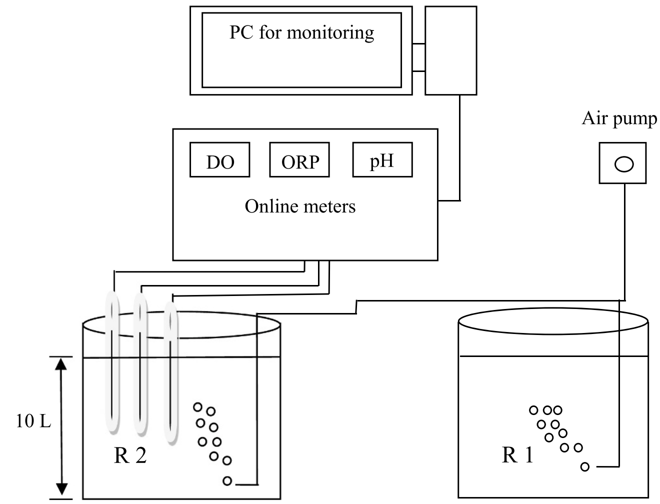

Fig. 1. Simplified schematic representation of the SBR system.

2.4. Experimental procedures

10 liters of clean water and a handful of bacteria, nearly 200 g, were added to the reactor (R1), which was utilized for biomass growth and backup. On the other hand, 10 liters of synthetic wastewater were placed in the reactor (R2), which was used to remove the specified pollutants and to assess the entire SBR system. Aeration was used in both reactors to promote microbial activity and growth (an increase in microbial mass). For biological wastewater treatment, 1.25 L of bacteria (biomass) was taken from the reactor (R1) after their growth and added to the reactor (R2), followed by filling the reactor (R2) with the synthetic industrial wastewater to start the treatment cycle. The steps of the SBR system adopted to treat the wastewater were in a sequence order, involving filling, where the wastewater entered the tank, followed by aeration, where the microorganisms broke down the organic matter, and the wastewater underwent biological treatment. The next step was settlement, where the treated water was separated from the sludge, and decanting, where the clarified water was discharged.

The duration of each stage of the cycle is as shown in Table 2. The following analytical methods are used to assess water quality parameters:

2.4.1. COD

The HACH DR 2010 analyzing reactor model was employed to measure the COD in this study. The initial step in the procedure involves extracting 250 mL of the sample from the treatment reactor of the SBR for analysis. The digestion solution reagent is within the COD range of 0–1500 ppm (high range). Then add 2 mL of the wastewater sample to the reagent vial and ensure thorough mixing. Subsequently, place the vial in the COD reactor, which maintains a temperature of 150 ℃ for a duration of two hours. Upon completion of the setting reaction, the vial should be removed from the COD reactor and allowed to cool at room temperature for 30 min. After the vial has cooled, clean it and utilize the DR/2010 spectrophotometer to measure the COD concentration. If the sample reading exceeds the range, dilution of the sample is necessary.

To operate the spectrophotometer, first enter the stored program number for COD (high range) by inputting "435" and pressing "ENTER." The display will indicate "Dial nm to 620." Subsequently, adjust the wavelength dial until the small display reads "620 nm." Upon setting the appropriate wavelength, the display will indicate "Zero Sample, mg/L COD HR." Subsequently, insert the COD vial adapter into the cell holder and prepare the blank vial with 2 mL of distilled water. Prior to use, the

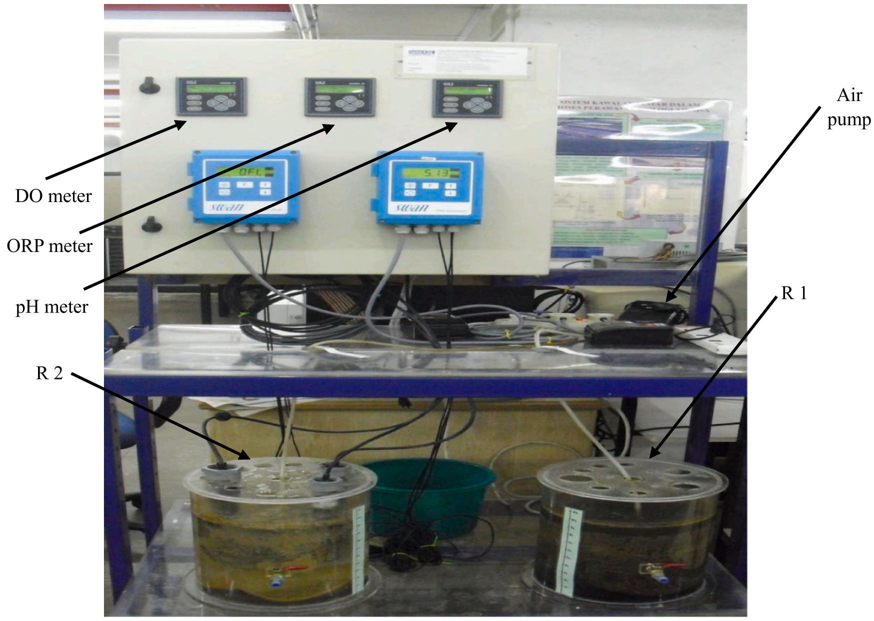

Fig. 2. A lab-scale SBR system used in this study.

Table 2
Duration time of each stage for one cycle.

Stage	8 h Time (min)	24 h Time (min)
Filling	30	30
Reaction	180	360
Settling	60	180
Decanting	30	30
Idling	20	60

vial must be cleaned to ensure an accurate measurement by the spectrophotometer. Insert the blank into the adapter with the Hach logo oriented towards the front of the instrument, then secure the cover onto the adapter. The spectrophotometer requires cleaning prior to use. This can be accomplished by zeroing the meters; pressing "Zero" will result in the display indicating "Zeroing, 0. mg/L COD HR." Finally, place the sample vial in the adapter with the Hach logo oriented towards the front of the instrument, and then secure the cover onto the adapter. The spectrophotometer will display the reading upon selecting “Press READ,” with results presented in mg/L COD.

2.4.2. NH_3-N

The initial step in measuring ammonium-nitrogen involves putting the designated program number into the spectrophotometer for NH_3-N analysis. Rotate the wavelength dial until the small display matches the number indicated in the clue on the same display. The subsequent step involves preparing a blank sample using deionized water in a 25 mL cylinder. Subsequently, prepare a sample with an equivalent volume in the cylinder. Add three drops of polyvinyl alcohol and three drops of mineral stabilizer to the samples, including the blank sample, and mix thoroughly. Add 1 mL of Nessler reagent to all samples, including the blank, and mix thoroughly. Subsequently, activate the SHIFT TIMER on the spectrophotometer to initiate a one-minute reaction period. After that, transfer each sample into the designated sample cells. Upon completion of the one-minute reaction time, insert the blank sample into the spectrophotometer and press “ZERO” to calibrate the instrument. Then, insert the sample into the spectrophotometer and select “READ” to obtain the NH_3-N measurement. The result will be expressed in mg/L. If the sample reading exceeds the range, diluting the sample is necessary.

2.4.3. NO_3-N

The initial step in measuring high-range nitrate concentration involves inputting the designated program number into the spectrophotometer for NO_3-N estimation. Subsequently, adjust the wavelength dial to match the prompt displayed on the small screen and press “ENTER.” Fill the sample cell with 25 mL of the sample and add the contents of the high-range nitrate reagent power pillow. Shake the cell vigorously for 1 min and allow it to react for 5 min. At that time, fill an additional sample cell with a blank sample. Upon completion of the 5-minute reaction time, utilize the blank sample to initialize the equipment. Subsequently, insert the sample into the spectrophotometer and select “READ” to obtain the NO_3-N reading. The result will be expressed in mg/L. If the sample reading exceeds the range, diluting the sample is necessary.

2.4.4. NO_2-N

The first stage in measuring low-range nitrite concentration involves entering the designated program number into the spectrophotometer for NO_2-N estimation. Subsequently, adjust the wavelength dial to match the prompt displayed on the small screen and press “ENTER.” Afterwards, fill a sample cell with 25 mL of the sample and introduce the contents of the low-range nitrite reagent power pillow into the cell. Then, agitate the cell vigorously for one minute and activate the “SHIFT TIMER,” initiating a 20-minute reaction period. At that time, fill an additional sample cell with the blank sample. Upon completion of the 20-minute reaction time, utilize the blank sample to initialize the equipment. Subsequently, insert the sample into the spectrophotometer and press “READ” to obtain the NO_2-N reading. The outcome will be expressed in mg/L. If the sample reading exceeds the range, diluting the sample is necessary.

2.5. Experimental workflow

The experimental procedures used in this study are demonstrated in Fig. 3. The chemical components (synthetic wastewater) were added to the treatment reactor (R2) of SBR, followed by the analysis of the influent sample and monitoring of online parameters. The samples were analyzed based on COD, NH_3-N, NO_3-N, and NO_2-N concentrations. The SBR system operated under aeration conditions, and pH, DO, and ORP profiles were monitored during the experimental cycles of 24 and 8 h of HRT. The effluent sample was also taken from the treatment reactor (R2)

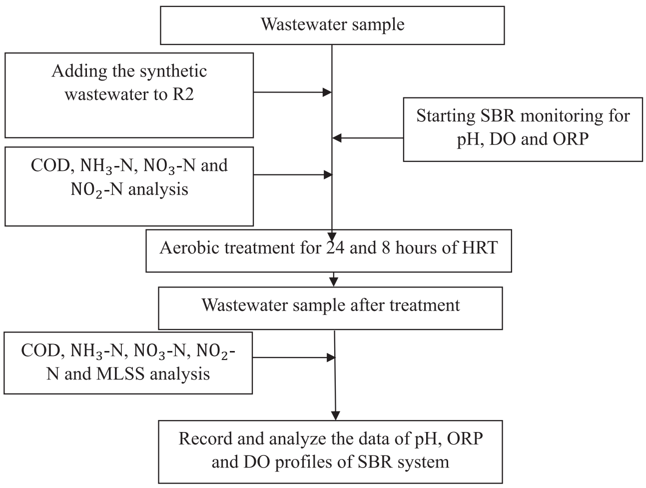

Fig. 3. Workflow chart of the experimental procedures.

to analyze the removal rates of pollutants and to evaluate the SBR performance. All samples were taken from the treatment reactor (R2) and analyzed before and after the specified operational hours of the laboratory SBR were completed. The SBR data is collected and assessed, and the DO, pH, and ORP profiles are saved automatically to the computer linked to the SBR system.

3. Results and discussions

3.1. Removal of COD

The experimental setup depicted in Fig. 2 was conducted at two hydraulic retention times (HRTs) 24 h and 8 h to assess the efficacy of COD removal, with data analysis techniques presented in Fig. 3. Fig. 4 illustrates the influent and effluent COD concentrations alongside the removal efficiencies for both HRT conditions. In the 24-hour HRT, influent COD values varied between 504 and 771 mg/L, whereas effluent values ranged from 101 to 565 mg/L. The average COD removal efficiency was 55.6 %, with an average removal rate of 84.24 %. Conversely, with the 8-hour HRT, influent COD concentrations varied between 269 and 571 mg/L, while effluent values ranged from 70 to 222 mg/L. The mean COD removal efficiency was 78.4 %, with a peak of 86.74 %. The results demonstrate that HRT has a significant impact on COD removal performance. Operating the SBR with an 8-hour hydraulic retention time resulted in higher average and maximum removal efficiencies compared to a 24-hour hydraulic retention time. This indicates that extended retention times do not necessarily improve COD removal and may instead encourage endogenous respiration or microbial decay, thereby reducing treatment efficiency.

3.2. Removal of NH_3-N

Ammonium nitrogen (NH_3-N) is a significant contaminant necessitating biological elimination in wastewater treatment systems employing an SBR. Fig. 5 demonstrates that alterations in HRT influenced the removal efficiency and concentrations of influent and effluent NH_3-N, aligning with the observed pattern in COD removal. At an HRT of 24 h, influent NH_3-N concentrations varied between 3.76 and 6.9 mg/L, whereas effluent concentrations ranged from 0.23 to 4.28 mg/L. Under these conditions, the average removal efficiency of NH_3-N was 65.23 %, with a maximum removal rate of 96.49 %. In an 8-hour HRT, influent concentrations ranged from 4.2 to 6.96 mg/L, while effluent concentrations varied between 0.3 and 1.9 mg/L. The average removal efficiency under these conditions increased to 88.6 %, with a maximum of 95.64 %.

The findings indicate that a shorter hydraulic retention time (8 h) improved microbial activity and ammonia removal in comparison to a longer retention time of 24 h. This results from enhanced environmental conditions for nitrifying bacteria, specifically Nitrosomonas and Nitrobacter, which oxidize ammonia to nitrite and nitrate, respectively. Autotrophic bacteria have significant sensitivity to environmental stressors, which may lead to inhibition due to toxicity or inadequate operational management. Their propagation and metabolic processes within the SBR system directly influenced the removal rates. Eq. (2) illustrates that Nitrosomonas converts ammonia (NH_3) into nitrite (NO_2^-), an essential phase in the biological nitrification process [34, [35,36].

$$NH_3 + \frac{3}{2} \quad O_2 \rightarrow NO_2^- + H^+ + H_2O.............. \quad (2)$$

The oxidation of ammonia (NH_3) to nitrite (NO_2^-) releases energy that is harnessed by autotrophic nitrifying bacteria, including Nitrosomonas. These bacteria utilize the chemical energy obtained from the oxidation process to fix carbon dioxide (CO_2) as a carbon source for cellular synthesis and growth. Chemolithoautotrophic metabolism is essential to the nitrification process in biological wastewater treatment systems such as sequencing batch reactors (SBRs) [37].

3.3. Removal of NO_2-N

Fig. 6 depicts the variations in influent and effluent NO_2-N concentrations within the SBR treatment reactor during two hydraulic retention times: 24 h and 8 h. Fig. 7 demonstrates substantial fluctuations in NO_2-N removal effectiveness across the experimental phases, indicating the variable dynamics of nitrite within the system. At 24 h of HRT, influent NO_2-N concentrations varied between 0.005 and 0.095 mg/L, whereas effluent concentrations ranged from 0.003 to 0.131 mg/L. The

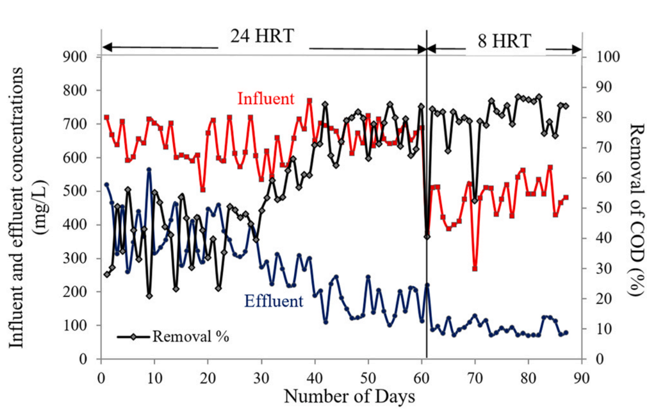

Fig. 4. The influent-effluent concentrations and COD removal rates at 24 and 8 h of HRT.

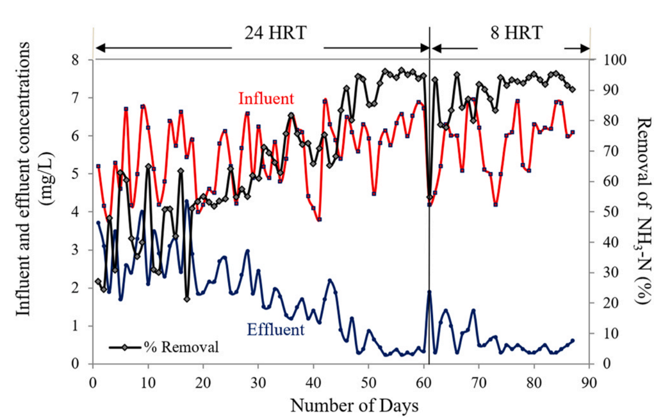

Fig. 5. The influent-effluent concentrations and removal rates of NH3-N at 24 and 8 h of HRT.

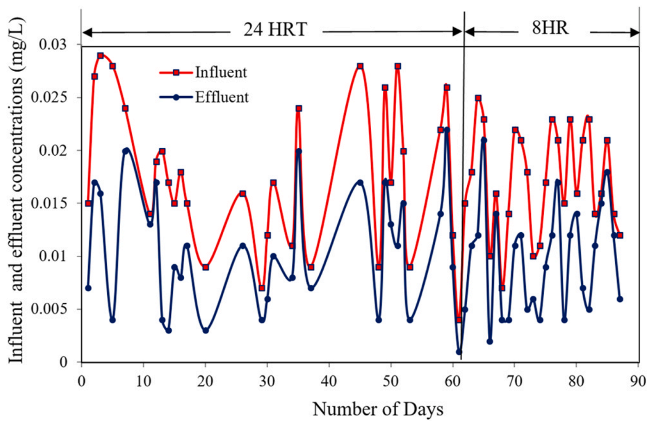

Fig. 6. The influent-effluent concentrations of NO_2-N at 24 and 8 h of HRT.

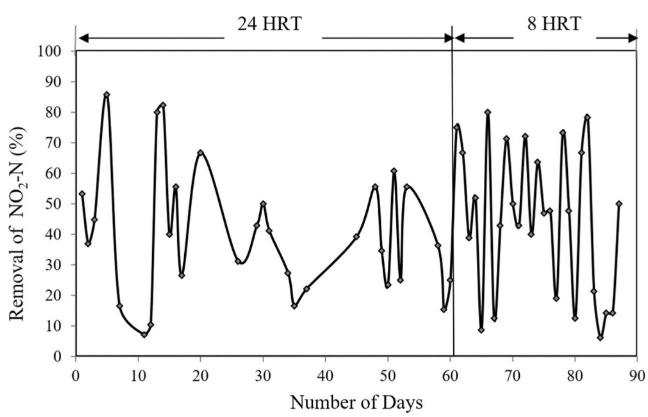

Fig. 7. The removal rate percentage of NO_2-N at 24 and 8 h of HRT.

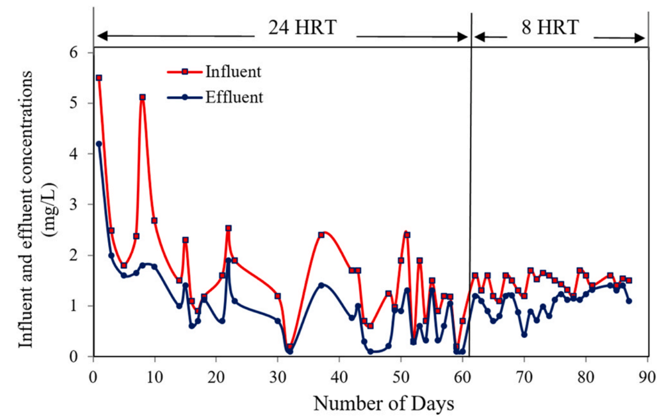

Fig. 8. The influent-effluent concentrations of NO_3-N at 24 and 8 h of HRT.

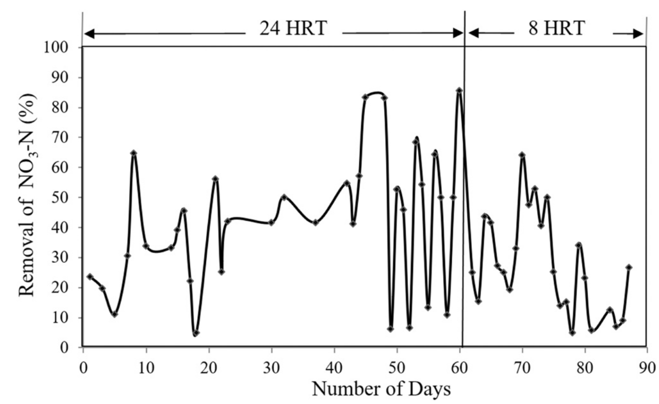

Fig. 9. The removal rate percentage of NO_3-N at 24 and 8 h of HRT.

average NO_2-N removal rate during this interval was 40.29 %, with a maximum removal rate of 85.71 %. In In contrast, the influent and effluent NO_2-N concentrations ranged from 0.004 to 0.025 mg/L and 0.001–0.021 mg/L, respectively, with less than 8 h of HRT. The average removal rate at this reduced hydraulic retention time was 45.01 %, with a maximum removal efficiency of 80 %.

These findings indicate that NO_2-N concentrations in the reactor exhibited instability and variations, presumably due to the sensitive characteristics of nitrite as an intermediary in the nitrogen cycle. The accumulation of nitrite is influenced by the activity of nitrifying bacteria, specifically Nitrosomonas, which oxidizes NH_3 to NO_2^-, and Nitrobacter, which transforms NO_2^- into NO_3^-, along with the prevailing conditions for denitrification. The biological SBR treatment method efficiently eliminates NO_3-N by nitrification, converting it to nitrate in aerobic environments, and denitrification, which turns it into nitrogen gas in anoxic environments. The dual mechanism highlights the flexibility and effectiveness of the SBR system in handling nitrogenous substances in industrial wastewater.

3.4. Removal of NO_3-N

Fig. 8 depicts the variations in influent and effluent NO_3^--N concentrations within the SBR treatment reactor operating under HRT conditions: 24 h and 8 h. Fig. 9 illustrates the change in NO_3^--N removal efficiency during the investigation. Variations in nitrate concentration were detected in both influent and effluent samples, indicating active biological processes and nitrogen transformations within the reactor. After 24 h of HRT, influent NO_3^--N concentrations ranged from 0.2 to 7.22 mg/L, whereas effluent concentrations ranged between 0.1 and 8.37 mg/L, yielding an average nitrate removal efficiency of 41.58 % and a maximum removal rate of 85.71 %. At 8 h of HRT, influent NO_3^--N concentrations increased from 1.1 to 1.7 mg/L, whereas effluent levels varied between 0.43 and 1.65 mg/L. The reduction in HRT yielded an average removal efficacy of 27.64 %, with the highest removal rate of 64.16 %. The findings indicate that prolonged HRT enhances nitrate removal, perhaps owing to persistent anoxic conditions that promote denitrification. The removal of nitrate in biological treatment systems typically involves two microbiological phases as shown in Eqs. 3 and 4:

- Nitrification is the process in which a nitrite-oxidizing bacterium, such as Nitrosomonas, oxidizes ammonia (NH_3) to nitrite (NO_2^-), followed by the oxidation of that nitrite to nitrate (NO_3^-) by Nitrobacter under aerobic conditions.
- Denitrification is the process by which facultative heterotrophic bacteria convert nitrate into nitrogen gas under anoxic circumstances, utilizing organic carbon as an electron source.

These reactions are essential for nitrogen removal in SBRs. The diminished nitrate removal during a shorter hydraulic retention period (8 h) is likely due to inadequate duration in the anoxic phase, constraining the degree of denitrification despite efficient nitrification [33,36, [38,39]].

$$NO_2^- + \frac{1}{2}\quad O_2 \rightarrow NO_3^- \tag{3}$$

$$NH_4^+ \xrightarrow{\text{Nitrosomonas}} NO_2^- \xrightarrow{\text{Nitrobacter}} NO_3^- \tag{4}$$

3.5. Concentrations and removals of COD, NH_3-N, NO_2-N, and NO_3-N

The average influent-effluent concentrations of COD, NH_3-N, NO_2-N, and NO_3-N at various HRTs are given in Table 3. Because more frequent cycling at 8 h of HRT improves the removal of these contaminants due to higher microbial activity and growth compared to longer durations of HRT. The findings of this study demonstrate that when the system is operated at an 8-hour HRT rate, the SBR performance is more effective. Additionally, after 24 h of HRT, the average elimination percentages of COD, NH_3-N, NO_2-N, and NO_3-N were found to be as high as 55.6, 65.23, 40.29, and 41.58 percent, respectively. On the other hand, within the 8-hour HRT, the average removal rates of COD, NH_3-N, NO_2-N, and NO_3-N were found to be as high as 78.4, 88.6, 45.01, and 27.64 percent, respectively. To highlight the novelty of the present work, Table 4 shows that the average removal percentages of COD, NH_3-N, NO_2-N, and NO_3-N, which were determined in this investigation, are comparable with those reported in the literature. Despite many differences that can be noticed between this work and others, such as SBR design, type and volume of wastewater, operating conditions, and concentration of contaminants, however, the present study showed good and promising results in synthetic wastewater treatment, which may become the first step to remove these types of contaminants from real industrial wastewater.

Table 4
The average removal percentage of COD, NH_3-N, NO_2-N, and NO_3-N at different values of HRT.

References	HRT	COD (%)	NH_3-N (%)	NO_2-N (%)	NO_3-N (%)
This study	24 h	55.6 ± 17.5	65.23 ± 20.9	40.29 ± 21	41.58 ± 22.3
	8 h	78.4 ± 10.2	88.6 ± 8.6	45.01 ± 24	27.64 ± 16.3
Ganesh et al. [40]	12 h	80–82	83–99	–	–
Mohan et al. [31]	1 day	66.4	–	–	–
Boopathy et al. [41]	24 h	0 ± 0	10.8 ± 4.7	75.0 ± 0	68.1 ± 19.3
Dockhorn et al. [42]	8 days	88.5	–	–	–
Kennedy & Lentz [43]	24 h	71–92	–	–	–
Sedolfo et al. [44]	8 h	75.9	–	–	–
Nadeem et al. [45]	6 h	93	–	–	–
Leal et al. [46]	6 h	82	92	–	–
Kumari et al. [47]	6.8 h	93.9	84.6	–	–

3.6. Mixed liquor suspended solids (MLSS)

The concentrations of suspended solids, such as microorganisms that actively treat wastewater in the SBR reactor, are measured by mixed liquor suspended solids, or MLSS. To ensure effective operation of the SBR, it is necessary to keep the reactor's MLSS level within an appropriate range. As a result, MLSS was investigated weekly for the SBR treatment reactor (R2) at ambient temperature and 24 and 8 h of HRT samples. As mentioned earlier, Nitrosomonas and Nitrobacter consider the first and second steps for the nitrification process (see Eq. 4). However, Nitrobacter typically grows more quickly than Nitrosomonas, so nitrifiers need essential requirements like the micronutrient ammonia/nitrite, dissolved oxygen, and carbon dioxide for their growth [48]. Fig. 10 depicts the variations in biomass growth (MLSS concentration) observed during this study. Consequently, many physical and chemical factors have a significant impact on biomass growth (MLSS concentration), such as temperature, pH, oxygen concentration, moisture, nutrient levels, and minerals. Moon et al. investigated the optimum temperature for biomass growth, and they found that at temperatures below water freezing or above 100°C, the growth might take place [49]. In another work, they revealed that the ideal pH for microbial development is about 7, and oxygen is required for nitrifiers to convert ammonia to nitrate [50].

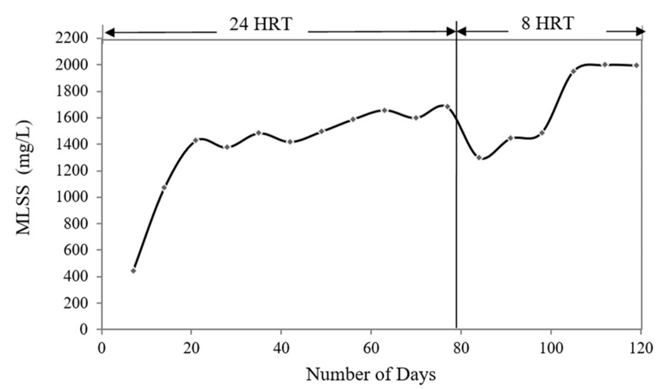

Fig. 10. MLSS concentrations (mg/L) at 24 and 8 HRT for the SBR system.

3.7. Online monitoring of sequencing batch reactor (SBR) parameters

The SBR was operating with aeration in the environmental laboratory for four months. The research was performed at 8 and 24 h of HRT to assess the treatment system and bacterial activities. The evaluation of SBR performance has been conducted through the analysis of pH, ORP, and DO profiles. For that, the monitoring data was collected daily during the SBR operating periods because these parameters have important operating points and profiles that provide beneficial information about the start and end of biological reactions. Figs. 11 and 12 show the results of pH, ORP, and DO profiles obtained at 24 and 8 HRT.

As can be observed in Figs. 11 and 12, the pH curve drops, and this drop may be attributed to the activity of nitrifying bacteria, which consume alkalinity during the oxidation of the ammonia; in other words, the pH variations noted in the SBR treatment reactor were mainly attributed to the nitrification and denitrification processes. Nitrification results in a gradual decrease in pH, attributed to the production of hydrogen ions that consume alkalinity. After the completion of nitrification and the initiation of denitrification in anoxic conditions, there is a typical increase in pH as alkalinity is partially restored. The reduction in pH led to microbial inactivation and then reduced treatment efficiency. To maintain optimal pH levels, some suggested chemicals that help raise alkalinity include sodium bicarbonate, soda ash, and sodium hydroxide [51]. Tanwar et al. also investigated the role of pH in ammonia oxidation process (nitrification) and confirmed that the pH profile can serve as a controlling factor in several SBR operations [52]. In contrast, the work done by Akın and Ugurlu [53] explains that the pH profile is ineffective

Table 3
Average influent and effluent concentrations of COD, NH_3-N, NO_2-N, and NO_3-N at 24 and 8 h of HRT.

HRT	COD (mg/L)		NH_3-N (mg/L)		NO_2-N (mg/L)		NO_3-N (mg/L)	
	influent	effluent	influent	effluent	influent	effluent	influent	effluent
24	651.2 ±54.2	286.7 ±114	5.52 ±0.90	1.74 ±1.08	0.025 ±0.019	0.026 ±0.028	1.74 ±1.33	1.40 ±1.38
8	470.7 ±65.9	96.7 ±31.3	5.80 ±0.82	0.63 ±0.40	0.016 ±0.005	0.0094 ±0.005	1.44 ±0.17	1.09 ±0.27

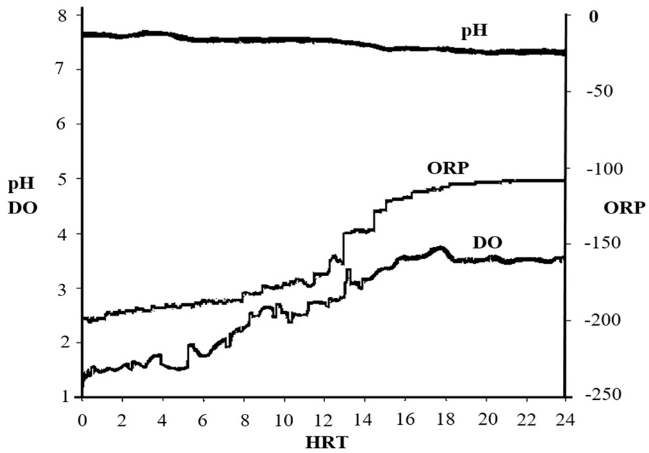

Fig. 11. The performance of SBR within 24 h of HRT.

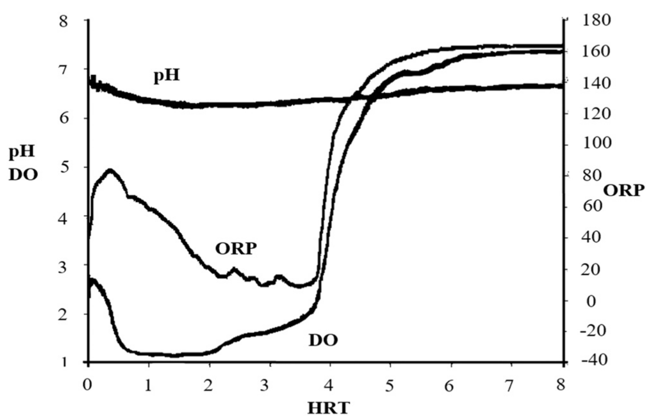

Fig. 12. The performance of SBR within 8 h of HRT.

for controlling the anoxic phase (denitrification) because of the limited and inconsistent pH variations observed during denitrification

In the denitrification process within an SBR, the ORP value generally decreases as a result of the reducing conditions. As nitrate consumption progresses and the denitrification phase approaches completion, the ORP increases, indicating a transition point. Additionally, the COD decreases while the system transitions to a more oxidizing state, resulting in an increase in the ORP. The ORP experiences a further increase after nitrification begins and DO concentration rises. ORP is affected by factors including DO, organic substrate concentration, microbial activity, and system loading, making it a significant indicator of reactor conditions. ORP is effective for identifying the end of the anoxic phase and can be utilized for controlling its duration in SBR operations. In the same context, Zekker et al. concluded that the ORP acts as a control parameter, effectively lowering energy requirements for aeration while facilitating a high rate of autotrophic nitrogen removal [54].

One crucial aspect influencing the aerobic operation in the biological treatment of SBR is the DO content [47]. During the filling phase of the treatment reactor (R2), dissolved oxygen levels declined as a result of the introduction of oxygen-depleting influent. During the subsequent aerobic phase, the initiation of aeration led to a gradual increase in DO levels, indicating the beginning of microbial oxidation processes and a decrease in oxygen demand over time. As previously suggested in the study of Soliman and Eldyasti [55], in the treatment reactor, microbial activity oxidized ammonia and COD, using dissolved oxygen in the process. Fig. 12 illustrates a significant increase in DO concentration corresponding with a decrease in NH_3-N and COD levels, which indicates a reduction in substrate availability. The increase in DO correlates with a reduction in bacterial respiration activity, considering it an effective indicator of treatment progress and phase completion in SBR operations. Therefore, DO can be considered a crucial real-time control parameter that facilitates the optimization of aeration duration, enhances process efficiency, and reduces energy consumption. In conclusion, the SBR was operated and tested at 24 and 8 h of HRT, as seen in Figs. 11 and 12, the investigation results demonstrated that the SBR performed better during 8 h of HRT than when the system was operated for 24 h of HRT.

4. Limitations and future prospects

The laboratory Sequencing Batch Reactor needs to improve its accuracy in recording the variations in dissolved oxygen (DO), pH, and oxidation-reduction potential (ORP) profiles. The program requires modification to ensure that profiles for each variable are saved every five minutes. The SBR computer currently records data every two seconds, leading to numerous issues and complicating data collection and profile generation. Additionally, the laboratory SBR should be operated with varying hydraulic retention times (HRT) of 2, 4, and 6 h to ascertain the optimal HRT for SBR. The procedure will involve monitoring relevant parameters at these intervals and evaluating the removal rates of inorganic contaminants. Finally, it is strongly advised to monitor SBR performance across varying chemical concentrations and diverse contaminants, including microplastics, heavy metals, and pathogenic microorganisms, as this research indicates that SBR is an effective method for treating inorganic contaminants in synthetic wastewater.

5. Conclusions

This study involved the treatment of synthetic wastewater, comprising a complex mixture of compounds, utilizing a laboratory-scale sequencing batch reactor (SBR). The biological treatment process successfully eliminated pollutants such as chemical oxygen demand (COD), ammonium-nitrogen (NH_3-N), nitrate (NO_3^-), and nitrite (NO_2^-). The SBR was conducted at two hydraulic retention times: 24 h and 8 h. Maximum removal efficiencies were recorded as follows:

- NH_3-N: 96.49 % (24 h) and 95.64 % (8 h).
- COD: 84.24 % (24 h) and 86.74 % (8 h).
- NO_2^--N: 85.71 % (24 h) and 80.00 % (8 h).
- NO_3^--N: 85.71 % (24 h) and 64.16 % (8 h).

Monitoring of dissolved oxygen (DO), pH, and oxidation-reduction potential (ORP) was performed in real-time throughout the 120-day experimental period. The analysis of these profiles revealed that an 8-hour duration is optimal for Hydraulic Retention Times (HRT) in terms of efficient pollutant removal and operational performance. The results indicate that the SBR is an effective and viable technology for the treatment of industrial wastewater under control conditions.

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CRediT authorship contribution statement

Alhafadhi Mahmood: Visualization, Formal analysis. **Mohammad M. Abed:** Investigation, Formal analysis. **Siti Rozaimah Sheikh Abdullah:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Haidar Hasan Mohammed:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Hassan Majeed Hameed:** Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Adnan A. Abdulrazak:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Amjad W. Dhuyool:** Writing – review &

editing, Visualization, Investigation, Formal analysis. **Oleksandr Skrylnyk:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Khalid T. Rashid:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Mohammed Faleh Abd Al-Ogaili:** Visualization, Formal analysis. **Mohammed Ahmed Shehab:** Writing – review & editing, Visualization, Investigation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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