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Towards the development of a novel construction solid waste (CSW) based constructed wetland system for tertiary treatment of secondary sewage effluents

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Abstract: This study was conducted to examine the possibility of using construction solid waste (CSW), an inevitable by-product of the construction and demolition process, as the main substrate in a laboratory scale multi-stage constructed wetland system (CWs) to

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improve phosphorus (P) removal from secondary sewage effluent. A tidal-flow operation strategy was employed to enhance the wetland aeration. This will stimulate aerobic biological processes and benefit the organic pollutants decomposition and nitrification process for ammoniacal-nitrogen ($\text{NH}_4^+\text{-N}$) removal. The results showed that the average P concentration in the secondary sewage effluent was reduced from 1.90 mg-P/L to 0.04 mg-P/L. CSW presents excellent P removal performance. The average $\text{NH}_4^+\text{-N}$ concentration was reduced from 9.94 mg-N/L to 1.0 mg-N/L through nitrification in the system. The concentration of resultant nitrite and nitrate in the effluent of the CSW based CWs ranged from 0.1 to 2.4 mg-N/L and 0.01 to 0.8 mg-N/L, respectively. The outcome of this study has shown that CSW can be successfully used to act as main substrate in CWs. The application of CSW based CWs on improving N and P removals from secondary sewage effluent presents a win-win scenario. Such the reuse of CSW will benefit both the CSW disposal and nutrient control from wastewater. More significantly, such the application can transfer the CSW from a 'waste' to 'useful' material and can ease the pressure of construction waste solid management. Meanwhile, the final effluent from the CSW-based CWs can be used as non-potable water source in landscape irrigation, agriculture and industrial process.

Keywords: Construction solid waste, constructed wetland, nutrient removal, reuse, tertiary treatment.

INTRODUCTION

The secondary effluent derived from sewage treatment plant should be further treated when it is reused for industrial and agricultural process. In particular, when it is discharged into a

polluted river or lake that requires a higher water quality, tertiary treatment is then a crucial necessity in eliminating the possible danger of causing further pollution of receiving waters. [1-3] However, the most suitable and acceptable tertiary treatment route differs from plant to plant. The selection of the treatment method is highly dependent on process control capabilities and cost. Among the various tertiary treatment processes, constructed wetland (CW) is increasingly applied worldwide as a low-cost, low energy consumption and easy management technology for various kinds of wastewater treatment and/or tertiary treatment. [4,5] Extensive studies have been conducted to improve the removal performance of CW. [6] One of the main aims of research in CW technology today is to discover new medium material that can increase the pollutants removal efficiency since the media in wetland treatment systems plays an important role in integrated physical, chemical and biological processes that remove pollutants in wastewater. [7,8] It is known that phosphorus (P) removal in CWs is poor due to the fact that P removal is limited by the capacity of the media to adsorb, bind or precipitate the incoming P. Therefore, a number of studies have been conducted into screening alternative materials and/or industrial by-products for P removal ability and suitability as main medium in CWs. [7,8]

Construction solid waste (CSW), an inevitable by-product generated in most cases of the construction and demolition process, is disposed of as waste to landfill site. In recent years, the management of CSW has become a significant issue in environmental engineering due to the enormous quantities generated, lack of landfill site and the associated disposal costs. In China, approximately 40 million tons of CSW are generated per year and a two-fold increase has been forecasted by the end of the next decade due to the increased urbanisation. Therefore, seeking alternative pathway for CSW disposal is crucial for construction waste solid management. [11] Most of the research efforts, to date, have been done to investigate the feasibility of reusing such the CSW as pavement or other

construction materials. Considering the issues in the final disposal of CSW and P removal in CW, this study attempts to reuse CSW as treatment wetland substrate for P removal from secondary sewage effluent and to demonstrate ammoniacal-nitrogen (N) and organic matter removal performance of the CSW-based CWs.

MATERIALS AND METHODS

CSW collection and preparation

The experimental CSW, which contains mainly waste concrete, was collected from a demolition site in Xi'an city, China. Thereafter, the CSW was ground and sieved into particle size of 6-40mm as the N removal substrate to be used in a laboratory scale CWs. Meanwhile, the waste light-block CSW that made by coal ash was ground and sieved into particle size of 3-40mm as the P adsorbent in the CWs.

Secondary effluent collection

The secondary effluent studied was obtained from the disinfection tank of NO.4 Municipal Wastewater Treatment Plant of Xi'an city, China. The WWTP employs an anaerobic/anoxic/aerobic (A²/O) process for municipal wastewater treatment. Table 1 summarizes the characteristics of secondary effluent used in this study.

[Insert Table 1 here]

Laboratory scale CW set-up and operation

To examine the proposed use of CSW as media in CWs, a four-stage laboratory scale CWs was constructed using Pyrex tubes (100cm in height with an internal diameter of 9.4cm) to act as 1st stage and 3rd stage while the PVC tanks (100cm long with width of 15 cm and height of 75cm) were used for 2nd stage and 4th stage of the CW. The 1st stage, 2nd stage and 3rd stage, which were designed for N and organic matter removal, were packed firstly with CSW (with size ranging from 20 to 40mm) to 5 cm at the bottom to act as supporting layer followed by 60 cm in depth of prepared CSW with particle size ranging from 6 to 12mm. The 4th stage, which was designed for P removal, was packed firstly with CSW (with size ranging from 20 to 40mm) to 10 cm at the bottom to act as supporting layer followed by 55 cm in depth of prepared coal ash-based CSW with particle size ranging from 3 to 20mm.

Typha angustifolia was planted in each stage of the wetland system. Figure 1 shows schematic description of the system. The characteristics and configuration of the CSW based multi-stage vertical subsurface flow (VSF) CWs is summarized in Table 2. A tidal flow strategy was employed in each stage to improve oxygen supply. During the tidal flow operation, each matrix of the CW was alternately filled with effluent from the previous stage and then drained. When the bed is drained, the retreating wastewater acts as a 'passive pump' to draw air from the atmosphere into the matrix. This creates an oxygen-transferring period in each stage of the wetland system. When the bed is filled, the oxygen consumption occurs in each stage of the system. Such intermittently filling and draining of the bed matrices was generated by peristaltic pumps that were connected to the outlet of previous bed and inlet of next bed. The pumps were controlled by pre-set digital electronic timers. In each stage, the 'tide' took place once every 6 hrs and gave 4 cycles per day. Each cycle allows 1.76 L of raw water to pass through, giving a hydraulic loading rate (HLR) of 1.0

$\text{m}^3/\text{m}^2 \text{ d}$ for 1st stage and 3rd stage and HLR of $0.047 \text{ m}^3/\text{m}^2 \text{ d}$ for 2nd stage and 4th stage of the CWs, respectively.

[Insert Fig. 1 here]

Analysis

The coal ash based CSW obtained from the waste light-block, which was further oven dried at $103 \pm 2 \text{ }^\circ\text{C}$, was used for examining its physical and chemical properties. Three parallel samples were digested using the standard method of nitric acid digestion (3030 E, APHA, 1992). Thereafter, the chemical composition of the CSW was determined using Inductively Coupled Plasma-Atomic Emission Spectrometer (ICP-AES) (IRIS Advantage, Thermo Elemental, Franklin, Massachusetts, USA). The surface areas of the CSW samples were conducted using an Accelerated Surface Area and Porosimetry System (ASAP2020, Micromeritics Instrument Corporation, Norcross, Georgia, USA). During the testing period, samples of influent and effluent from each bed of the multi-stage VSF CWs were collected and then filtered using $0.45 \mu\text{m}$ filter membrane for soluble chemical oxygen demand (SCOD), N and P measurement. The filtered samples were analysed for P concentration using ICP-MS (X series, Thermo Elemental, Franklin, Massachusetts, USA) (for P concentration less than 0.05 mg-P/L) and the stannous chloride method (for P concentration higher than 0.05 mg-P/L) (4500-P D).^[12] SCOD and Ammoniacal-nitrogen were analysed using standard methods of 5210 B and 4500-NH₃ C, respectively.^[12]

[Insert Table 2 here]

RESULTS AND DISCUSSION

Physical and chemical properties of the coal ash-based CSW

The principal physical and chemical properties of the coal ash-based CSW are shown in Table 3. Specific elemental metal component of aluminium, iron and calcium content (expressed as oxidized metal) in the CSW was 174.7, 96.7 and 127.3 mg/g-CSW, respectively. The other principal chemical components were silicon oxide and orthophosphate (expressed as phosphorus) with mass content of 46.9 and 0.1 mg/g-CSW, respectively. As shown in Table 3, aluminium, iron and calcium are the dominant component that relate to P-metal adsorption and/or precipitation. This can potentially contribute to adsorption and/or chemical precipitation of P onto the CSW. ^[13]

[Insert Table 3 here]

In the adsorption process, the adsorbent must have sufficient surface area which allows the adsorbate to be adsorbed on it. The required surface for phosphate ion is determined to be approximately 23 Å². ^[14] Olsen ^[15] used radio phosphorus as radioactive tracer to characterize P adsorption on hydroxylapatite and showed that the effective area per phosphate molecule is 21.6 Å². Assuming phosphate was adsorbed on CSW surface in monolayers, removal of 1 milligram of phosphate (expressed as phosphorus) from wastewater onto CSW may occupy approximately 4.21 m² of surface area. The specific surface area of the coal ash-based CSW, calculated from Brunauer-Emmett-Teller (BET) model, was 48.6 m²/g-CSW. This indicates that coal ash-based CSW has sufficient surface area which allows the adsorbate to be adsorbed on it.

Characteristics of P removal

Figure 2 presents the P removal performance of the CSW based multi-stage VSF CWs treating the secondary sewage effluent. The phosphate concentration in the secondary effluent ranged from 0.15 to 3.06 mg-P/L. The phosphate in the effluent of the CWs in the operation period (up to 122 days) was in the range of 0.009 to 0.13 mg-P/L. Accordingly, the P removal efficiency was in the range from 89.9 to 99.7% while the average P removal efficiency was 96.7%. The very low P concentration and very high P removal efficiency achieved at the operation period indicate the excellent P removal ability of the CSW. Figure 3 shows the plot of cumulative P removal against cumulative P loaded in the CWs. It shows a straight line with slope of 0.984. This line indicates that nearly all the loaded P has been adsorbed on to the CSW.

[Insert Fig. 2 here]

[Insert Fig. 3 here]

Characteristics of nitrogen removal

Figure 4 shows the ammoniacal-nitrogen removal performance of the CSW-based CWs. The ammoniacal-nitrogen concentration in the secondary effluent ranged from 0.5 to 14.7 mg-N/L with an average of 9.94 mg-N/L. The ammoniacal-nitrogen in the effluent of the CWs at the start-up period (0 to 46 days) was decreased from 10.7 to 1.1 mg-N/L while the ammoniacal-nitrogen removal efficiency was increased from 0 to 87.5% in the same period.

At the operation period (47 to 122 days), the ammoniacal-nitrogen in the effluent ranged from 0.1 to 2.4 mg-N/L with an average of 1.0 mg-N/L. This gives average removal of $89.0 \pm 7.7\%$. This high ammoniacal-nitrogen removal efficiency could be attributed to the enhanced oxygen supply in the multi-stage VSF CWs. Typically, oxygen can be transferred into the CW system through air diffusion during the filling and/or draining process of the tidal flow operation strategy and the roots of the plant. However, the root of *Typha angustifolia* was not well developed in this study. Therefore, the amount of oxygen supply through the roots of plant is insignificant. The tidal flow operation strategy may supply sufficient amount of dissolved oxygen and lead to the enhanced nitrification in the treatment system. The theoretical oxygen supply rate of the CWs using tidal flow operation strategy is $137.2 \text{ g/m}^2 \text{ d}$.^[8]

[Insert Fig. 4 here]

Figure 5 shows the nitrate removal performance of the CWs. The nitrate concentration in the secondary effluent ranged from 8.1 to 22.9 mg-N/L. While in the effluent of the CWs, the nitrate at the start-up period (0 to 46 days) was decreased from 6.7 to 2.7 mg-N/L. As shown in Figure 5, at the operation period (47 to 122 days), the nitrate in the effluent ranged from 0.1 to 2.4 mg-N/L. This gives $96.0 \pm 4.2\%$ of nitrate removal from the secondary sewage effluent through denitrification.

[Insert Fig. 5 here]

Figure 6 shows the nitrite removal performance of the system. The nitrite concentration in the secondary sewage effluent ranged from 0.05 to 1.1 mg-N/L while in the effluent of the

CWs it ranged from 0.09 to 2.1 mg-N/L at the start-up period (0 to 46 days). The nitrite in the effluent of the CWs ranged from 0.01 to 0.8 mg-N/L while that of the secondary sewage effluent ranged from 0.2 to 6.4 mg-N/L at the operation period (47 to 122 days).

[Insert Fig. 6 here]

As shown in Figures 5 and 6, the CSW-based CWs also presents higher nitrate and nitrite removal efficiency. Regarding to the pathway of ammoniacal-nitrogen removal, it can be a collective result of plant uptake and nitrification. The resultant nitrate and nitrite are further removed through denitrification.^[16] However, the amount of *Typha angustifolia* growth in this study is insignificant (approximately 0.2g/m² during the operation period). This indicates that plant uptake is not the major pathway for ammoniacal-nitrogen removal. While, the microorganisms involved in the nitrification and denitrification process in the CSW-based CWs still need to be studied to reveal the ammoniacal-nitrogen, nitrate and nitrite removal mechanisms in such system.

Characteristics of organic matter removal

Figure 7 presents the SCOD removal performance of the CWs. The SCOD concentration in the secondary effluent ranged from 19.8 to 53.5 mg/L with an average of 32.83 mg/L. The SCOD in the effluent at the operation period (up to 122 days) ranged from 20.6 to 57.5 mg/L with an average of 35.9 mg/L. This indicates that there was no obvious change in the SCOD in the inflow and outflow of CSW-based constructed wetland. Considering the characteristics and mechanisms of nitrate and nitrite removal through heterotrophic denitrification, the insignificant amount of SCOD removal in the CSW-based CWs indicates

that the carbon source, which is necessary for heterotrophic denitrification^[17,18], was not involved in denitrification process. This limited change of SCOD implies that there are some other mechanisms contributed to the N removal in the system.

[Insert Fig. 7 here]

Changes in effluent pH

Figure 8 presents the characteristics of pH changes in the effluent of different stages in the CWs. During the operation period, the pH value of the influent ranged from 6.91 to 7.68 with an average of 7.24. The average effluent pH of different stages is respectively 7.22 (1st stage), 8.02 (2nd stage), 7.72 (3rd stage) and 11.08 (4th stage). During the adsorption process, the pH value of the effluent is controlled by hydrolysis of the CSW and the release of the hydroxide ion from the CSW into the aqueous phase due to the adsorption of P onto the CSW. The pH increase due to hydroxide ion release can be observed in 2nd stage and in particular in 4th stage where dominating P removal occurs. This provides evidence that P adsorption onto the coal ash based CSW is probably through ligand exchange.^[13]

[Insert Fig. 8 here]

CONCLUSIONS

The characteristics of P, N and SCOD removal from the secondary sewage effluent using a novel CSW-based multi-stage vertical subsurface flow CWs were investigated to present the applicability of CSW reuse as a media in CW. The tidal flow operation strategy was

employed to demonstrate N and organic matter removal performance of the CSW-based CW. The results have shown that significant amount of P removal can be achieved using such the system. The CSW presents excellent P removal performance. The ammoniacal-nitrogen removal performance was improved due to the oxygen supply capacity and nitrification performance can potentially be enhanced by using the tidal flow operation strategy in the system. The application of CSW as a media in CWs treating secondary sewage effluent not only improves water quality, but also provide a good showcase for beneficially reuse of the CSW. Such the application can transfer the CSW from 'waste' to 'useful' material and can ease the pressure of construction waste solid management. More significantly, such the application can transfer the CSW from a 'waste' to 'useful' material and can ease the pressure of construction waste solid management. The treated effluent after the CWs could be a water source for non-potable use in landscape irrigation, agriculture and industrial process.

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Table 1 Characteristics of the secondary effluent

Parameters	Average \pm SD (n=37)	Minimum	Maximum
pH	7.25 \pm 0.21	6.91	7.68
PO ₄ ³⁻ -P (mg/L)	1.90 \pm 0.70	0.15	3.06
NH ₄ ⁺ -N (mg/L)	7.43 \pm 4.31	0.45	14.74
SCOD (mg/L)	33.35 \pm 8.40	19.77	53.50

Table 2 Characteristics and configuration of the multi-stage VSF CWs

Parameters	Constructed wetland system			
	1 st Stage	2 nd Stage	3 rd Stage	4 th Stage
Type of CSW	Waste concrete	Waste concrete	Waste concrete	Coal ash
Bed depth (cm)	65	65	65	65
CSW layer (cm)	60	60	60	55
Particle size (mm)	6-12	6-12	6-12	3-20
Supporting layer (cm)	5	5	5	10
Particle size (mm)	20-40	20-40	20-40	20-40
Contact time (min)	345	345	345	345
Drain time (min)	15	15	15	15
HLR (m ³ /m ² d)	1.0	0.047	1.0	0.047

Table 3 The physical and chemical properties of the coal ash-based CSW

Properties	Unit	Average \pm SD (n=3)
Aluminium (as Al ₂ O ₃)	mg/g-CSW	174.7 \pm 24.1
Iron (as Fe ₂ O ₃)	mg/g-CSW	96.7 \pm 21.6
Calcium (as CaO)	mg/g-CSW	127.3 \pm 20.7
Silicon oxide (as SiO ₂)	mg/g-CSW	46.9 \pm 18.8
PO ₄ ³⁻ (as phosphorous)	mg/g-CSW	0.1 \pm 0.04
Specific surface area	m ² /g-CSW	48.6 \pm 0.9

FIGURE CAPTIONS

Figure 1 Schematic description of the CSW based multi-stage VSF constructed wetland system

Figure 2 Characteristics of P removal during the operation period

Figure 3 Plot of cumulative P removal against cumulative P loaded in the CWs

Figure 4 Characteristics of NH_4^+ -N removal during the operation period

Figure 5 Characteristics of NO_3^- -N removal during the operation period

Figure 6 Characteristics of NO_2^- -N removal during the operation period

Figure 7 SCOD removal performance of the CSW-based CWs

Figure 8 Characteristics of pH changes in the effluent of different stages in the CSW-based CWs

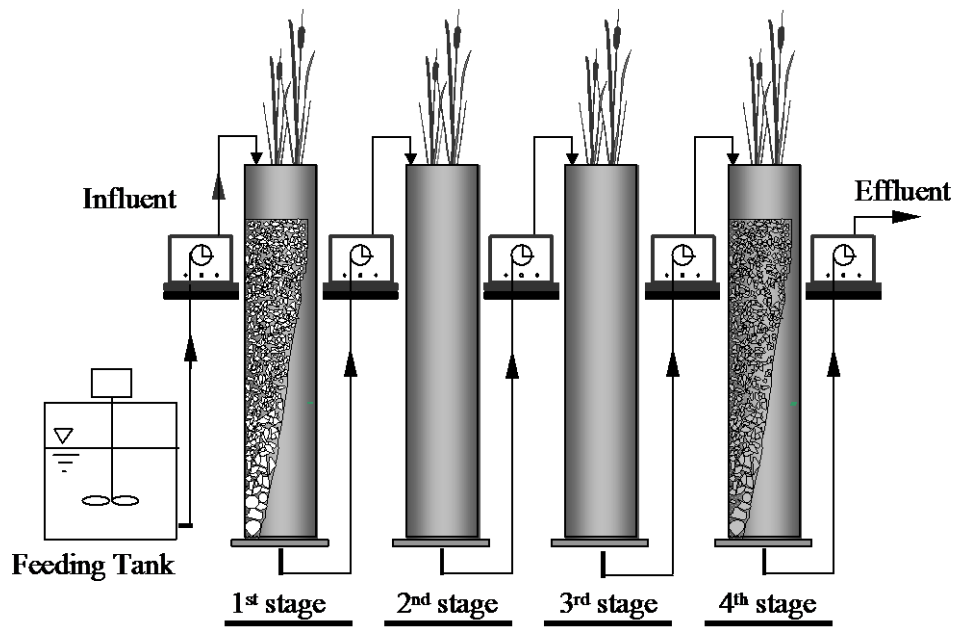


Fig. 1.

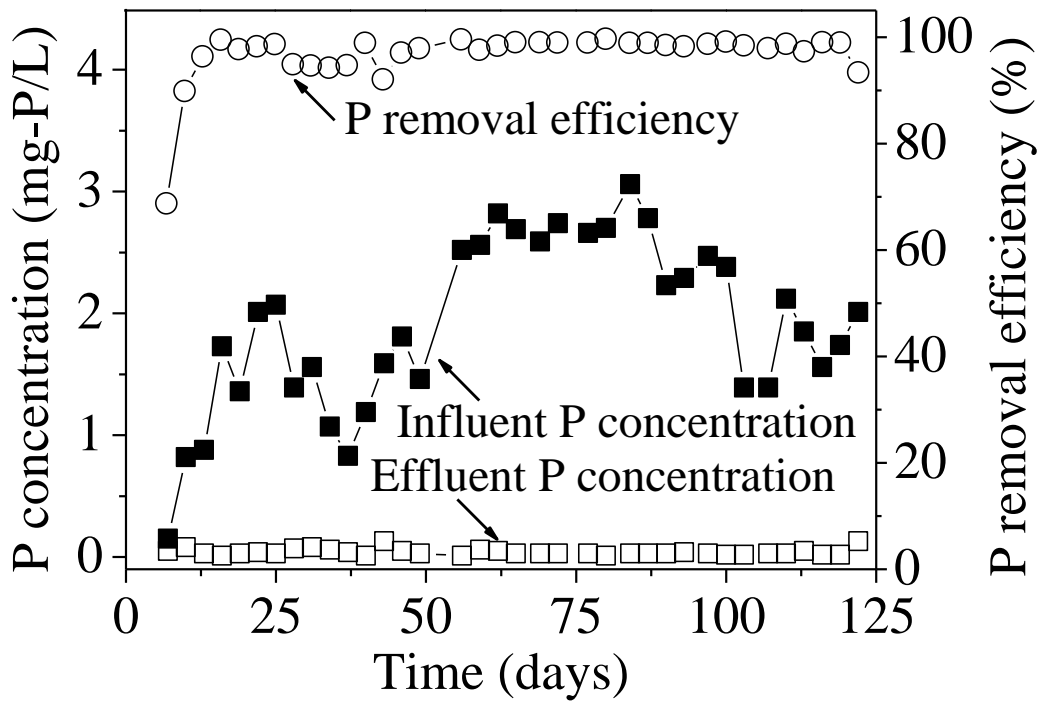


Fig. 2.

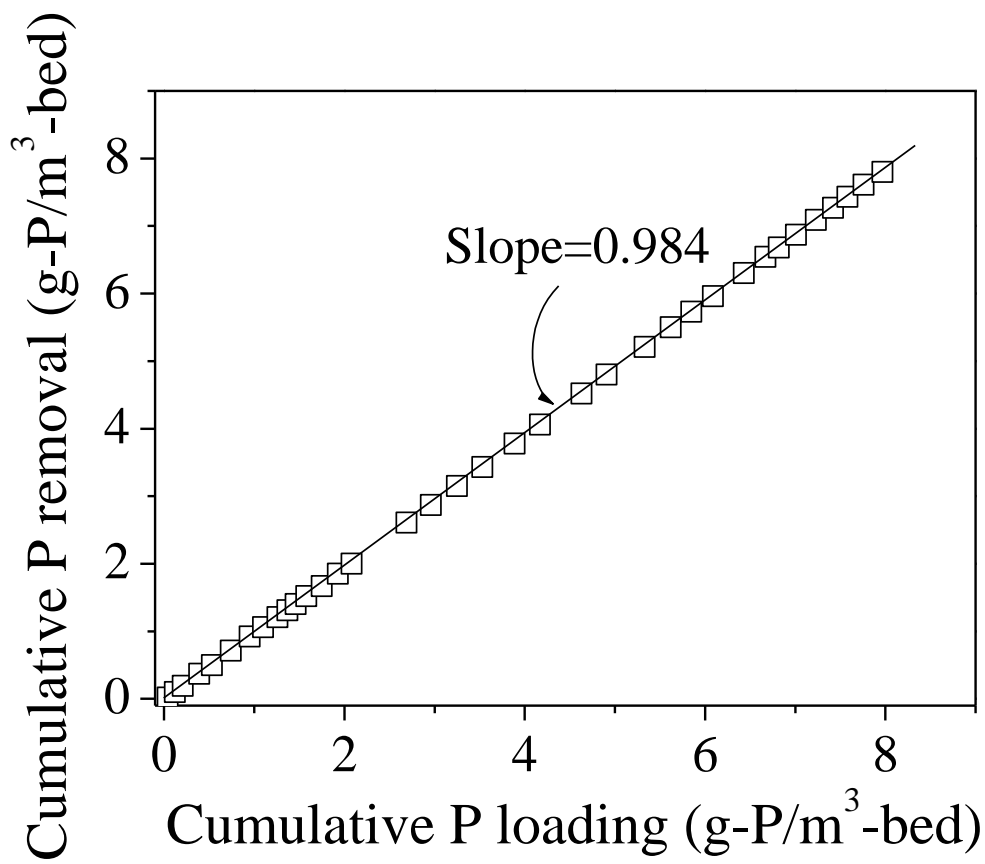


Fig. 3.

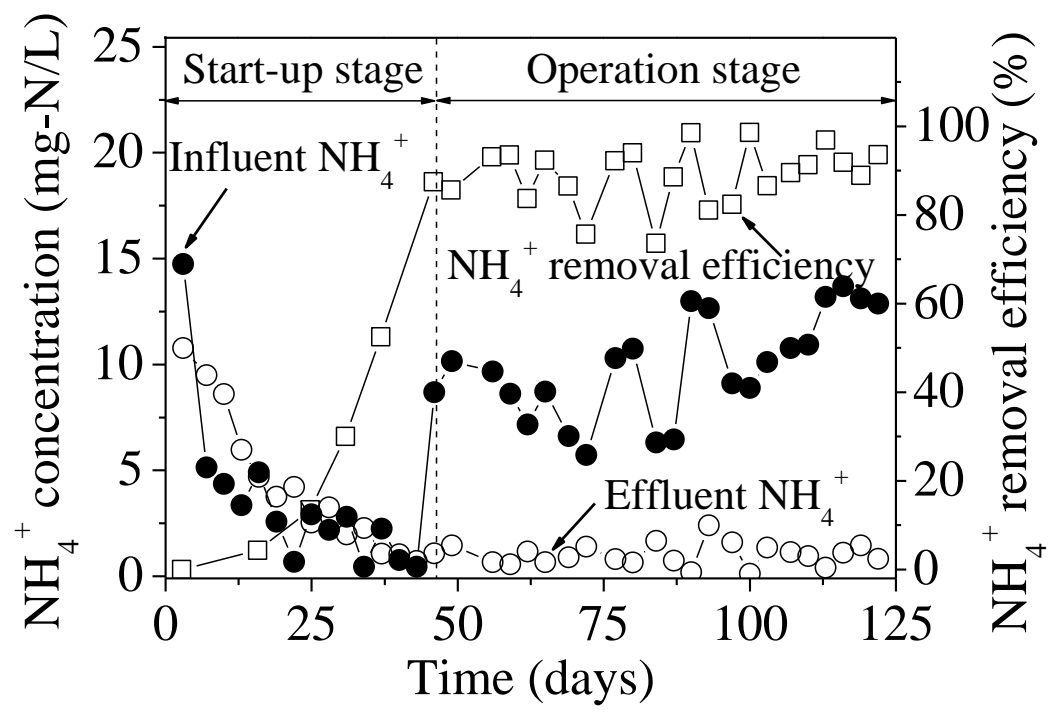


Fig. 4.

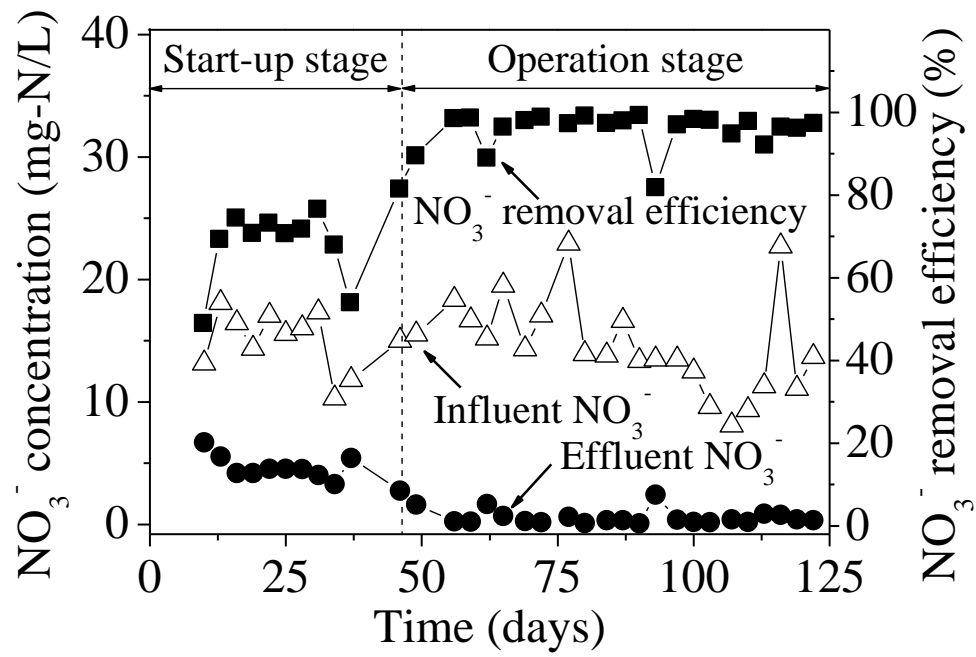


Fig. 5.

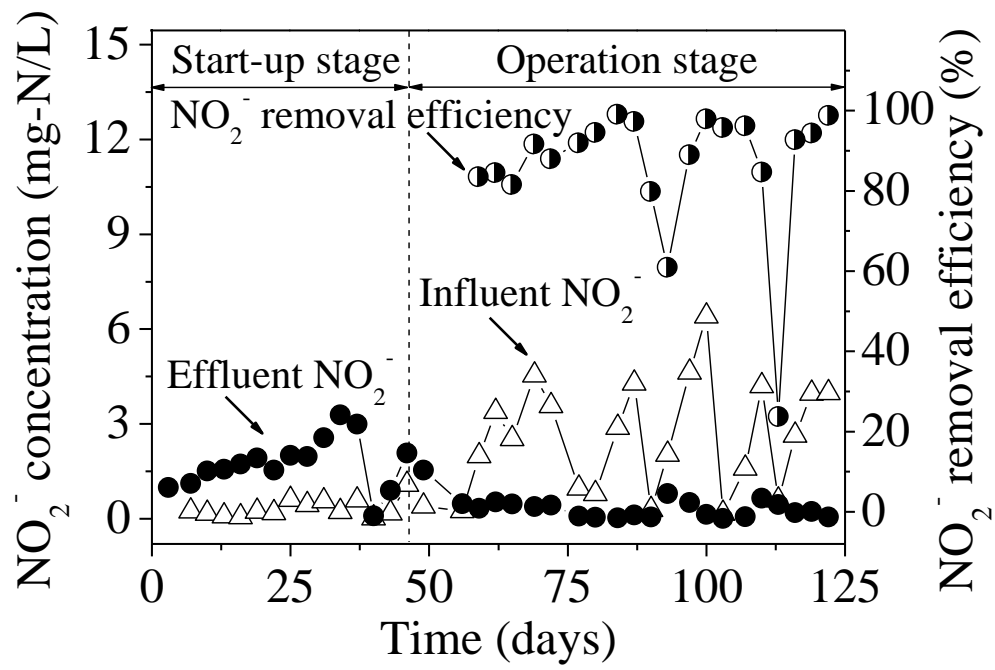


Fig. 6.

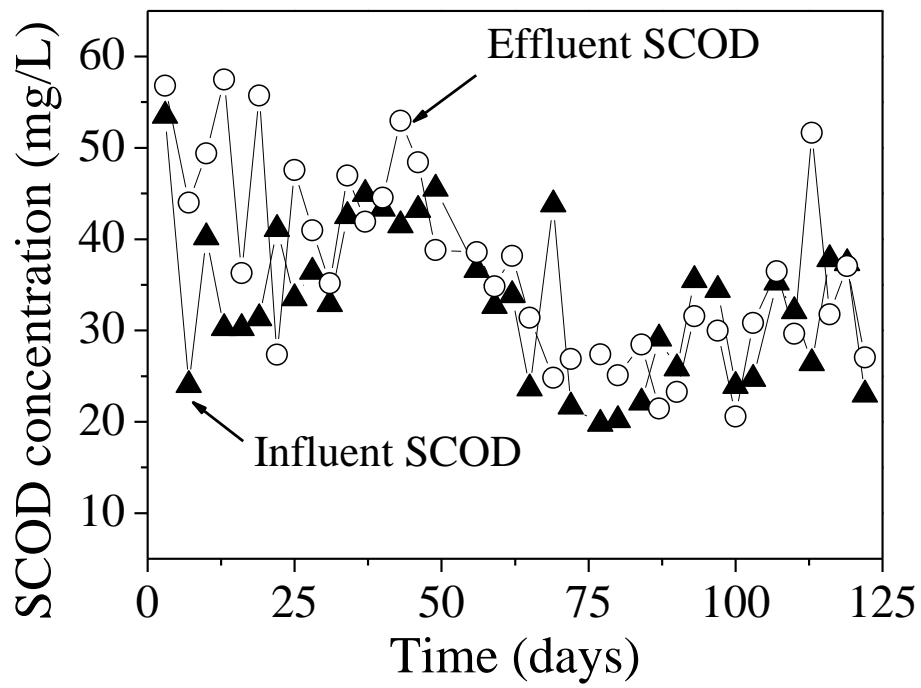


Fig. 7.

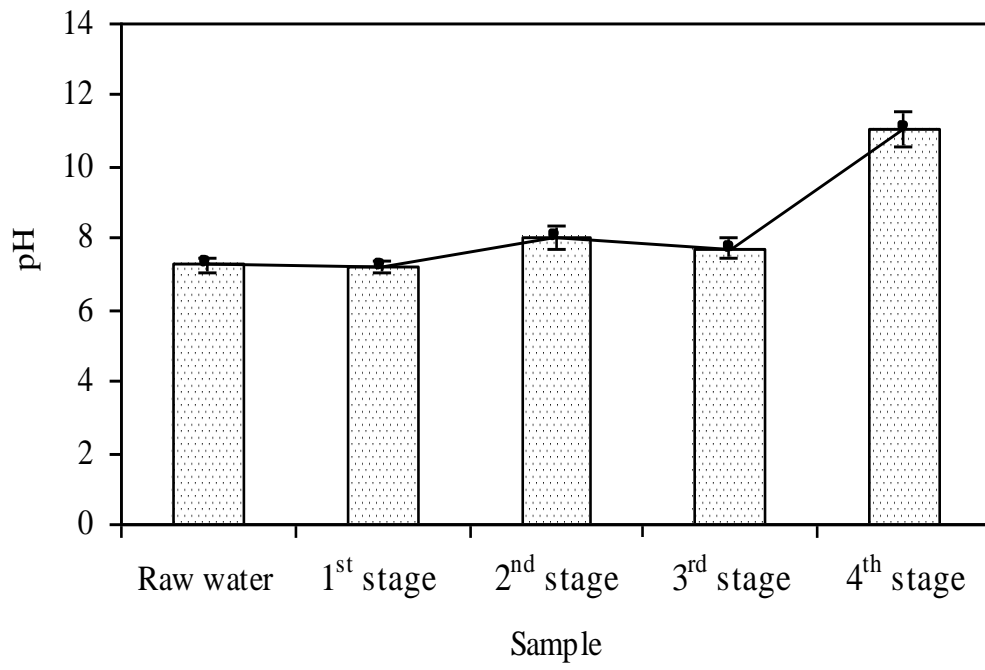


Fig. 8.