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Effect of anoxic:oxic ratio on the efficiency and performance of sequencing batch reactor (SBR) system for treatment of industrial estate wastewater containing Cr^{3+} and Ni^{2+}

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ABSTRACT

Application of sequencing batch reactor (SBR) system for treatment of synthetic industrial estate wastewater (SIWW) containing high Cr^{3+} and Ni^{2+} concentrations of 3.0 mg/L (SIWW + Cr^{3+} and SIWW + Ni^{2+}) at hydraulic retention time (HRT) of 1.5 d at various oxic: anoxic ratios of 19:0, 13:6, 11:8, and 9:10 in the reaction step of operation was examined. The highest Ni^{2+} and Cr^{3+} removal efficiencies of 93.1 ± 0.9% and 95.4 ± 0.2%, respectively, were detected with SIWW + Cr^{3+} and SIWW + Ni^{2+} at the oxic:anoxic ratio of 9:10. Moreover, the maximum Cr^{3+} and Ni^{2+} adsorption abilities of bio-sludge in the system were 36.00 ± 9.80 and 31.59 ± 9.67 mg/g of bio-sludge at the 19:0 oxic:anoxic ratio. Heavy metals (HM) adsorption abilities could be increased by adding anoxic period in the reaction step. The average Cr^{3+} and Ni^{2+} adsorption abilities of bio-sludge at oxic:anoxic ratio of 9:10 were 20.8 ± 4.1 mg Ni^{2+}/g bio-sludge and 23.12 ± 6.0 mg Cr^{3+}/g bio-sludge. Cr^{3+} and Ni^{2+} concentrations of 3.0 mg/L had a strong repression effect on the growth and activity of the carbonaceous BOD_5 removal microbes (heterotrophic bacteria). However, they slightly affected nitrifying and denitrifying bacteria. Nitrifying and denitrifying bacteria were the main microbes for HM adsorption mechanism in the SBR system. The advantage of SBR system was that after adding anoxic period in the reaction step, removal efficiencies of organic matter and HM increased.

Keywords: Adsorption; Chromium; Heavy metals; Industrial estate wastewater; Nickel; Sequencing batch reactor (SBR)

1. Introduction

Industrial estate parks are established on the concept of easy operation and controlled use of resources and wastes treatment [1,2]. Therefore, the projects are considered on areas that are suitable for future exploitation and have sufficient amount of resources and facilities such as water, electricity, and waste treatment system for the factories [2,3]. Normally, in an industrial estate park there is only one type of industry, e.g. petrochemical, food processing, electronic industrial estates, that are easy to manage and operate. In such case, a wastewater treatment system is easy to select and operate. However, some

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industrial estate parks consist of several types of industry such as food processing, electroplating, metal-processing, paint and batteries industries together [2,3]. Wastewater from above-mentioned parks contains not only organic matter but also inorganic matter, especially heavy metals (HM). Selection of wastewater treatment process for the above-mentioned type of wastewater should be carefully considered [1,2]. Theoretically, biological treatment is suitable for organic wastewater [2,4,5] while chemical treatment is suitable for inorganic wastewater [2,6–8]. It is well known that wastewater containing both organic and inorganic matter cannot be treated by the usual biological treatment process [1,2]. Many researchers reported that biological process could be applied for treating organic wastewater contaminated with HM, considering type and concentration of HM which are toxic to the growth and activity of bio-sludge [9–15]. Moreover, several kinds of HM such as lead, cadmium, copper, and zinc could be adsorbed on the surface of microbial cells [3,16–19]. HM adsorption capacity of the bio-sludge depended on the type of microbes [4,18–25]. According to that information, the application of sequencing batch reactor (SBR) for the treatment of wastewater containing both organic waste and HM might be most suitable. However, operation conditions should be investigated to find the dominant microbe for removing both organic matter and HM. In this study, various anoxic–oxic ratios in the reaction step in the SBR system operation were tested with synthetic industrial estate wastewater (SIWW) containing Cr^{2+} and Ni^{2+} to determine highest removal efficiencies.

2. Materials and methods

2.1. Wastewater samples

Three kinds of SIWW samples prepared according to the Ladkrabang Industrial Estate Wastewater (LIWW) (Table 1) were used in this study as follows: synthetic industrial estate wastewater without HM (SIWW), SIWW containing 3.0 mg/L Ni^{2+} (SIWW + Ni^{2+}), and SIWW containing 3.0 mg/L Cr^{3+} (SIWW + Cr^{3+}). Chemical compositions of each type of wastewater are shown in Table 1. The 6.6 mg/L of $NiCl_2$ and 18.0 mg/L $Cr(NO_3)_3 \cdot 9H_2O$ were added to SIWW for preparing SIWW + Ni^{2+} and SIWW + Cr^{3+}, respectively.

2.2. Acclimatization of bio-sludge

Bio-sludge from bio-sludge storage tank of the Bangkok Municipal Sewage Treatment Plant, Thailand (Sripaya Sewage Treatment Plant) was acclimatized with SIWW at HRT of 1.5 d for 1 week before using as inoculum in the SBR system.

2.3. Sequencing batch reactor (SBR)

Ten 10 L reactors, made from acrylic plastic (5 mm thick), as shown in Fig. 1, were used in the experiments. Each reactor had 18 cm diameter and 40 cm height with a working volume of 7.5 L. Complete mixing in the reactor was adjusted by controlling the speed of the paddle-shaped impeller to 60 rpm. A low speed gear motor, P 630A-387 model, 100 V, 50/60 Hz, 1.7/1.3 A (Japan Servo Co., Ltd, Japan) was used for driving the impeller. One set of air pumps, model EK-8000, 6.0 W (President Co., Ltd, Thailand), was used for supplying air for two sets of reactors (the system had enough oxygen as evidenced by the dissolved oxygen in the system of about 2–3 mg/l). The excess of sludge was removed during the draw and idle period to control mixed liquor suspended solids (MLSS) of the system (Table 2a).

2.4. Operation of SBR system

SBR system was operated at 1 cycle/d under a HRT of 1.5 d. Exactly 1.4 L of 10 g/L of acclimatized bio-sludge from Section 2.2 was inoculated in each reactor and the three types of SIWW were added (final volume of 7.5 L) within 1 h. During the reaction period (19 h), the system was sequenced into anoxic and oxic periods; anoxic–oxic ratios were 13:6, 11:8, and 9:10, as shown in Table 2b. Then, the reactor was shut down for 3 h. After the sludge was fully settled, the supernatant was drawn out within 0.5 h and the system was kept under anoxic conditions for 0.5 h. After that, the reactor was filled with fresh wastewater to the final volume of 7.5 L and the operation was repeated. Operation parameters of the SBR system with SIWWs are described in Table 2a. The samples were taken for chemical analysis during the operation, as shown in Table 2b.

2.5. Chemical analysis

Chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), organic-N, NH_4^+-N, NO_3^--N, NO_2^--N, total nitrogen (TN), Cr^{3+}, Ni^{2+}, suspended solids (SS), total dissolved solids (TDS), MLSS, mixed liquor volatile suspended solids (MLVSS), organic (organic) and inorganic matter (inorganic) as well as the pH of influent and effluent, as well as sludge volume index (SVI) of the SBR system were determined

Table 1
Chemical compositions and properties of LIWW and SIWWs

Parameters	Chemical properties				Chemical composition	
	LIWW[a]	SIWW[b]	SIWW + Ni^{2+}[c]	SIWW + Cr^{3+}[d]	Parameters	Concentration (mg/L)
COD (mg/L)	369 ± 76	480 ± 7	480 ± 6	480 ± 5	Glucose	282
BOD_5 (mg/L)	222 ± 12	230 ± 3	230 ± 3	230 ± 3	$Cr(NO_3)_3 \cdot 9H_2O$[e]	18.0
Organic-N (mg/L)	8.3 ± 0.6	8.1 ± 0.4	8.1 ± 0.4	8.1 ± 0.4	$NiCl_2$[f]	6.6
NH_4^+-N (mg/L)	8.3 ± 0.5	8.5 ± 0.2	8.5 ± 0.2	8.5 ± 0.2	Urea	21.4
NO_2^--N (mg/L)	6.7 ± 0.2	2.2 ± 0.2	2.2 ± 0.2	2.2 ± 0.2	KH_2PO_4	8.72
NO_3^--N (mg/L)	5.8 ± 0.7	5.3 ± 0.3	5.3 ± 0.3	5.3 ± 0.3	$FeSO_4 \cdot 7H_2O$	4.978
TN (mg/L)	29.2 ± 0.9	24.1 ± 0.3	24.1 ± 0.3	24.1 ± 0.3		
Ni^{2+} (mg/L)	0.30 ± 0.03	0.00 ± 0.00	3.03 ± 0.07	0.00 ± 0.00		
Cr^{3+} (mg/L)	0.13 ± 0.02	0.00 ± 0.00	0.00 ± 0.00	3.01 ± 0.05		
SS (mg/L)	149 ± 42	11 ± 4	21 ± 3	21 ± 3		
Others heavy metals (mg/L)	6.29 ± 0.05	–	–	–		
Organic/SS	0.3 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.6 ± 0.1		
Inorganic/SS	0.7 ± 0.1	0.4 ± 0.1	0.4 ± 0.1	0.4 ± 0.1		
TDS (mg/L)	383 ± 43	341 ± 20	354 ± 4	383 ± 43		
Organic/TDS	0.3 ± 0.1	0.6 ± 0.1	0.6 ± 0.1	0.6 ± 0.1		
Inorganic/TDS	0.7 ± 0.1	0.4 ± 0.1	0.4 ± 0.1	0.4 ± 0.1		

[a]LIWW: Raw Ladkrabang Industrial Estate Wastewater.
[b]SIWW: synthetic industrial estate wastewater.
[c]SIWW + Ni^{2+}: SIWW containing 6.6 mg/L $NiCl_2$.
[d]SIWW + Cr^{3+} : SIWW containing 18.0 mg/L $Cr(NO_3)_3 \cdot 9H_2O$.
[e]For SIWW + Cr^{3+} and LIWW + Cr^{3+}.
[f]For SWW + Ni^{2+} and LIWW+Ni^{2+}.

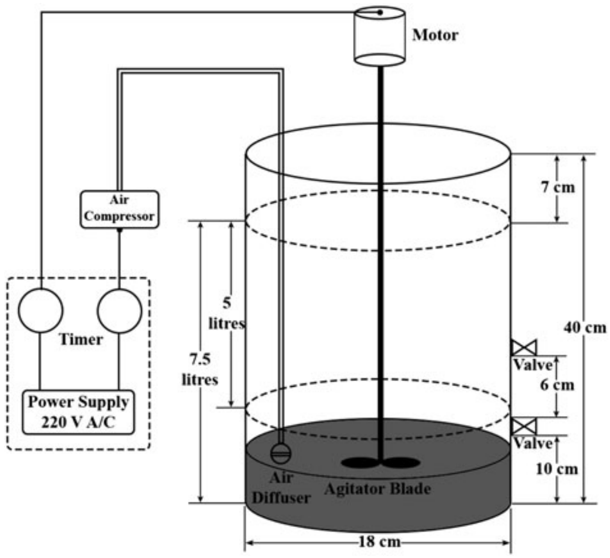

Fig. 1. Schematic diagram of SBR treatment system.
Notes: The physical operation control was 60 rpm of impeller speed, full aeration with an air-pump system model EK-8000, 6.0 W (one set of air pumps supplied for two sets of reactors). Working volume of the reactor was 75% of the total volume (7.5 L). Chemical and biological operations controls were described in the text according to each experiment.

according to standard methods for the examination of water and wastewater [26]. Bio-sludge age was determined by the ratio of total biomass (mixed liquor suspended solids: MLSS) of the system to the amount of the excess of sludge wasted per day.

2.6. Statistical analysis method

Each experiment was repeated at least three times. All the data were subjected to two-way analysis of variance using SAS Windows Version 6.12 [27]. Statistical significance was tested using least significant difference at the $p < 0.05$ level. The results shown are the mean ± standard deviation.

3. Results

3.1. Effects of Ni^{2+} and Cr^{3+} on the efficiency and performance of the SBR system with SIWWs

The experiments were carried out in a laboratory SBR system with SIWWs at HRT of 1.5 d and oxic: anoxic ratio of 19:0 for 80 d. The effects of Ni^{2+} and Cr^{3+} on the SBR system efficiency and performance with SIWWs were described as follows:

3.1.1. BOD_5 and COD

The system with SIWW at HRT of 1.5 d showed the BOD_5 and COD removal efficiencies of 79 ± 3% and 82 ± 2%, respectively, as shown in Table 3a. BOD_5 removal efficiencies decreased after adding HM (3.0 mg/L Ni^{2+} or 3.0 mg/L Cr^{3+}). BOD_5 removal efficiencies with SIWW + Ni^{2+} and SIWW + Cr^{3+} decreased to 67 ± 4 and 67 ± 3%, respectively, as shown in Table 3a. Also, COD removal efficiencies decreased to 74 ± 3 and 73 ± 3%, respectively, as shown in Table 3a. Moreover, effluent BOD_5 with SIWWs reached the steady state after 2 weeks of operation; then, it remained stable during 80 d of operation, as shown in Fig. 2.

3.1.2. Nitrogen compounds

TN removal efficiency in the SBR system with SIWW was 30.6 ± 5.5%, as shown in Table 3a. Moreover, Cr^{3+} and Ni^{2+} had a repression effect on the nitrogenous compounds removal efficiency, as shown

Table 2a
Operation of the SBR system used to treat SIWWs

Parameter	SIWW	SIWW + Ni^{2+}	SIWW + Cr^{3+}
HRT (d)	1.5	1.5	1.5
MLSS (mg/L)	2,000	2,000	2,000
Flow rate (mL/d)	5	5	5
F/M ratio	0.075	0.075	0.075
BOD_5 loading (g/d)	1.15	1.15	1.15
Volumetric BOD_5 loading (kg BOD_5/m^3 d)	0.15	0.15	0.15
Volumetric Ni^{2+}loading (g Ni^{2+}/m^3 d)	0.00	2.02	0.00
Volumetric Cr^{3+}loading (g Cr^{3+}/m^3 d)	0.00	0.00	2.01

Notes: Each operation cycle of the SBR system lasted 24 h. Each cycle consisted of four steps: fill-up step, reaction step, settling step, and draw and idle step, consecutively.
Total period of the reaction step was about 19 h. During the reaction step, operation was controlled to be oxic and anoxic consecutively, as shown below.

Table 2b
Operation of the SBR system used to treat SIWWs

(1) Cycle of operation (24 h) Step of operation (h)		Reaction step of SBR operation: oxic:anoxic ratio (h) 13:6	11:8	9:10	19:0[a]	Sampling point
1: Fill		1	1	1	1	Sampling[b]
2: Reaction The system	Anoxic	4	5	0		Sampling[b]
was operated under	Oxic	6	5	10		
anoxic and oxic	Anoxic	4	5	0		
conditions consecutively	Oxic	5	4	9		
3: Settling		3	3	3	3	Sampling[b]
4: Draw and idle		1	1	1	1	

[a]The samples were taken for determining chemical properties at settling step only.
[b]The samples were taken after each step of the operation to determine heavy metals in wastewater and bio-sludge for determining chemical properties.

Table 3a
Effluent properties, bio-sludge properties, and removal efficiency in the SBR system operated with SIWW, SIWW + Ni^{2+}, and SIWW + Cr^{3+} at HRT of 1.5 d and oxic:anoxic ratio of 19:0 for 80 d

Parameters of supernatant	SIWW		SIWW+Ni^{2+}		SIWW+Cr^{3+}	
	Effluent (mg/L)	Removal (%)	Effluent (mg/L)	Removal (%)	Effluent (mg/L)	Removal (%)
BOD_5	49 ± 4	79 ± 3	77 ± 8	67 ± 4	75 ± 5	67 ± 3
COD	84 ± 9	82 ± 2	124 ± 10	74 ± 3	130 ± 4	73 ± 3
Organic-N	3.2 ± 0.1	59.3 ± 1.3	4.0 ± 0.3	49.1 ± 3.7	3.8 ± 0.3	51.2 ± 3.7
NH_4^+-N	4.4 ± 0.3	48.9 ± 3.5	5.3 ± 0.4	38.5 ± 4.2	5.5 ± 0.6	35.8 ± 6.8
NO_2^--N	1.5 ± 0.2	–	1.5 ± 0.1	–	1.6 ± 0.1	–
NO_3^--N	7.8 ± 1.1	–	7.7 ± 0.6	–	8.5 ± 0.6	–
TN	16.8 ± 1.3	30.6 ± 5.5	18.4 ± 0.6	24.0 ± 2.5	19.4 ± 1.0	20.2 ± 4.0
Ni^{2+}	–	–	0.43 ± 0.27	85.9 ± 8.8	–	–
Cr^{3+}	–	–	–	–	0.25 ± 0.12	91.6 ± 3.9

in Table 3a. Cr^{3+} and Ni^{2+} could repress TN removal efficiencies from 30.6 ± 5.5% to 24.0 ± 2.5% and 20.2 ± 4.0%, respectively, as shown in Table 3a. Moreover, organic-N and NH_4^+-N removal efficiencies were repressed by adding Cr^{3+} and Ni^{2+}, as shown in Table 3a. The amount of effluent organic-N and NH_4^+-N was increased by adding Cr^{3+} and Ni^{2+}. However, the system with SIWW, SIWW + Cr^{3+}, and SIWW + Ni^{2+} did not show any significant differences in the NO_2^--N and NO_3^--N effluents, as shown in Table 3a.

3.1.3. HM (Cr^{3+} and Ni^{2+})

The SBR system with SIWW + Cr^{3+} and SIWW + Ni^{2+} at HRT of 1.5 d showed high Cr^{3+} and Ni^{2+} removal efficiencies of 91.6 ± 3.9% and 85.9 ± 8.8%, respectively, as shown in Table 3a. Influent and effluent Cr^{3+} with SIWW + Cr^{3+} were 3.01 ± 0.05 mg/L and 0.25 ± 0.27 mg/L, respectively, as shown in Table 3a. Influent and effluent Ni^{2+} with SIWW + Ni^{2+} were 3.03 ± 0.07 mg/L and 0.43 ± 0.27 mg/L, respectively, as shown in Table 3a. In terms of adsorbed HM on the bio-sludge, it showed highest Ni^{2+} and Cr^{3+} adsorption yields of 31.59 ± 9.67 mg/g bio-sludge and 36.00 ± 9.80 mg/g bio-sludge, respectively as shown in Table 3b. However, the average adsorbed Ni^{2+} and Cr^{3+} of bio-sludge in the SBR system with SIWW + Cr^{3+} and SIWW + Ni^{2+} at HRT of 1.5 d were 14.49 ± 8.94 mg/g and 23.18 ± 8.64 mg/g, respectively. Moreover, the effluent HM increased after three and eight weeks of the operation; also, the amount of adsorbed HM on the bio-sludge decreased, as shown in Fig. 2. Observation of the profiles of the effluent HM and adsorbed HM on the bio-sludge showed that the systems with SIWW + Cr^{3+} and SIWW + Ni^{2+} had almost the same patterns as the effluent HM decreased while the adsorbed HM on the bio-sludge increased. However, HM adsorption abilities of the bio-sludge depended on the time of

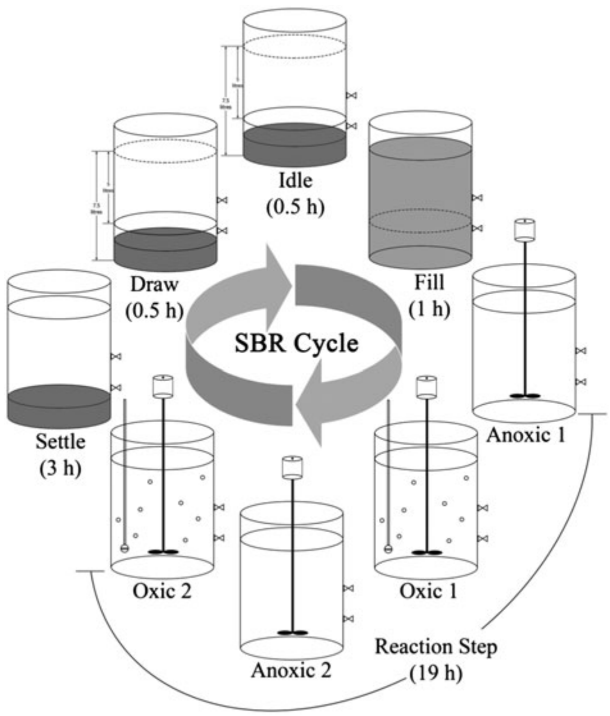

Fig. 2. Flow diagram of the SBR treatment system operation steps of each cycle.

operation. For example, the HM adsorption abilities after 60 d operation were 20% higher than those after 30 d operation, as shown in Fig. 2.

3.1.4. SS and TDS

The system with SIWWs at HRT of 1.5 d gave interesting results according to which effluent SS and TDS increased by adding HM (Ni^{2+} or Cr^{3+}). Effluent SS with SIWW was 12 ± 4 mg/L, while the effluent SS with SIWW + Cr^{3+} and SIWW + Ni^{2+} were 33 ± 7 mg/L and 40 ± 7 mg/L, respectively, as shown in Table 3a. Effluent TDS with SIWW, SIWW + Cr^{3+} and SIWW + Ni^{2+} were 120 ± 23 mg/L, 149 ± 17 mg/L, and 144 ± 29 mg/L, respectively. Determination of organic content of SS and TDS, organic/SS and organic/TDS with SIWW, SIWW + Cr^{3+} and SIWW + Ni^{2+} showed that they accounted for 0.7 ± 0.2 and 0.5 ± 0.2, 0.6 ± 0.1 and 0.5 ± 0.1, and 0.6 ± 0.2 and 0.6 ± 0.2, respectively. Moreover, the MLVSS/MLSS of the system with SIWW, SIWW + Cr^{3+}, and SIWW + Ni^{2+} were mostly the same and accounted for 0.8 ± 0.1, as shown in Table 3b. However, effluent SS with SIWWs slightly increased during the operation, as shown in Fig. 2.

Observation of SS profiles showed that the amount of effluent SS with SIWW + Cr^{3+} and SIWW + Ni^{2+} increased after long time operation (80 d) as shown in Fig. 2. However, effluent SS of the system with SIWW was almost stable during 80 d of operation, as shown in Fig. 2.

3.1.5. Bio-sludge performance

Cr^{3+} and Ni^{2+} strongly affected bio-sludge age (SRT) of the SBR system, as shown in Table 3a. SRT increased by adding Cr^{3+}or Ni^{2+}. SRTs with SIWW, SIWW + Cr^{3+}, and SIWW + Ni^{2+} at HRT of 1.5 d were 5.5 ± 1.5 d, 8 ± 2 d, and 8 ± 1 d, respectively. Moreover, SVI with SIWW, SIWW + Cr^{3+}, and SIWW + Ni^{2+} were 90 ± 3 mL/g, 140 ± 8 mL/g, and 130 ± 7 mL/g, respectively.

Table 3b
Effluent properties, bio-sludge properties, and removal efficiency in the SBR system operated with SIWW, SIWW + Ni^{2+}, and SIWW + Cr^{3+} at HRT of 1.5 d and oxic:anoxic ratio of 19:0 for 80 d

Parameter of bio-sludge	SIWW	SIWW + Ni^{2+}	SIWW + Cr^{3+}
Ni^{2+} in bio-sludge (mg/g) in SBR system	–	14.49 ± 8.94	–
Max Ni^{2+} in bio-sludge (mg/g) in Jar test	–	31.59 ± 9.67	–
Cr^{3+} in bio-sludge (mg/g) in SBR system	–	–	23.18 ± 8.64
Max Cr^{3+} in bio-sludge (mg/g) in Jar test	–	–	36.00 ± 9.80
Effluent SS (mg/L)	12 ± 4	40 ± 7	33 ± 7
Organic/SS	0.7 ± 0.2	0.6 ± 0.1	0.6 ± 0.1
Effluent TDS (mg/L)	120 ± 23	149 ± 17	144 ± 29
Organic/TDS	0.5 ± 0.2	0.6 ± 0.2	0.5 ± 0.1
MLVSS/MLSS	0.8 ± 0.1	0.8 ± 0.1	0.8 ± 0.1
SVI (mL/g)	84 ± 9	121 ± 7	141 ± 9
Bio-sludge age or SRT (d)	7 ± 2	11 ± 4	9 ± 2

Table 4
Removal efficiencies and effluent properties in the SBR system with SIWWs.

		BOD_5		COD		Effluent qualities			
Type of wastewater	Oxic:anoxic	Effluent (mg/L)	Removal (%)	Effluent (mg/L)	Removal (%)	SS (mg/L)	Org./SS	TDS (mg/L)	Org./TDS
SIWW	19:0	44 ± 2	81 ± 1	91 ± 15	81 ± 1	15 ± 2	0.6 ± 0.1	152 ± 5	0.4 ± 0.1
SIWW + Ni^{2+}	19:0	73 ± 7	68 ± 3	132 ± 14	73 ± 3	26 ± 3	0.5 ± 0.1	142 ± 3	0.6 ± 0.1
SIWW + Cr^{3+}	19:0	70 ± 3	70 ± 2	130 ± 5	73 ± 2	27 ± 3	0.5 ± 0.1	140 ± 2	0.5 ± 0.1
SIWW	13:6	40 ± 1	85 ± 1	53 ± 3	86 ± 1	25 ± 2	0.5 ± 0.0	132 ± 1	0.5 ± 0.1
SIWW + Ni^{2+}	13:6	59 ± 2	78 ± 1	89 ± 2	77 ± 1	40 ± 4	0.6 ± 0.1	149 ± 3	0.6 ± 0.1
SIWW + Cr^{3+}	13:6	59 ± 2	77 ± 1	88 ± 4	77 ± 1	38 ± 4	0.6 ± 0.1	130 ± 5	0.6 ± 0.0
SIWW	11:8	38 ± 2	86 ± 1	51 ± 2	87 ± 1	23 ± 1	0.5 ± 0.0	124 ± 2	0.5 ± 0.0
SIWW + Ni^{2+}	11:8	55 ± 3	79 ± 1	86 ± 3	78 ± 1	36 ± 3	0.6 ± 0.0	140 ± 7	0.6 ± 0.0
SIWW + Cr^{3+}	11:8	56 ± 2	78 ± 1	84 ± 3	78 ± 1	32 ± 3	0.6 ± 0.0	125 ± 5	0.6 ± 0.1
SIWW	9:10	35 ± 2	87 ± 1	48 ± 2	88 ± 1	20 ± 2	0.5 ± 0.0	123 ± 7	0.6 ± 0.1
SIWW + Ni^{2+}	9:10	53 ± 3	80 ± 1	82 ± 4	79 ± 1	30 ± 3	0.6 ± 0.1	144 ± 4	0.6 ± 0.0
SIWW + Cr^{3+}	9:10	54 ± 3	79 ± 1	81 ± 3	79 ± 1	28 ± 4	0.6 ± 0.1	120 ± 10	0.6 ± 0.0

Table 5
Nitrogenous compounds removal efficiencies and effluent properties in the SBR system with SIWWs

		Organic-N (mg/L)		NH_4^+-N (mg/L)		NO_2^--N (mg/L)		NO_3^--N (mg/L)		TN	
Type of wastewater	Oxic:anoxic	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Effluent (mg/L)	Removal (%)
SIWW	19:0	8.1 ± 0.4	3.2 ± 0.1	8.5 ± 0.2	4.5 ± 0.5	2.2 ± 0.2	1.5 ± 0.1	5.3 ± 0.3	9.2 ± 0.6	18.4 ± 0.7	24.2 ± 3.0
SIWW + Ni^{2+}	19:0	8.1 ± 0.4	3.8 ± 0.4	8.5 ± 0.2	5.4 ± 0.5	2.2 ± 0.2	1.5 ± 0.2	5.3 ± 0.3	8.7 ± 0.7	19.5 ± 0.9	19.7 ± 3.8
SIWW + Cr^{3+}	19:0	8.1 ± 0.4	3.6 ± 0.1	8.5 ± 0.2	6.1 ± 0.5	2.2 ± 0.2	1.6 ± 0.1	5.3 ± 0.3	9.0 ± 0.4	20.3 ± 0.9	18.4 ± 3.6
SIWW	13:6	8.1 ± 0.4	3.1 ± 0.2	8.5 ± 0.2	3.5 ± 0.2	2.2 ± 0.2	1.5 ± 0.1	5.3 ± 0.3	5.7 ± 0.2	13.8 ± 0.3	42.8 ± 1.4
SIWW + Ni^{2+}	13:6	8.1 ± 0.4	3.4 ± 0.2	8.5 ± 0.2	3.6 ± 0.2	2.2 ± 0.2	1.2 ± 0.1	5.3 ± 0.3	7.0 ± 0.3	15.1 ± 0.4	37.4 ± 1.8
SIWW + Cr^{3+}	13:6	8.1 ± 0.4	3.5 ± 0.2	8.5 ± 0.2	3.7 ± 0.2	2.2 ± 0.2	1.5 ± 0.1	5.3 ± 0.3	6.8 ± 0.3	15.5 ± 0.5	35.8 ± 2.2
SIWW	11:8	8.1 ± 0.4	3.5 ± 0.2	8.5 ± 0.2	3.6 ± 0.2	2.2 ± 0.2	1.5 ± 0.1	5.3 ± 0.3	5.0 ± 0.1	13.6 ± 0.2	43.4 ± 0.9
SIWW + Ni^{2+}	11:8	8.1 ± 0.4	4.0 ± 0.2	8.5 ± 0.2	3.8 ± 0.2	2.2 ± 0.2	1.3 ± 0.1	5.3 ± 0.3	5.8 ± 0.2	14.9 ± 0.4	38.4 ± 1.8
SIWW + Cr^{3+}	11:8	8.1 ± 0.4	4.2 ± 0.3	8.5 ± 0.2	3.9 ± 0.1	2.2 ± 0.2	1.4 ± 0.1	5.3 ± 0.3	5.8 ± 0.2	15.3 ± 0.6	36.6 ± 2.3
SIWW	9:10	8.1 ± 0.4	4.0 ± 0.3	8.5 ± 0.2	3.7 ± 0.2	2.2 ± 0.2	1.5 ± 0.1	5.3 ± 0.3	4.3 ± 0.1	13.5 ± 0.4	44.2 ± 1.8
SIWW + Ni^{2+}	9:10	8.1 ± 0.4	4.4 ± 0.2	8.5 ± 0.2	3.9 ± 0.1	2.2 ± 0.2	1.3 ± 0.2	5.3 ± 0.3	5.1 ± 0.2	14.6 ± 0.2	39.4 ± 0.9
SIWW + Cr^{3+}	9:10	8.1 ± 0.4	4.7 ± 0.4	8.5 ± 0.2	4.0 ± 0.1	2.2 ± 0.2	1.4 ± 0.2	5.3 ± 0.3	5.1 ± 0.2	15.2 ± 0.5	37.1 ± 1.9

Table 6
HM and bio-sludge properties in the SBR system with SIWWs

		Nickel				Chromium				Bio-sludge properties			
				Bio-sludge (mg/g bio-sludge)				Bio-sludge (mg/g bio-sludge)					
Type of wastewater	Oxic: anoxic	Effluent (mg/L)	Removal (%)	Average ($\bar{x}$ ± SD)	Maximum	Effluent (mg/L)	Removal (%)	Average ($\bar{x}$ ± SD)	Maximum	F/M	MLVSS/ MLSS	Sludge age (d)	SVI (mL/g)
SIWW	19:0	–	–	–	–	–	–	–	–	0.075	0.7 ± 0.1	5 ± 1	92 ± 2
SIWW + Ni^{2+}	19:0	0.34 ± 0.04	88.8 ± 1.2	11.6 ± 6.0	14.44	–	–	–	–	0.075	0.8 ± 0.1	8 ± 2	126 ± 6
SIWW + Cr^{3+}	19:0	–	–	–	–	0.28 ± 0.05	90.7 ± 0.9	11.3 ± 3.1	17.02	0.075	0.8 ± 0.1	8 ± 1	149 ± 9
SIWW	13:6	–	–	–	–	–	–	–	–	0.075	0.7 ± 0.0	7 ± 1	83 ± 6
SIWW + Ni^{2+}	13:6	0.27 ± 0.03	91.2 ± 1.0	14.0 ± 2.6	17.58	–	–	–	–	0.075	0.7 ± 0.0	10 ± 1	84 ± 4
SIWW + Cr^{3+}	13:6	–	–	–	–	0.19 ± 0.02	93.7 ± 0.6	15.8 ± 2.8	18.66	0.075	0.7 ± 0.0	11 ± 1	70 ± 5
SIWW	11:8	–	–	–	–	–	–	–	–	0.075	0.8 ± 0.0	8 ± 1	86 ± 2
SIWW + Ni^{2+}	11:8	0.23 ± 0.03	92.5 ± 1.0	17.2 ± 3.9	22.76	–	–	–	–	0.075	0.7 ± 0.0	11 ± 1	91 ± 2
SIWW + Cr^{3+}	11:8	–	–	–	–	0.17 ± 0.02	94.3 ± 0.5	20.2 ± 4.8	26.00	0.075	0.7 ± 0.0	11 ± 1	89 ± 2
SIWW	9:10	–	–	–	–	–	–	–	–	0.075	0.7 ± 0.0	8 ± 1	86 ± 4
SIWW + Ni^{2+}	9:10	0.21 ± 0.03	93.1 ± 0.9	20.8 ± 4.1	25.65	–	–	–	–	0.075	0.7 ± 0.0	12 ± 1	92 ± 5
SIWW + Cr^{3+}	9:10	–	–	–	–	0.14 ± 0.00	95.4 ± 0.2	23.9 ± 6.0	30.12	0.075	0.7 ± 0.0	12 ± 1	90 ± 3

3.2. Effects of various oxic:anoxic ratios in the reaction step on the SBR system efficiency and performance

The experiments were carried out in the SBR system with SIWWs at HRT of 1.5 d at various oxic: anoxic ratios of 19:0, 13:6, 11:8, and 9:10 for 30 d. The effects of various oxic:anoxic ratios on the SBR system efficiency and performance with SIWWs were described as follows:

3.2.1. BOD_5 and COD

The SBR system with SIWWs at HRT of 1.5 d and various oxic:anoxic ratios of 19:0, 13:6, 11:8, and 9:10 showed interesting results. Adding anoxic period in the reaction step could increase BOD_5 and COD removal efficiencies by about 5%, as shown in Table 4. However, the systems operated at oxic:anoxic ratios of 13:6 to 9:10 did not show any significant differences in their BOD_5 and COD removal efficiencies. The BOD_5 and COD removal efficiencies with SIWW, SIWW + Cr^{3+}, and SIWW + Ni^{2+} at the oxic:anoxic ratio of 19:0 were 81 ± 1% and 81 ± 1%, 85 ± 1% and 86 ± 1%, and 86 ± 1% and 87 ± 1%, respectively. At the oxic:anoxic ratio of 9:10, they were 87 ± 1% and 88 ± 1%, 80 ± 1% and 80 ± 1%, and 79 ± 1% and 79 ± 1%, respectively, for SIWW, SIWW + Cr^{3+}, and SIWW + Ni^{2+}, as shown in Table 4.

3.2.2. Nitrogen compounds

The SBR system with SIWWs showed interesting results for TN removal efficiencies, as shown in Table 5. TN removal efficiency increased concomitantly with the decrease in the duration of aeration period in the reaction step. TN removal efficiencies with SIWW, SIWW + Ni^{2+}, and SIWW + Cr^{3+} at the oxic:anoxic ratio of 19:0 were 24.2 ± 3.0%, 19.7 ± 3.8%, and 18.4 ± 3.6%, respectively, while they were 44.2 ± 1.8%, 39.4 ± 0.9%, and 37.1 ± 1.9%, respectively, at the oxic:anoxic ratio of 9:10, as shown in Table 5. Moreover, effluent NH_4^+-N with SIWWs decreased with the decrease in the length of aeration period in the reaction step. Effluent NH_4^+-N with SIWW, SIWW + Ni^{2+}, and SIWW + Cr^{3+} at oxic:anoxic ratio of

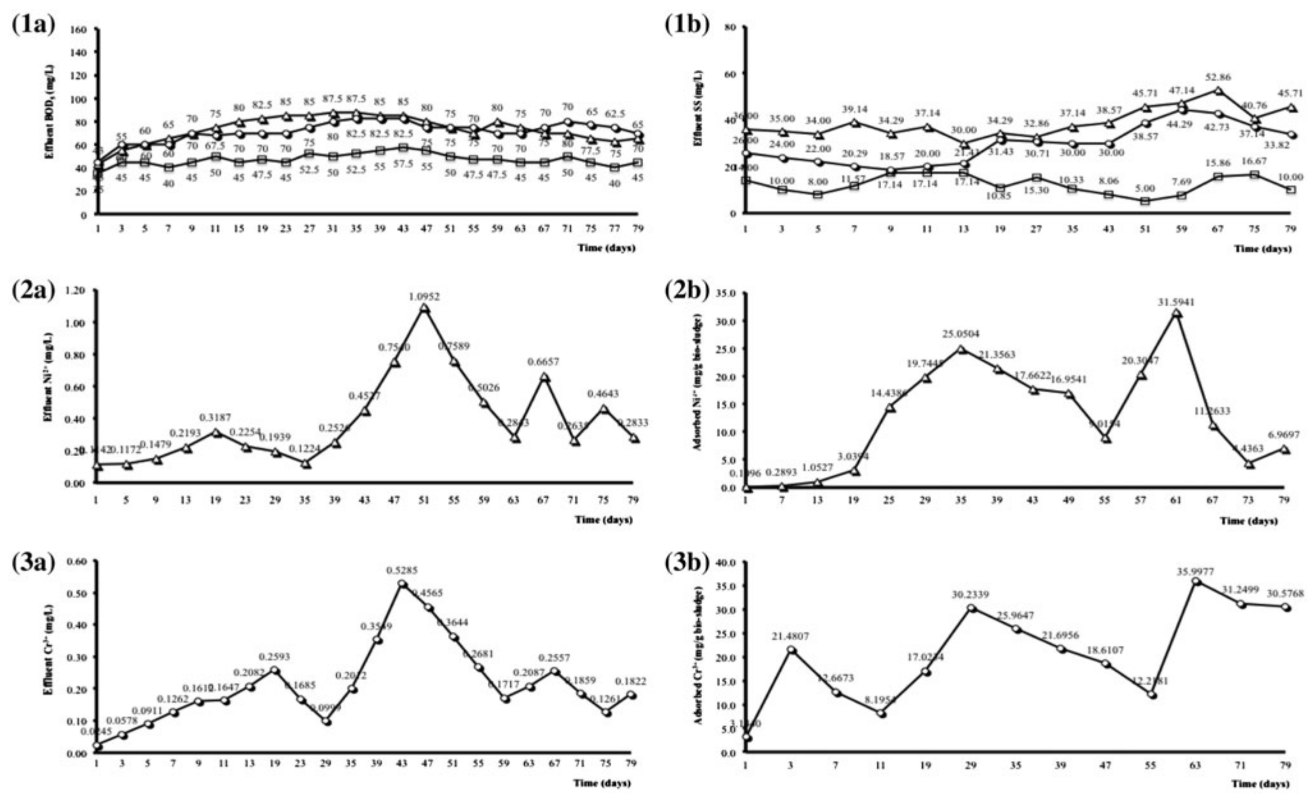

Fig. 3. Chemical profiles of effluents and bio-sludge of the SBR system operated with SIWW, SIWW+Ni^{2+} and SIWW+Cr^{3+} under HRT of 1.5 days and oxic:anoxic ratio of 19:0 for about 80 d

Notes: (1a) Effluent BOD_5, (1b) effluent SS, (2a) effluent Ni^{2+}, (2b) adsorbed Ni^{2+} in bio-sludge, (3a) effluent Cr^{3+}, and (3b) adsorbed Cr^{3+} in bio-sludge. Symbols: □: SIWW, ▲: SIWW + Ni^{2+}, and ●: SIWW +Cr^{3+}.

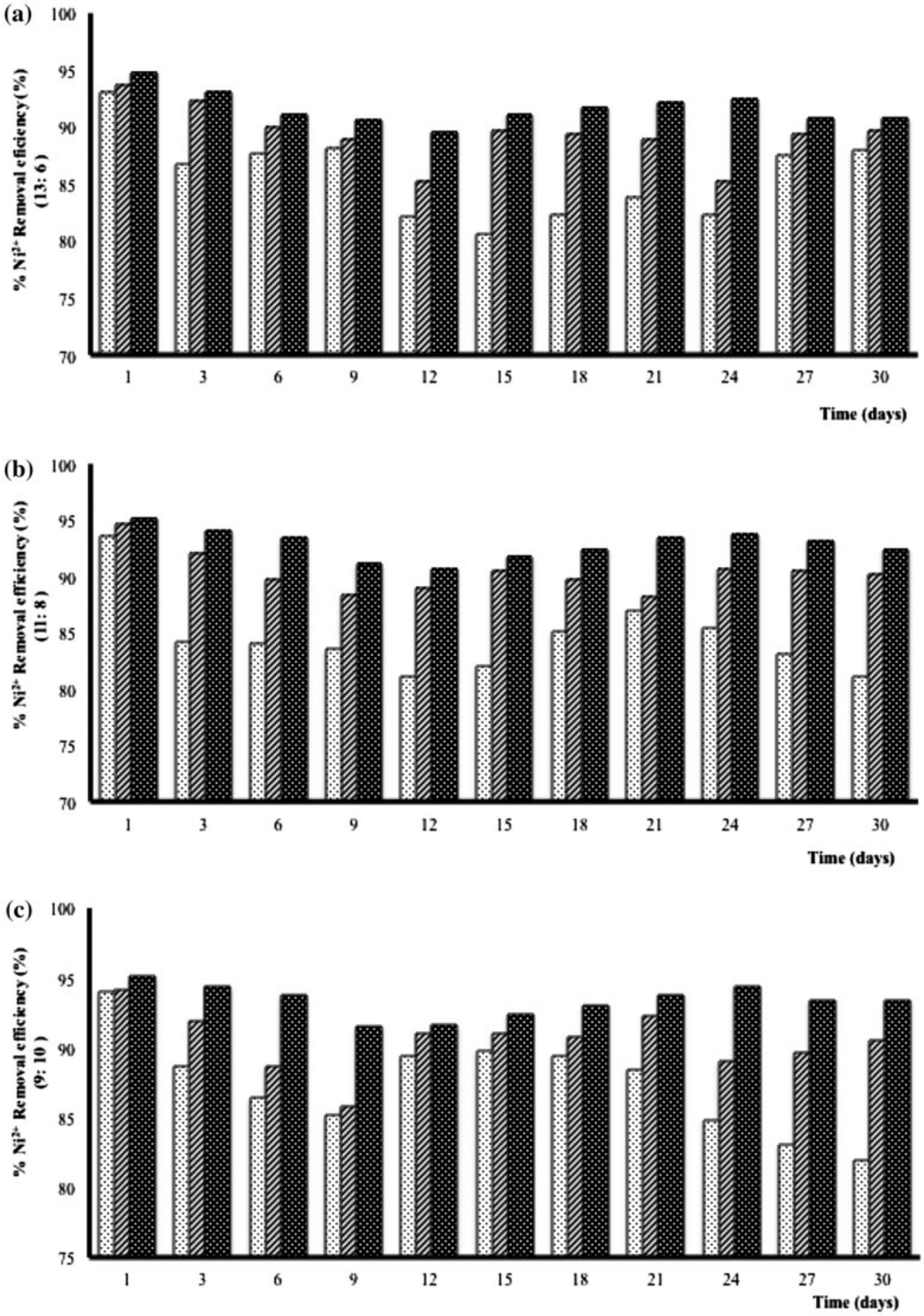

Fig. 4. Ni^{2+} removal efficiency profiles of the SBR system operated with SIWW + Ni^{2+} at various oxic:anoxic ratios in the reaction step. (a) 13:6, (b) 11:8, and (c) 9:10.
Symbols: ⬚: anoxic 1, ▨: oxic 1, ■: settle.

19:0 were 4.5 ± 0.5 mg/L, 5.4 ± 0.5 mg/L, and 6.1 ± 0.5 mg/L, respectively. They were 3.5 ± 0.2 mg/L, 3.6 ± 0.2 mg/L, and 3.7 ± 0.2 mg/L, respectively, at the 13:6 oxic:anoxic ratio. Also, NO_3^--N with SIWWs effluents decreased with the decrease in the length of aeration period in the reaction step. Ni^{2+} and Cr^{3+} had the

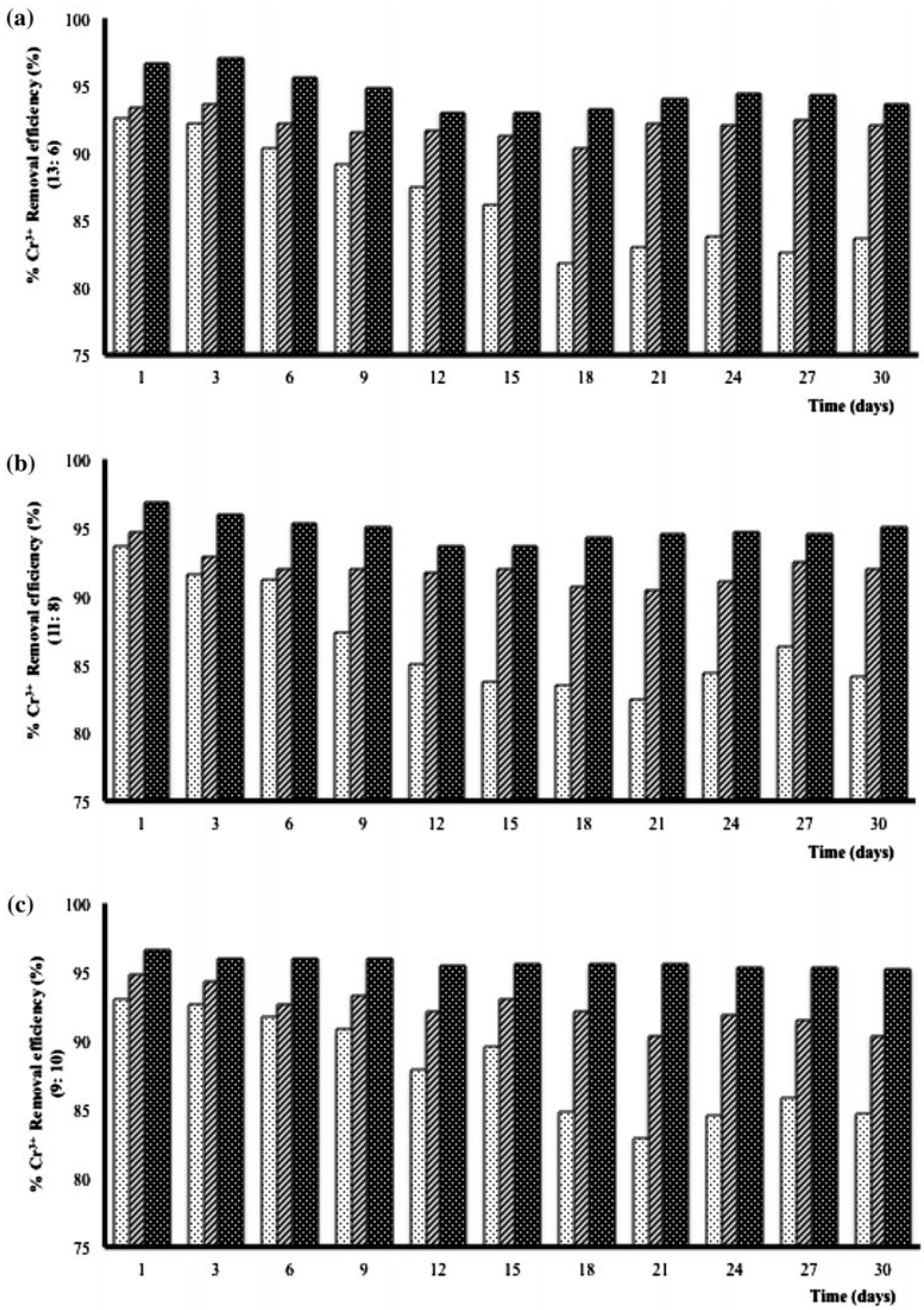

Fig. 5. Cr^{3+} removal efficiency profiles of the SBR system operated with SIWW + Cr^{3+} at various oxic:anoxic ratios in the reaction step. (a) 13:6, (b) 11:8, and (c) 9:10.
Symbols: ▨: anoxic 1, ▨: oxic 1, and ▩: settle.

same repression effect on TN removal efficiency, as shown in Table 5. Ni^{2+} and Cr^{3+} at the concentration of 3 mg/L could reduce the TN removal efficiency by about 16–25%.

3.2.3. HM (Cr^{3+} and Ni^{2+})

SBR systems with SIWW + Ni^{2+} and SIWW + Cr^{3+} showed almost the same HM removal efficiencies of

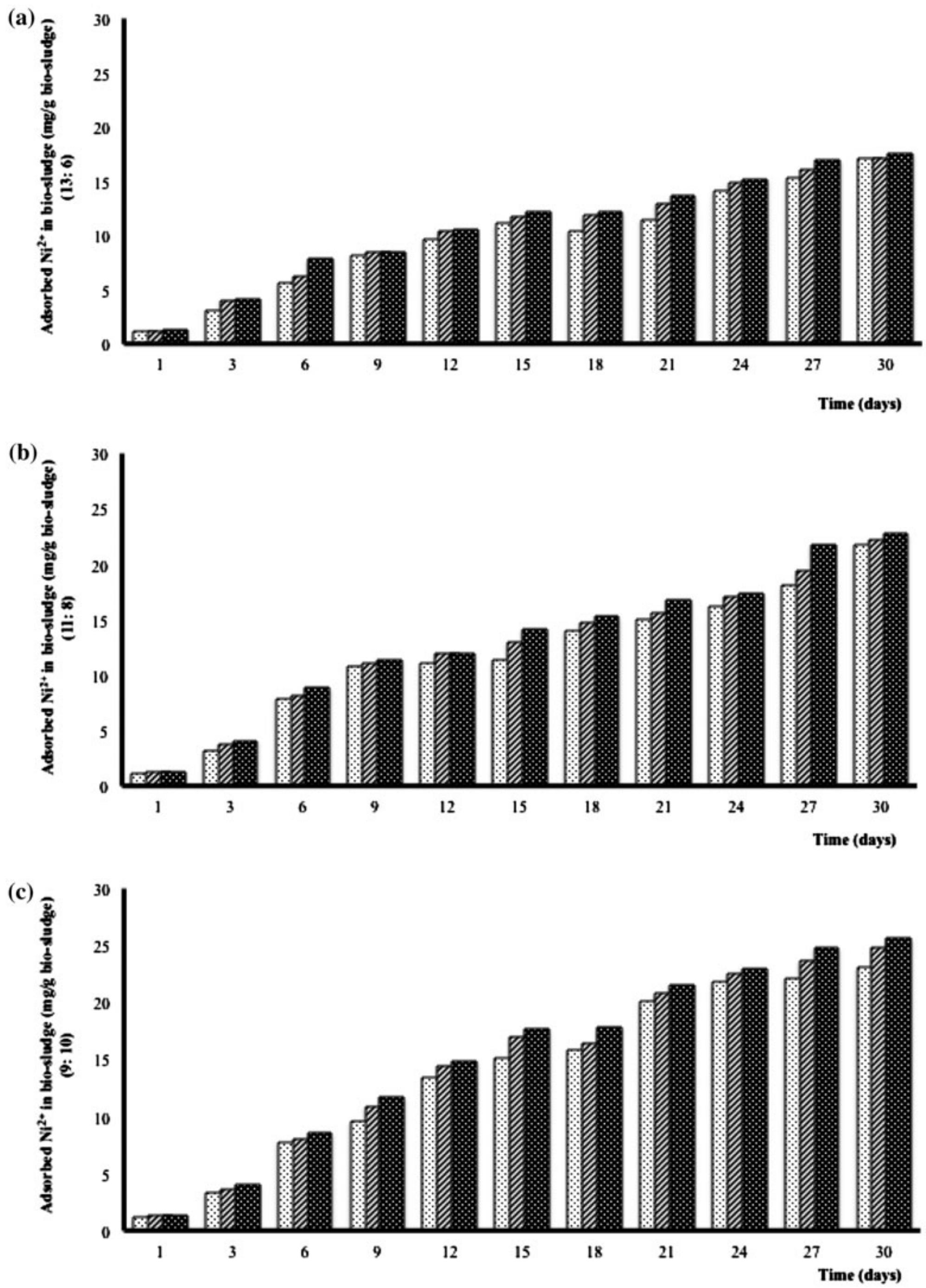

Fig. 6. Ni^{2+} profile of bio-sludge in the SBR system operated with SIWW + Ni^{2+} at various oxic:anoxic ratios in the reaction step. (a) 13:6, (b) 11:8, and (c) 9:10.
Symbols: ▫: anoxic 1, ▨: oxic 1, and ■: settle.

over 90%, as shown in Table 6. Moreover, the bio-sludge showed maximum and average Cr^{3+} and Ni^{2+} adsorption yields of 17.02 mg Cr^{3+}/g of bio-sludge, 11.3 ± 3.1 mg Cr^{3+}/g of bio-sludge, 14.44 mg Ni^{2+}/g of bio-sludge, and 11.6 ± 6.0 mg Ni^{2+}/g of bio-sludge, respectively, at the oxic:anoxic ratio of 19:0, as shown in Table 6. HM removal efficiencies of the system increased with the decrease in the length of aeration period in the reaction step. Cr^{3+} and Ni^{2+} removal efficiencies at the oxic:anoxic ratio of 9:10 were 95.4

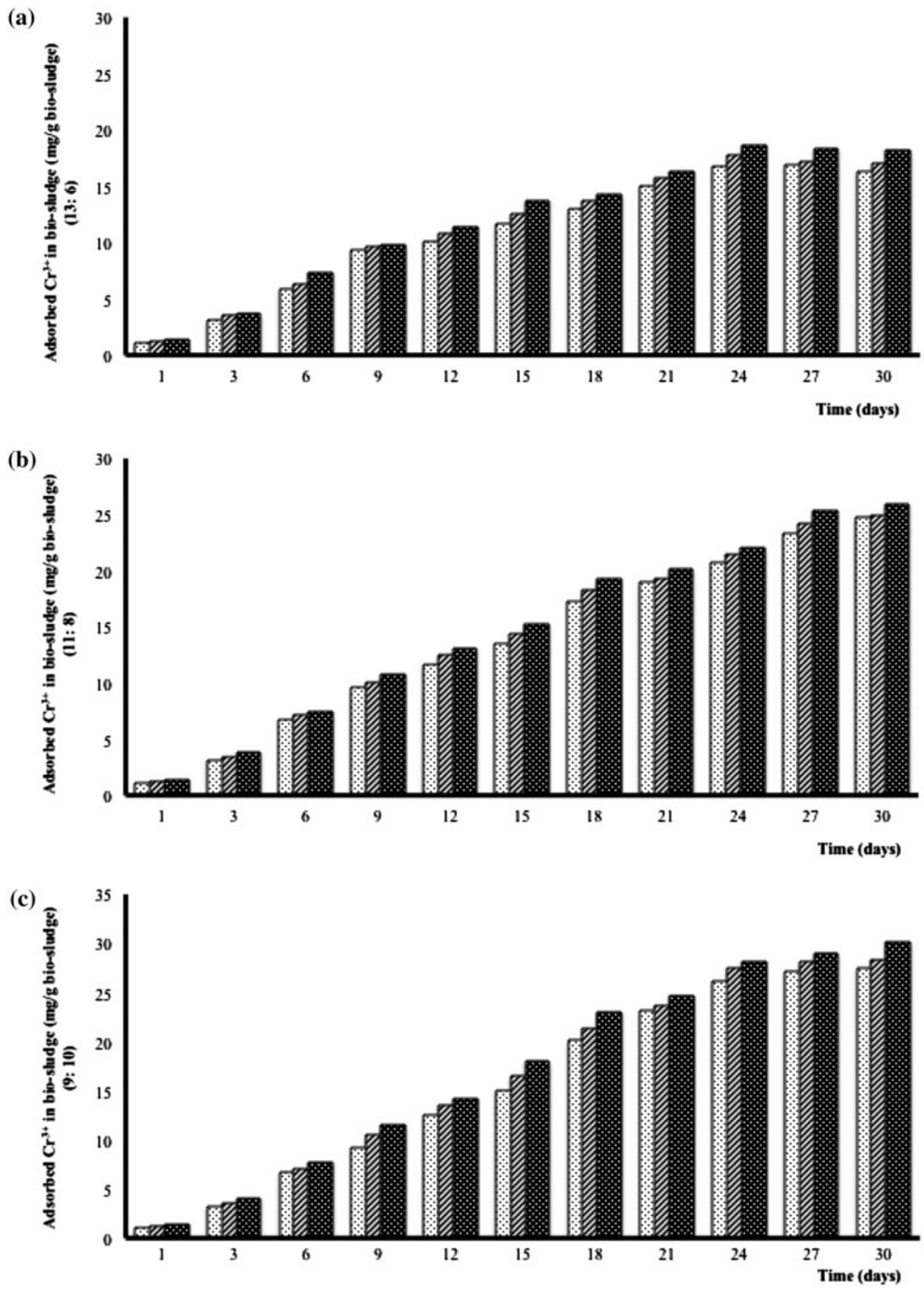

Fig. 7. Cr^{3+} profile of bio-sludge in the SBR system operated with SIWW + Cr^{3+} at various oxic:anoxic ratios in the reaction step: (a) 13:6, (b) 11:8, and (c) 9:10.
Symbols: ▒: anoxic 1, ▨: oxic 1, and ▩: settle.

± 0.2% and 93.1 ± 0.9%, respectively, as shown in Table 6. Also, HM adsorption yields of bio-sludge increased with the decrease in the length of aeration period in the reaction step, as shown in Table 6. The average Cr^{3+} and Ni^{2+} adsorption yields of bio-sludge at oxic:anoxic ratio of 9:10 were 23.9 ± 6.0 mg Cr^{3+}/g of bio-sludge and 20.8 ± 4.1 mg Ni^{2+}/g of bio-sludge. During the observation of the profiles of HM removal efficiencies and HM adsorbed on bio-sludge, it was found that HM in the wastewater was removed in the first anoxic step of the reaction and the effluent HM was almost stable during 30 d of operation, as shown in Figs. 3 and 4. HM adsorption yield of the bio-sludge increased with the increase in operation time, as shown in Figs. 5 and 6. Moreover, most of the HM was adsorbed on the bio-sludge during the first anoxic step of the reaction. And the HM adsorption yield was slightly increased during oxic two of the reaction step and the settling step, as shown in Figs. 5–7.

3.2.4. SS and TDS

The amount of SS effluents with SIWWs increased by adding HM (Cr^{3+} and Ni^{2+}), as shown in Table 4. The organic contents of effluent SS with SIWW, SIWW + Ni^{2+}, and SIWW + Cr^{3+} at the 19:0 oxic:anoxic ratio were 15 ± 2 mg/L, 26 ± 3 mg/L, and 27 ± 3 mg/L, respectively, as shown in Table 4. The addition of anoxic period in the reaction step caused an increase in the amounts of effluent SS. They were 20 ± 2 mg/L, 30 ± 3 mg/L, and 28 ± 4 mg/L, respectively, at the 9:10 oxic:anoxic ratio. For the determination of effluent TDS, they did not show any significant differences on the effluents TDS in all experiments tested as shown in Table 4. Effluent TDS was in the range of 123–152 mg/L. Moreover, the organic contents in SS and TDS were 50–60% and 40–60%, respectively.

3.2.5. Bio-sludge performances

Cr^{3+} and Ni^{2+} could increase SRT. SRTs with SIWW, SIWW + Ni^{2+}, and SIWW + Cr^{3+} at the oxic: anoxic ratio of 19:0 were 5 ± 1 d, 8 ± 2 d, and 8 ± 1 d, respectively, as shown in Table 6. Moreover, SVIs of the SBR system with SIWW, SIWW + Ni^{2+}, and SIWW + Cr^{3+} at the oxic:anoxic ratio of 19:0 were 92 ± 12 mL/g, 126 ± 6, and 149 ± 9 mL/g, respectively. MLVSS/MLSS of the system with SIWWs was quite stable and accounted for 0.7–0.8 in all experiments, as shown in Table 6. However, a decrease in the length of aeration period in the reaction step could improve the quality of bio-sludge in the system. SVIs of the system with SIWW + Ni^{2+} and SIWW + Cr^{3+} at the HRT of 1.5 d at the 9:10 oxic:anoxic ratio were 92 ± 5 mL/g and 90 ± 3 mL/g, respectively, as shown in Table 6. Moreover, a decrease in the length of aeration period in the reaction step could increase the age of bio-sludge. The bio-sludge age with SIWW + Ni^{2+} and SIWW + Cr^{3+} at oxic:anoxic ratios of 19:0 and 9:10 was 8 ± 2 d and 8 ± 1, 12 ± 1 and 12 ± 1 d, respectively.

4. Discussion

LIWW showed high inorganic matter content in both SS and TDS accounting for about 70% which resulted in high HM contents. LIWW contained not only Ni^{2+} and Cr^{3+}, but also 6.29 ± 0.05 mg/L of other HM, as shown in Table 1. Moreover, LIWW contained not only inorganic matter but also 222 ± 12 mg BOD_5/L of organic matter. According to the chemical characteristic of LIWW, the biological treatment process in the form of SBR system could be applied for treating wastewater containing both organic matter and HM [2,4,9–15]. However, operation conditions and types of microbes should be considered. According to our previous work, type of a microbe affected HM removal or adsorption efficiency [3,18,19,25,28]. Moreover, HM had a repression effect on the growth and activity of the microbes and each HM showed different level of repression effect [3,8,29–33]. The SBR system was operated with SIWW + Ni^{2+} and SIWW + Cr^{3+} for a long time (80 d) and it was confirmed that Cr^{3+} and Ni^{2+} adsorption yields reached up to 31.59 ± 9.67 mg Ni^{2+}/g bio-sludge and 36.00 ± 9.80 mg Cr^{3+}/g bio-sludge, respectively, after 3 weeks of operation. HM adsorption yield decreased after reaching the maximum yield and effluent SS increased as shown in Table 3b and Fig. 2. This might be the effect of the wastewater composition and treatment conditions to dominate HM adsorbing microbes (nitrification and denitrification bacteria) in the SBR system. But, the high amount of adsorbed HM on the bio-sludge gave the repression effect to the growth and activity of bio-sludge [3,12,16,19,24,34,35]. It was confirmed that after adsorbed HM reached the maximum level, the bio-sludge was killed resulted by the increase of effluent SS and effluent HM (Tables 3a, 3b and Fig. 2). Moreover, the system showed higher Cr^{3+} than Ni^{2+} removal efficiency. This could be caused by the fact that Cr^{3+} (molecular weight 51.9962, atomic number 24) has smaller molecular size than Ni^{2+} (molecular weight 58.6934, atomic number of 28) [36]. Then, Cr^{3+} could be more easily adsorbed onto the bio-sludge than Ni^{2+}. This could confirm the fact that Cr^{3+} adsorption ability of the bio-sludge with SIWW + Cr^{3+} was 23.18 ± 08.64 mg/g bio-sludge while Ni^{2+} adsorption ability with SIWW + Ni^{2+} was only 14.49 ± 8.94 mg/g bio-sludge, as shown in Table 3b. Moreover, HM as Ni^{2+} and Cr^{3+} gave a repression effect on the growth and activity of the bio-sludge as mentioned above [3,7,10,11,16]. Some microbes, particularly carbonaceous BOD removal microbes (heterotrophic bacteria), were killed by the adsorbed Ni^{2+} or Cr^{3+} at high concentration [3,19,29]. It was confirmed by the increase in the amount of effluent SS during the long-time operation (80 d of operation), as shown in Fig. 2. Then, it was suggested that the biological treatment in the form of SBR system could be used for acclimatization and finding the most suitable microbes for treating organic wastewater contaminated with HM [3,19]. It was not necessary to inoculate special microbes into the system. Moreover, previous works presented that HM had stronger repression effect on the growth and activity of the carbonaceous BOD_5 removal microbes (heterotrophic bacteria) than on the other (nitrogenous BOD_5 removal microbes: nitrification and denitrification bacteria) [3,18,19]. Then, to increase the growth and activity of HM adsorption microbes, the operation of SBR system should be considered. Various oxic: anoxic ratios of the reaction step (19:0, 13:6, 11:8, and 9:10) were applied to determine the carbonaceous BOD_5 and nitrogenous BOD_5 removal efficiencies together with HM adsorption yields. It was found that the reduction of aeration period in the reaction step did not have any repression effect on BOD_5 and COD removal efficiencies. Moreover, their removal efficiencies with SIWW + Ni^{2+} and SIWW + Cr^{3+} could increase with the increase in anoxic period in the reaction step. This might be the effect of Ni^{2+} and Cr^{3+} on the growth and activity of carbonaceous BOD_5 removal microbes. However, they showed a slight repression effect on the growth and activity of nitrogenous BOD_5 removal microbes as nitrifying and denitrifying bacteria because TN removal efficiencies with SIWW + Ni^{2+} and SIWW + Cr^{3+} were higher than those with SIWW and the effluent NO_3^--N with SIWW + Ni^{2+} and SIWW + Cr^{3+} which were almost same as with SIWW. This might suggest that 3 mg/L of Ni^{2+} and Cr^{3+} had a repression effect on carbonaceous BOD_5 removal microbes but they did not have a strong repression effect on nitrogenous BOD_5 removal microbes [3,15,24,34,37]. To increase the growth and activity of nitrogenous compounds removal microbes, length of anoxic period in the reaction step should be increased. Moreover, the increase in the length of anoxic period in the reaction step gave more advantages on HM removal efficiency; the highest Ni^{2+} and Cr^{3+} adsorption efficiencies of 93.1 ± 0.9% and 95.4 ± 0.2% were detected with SIWW + Ni^{2+} and SIWW + Cr^{3+}, respectively, at the oxic:anoxic ratio of 9:10. From above-mentioned results, it can be inferred that an increase in the duration of anoxic period in the reaction step could increase the growth and activity of nitrogenous BOD removal microbes which showed a HM adsorption ability too. Then, after the operation, HM was adsorbed on the nitrogen removal microbes' cells resulting in the reduction in HM concentration in the wastewater. Then, the growth and activity of carbonaceous BOD_5 microbe was not affected by above-mentioned HM concentration resulting in the increase in BOD_5 and COD removal efficiencies, as mentioned earlier [38–44]. Moreover, HM adsorption abilities of the bio-sludge increased during the operation, as shown in Figs. 5 and 6. Inorganic content of the bio-sludge with SIWW + Ni^{2+} or SIWW + Cr^{3+} was higher than that with SIWW. This might be the result of HM adsorption abilities of nitrogenous BOD_5 compounds removal microbes (nitrification and denitrification bacteria) [3,38,40]. This was confirmed by the increase in the age of bio-sludge or SRT by adding Ni^{2+} and Cr^{3+}. SRT with SIWW, SIWW + Ni^{2+}, and SIWW + Cr^{3+} at the oxic:anoxic ratio of 9:10 were 8 ± 1, 12 ± 1 and 12 ± 1 d, respectively. Then, it was suggested that HM adsorption yields or abilities of the system depended on the type of a microbe in the bio-sludge; nitrification and denitrification bacteria showed the highest HM adsorption ability [2,4,12,16,45–47]. This confirmed that 3 mg/L of Ni^{2+} and Cr^{3+} had repression effect on carbonaceous BOD_5 removal microbes, but they did not have a strong repression effect on nitrogenous BOD_5 removal microbe due to the increase in SRT, SS, and SVI as shown in Tables 4 and 5 [2,3,19,48]. To decrease SVI and effluent SS of the SIWW + HM system, duration of the anoxic period of the reaction should be increased. However, SVI accounted for less than 95 mL/g in all oxic:anoxic ratios tested. As far as the disadvantages of the system with SIWW containing HM as Ni^{2+} and Cr^{3+} are concerned, the system showed more effluent SS than that with SIWW; the SS and TDS contained more inorganic matter than the system with SIWW. The inorganic content of SS and TDS effluents was high by about 40% due to the HM contamination [2].

5. Conclusion

SBR system at HRT of 1.5 d could be applied for the treatment of SIWWs for over 2.5 months with a stable removal efficiency. Moreover, the system could be applied for removing HM. Both Cr^{3+} and Ni^{2+} in SIWW could repress the growth and activity of carbonaceous BOD_5 removal microbes (heterotrophic bacteria) while they had quite an insignificant effect on nitrogenous compounds removal microbes (nitrifying and denitrifying bacteria). Moreover, the growth and activities of both nitrifying and denitrifying bacteria could not be repressed even when the concentration of Ni^{2+} reached up to 3.0 mg/L, while denitrifying bacteria were affected by 3.0 mg/L Cr^{3+}. Bio-sludge in the system with SIWWs showed high Cr^{3+} and Ni^{2+} adsorption abilities of 36.00 ± 9.80 mg/g and 31.59 ± 9.67 mg/g, respectively. To increase the growth and activity of nitrogenous compounds removal microbes, the application of anoxic period in the reaction step was investigated. The increase in the duration of anoxic period in the reaction step could increase the TN removal yield together with the HM removal yield. Moreover, the growth and activity of carbonaceous BOD_5 removal microbes was improved resulting in the increase in BOD_5 and COD removal efficiencies. Moreover, the quality of bio-sludge was also improved.

Acknowledgments

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Nomenclature

BOD_5	—	biochemical oxygen demand
COD	—	chemical oxygen demand
Cr^{3+}	—	chromium ion
F/M	—	food (BOD_5 loading)/microbe (total bio-sludge)
HRT	—	hydraulic retention time
MLSS	—	mixed liquor suspended solids
MLVSS	—	mixed liquor volatile suspended solids
NH_4^+-N	—	ammonium nitrogen
Ni^{2+}	—	nickel ion
NO_2^--N	—	nitrite nitrogen
NO_3^--N	—	nitrate nitrogen
Organic-N	—	organic nitrogen
SBR	—	sequencing batch reactor
SS	—	suspended solids
SIWW	—	synthetic industrial estate wastewater
SVI	—	sludge volume index
TDS	—	total dissolved solids
TN	—	total nitrogen

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