Feasibility study of sequencing batch reactor system for upgrading wastewater treatment in Malaysia

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Abstract The objective of this study was to assess the feasibility of the Sequencing Batch Reactor (SBR) system for implementation in Malaysia. Theoretical, field, laboratory investigations, and modelling simulations have been carried out. The results of the study indicated that the SBR system was robust, relatively cost-effective, and efficient under Malaysian conditions. However, the SBR system requires highly skilled operators and continuous monitoring. This paper also attempted to identify operating conditions for the SBR system, which optimise both the removal efficiencies and the removal rates. The removal efficiencies could reach 90–96% for COD, up to 92% for TN, and 95% for SS. An approach to estimate a full operational cycle time, to estimate the de-sludging rate, and to control the biomass in the sludge has also been developed. About 4 hours react time was obtained, as 2.25 hours of nitrification with aerated slow fill and 1.75 hour of denitrification with HAc addition as an additional carbon source. Inefficient settling was one of the problems that affect the SBR effluent quality. The settling time was one hour for achieving Standard B (effluent quality) and 2 hours for Standard A.

Keywords Malaysia; react time; removal efficiency; removal rate; Sequencing Batch Reactor (SBR)

Introduction

The wastewater treatment (WWT) sector in Malaysia has been developed parallel with the urbanization process, in which the concepts of small and decentralised plants have been adopted and extensively implemented since the 1960s particularly in major towns and cities. Simple and low-cost systems such as waste stabilization ponds (WSPs), Imhoff tanks and communal septic tanks have been widely used both for residential and commercial areas. In the early 1980s, mechanical WWT plants were introduced, such as rotating biological contactors (RBC), extended aeration activated sludge (EAAS) and aerated lagoons to improve the wastewater treatment capability. However due to financial constraints faced by the local authorities, and poor operation and maintenance, the Malaysian Government introduced the Sewerage Service Act (1993) to privatise the operation and maintenance of the WWT sector to the Indah Water Konsortium (IWK), a national sewerage company, in order to improve the sewerage infrastructure and facilities.

The upgrading of the WWT infrastructure is parallel with the intention of the Government to introduce more stringent effluent quality criteria. Under the latest sewerage master plan, about US$1.6 billions were approved for the upgrading of the WWT infrastructure (IWK, 1997). This has created a need to evaluate different options for the WWT plants in order to determine the feasibility of implementing these options, in terms of reliance and efficiency under Malaysian conditions.

The SBR system is one of the proposed systems to upgrade WSPs in Malaysia, to mechanical plants (Ujang *et al.*, 2001). The goal of this study, therefore, was to determine the feasibility of implementing the SBR system in Malaysia by evaluating the reliability, flexibility, robustness, and partly the economical feasibility of the system. In addition,

Water Science and Technology **Vol 48 No 11–12 pp 327–335** © IWA Publishing 2003

proposed standards for Malaysian effluent quality are going to be proposed based on the investigated efficiency of the SBR system in this study. It should be noted here that only the carbon removal and the nitrogen removal have been investigated in this study, without taking the phosphorus removal into consideration, as it is not likely that Malaysia will implement effluent quality criteria on phosphorus in the near future.

The Malaysian standards cover currently carbon (based on BOD and COD), suspended solids, and metal removal. Based on the results of this study, operating conditions suitable for Malaysia (with average temperature of 28°C, and average rainfall intensity of 2,500 mm) will be suggested. In general this study consists of three phases:

- Phase I: Field investigation in Malaysia to observe the efficiency of selected WWT plants.
- Phase II: Laboratory work on SBR experiments in order to investigate the performance of the SBR under the Malaysian climate.
- Phase III: Analysis of results including modelling using IWA Activated Sludge Models.

Theoretical investigation and field investigation

The theoretical investigation phase covers a literature survey of cost-effectiveness reports, theoretical studies, and technical reports for the SBR system; and field investigation.

The SBR system is a batch reactor system (fill-and-draw system) and not a continuous flow system (CFS: plug flow or/and mixed flow system). It is a system where the biological nutrient removal is carried out in one reactor. Aerobic and anoxic-anaerobic processes are performed sequentially in the same reactor. The aerobic process achieves carbon removal and nitrification, while the anoxic-anaerobic processes achieve denitrification-phosphorus removal. Aerobic conditions are created via aeration, while anoxic-anaerobic conditions are generated via mixing with no aeration. Traditionally, aerobic processes occur before the anoxic-anaerobic processes. It is possible for the opposite to operate, depending on the availability of the necessary organic carbon and nitrate. This sequence is mostly implemented for rich carbon source or/and when high COD concentrations are found at the inlet. The operational phases of the SBR system are described by the following: Fill, React, Settle, Decant, and Idle.

Technical advantages and disadvantages of the SBR system are stated in many publications (Wilderer *et al.*, 2001; Wun-Jern and Droste, 1989; Ketchum, 1997).

Economic aspects

No studies were found comparing the overall cost (infrastructure, maintenance and personnel) of the SBR system to that of the others (CFS). This aspect should be paid significant attention in the future before going further in design. However, within this study preliminary cost-effectiveness aspects are investigated, which might be significant at the planning and the design stage. In general, SBR has the following advantages with regard to the cost-effectiveness.

- The SBR system is relatively compact and occupies a limited area compared to a CFS activated sludge system. The available land in Malaysia is limited and the cost of land is high, particularly in urban areas (Ujang *et al.*, 2001; Ujang, 2000).
- The required total tank volume in the SBR system is smaller than the volume needed in the CFS activated sludge system to achieve the same level of treatment. Moreover, as no separate secondary clarifier in the SBR system is needed, since the SBR tank can perform the clarifier task, the capital cost is minimised making the SBR system more economical than other systems (Wun-Jern and Droste, 1989).
- In a treatment of cheese factory effluent equivalent to 300 PE in France, a "comparison with continuously loaded activated sludge processes shows that the SBR solution entails

lower running costs, largely because of the limited time required for controlling the treatment unit". Only 1–2 hours per week is required to monitor the SBR treatment plant compared with 4–7 hours per week for an activated sludge CFS treatment plant (Wilderer *et al*., 2001).

On the other hand the major economic disadvantage of the SBR system compared to the CFS activated sludge system is that the SBR system needs highly trained operators, which requires more educational budget to be spent on the operators.

Performance analysis of selected wastewater treatment plants in Malaysia

In order to get a rough idea about the performance level of different WWT systems, a sampling campaign was conducted at nine different wastewater treatment plants (WWTPs) in Malaysia (Kuala Lumpur and Johor Bahru), representing urban areas with more than 20,000 PE. Five plants were batch reactor system plants (BRSPs), which are SBR system and intermittent decanted extended aeration (IDEA) system plants and the rest were CFS activated sludge systems. The results showed that the BRSPs are robust compared with the CFS plants, although the operation and maintenance were poor on site for all the plants, although it is expected that poor operation and maintenance have more negative effects on the BRSPs than the CFS plants. The results of the performance investigation of the nine plants are illustrated in Table 1. The efficiency of BOD, COD, N, and SS removal were higher in the BRSPs than the CFS plants.

Experimental investigation

Sixteen experiments on a single ten litre SBR tank were carried out in order to investigate the removal efficiency and the removal rates of the organic matter and the nitrogen at 28°C liquor temperature (average temperature in WWTPs liquors in Malaysia). The operational phases of the experiments follow the order: Fill, React (aeration for aerobic condition and then mixing without aeration for the anoxic condition), Settle, and Decant. The sludge and the raw wastewater that were used to run the experiments were brought from Lundtofte wastewater treatment plant nearby the Technical University of Denmark, assuming that the contents are similar to the Malaysian wastewater. To replicate the conditions in Malaysia, the sludge and the raw wastewater was warmed up before running the experiment from below 20°C to about 28°C over at least 3 hours. The temperature of the mixed liquor was regulated during the experiment to meet the Malaysian condition by a warm water bath. The tank was partly submerged in the warm bath. Aeration was monitored by an oxymeter over time to measure the oxygen concentration in the mixed liquor during the aeration, and during mixing with monitoring the oxygen was always at 0 mg/l to avoid denitrification inhibition. Experimental setup is shown in Figure 1. All analytical methods were conducted according to the *Standard Methods for the Examination of Water and Wastewater* (1995).

The efficiencies of the SBR experiment regarding carbon, nitrogen and suspended solid removal are illustrated in Table 2 in comparison with the efficiencies in the literature.

The removal efficiencies as shown in Table 2 indicate that the efficiencies at the Malaysian condition (28°C) are within the range of the efficiencies stated in the literature.

Table 1 Comparison between the removal efficiency of the nine investigated BRSPs and the CFS activated plants

Performance indicators	CFS plants	SBR and IDEA plants
BOD removal (%)	51 (± 6)	64 (± 7)
COD removal (%)	47 (± 9)	62 (± 6)
N removal (%)	35 (± 15)	50 (± 5)
SS removal (%)	58 (± 18)	64 (± 10)

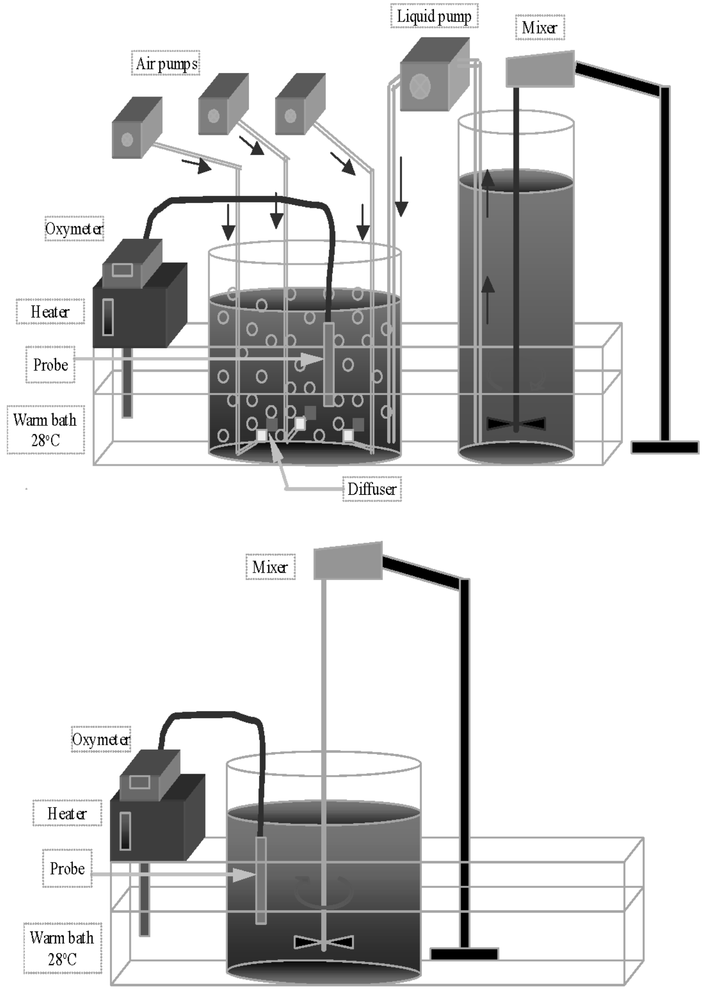

Figure 1 Schematic illustration for the experimental rig: During slow aerated fill and aeration. The wastewater was pumped from a tank into the reactor (Top). The experiment during mixing with no aeration (Bottom)

Table 2 The removal efficiencies of the single tank SBR system in comparison with those in the literature

Parameters	Experiments (%)	Literature (%)
Biochemical Oxygen Demand (BOD)	93–99	>98[I, II, V]
Chemical Oxygen Demand (COD)	90–96	>95[II, V]
Total Nitrogen (TN)	92	≤86[III, IV, V]
Suspended Solid (SS)	92.5 ± 2	90[II]

I: (Tilche *et al.*, 1999). II: (Umble and Ketchum, 1997). III: (de Sousa and Foresti, 1996). IV: (Kabasiniski *et al.*, 1998), V: (Wilderer *et al.*, 2001, Chp. 6)

The removal rates of nitrogen in nitrification and denitrification averaged 4.2 mgNO_x/(kg VSS.h) and 5.75 mg NO_x/(kgVSS.h), respectively. The slow aerated fill (SAF) instead of the dump fill has significantly increased the nitrification rate at least 2 times. The addition of the acetic acid (HAc) as an additional carbon source for denitrification has increased the denitrification rate at least 3 times. In both SAF and HAc addition, higher efficiencies of carbon, organic nitrogen, and ammonium removal have been achieved. About 4,000 mgSS/l (≈3,000 mgVSS/l) sludge concentration in the liquor achieved good removal efficiencies, rates and settling. Poor settling is one of the characteristics of the SBR that occurred in the experiments that affect the effluent quality. A relatively long time for settling (1 to 2 hours for Malaysian standards B and A, respectively) is required to achieve high removal efficiency. Results of one of the SBR experiments, including removal efficiencies and nitrification-denitrification processes curves, are presented in Table 3 and Figure 2. Relying on the results of the single tank SBR experiments, a full cycle time of the SBR operational phases are proposed in Figure 3.

Modelling

A 10 litre single tank modelling is adopted in order to analyse the experiments, particularly the bacterial activity in the sludge and its influence on the biological processes in terms of efficiencies and process rates. It is intended that the analytical model of the one tank experimental scale that can be used afterwards in the multiple tanks real scale models will

Table 3 Results of SBR experiment no. 16 (Total react time = 4.75 hr, MLVSS = 3,175 mg/l)

Parameters	Influent (mg/l)	Effuent (mg/l)	Efficiency (%)
BOD	152	0.16	99.9
COD	398	47	88.2
SS	329	18	94.5
TN (Total Nitrogen)	69	6.86	90
TON (Total Organic Nitrogen)	25.8	5.9	77
NH_4^+	43.2	0.4	99.1
NO_x^-	≈ 0 (In) 26 (Highest)	0.56	97.85

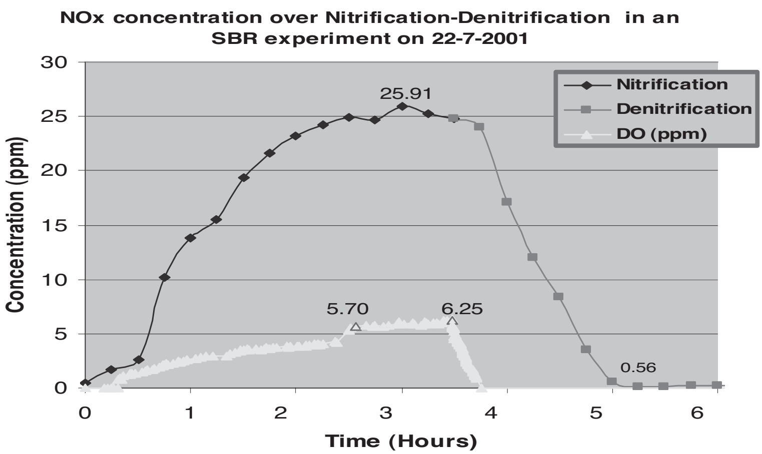

Figure 2 NO_x^- and dissolved oxygen (DO) concentrations during nitrification–denitrification in SBR

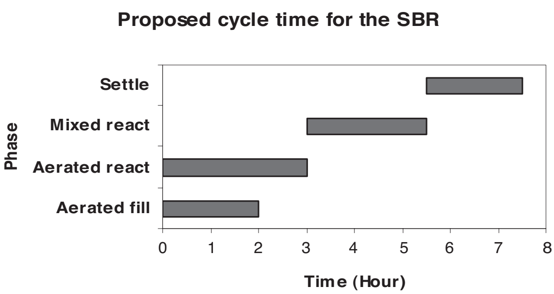

Figure 3 Proposed cycle time for the SBR experiment

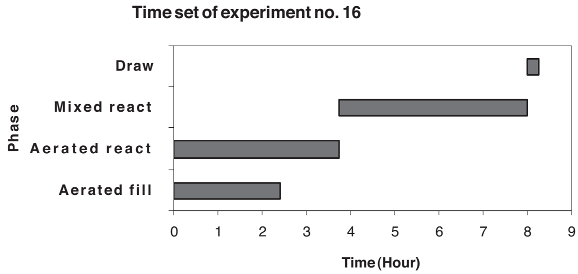

Figure 4 Selected cycle time for the modelling (exp. no. 16)

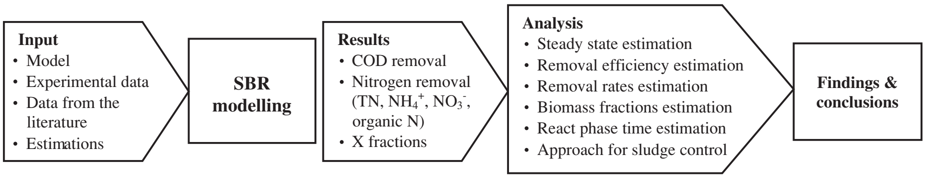

Figure 5 Schematic presentation of the modelling investigation. Parameters and symbols used are similar to Henze *et al.* (2000)

enable us to set up the basis for the SBR system design in Malaysia. Figure 5 illustrates the stages of the modelling investigation.

It is important to mention here that it was not possible to conduct the sludge building up process in the single tank experiments due to experimental difficulties. This process is examined in the modelling. Activated Sludge Models (ASM1, 2 and 2d) as proposed by Henze *et al.* (2000) were implemented to form the structure of the model. AQUASIM Version 2.0, a computer programme for identification and simulation of aquatic systems (Reichert, 1998), was used as a modelling tool. The data of experiment no. 16 in Table 3 and Figure 2 were used as the input of the modelled single SBR tank and as a reference for calibration.

100 full cycles (aerated fill – aerated react – mixed react – draw) were carried out in the modelling in order to achieve the accumulation of the required sludge for wastewater treatment until the steady state was achieved. The growth of the heterotrophic bacteria (X_H) reached a steady state at cycle no. 25, while the autotrophic bacteria (X_A) reached the steady state at cycle no. 40. Therefore a full steady state is considered to take place at cycle no. 40, when the MLSS reach a concentration equal to 3,260 mgSS/l. The estimated rate of sludge accumulation (production) was 20.3 mg SS/(l.cycle), which is supposed to be the desludging rate. The efficiencies of the modelled SBR compared with the efficiencies in experiments no. 15 and no. 16 are presented in Table 4.

The rates of nitrification and denitrification processes were estimated in cycle 41 right after reaching a full steady state. A comparison between the modelled rates and the observed rates in selected experiments is presented in Table 5.

The fractions of the particulates of the sludge in the mixed liquor are divided into two categories:

- The inert fractions, which keep on accumulating and do not reach a steady state.
- The biomass fractions, which reached a steady state at cycles no. 25 and 40. The values of these fractions at the steady state are presented in Table 6.

The time estimation of the react phase (t_{total}), which is the summation of the nitrification time ($t_{nitrification}$) and the denitrification time ($t_{denitrification}$), is presented in Table 7.

The total react time is about 4 hours distributed as 2.25 hours for nitrification and 1.75

Table 4 The removal efficiency of COD, TN, and NH_4^+ in the modelled SBR compared with experimental efficiencies

Parameters	Unit	Model influent concentration	Model effluent concentration	Model efficiency (%)	Experiment no. 15 efficiency (%)	Experiment no. 16 efficiency (%)
COD	mgCOD/l	400	13–44	≤96.75	90.7	88.2
TN	mgN/l	70.43	0.43–6	≤99.4	92.1	90.06
NH_4^+	mgN/l	42	0.42	99	98.23	99.07
NO_x^-	mgN/l	41.14*	0.01	≈100	99.6	97.85

* This value represents the highest value of the NO_x^- generated by nitrification. The influent value is 0.43 mgNO_x^--N/l

Table 5 Comparison between the modelled rates and the observed rates of nitrification and denitrification

Rate: $r_{v,s}$ [mgNO_x^--N/(l.h)]	Modelled	Experiment no. 15	Experiment no. 16
Nitrification	13.7	13.38	13.28
Denitrification	18.29	17.86	18.41

Table 6 The fractions of biomass at the steady state condition

Component	Start of steady state [Cycle]	Concentration X_{COD} [mgCOD/l]	Concentration X_{VSS} [mgX/l] = (X_{COD} × 0.7 mgX/mgCOD)*
Autotrophic bacteria (X_A)	40	75	53
Heterotrophic bacteria (X_H)	25	1,290	900
Slowly biodegradable substrate (X_S)	25	350	245
Particulate organic nitrogen (X_{ND})	25	27	19

* This unit conversion is derived from Table 4.5 in Henze *et al.*, 1997

Table 7 Time estimation of the react phase (t_{total}) for the modelled SBR and experiments no. 15 and 16

Experiment	Nitrification rate*			Denitrification rate**		
	$r_{V,S}$ [mgN/(l.h)]	$\mu = r_{v,s}/X_{A,COD}$ [mgN/(gCOD$_{XA}$.h)]	$\mu^* = r_{v,s}/X_{A,VSS}$ [mgN/(gX$_A$.h)]	$r_{V,S}$ [mgN/(l.h)]	$\mu = r_{v,s}/X_{H,COD}$ [mgN/(gCOD$_{XH}$ .h)]	$\mu^* = r_{v,s}/X_{H,VSS}$ [mgN/(gX$_H$.h)]
Modelled	13.7	182.7	258.5	18.29	14.18	20.32
No. 15	13.38	178.4	252.4	17.86	13.84	19.84
No. 16	13.28	177.1	250.6	18.41	14.27	20.46

* X_A = 75 mgCOD$_{XA}$/l and 53 mgX$_A$/l
** X_H = 1,290 mgCOD$_{XH}$/l and 900 mgX$_H$/l. (See Table 6)

Experiment	Influent concentration of ammonium ($S_{NH4,in}$) [mgN/l]	V_{fill} [l]	V_{total} [l]	$t_{nitrification} = \frac{S_{NH_4^+,in} \cdot V_{fill}}{\mu_{nitrif.} \cdot X_A \cdot V_{total}}$ [h]	$t_{denitrification} = \frac{S_{NH_4^+,in} \cdot V_{fill}}{\mu_{denitrif.} \cdot X_H \cdot V_{total}}$ [h]	$t_{total} = t_{nitrif.} + t_{denitrif.}$ [h]
Modelled	42	7.5	10	2.3	1.72	≈ 4
No. 15	39.6	7.5	10	2.22	1.66	≈ 3.9
No. 16	43.22	7.5	10	2.25	1.76	≈ 4

for denitrification. This procedure can be implemented to control the biomass for the purpose of design and operation. By identifying the required time to remove a certain ammonium concentration in the influent i.e. by knowing the required nitrification and denitrification rates, the required concentration of the biomass (X_H and X_A) can be controlled by either feeding with nutrients or by desludging.

In terms of reliability to the Malaysian condition, the SBR system, according to both the

Table 8 A comparison between different influents and different effluents

	Parameter	Reference	COD [mgCOD/l]	N [mgN/l]	SS [mgSS/l]
Influent	Malaysian	Christensen *et al.* (2001)	223	–	146
	Malaysian	SBR field investigation	262 ± 99	28 ± 12	174 ± 56
	Danish	SBR experimental investigation	415 ± 89	67 ± 6.5	243 ± 58
	Modelling	SBR modelling investigation	400	70.43	–
Effluent	Malaysian	SBR field investigation	116 ± 50	16 ± 7	64 ± 19
	Danish	SBR experimental investigation	49 ± 11	10.5 ± 2.5	17 ± 4
	Modelling	SBR modelling investigation	44	6	–
	Malaysian	Standard A	50	–	50
	Malaysian	Standard B	100	–	100

Table 9 The suggested standards for the Malaysian condition, compared with the Danish standards

Parameter	Unit	Standard A		Standard B		Danish standards
		Current	Suggested	Current	Suggested	
BOD	mgBOD/l	20	20	50	50	10–30*
COD	mgCOD/l	50	50	100	100	25–75**
Total nitrogen	mgN/l	–	8	–	15	5–10*
SS	mgSS/l	50	30	100	50	30**

* (Christensen *et al.*, 2001). **(Henze, 2001)

experimental and modelling results, is able to meet the average concentrations in the Malaysian wastewater as illustrated in Table 8.

Due to the different effluent results achieved by this study compared with the Malaysian standards of effluent, Table 9 is proposed to upgrade the Malaysian effluent quality standards. The current Danish standards are listed in the same table for the purpose of comparison.

Conclusions and recommendations

The SBR system is robust compared with other wastewater treatment systems in Malaysia. It is also able to meet the current Malaysian standards. It is highly efficient, if a suitable operating condition is available. SBR can remove higher pollution loading than the average systems in Malaysia. The SBR could achieve efficiencies between 90–96% for COD removal, up to 92% for TN removal, and 95% for SS removal. Relatively long settling time is required in the SBR in order to produce high quality effluent: 1 hour settling time is required to comply with Malaysian Standard B and 2 hours settling is required to comply with Standard A. Modelling the SBR gave further data, in addition to the experimental data, especially concerning the bacterial activities during the removal processes. The computer modelling can be used as a tool to upgrade and monitor the performance of the SBR, particularly, the biomass development. A standard for TN concentration in the Malaysian effluent could be suggested from this study, according to the SBR performance. In particular, 8 mg N/l is suggested for Standard A and 15 mg N/l is suggested for Standard B.

Further studies are required on a pilot scale and/or an industrial scale in order to investigate more than one tank SBR system, to optimise the control requirement for the SBR plant, to optimise different shapes and sizes of the tanks, and to observe different strategies of operational phases. The modelling part can also be integrated into various technical aspects, including the socio-economic dimension of the Malaysian condition. Further studies are also needed to investigate the feasibility in terms of cost-effectiveness and flexibility in industrial scales before the design stage.

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