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Sequencing Batch Reactor (SBR) for the removal of Hg^{2+} and Cd^{2+} from synthetic petrochemical factory wastewater

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ABSTRACT

Petrochemical factories which manufacture vinyl chloride monomer and poly vinyl chloride (PVC) are among the largest industries which produce wastewater contains mercury and cadmium. The objective of this research is to evaluate the performance of a lab-scale Sequencing Batch Reactor (SBR) to treat a synthetic petrochemical wastewater containing mercury and cadmium. After acclimatization of the system which lasted 60 days, the SBR was introduced to mercury and cadmium in low concentrations which then was increased gradually to 9.03 ± 0.02 mg/L Hg and 15.52 ± 0.02 mg/L Cd until day 110. The SBR performance was assessed by measuring Chemical Oxygen Demand, Total and Volatile Suspended Solids as well as Sludge Volume Index. At maximum concentrations of the heavy metals, the SBR was able to remove 76–90% of Hg^{2+} and 96–98% of Cd^{2+}. The COD removal efficiency and MLVSS (microorganism population) in the SBR was affected by mercury and cadmium concentrations in influent. Different species of microorganisms such as *Rhodospirilium*-like bacteria, *Gomphonema*-like algae, and sulfate reducing-like bacteria were identified in the system. While COD removal efficiency and MLVSS concentration declined during addition of heavy metals, the appreciable performance of SBR in removal of Hg^{2+} and Cd^{2+} implies that the removal in SBR was not only a biological process, but also by the biosorption process of the sludge.

1. Introduction

A mercury cell is one of three basic units for the manufacture of chlorine and caustic soda at chlor-alkali plants, which produce hazardous wastes containing mercury [1]. The major process involved in chlor-alkali plants is the electrolysis of aqueous sodium chloride (NaCl) to produce sodium hydroxide (NaOH) and chlorine (Cl_2). In this process, aqueous chloride ion is oxidized at a carbon anode and water is reduced at a liquid mercury cathode [2]. Because mercury is highly volatile, mercury contamination occurs throughout the process, commonly leading to both the product (caustic soda) and the wastewater stream containing of mercury. Since chlorine cannot be economically stored or moved over long distances, chlor-alkali facilities are often located near industries that require chlorine. One of the largest industries for chlorine is vinyl chloride monomer manufacturing. Bandar Imam Petrochemical Company (BIPC) which is located in Bandar Imam Region of Khuzestan province, Iran produces 180×10^3 tonnes vinyl chloride monomer annually [3]. The vinyl chloride is sent to poly vinyl chloride unit to produce PVC. Annual production of PVC in the BIPC is 175×10^3 tonnes. PVC is the only plastic in which cadmium is used to import useful properties to it. Pure PVC is a rigid material, which is mechanically tough, fairly weather resistant, water and chemicals resistant, electrically insulating, but relatively unstable to heat and light. Heat and ultraviolet light lead to a loss of chlorine in the form of hydrogen chloride (HCl) [4]. This can be avoided through the addition of stabilizers. Cadmium is used to stabilize PVC in some applications and also as a pigment in PVC and other applications [5].

The first indication that mercury in the marine environment could be hazardous to human life came in the late 1950s when more than a hundred people in Minamata bay, Japan were killed or disabled through eating fish and shellfish contaminated with methyl mercury. Mercury is taken up by shellfishes (especially bivalve mollusks) and by fishes and moves up the food chain. UN Food and Agriculture Organization (FAO) recommended Provisional Tolerable Weekly Intake (PTWI) for methylmercury to be 1.6 μg/kg body weight in order to sufficiently protect the developing foetus. The foetus is exposed to methylmercury through contaminated food

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Table 1
Previous application of SBR and GAC-SBR for heavy metals removal.

Parameters	[10]	[16]	[17]
System[a]	SBR	SBR	GAC-SBR
Type of ww[b]	SW	SIEWW	SIEWW
Type of heavy metals	Cu^{2+} and Cd^{2+}	Zn^{2+} and Cu^{2+}	Pb^{2+} and Ni^{2+}
Influent heavy metals (mg/L)	5 and 15	10 and 10	5 and 5
Heavy metals removal (%)	80 and 73	84.9 ± 0.4 and 87.0 ± 1.1	88.6 ± 0.9 and 94.6 ± 0.1
Influent COD (mg/L)	550–650	1650 ± 26	750 ± 10
COD removal (%)	75	92 ± 2	87.4 ± 0.8
HRT[c] (h or d)	8 h	3 d	3 d
MLSS[d] (mg/L)	4000–9000	4500	3000

[a] System: SBR, Sequencing Batch Reactor; GAC-SBR, Granular Activated Carbon Sequencing Batch Reactor.
[b] Type of wastewater (ww): SW, synthetic wastewater contains Cu^{2+} and Cd^{2+}; SIEWW, synthetic industrial estate wastewater.
[c] Hydraulic retention time: h, hour; d, day.
[d] Mixed liquor suspended solid.

eaten by the pregnant mother [6]. Even though the average cadmium concentration in the earth's crust is generally placed between 0.1 and 0.5 ppm, much higher levels may accumulate in sedimentary rocks and marine phosphates. Annual input of cadmium to the sea is 8000 tonnes, of which half is from human sources. Some marine organisms such as oceanic squids and oysters accumulate large concentrations of cadmium, but no environmental effect has been detected. Even so, cadmium is included in the blacklist of substance that should not be discharge to the sea [7]. The recommended PTWI for cadmium is 7 μg/kg body weight [6]. US EPA (1995) recommends the daily effluent limitation concentrations of 0.013 mg/L and 0.73 mg/L for mercury and cadmium, respectively, when best practicable control technology (BPT) is applied [8,9]. BPT is a national goal in the United States under the Water Pollution Control Act of 1972 which provides that industry shall use the best treatment practices, with due consideration to cost, age of the plant and equipments.

Conventional methods of heavy metals removal from aqueous solutions usually involve physico-chemical treatments such as precipitation, filtration, ion exchange, electron-deposition, and reverse osmosis [10]. There are some common problems associated with these methods e.g. they are more costly compared to biological treatment methods and can themselves produce other waste problems; which has limited their industrial applications [11,12].

Among the available treatment methods, the application of biological processes is gradually gaining momentum due to reasons such as reduced chemicals requirement for the overall treatment process, low operating costs, eco-friendly and cost-effective alternative of conventional techniques and, efficient at lower levels of contamination [13]. Due to their simplicity and flexibility in operation, Sequencing Batch Reactors (SBRs) are an attractive alternative to conventional biological wastewater treatment systems. An SBR is a periodically operated, fill-and-draw reactor [14]. It has five discrete periods in each operation cycle: fill, react, settle, draw, and idle [10]. Reactions start during fill and complete during react. After react, the mixed liquor suspended solids (MLSS) are allowed to separate by sedimentation during settle in a defined time period; the treated effluent is withdrawn during draw. The time period between the end of the draw and the beginning of the new fill is termed idle [15]. A number of papers which provide good description and evaluation of the SBR systems in treatment of heavy metals have been published [10,16–18]. An overview pertaining to the performance of SBR and GAC-SBR for heavy metals removal is summarized in Table 1. But no research is done which has examined the performance of SBR for the treatment of petrochemical wastewater containing Hg and Cd concurrently. In this study the removal efficiency and effect of these heavy metals on performance of a lab-scale SBR is investigated. In addition identification of microorganisms through morphology inspection is conducted.

2. Materials and methods

2.1. Wastewater preparation and preservation

The real wastewater was analyzed and synthetic wastewater was prepared according to the real sample characteristics. Sugar, powdered milk and urea added as organic sources to represent the COD as well as Na_2HPO_4 and NaH_2PO_4 for substrate preparation. Mercury and cadmium salts were then added at selected concentrations in each step. Typical composition of the feed wastewater was COD = 110 ± 30 mg/L, urea = 33 ± 0.4 mg/L, Na_2HPO_4 = 5.4 ± 0.1 mg/L, NaH_2PO_4 = 2.6 ± 0.1 mg/L, Hg (II) = 0.1–9 mg/L and Cd (II) 0.1–15.5 mg/L. pH was about 6.9 in the feed wastewater which was increased to over 7.5 in the aeration tank due to release ammonia from urea biodegradation. Initially, stock solution was prepared and kept in the fridge. Then when feeding of reactor was needed part of that was diluted with tap water, brought to room temperature and then added to the SBR.

2.2. Reactor setup

As illustrated in Fig. 1, a cylindrical aerobic Sequencing Batch Reactor was used for this study. The cylindrical-shape plexiglass reactor had 25 cm initial diameter and 60 cm height with a working volume of 24 L. The reactor was connected by polietilen pipes to feed tank (120 L), treated wastewater tank (120 L) and sludge tank (60 L). The treated wastewater and sludge were sampled from the tanks which were equipped with PVC valves size 3/4 in. (1.9 cm). Each connection between the SBR and tanks had a three-way spherical electric valve size 1/2 in. (1.3 cm) (Moonze Ball Valve), Honeywell, USA. The maximum designed pressure for each valve was 860 kPa. Electric valves and an intelligence system control were used in this study for proper operating and controlling of fill, react, settle, draw, and idle periods in the reactor. Intelligence system control was programmed using QBasic with 8 internal ports with voltage of 0–24 V for each. It was calibrated using internal oscilloscope with minimum sampling time of 0.0002 s and maximum frequency of 3 kHz in on-line mode. A compressor (Pars Compressor, Iran), with a capacity of 150 L was used to provide oxygen for microorganisms and mixing of wastewater. The wastewater level in the reactor was controlled using floater which was connected to the intelligence system control.

2.3. Seed organisms

Returned sludge brought from an activated sludge process based municipal wastewater treatment plant in Gheytarieh, Tehran and was used as seed material. The sludge was collected from the sludge return pipeline and immediately brought to the laboratory. The

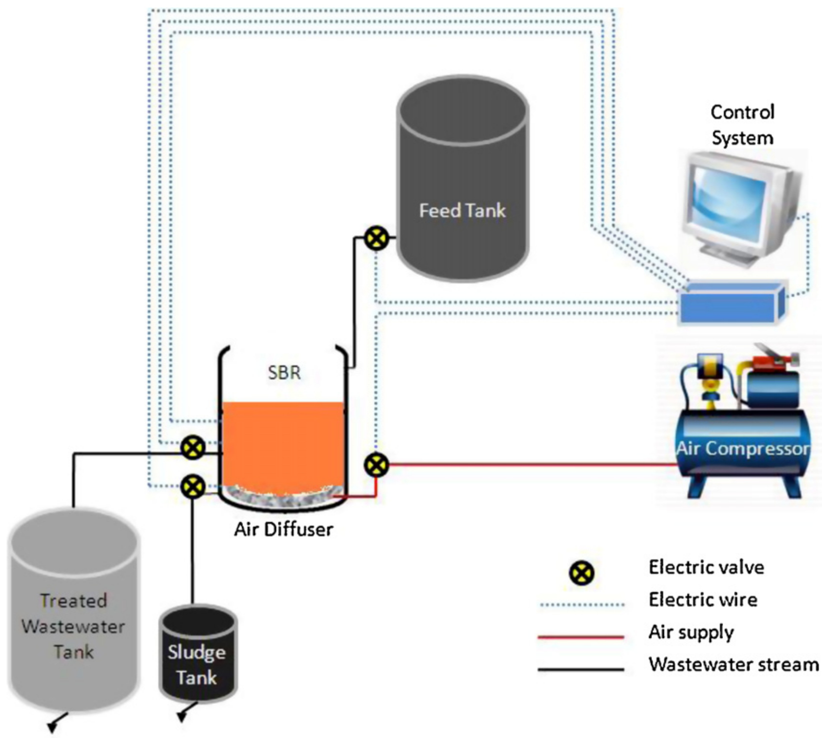

Fig. 1. Schematic of experimental setup.

activated sludge culture was grown in an aeration tank using the same synthetic wastewater with no Hg^{2+} and Cd^{2+} ions.

2.4. Phases of the study

This study was carried out in two phases. In the first phase the adaptability of the SBR with synthetic industrial wastewater and the acclimatization of microorganisms with the new environment were studied for 60 days. The second phase, which was the treatment of synthetic wastewater with different concentrations of mercury and cadmium, lasted 50 days. In order to allow the activated sludge to acclimatize with the wastewater containing mercury and cadmium, the heavy metals were added into the SBR gradually in order of 0.09 ± 0.01 mg/L, 1.03 ± 0.01 mg/L, 4.95 ± 0.01 mg/L and 9.03 ± 0.02 mg/L for mercury and 0.09 ± 0.01 mg/L, 2.22 ± 0.02 mg/L, 10.52 ± 0.22 mg/L, 15.52 ± 0.02 mg/L for cadmium.

2.5. Operation of the SBR

The SBR was operated on an 8-h cycle basis which consists of five distinct modes: fill, react, settle, draw and idle. Table 2 contains operational setting of the SBR and duration for each step in a cycle. At the beginning of each cycle a pre-defined volume was fed into the mixed liquor remaining in the reactor from the previous cycle. Then the reactor was aerated during reaction phase. After total reaction time of 4 h the reactor was allowed to settle for 2 h and the clarified supernatant was discharged from the SBR to the treated wastewater tank. A sample of treated effluent and discharged sludge was collected for analysis. Subsequently, the reactor was filled for the next cycle of reaction after 1.5 h of idle period.

Table 2
Operational setting of Sequencing Batch Reactor (SBR) system.

Parameters	Amount
Hydraulic retention time (HRT)	15 days
Cycle	3
Fill up step	15 min
React step	4 h
Settle step	2 h
Draw step	15 min
Idle step	1.5 h
Feed volume	1.6 L/day

2.6. Analyses

Chemical Oxygen Demand (COD), mixed liquor suspended solid (MLSS), mixed liquor volatile suspended solid (MLVSS), Sludge Volume Index (SVI), and mercury (Hg) and cadmium (Cd) concentrations were determined in accordance with the Standard Methods for the Examination of Water and Wastewater (APHA, 1992) [19]. COD was analyzed using reflux method and titration according to Standard Method 5220 B. MLSS and MLVSS are both used as measures of microorganism concentration in the activated sludge system. MLSS includes both the volatile and inert solids in the mixed liquor. MLVSS more closely approximates the biologically active portion of the solids in the mixed liquor, as microbial cellular material is organic and volatilizes or burns at 550 °C. Total suspended solids (TSS) and volatile suspended solids (VSS) were determined according to the Standard Methods 2540 D and E, respectively. SVI was analyzed before end of reaction phase by measuring the volume in millimeters occupied by 1 g of suspension after 30 min of settling. TSS was determined by filtering a sample through a glass fiber filter (Whatman grade GF/A, 1.6 μm) and the residue retained on the filter was dried in an oven (Therma, Germany), at 105 °C, whereas VSS was determined by ashing the dry sample in a 550 °C muffled furnace (Nabertherm, Germany), for 15 min. Mercury and cadmium were measured according to the Standard Methods 3112 (Cold-Vapor Atomic Absorption Spectrometric Method) and 3111 B (Direct Air-Acetylene Flame Method), respectively using atomic absorption spectrophotometer (AAS), Shimadzu, Japan. For the wastewater samples according to Standard Method 3030 B the samples were first filtered at the time of collection using a preconditioned plastic filtering device with vacuum containing a filter support of plastic, through a pre-washed ungridded 0.45-μm polycarbonate membrane filter. Mercury analysis was conducted at the wavelength of 253.7 nm. The absorption cell was installed and aligned in light path to give maximum transmission. The air flow rate was adjusted to 2 L/min and it was allowed to flow continuously and samples in the volume of 100 mL were measured. The cadmium samples were aspirated into a flame and atomized. A light beam was directed through the flame, into a monochromator, and onto a detector that measures the amount of light absorbed by the atomized cadmium in the flame.

2.7. Microbiological observations

Sludge was collected at idle stage to identify the microorganisms in the SBR. The identification of microorganisms and their metabolic characteristics is very important as certain conditions in engineered systems may be controlled to create selective pressure that will favor the growth of preferred microorganisms [20]. The method used to identify microorganisms relied on morphology. Collection of samples was done in nonreactive borosilicate glass which have been cleansed with distilled water and sterilized by dry heat for 60 min at a temperature of 170 °C. Photomicrography was carried out using an optical light microscope (Carl Zeiss, Germany), equipped with a camera (Nikon, Japan).

3. Results and discussion

3.1. Acclimatizing phase

Throughout the acclimatizing phase, the MLSS concentration demonstrated a steady rise from 1500 to 2200 mg/L as shown in Fig. 2a. Same trend was observed for MLVSS whereas it was increased from 1275 to 1870 mg/L. The rise in MLSS and MLVSS concentrations reflect the active growth of bacteria which indicates the success of start-up. The bacteria consumed organic matter and multiplied to form new cells. It was also found that the volatile fraction (MLVSS:MLSS ratio) coincides with the typical values given by Metcalf and Eddy (0.85) and Woodside and Kocurek (0.80) [20,21]. An adequate MLVSS concentration is maintained to ensure biomass concentration (bacterial population) is sufficient for biological reaction to take place during the aerobic degradation, so that process does not become overloaded [22,23]. A minimum MLVSS concentration is also critical to allow the development of a flocculent biomass. If the process is operated at MLVSS concentrations which is below the minimum value, bioflocculation will be poor, entrapment of particulate organic matter will be inadequate, and a good settling activated sludge floc will not be obtained [24]. As illustrated in Fig. 2b the acclimation was considered complete since the effluent COD was relatively constant after 17 days. COD removal efficiencies were between 66 and 88% in the startup stage and despite some fluctuations in the first few days, shows 80% removal efficiencies on average. An adapted population can be indicated by the effluent COD concentration reaching constant values, and the reactor MLVSS concentration gradually increasing [25]. Therefore, at this point the reactor was considered ready for receiving the heavy metals dosages. SVI is one of the important parameters to assess the stability of sludge in any aerobic suspended growth system. An SVI of 150 mg/L is often considered to be the dividing line between good (SVI < 150) and poor (SVI greater than 150) settling sludge [26]. In this study, the sludge exhibited good settling properties in the startup phase with average SVI of 58 as shown in Fig. 2c.

3.2. Reactor performance with Hg^{2+} and Cd^{2+} addition

For most industrial wastewaters, it is necessary to gradually expose the microbial community to potentially inhibitory or toxic organic compounds. This allows the development of appropriate enzyme producing genes that are essential to induce biodegradation [20]. Therefore, Hg^{2+} and Cd^{2+} were included in the feed from day 61 and their concentrations were gradually increased until day 110. Hg and Cd concentrations of 0.1 mg/L caused the COD removal to decrease from 84% to 75%. When mercury is introduced to water it will be transformed into methylated mercury by bacteria and becomes extremely toxic to biological systems [12]. As shown in Fig. 2b same trend was continued until the end of experiments and COD removal efficiencies was slightly decreased while the concentrations for Hg^{2+} and Cd^{2+} were increased gradually which indicates heavy metal inhibition of COD removal [27,28]. Reduction in COD removal efficiencies indicates the poor performance of microorganisms in the SBR and this can be observed through MLSS and MLVSS values during addition of Hg^{2+} and Cd^{2+}. From day 61 to day 85 the MLSS and MLVSS fell rapidly and then were decreased steadily until day 110 which shows the MLSS and MLVSS of 600 and 510 mg/L, respectively (Fig. 2a). Addition of heavy metals tends to result in poor settling behavior. Fig. 2c shows an upward trend in SVI results from day 61 to day 110 which reached 88. While average SVI after addition of heavy metals is 80 and less than 150 which is the benchmark for a good SVI, the comparison with its value before addition of heavy metals (58) indicates decrease in settleability of the sludge.

3.3. Mercury and cadmium removal efficiency in the SBR

As illustrated in Figs. 3 and 4, initially mercury and cadmium were added in low concentration of 0.10 mg/L. The results show mercury and cadmium removal was increasing and reached to 64% and 90%, respectively, on day 66. Following this the mercury and cadmium concentration was increased to 1.0 and 2.2 mg/L, respectively. An appreciable removal of heavy metals was observed in this period and the system could reduce the amounts of mercury from 1.0 mg/L to 0.08 mg/L and cadmium from 2.2 mg/L reached to 0.18 mg/L by day 73. Then the concentrations were increased by magnitude 5 which in this concentration for mercury, removal efficiency of SBR reduced sharply to 40%, but due to adaptation of microorganisms with new condition, it could reach more than 80% by day 85. In the same period, cadmium reduction was decreased slightly (76%) but it then rose to 95% by day 85. Finally, mercury and cadmium concentrations of 9.0 and 15.5 mg/L were introduced to the SBR. Decrease in mercury removal in the system was found on day 101, but finally it reached to 93.3% mercury removal while cadmium removal kept increasing from 95% to almost 99%.

Microorganisms have role to play in an increasing trend of biological treatment of metals. Fig. 5 illustrated the microorganisms' identification in the SBR. The microbiological observations indicated the presence of *Rhodospirilium*-like cells in the SBR system. This is in agreement with Srivastava and Majumder [29] who reported *Rhodospirilium* as a bacteria species which has the capability to treat wastewaters containing Hg and Cd. The diatom *Gomphonema*-like algae also was observed in the system. The presence of diatom *Gomphonema* in both unpolluted and metals polluted water bodies have been indicated [30]. It shows the activity of not only bacteria in the SBR but also algae. The presence of sulfate reducing bacteria (SRB) was observed in the SBR. McGregor et al. [31] have shown that SRB can be used to convert dissolved sulfate to sulfide, precipitating metals out as insoluble metal sulfides in the process. This treatment mechanism is potentially suitable for use with cobalt, cadmium, nickel, lead and zinc. Also it has

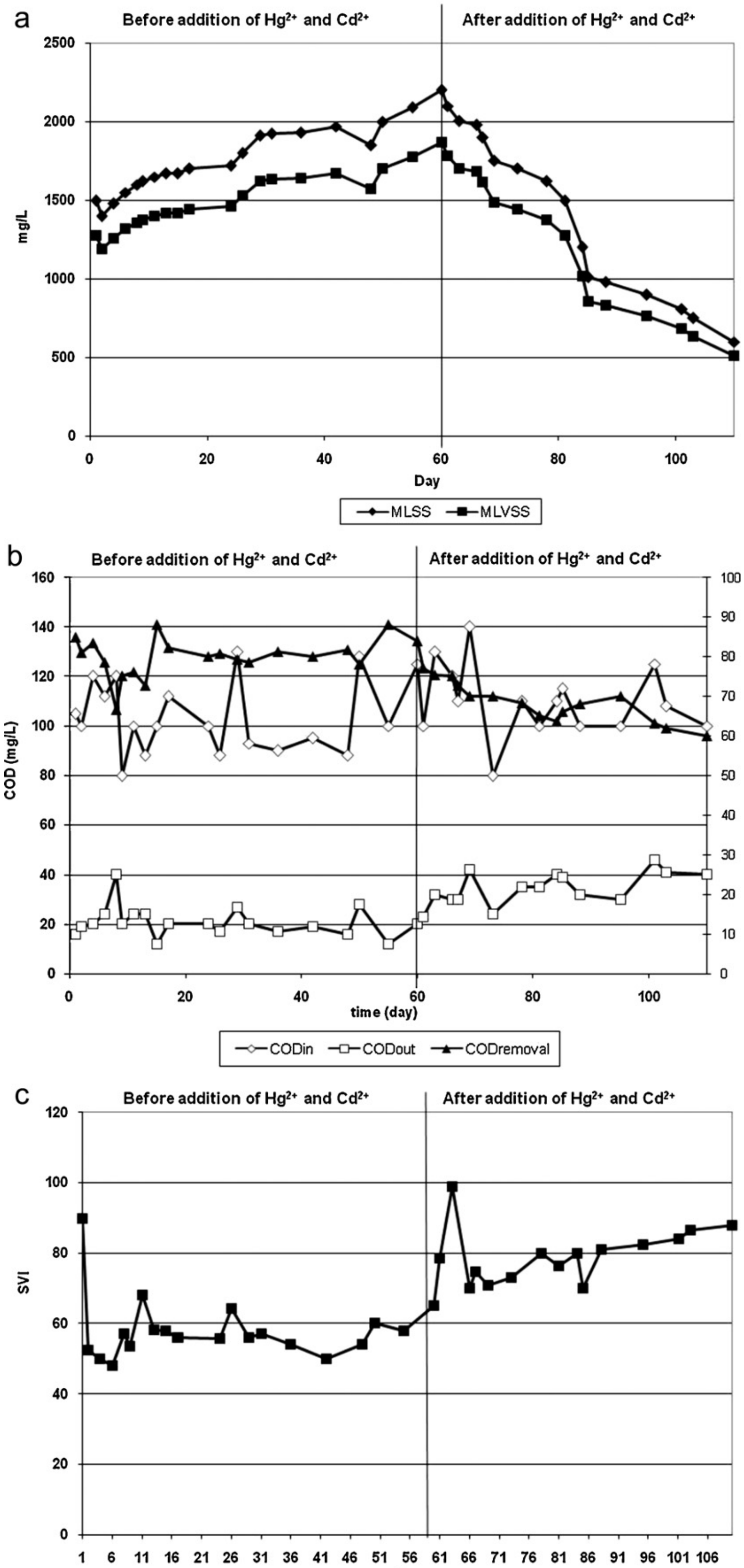

Fig. 2. SBR performance during 110-day operation: (a) MLSS and MLVSS concentrations, (b) COD removal efficiency and (c) SVI.

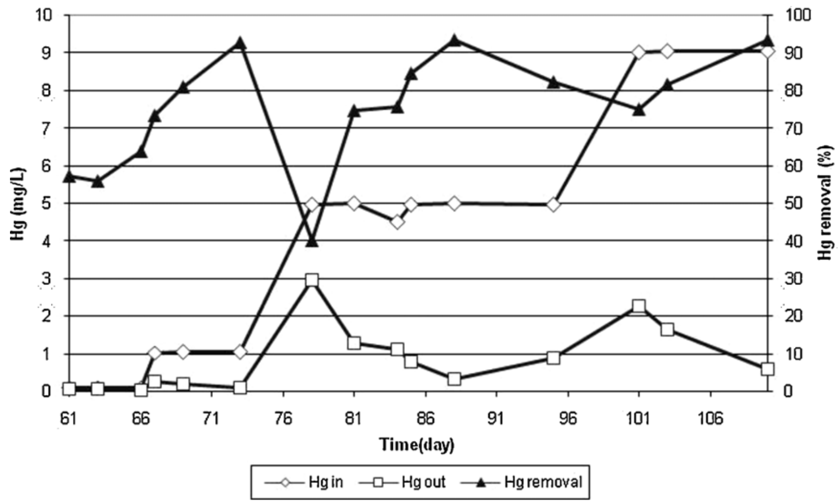

Fig. 3. Removal of different concentrations of mercury in SBR.

been proven that certain microorganisms have the ability to methylate metals such as selenium and mercury [32]. In a process called methylation, Hg is transformed into a form that can be accumulated in the cell of microorganisms. Microorganisms such as SRB can play an important role in the chemical transformation, including methylation, of mercury [33]. Although SRB are strict anaerobes, they should have developed adaptation strategies to protect themselves against oxygen in an aerobic SBR. These strategies can be

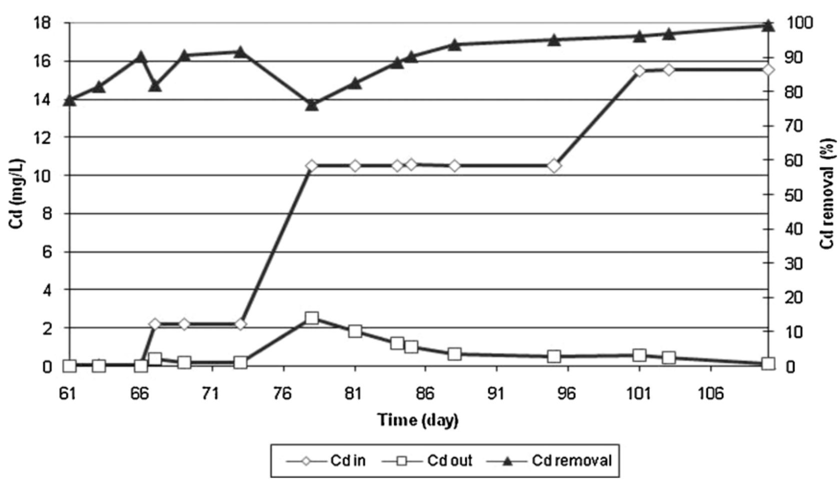

Fig. 4. Removal of different concentrations of cadmium in SBR.

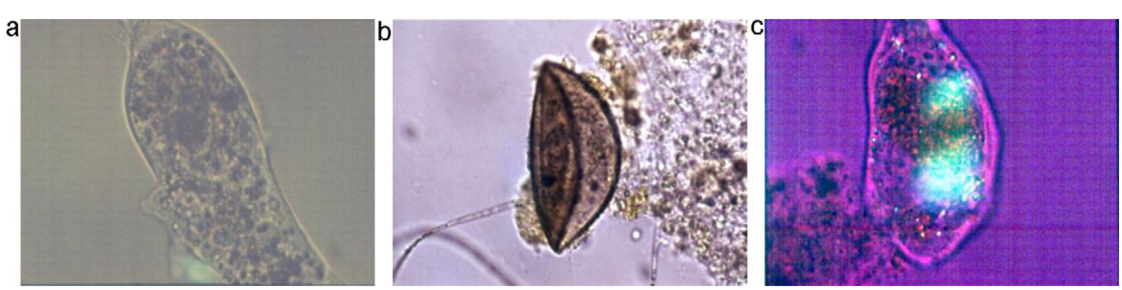

Fig. 5. Microscopic observation in the SBR during idle distinct mode: (a) *Rhodospirilium*-like bacteria, (b) *Gomphonema*-like algae and (c) sulfate reducing-like bacteria.

Table 3
Effect of heavy metals on COD removal efficiency in the SBR.

Mercury		Cadmium		COD	
Influent (mg/L)	Removal (%)	Influent (mg/L)	Removal (%)	Effluent (mg/L)	Removal (%)
0.09 ± 0.01	58.99 ± 3.54	0.09 ± 0.01	83.10 ± 5.32	28.33 ± 3.86	75.79 ± 0.87
1.03 ± 0.01	82.33 ± 7.93	2.22 ± 0.02	87.96 ± 4.45	32.00 ± 7.48	70.91 ± 1.29
4.95 ± 0.01	86.68 ± 4.82	10.52 ± 0.22	93.04 ± 2.01	33.67 ± 3.86	68.03 ± 1.60
9.03 ± 0.02	83.33 ± 7.63	15.52 ± 0.02	97.42 ± 1.28	42.3 ± 2.62	61.75 ± 1.32

distinguished into two groups: behavioral strategies and molecular strategies [34]. In addition, Lens et al. [35] have indicated that the SRB enumeration, together with activity and oxygen microprofile measurements showed that the biomass of aerobic wastewater treatment systems can serve as inoculum or as site for a wide spectrum of redox related biotransformation processes.

Table 3 contains the performance of the SBR in reduction of heavy metals as well as COD. It was observed that introducing any value of Hg and Cd to the SBR caused COD removal efficiencies to drop. Addition of heavy metals strongly affects COD removal efficiency (8–28%) the higher concentration of heavy metals the lower COD removal. On the other hand, in same duration, the removal efficiencies of heavy metals in each concentration were increased throughout the experiment. COD removal efficiency during addition of Hg and Cd to the SBR indicates the poor performances of microorganisms in the system. This can be proven by monitoring of population of active microbes via MLVSS concentrations which have been decreased from 1870 mg/L to 510 mg/L (Fig. 2a). However, the SBR has shown good performance in heavy metals removal (95% for mercury and 99% for cadmium) throughout the process even with considerable shortage of microorganisms.

It indicates that in addition to activities of microorganisms, removing some portion of heavy metals concentration from wastewater was done as a result of biosorption. This is in the agreement with other researches that have shown biosorption plays an important role in biological treatment of metals compounds [32,36–43]. Metal biosorption involves complex mechanisms of ion-exchange, chelation, adsorption by physical forces, and ion entrapment in inter and intrafibrillar capillaries and spaces of the cell structural network of a biosorbent [40]. Extracellular precipitation, complexing and subsequent accumulation, passive sorption at binding sites on the envelopes of cells and intracellular accumulation (metabolically mediated uptake) appear to be the main mechanisms for biosorption [44]. Free carboxyl groups in biomass change into carboxylate, which occurs during the reaction of the metal ions and carboxyl groups of the biosorbent. Furthermore, the ion-exchange process occur when the metal ions in the solution transfer from solution to biomass and chemical bonds form between the metal ions and the carboxyl, hydroxyl, and amine groups of the biomass [39,40,42,43].

4. Conclusions

The SBR shows a good performance for treatment of synthetic refinery wastewater containing Hg^{2+} and Cd^{2+}, which can achieve considerable COD, Hg^{2+} and Cd^{2+} removal. The study reveals that the COD removal efficiency is ranging from 66 to 88% before addition of heavy metals due to appropriate acclimatization of the biomass during start-up period and adequate retention of MLVSS concentration which contributes to high COD removal efficiency. MLVSS concentration (population of microorganisms) which has shown an appreciable growth during reactor start-up and reached to 1870 mg/L, was affected by heavy metals concentration increment in each step and finally its concentration has fallen to 510 mg/L. Settleability of the sludge also kept decreasing in same period by adding the heavy metals to the SBR. Both declination in MLVSS and poor sludge settling indicate the toxicity effects of Hg^{2+} and Cd^{2+} to microorganisms. Average Hg^{2+} and Cd^{2+} removal efficiencies is found to be 88.3% and 97.4% for the concentrations of 9.03 ± 0.02 mg/L Hg and 15.52 ± 0.02 mg/L Cd, respectively. It is caused by variety of microorganism such as bacteria and algae which have been generated in the SBR as well as heavy metals biosorption.

The obtained results in this study are useful in purposing SBR to the industries which have heavy metals in their effluents. High biomass retention, outstanding treatment efficiencies, easy operation, low cost, and minimal sludge bulking ascertain the SBR process as an attractive and promising alternative for biological treatment of industrial wastewater containing heavy metals.

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