Optimum backwashing conditions and ammonium-nitrogen treatment efficiency of iron oxide modified sands coated in biofilm

Dongmei Li, Jieman Lin, Yizhi Wang, Wen Zhang and Shaoxiu Li

ABSTRACT

In this study, iron oxide modified sands with nano-pores (IOMSNP) were enveloped in biofilm (B-IOMSNP) in order to treat the ammonium-nitrogen (NH$_4^+$-N) in micro-polluted raw water. The biomass, optimum backwashing conditions, treatment efficiency, and surface morphological properties of the B-IOMSNP were investigated via bio-filtration experiments. The raw quartz sands (RQS) and IOMSNP exhibited biomass levels of 24.32 nmol-P/(g-sand) and 83.71 nmol-P/(g-sand), respectively. The B-IOMSNP filter exhibited a lower swelling ratio, smaller initial head loss, and longer filtration period when water and air were used alternately for backwashing rather than water alone. In addition, the B-IOMSNP was most effective when air alone (at a strength of $q_{\text{air, I}} = 7$ L/(s·m$^2$) for $t_{\text{air, I}} = 6$ min), a combination of air and water (at strengths of $q_{\text{air, II}} = 7$ L/(s·m$^2$) and $q_{\text{water, II}} = 5$ L/(s·m$^2$) for $t_{\text{air-water, II}} = 6$ min, respectively), and water alone (at a strength of $q_{\text{water, III}} = 7$ L/(s·m$^2$) for $t_{\text{water, III}} = 4$ min) were used alternately for flushing. The results indicated that the proposed B-IOMSNP could efficiently resist the shock induced by high NH$_4^+$-N concentrations (4 mg/L). The ripening period of the B-IOMSNP column was equal to 30 minutes. Furthermore, the B-IOMSNP reduced the turbidity of the water to values of less than 0.2 NTU for 72 hours and exhibited an NH$_4^+$-N removal rate of up to 96% and a head loss of 132 cm. In contrast, the biofilm-coated RQS exhibited an NH$_4^+$-N removal rate varying from 60% to 82%, a filtration period of 16 hours, and a terminal head loss of 58 cm. Due to its nano-pores and rough surface, the IOMSNP exhibited a specific surface area 39 times greater than that of the RQS, resulting in a higher filtration performance and absorption capacity.

Key words | ammonia-nitrogen, backwashing condition optimization, bio-iron oxide modified sands, filtration behavior, morphological characteristics, removal efficiency

INTRODUCTION

In recent years, raw water pollution in the drinking water supply has become a significant problem in China. Micro-pollutants, especially dissolved organics and nutrients with low molecular weights, are not easily removed via conventional water treatment processes (Loo et al. 2012; Wang et al. 2013). Due to the new water quality standard requirements for treated water (GB5749-2006) in China, water treatment facilities must upgrade the conventional processes used to reduce water pollution (coagulation, sedimentation, filtration, disinfection) in a cost-efficient manner. Although biological methods can effectively remove NH$_4^+$-N, microorganisms easily slough from conventional media, such as raw quartz sands (RQS) and zeolites, resulting in low NH$_4^+$-N removal efficiency (Štembal et al. 2005; Loo et al. 2012). Thus, facilitating the adhesion of microorganisms to the surfaces of filter media could improve the effectiveness of NH$_4^+$-N removal (Yang et al. 2010; Xia et al. 2012; Gibert et al. 2013; Yang et al. 2013; Choi et al. 2014).
In previous studies, the specific surface area and adsorption capacity of filters have been improved by coating sands with Al/Fe metal oxides and hydroxides in order to efficiently remove trace heavy metals from polluted water (Erickson et al. 2012; Mahler & Persson 2013; Han et al. 2014). Studies concerning the use of modified sands to filter bacteria, viruses, and humic acid have also been promising (Han et al. 2014). However, the backwashing conditions, filtration behaviors, and surface morphological characteristics of biofilm-amended iron oxide coated sands as treatments for micro-polluted water containing NH₄⁺-N (Li et al. 2011) have not been systematically investigated.

The objective of this study was to determine the effects of the biomass, backwashing conditions, filtration behaviors, and surface morphological characteristics of a novel filtration medium coated with biofilm on the removal of NH₄⁺-N. Iron oxide modified sands with nano-pores (IOMSNP) were subjected to enhanced biofiltration experiments. The novel IOMSNP developed in this study was low in cost, had nano-porous surface structures, and exhibited a high ion-exchange ability and adsorption capacity (Li et al. 2011). Biofilm was firmly attached to the surface of the IOMSNP (namely B-IOMSNP). The B-IOMSNP was capable of both nitrification and adsorption exchange. In addition, the backwashing conditions of the B-IOMSNP were optimized in order to ensure the proper adhesion of microorganisms. The filtration and backwashing experiments were conducted in the Shakou water plants of Foshan in Guangdong Province, China. The biomass, backwashing conditions, filtration mechanisms, turbidity and NH₄⁺-N treatment efficiencies, and surface morphological properties of the filtration media were systematically analyzed before and after the application of the biofilm.

**METHODS AND MATERIALS**

**Materials**

The RQS was purchased from the Zhenxing Quartz Sand Factory in Luoyang, China. The size of the RQS ranged from 0.8 to 1.4 mm (d₁₀ = 0.95 mm). The IOMSNP was prepared at our laboratory using the RQS according to the procedure detailed by Li et al. (2011). The raw water influent, which consisted of supernatant obtained from the settling tank of Shakou Water Plant in China, had a turbidity of 1.5 ± 0.5 NTU and a pH of 7.4 ± 0.4. The raw water had a dissolved oxygen (DO) content of 7 ± 1 mg/L. The NH₄⁺-N content of the water was varied from 0.5 mg/L to 4 mg/L by adding NH₄Cl purchased from Wenrui Reagent Company in Guangzhou, China. C, N, and P were added at a ratio of C:N:P = 100:5:1 using glucose, NH₄Cl, and potassium dihydrogen phosphate, respectively.

**Experimental procedures**

**The preparation of the iron oxide modified sand with nano-pores**

The preparation of the IOMSNP was reported in detail by Li et al. (2011). Briefly, the FeCl₃ solution of 2 mol/L was mixed with RQS at a mass ratio of 0.33 mg FeCl₃/g RQS. Then, the NaOH solution of 3 mol/L was added to the mixture at a dose of 0.3 mL NaOH/g RQS with rigorous stirring. The mixture was dried up by heating at 110 °C in an oven for 2.5 h and then underwent calcination (0–600 °C) in the muffle furnace for different times (0–5 h). The solid was cooled at room temperature, followed by washing with distilled water to remove the loosely attached iron oxide particles on the surface of the RQS. The wet RQS was dried again in the oven to achieve IOMSNP. Morphology and surface elements were analyzed by scanning electron microscope/energy dispersive spectrometer (SEM/EDS), which confirmed the major form of Fe oxides on the surface of the IOMSNP was α-Fe₂O₃ (hematite). The size of α-Fe₂O₃ particles on the surface of the IOMSNP could be controlled by the calcining temperature.

**Biofilm formation**

In order to achieve efficient NH₄⁺-N removal, biofilm was applied to the surface of the IOMSNP via activated sludge inoculation and natural biofilm inoculation methods. First, an activated sludge suspension was prepared by mixing tap water and sludge obtained from a secondary sedimentation tank at Leide Sewage Plant in Guangzhou, China with nutrition liquid. Next, the spike sludge suspension was poured into the filtration column for 24 hours of continuous
aeration at an air flow-rate of 100 L/h. After 24 hours, the inoculation suspension was drained from the filtration column, and the filtration column was refilled with a fresh suspension for a subsequent 24 hours of aeration. This inoculation and aeration process was repeated nine times. Next, dynamic filtration was performed at a flow rate of 2 m/h for 48 hours without aeration. Once the turbidity and pH of the water matrix reached values of 1.5 ± 0.5 NTU and 7.4 ± 0.4, respectively, and the DO and NH$_4^+$-N contents of the raw water reached values of 7 ± 1 mg/L and 2.5 mg/L, respectively, air (6 L/(s·m$^2$)) and water (5 L/(s·m$^2$)) were used alternately for backwashing. After the biofilm biomass on the medium had stabilized, the filtration velocity was increased gradually to a rate of 7 ± 0.2 m/h.

**Dynamic filtration and backwashing**

The experimental setup of the dynamic filtration and backwashing procedures is shown in Figure 1. The micro-polluted raw water containing NH$_4^+$-N was lifted from the trough to the organic glass columns via pumps at a flow rate 308 L/h. Columns A and B (7 cm in diameter) were filled and packed with 8.5 kg of RQS and 8.9 kg of IOMSNP (80 cm in depth), respectively. A filtration velocity of 7 ± 0.2 m/h was used. The DO concentration was greater than 3 mg/L throughout the filtration layers, and the water temperature was equal to 28 ± 5 °C. Backwashing was performed using air alone or air and water alternately at the bio-filtration terminal. Filtered water turbidity and terminal head loss standards of 0.2 NTU and 1.5 m-H$_2$O were established according to the standards of Shakou Water Plant in Foshan, China.

**Orthogonal array design of the backwashing experiment**

In order to achieve optimal filtration performance, the orthogonal array design method was used to determine the optimum backwashing conditions. In the orthogonal array design, L$_n(f^m)$ was used to represent the effects of various factors, where $f$ and $m$ denote the number of levels and factors, respectively, and $n$ denotes the total number of experiments under different test conditions. The parameters of the backwashing experiments included the flushing strengths and flushing times of the water, air, and air–water steps. Thus, each factor was comprised of three levels. Two indices were used in the orthogonal array design: the turbidity of the drainage water and the amount of biomass reduction.

The orthogonal array design method consisted of several steps. First, a standard orthogonal array design table was...
selected. The ‘factor’ columns of the table were filled with their respective values. Next, experiments were conducted according to the orthogonal array design scheme. The test results were entered into the ‘index’ column in the L\textsubscript{n}(f\textsuperscript{r}) format. Then, the sum (S) of each index value corresponding to the same level of each factor column was calculated. In addition, the average values of E through S were divided by the number of occurrences in each level. Finally, the R value, the difference between the maximum and minimum values of E, was determined. E was used to denote the optimum combination of factors corresponding to the optimal experimental conditions, and R was used to denote the degree of influence of each factor during the backwashing process. Higher values of R were associated with higher levels of influence on an index.

Analytical methods

Biomass measurements

The amount of biomass on the sand particles in the filter columns was measured using a T6 UV spectrophotometer (Beijing, China) according to the lipid phosphorus method described by Yu et al. (2002). The absorbance values at a 720-nm wavelength were measured in order to determine the biomass levels of the sand particles in the filter columns. The relationship between the absorbance values and lipid-P levels (expressed in nmol of P per gram of sand, where 1 nmol of P was equated to 10\textsuperscript{8} E. coli cells) is shown in Figure S1 (Yu et al. 2002) (available with the online version of this paper).

NH\textsubscript{4}\textsuperscript{+}-N concentration

The absorbance values of the sand particles in the filter columns at a 420-nm wavelength were also measured using a T6 UV spectrophotometer according to the Nessler reagent method. Figure S2 (available with the online version of this paper) displays the relationship between the absorbance values and NH\textsubscript{4}\textsuperscript{+}-N concentrations.

Backwashing strength and time

After the breakthrough of the biofiltration column, backwashing was performed using water alone or air and water alternately in order to regenerate the filtration capacities of the filter media layers. Various flushing strengths and times were established based on the biomass reduction levels and residual turbidity of the drainage water at the backwashing terminal in order to determine the optimal backwashing conditions.

Surface morphological characteristics

The surface morphological characteristics of the filter media were analyzed in order to investigate changes in the characteristics (e.g., surface structures, porosity, and roughness), interception efficiencies, and pollutant adsorption properties of the filters during the filtration and backwashing processes. An S3400N scanning electron microscope (Hitachi, Japan) was used to acquire images of the filter media with and without biofilm in order to interpret the filtration behaviors and NH\textsubscript{4}\textsuperscript{+}-N removal rates of the filters.

RESULTS AND DISCUSSION

Biomass on the surface of the IOMSNP

Stable biofilm formation on the medium was achieved after 10 days. The IOMSNP exhibited a much higher quantity of biomass (83.71 nmol-P/g-sand) than the traditional RQS (24.32 nmol-P/g-sand). The distinct morphological structures on the surface of the media are shown in the SEM images in Figure 2. The surface of the IOMSNP appeared to be more complicated, rough, and porous than the relatively smooth surface of the RQS. The Brunauer–Emmett–Teller (BET) test results indicated that the specific surface area of the IOMSNP was 39 times larger than that of the RQS. The absolute value of the specific surface area of IOMSNP and RQS is 9.824 m\textsuperscript{2}/g and 0.258 m\textsuperscript{2}/g respectively. According to the semi-quantitative EDS analysis, the surface of the IOMSNP was primarily composed of \(\alpha\)-Fe\textsubscript{2}O\textsubscript{3} (hematite) and adhered best to negatively charged colloids. Thus, the large specific surface area and strong adsorption capacity of the IOMSNP promoted the adhesion of microorganisms.
Optimum backwashing conditions of the B-IOMSNP

The backwashing conditions significantly affected the porosity, biomass, microbial activity, and initial head loss of the media layers and, thereby, the interception capacity and filtration behaviors of the filter columns. Therefore, the optimum backwashing conditions of the B-IOMSNP were investigated.

Orthogonal experimental results of the filter columns after backwashing with water only

The orthogonal experimental results of the filter columns after backwashing with water only are shown in Table 1. The optimum backwashing conditions of the B-IOMSNP were determined based on two indices. Higher values of $R$ were associated with higher levels of influence on an index. For two factors, turbidity and biomass reduction, $R_{\text{strength}} > R_{\text{time}}$, indicating that the flushing strength influenced the properties of the B-IOMSNP surface to a greater extent than the flushing time ($q > t$). $E$ was used to represent the optimal combination of factors. Smaller values of $E$ were associated with lower levels of impact on an index. As shown in Table 1, the third level of both ‘strength’ and ‘time’ influenced the first index (drainage water turbidity) least, with $E$ values of 1.08 and 1.71, respectively. The first level of ‘strength’ and the second level of ‘time’ influenced the second index (biomass reduction) least, with $E$ values of 3.64 and 5.42, respectively. Therefore, the optimum flushing conditions for drainage water turbidity and biomass reduction included strengths of $q = 14$ L/(s·m²) and $q = 10$ L/(s·m²), respectively, and flushing times of $t = 10$ minutes and $t = 8$ minutes, respectively.

The amount of biomass influenced the micro-polluted raw water treatment efficiency most, with optimal water backwashing conditions of $q = 10$ L/(s·m²) and $t = 8$ minutes. The drainage water turbidity and amount of
biomass reduction of the backwashing terminal were equal to 3.17 NTU and 3.78 nmol-P/(g-sand), respectively. However, the filtration layers became clogged rapidly under these optimal conditions. Thus, although an adequate amount of biomass was entrapped on the surface of the RQS, the scouring process was incapable of preventing porosity in the interior filtration layers under the optimal backwashing conditions. Furthermore, high water backwashing strengths, such as a backwashing strength of $q = 14$ L/(s·m²) for $t = 10$ minutes, were associated with high swelling ratios (15%), which resulted in poor filtration efficiency in subsequent steps.

**Orthogonal experimental results of the filter columns after backwashing alternately with air and water**

Alternate air and water backwashing was also performed in order to improve the filtration behaviors of the B-IOMSNP. As shown in Table 2, the backwashing process consisted of air flushing alone (at a strength of $q_{\text{air,}I}$ for $t_{\text{air,}I}$), followed by

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<th>Experimental runs</th>
<th>$q_{\text{air,}I}$ (L/(s·m²))</th>
<th>$t_{\text{air,}I}$ (min)</th>
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<th>$q_{\text{water,}III}$ (L/(s·m²))</th>
<th>$t_{\text{water,}III}$ (min)</th>
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*$E_1$ (turbidity) = 2.22, $E_2$ (turbidity) = 1.35, $E_3$ (turbidity) = 1.15, $E_1$ (biomass reduction) = 10.76, $E_2$ (biomass reduction) = 14.68, $E_3$ (biomass reduction) = 16.84, $R$ (turbidity) = 1.07, $R$ (biomass reduction) = 12.16.

*The subscripts 1, 2, and 3 of $E$ were used to indicate the first, second, and third levels of each factor. For example, the three levels of ‘strength’ were denoted by 6, 7, and 10.

*The subscripts I, II, and III of $q$ were used to indicate the first, second, and third stages of backwashing, including the air flushing, air and water flushing, and water flushing stages, respectively.
a combination of air and water flushing (at strengths of \( q_{\text{air, I}} \) and \( q_{\text{water, II}} \) for \( t_{\text{air-water, II}} \)), and water flushing alone (at a strength of \( q_{\text{water, III}} \) for \( t_{\text{water, III}} \)). An \( L_{16}(3^7) \) orthogonal array was used to design the backwashing experiment. Factors with higher values of \( R \) were associated with higher levels of influence on an index. The drainage water turbidity index was predominantly influenced by \( q_{\text{water, II}} \), with an \( R \) value of 1.07. In contrast, the drainage water turbidity index was affected least by \( q_{\text{water, III}} \), with an \( R \) value of 0.25. The factors that influenced the drainage water turbidity index, in descending order of influence, included \( q_{\text{air, I}}, q_{\text{air, II}}, t_{\text{air-water, II}}, t_{\text{water, III}}, q_{\text{water, III}}, t_{\text{air, I}}, \) and \( q_{\text{water, II}} \). In descending order of influence, the biomass reduction index was affected by \( q_{\text{air, I}}, q_{\text{air, II}}, q_{\text{water, II}}, t_{\text{water, III}}, t_{\text{air, I}}, t_{\text{air-water, II}}, \) and \( q_{\text{water, II}} \). The results indicated that the optimum backwashing conditions included backwashing with air alone (at a strength of \( q_{\text{air, I}} = 7 \text{ L/(s·m²)} \) for \( t_{\text{air, I}} = 6 \text{ min} \)), followed by a combination of air and water (at strengths of \( q_{\text{air, II}} = 7 \text{ L/(s·m²)} \) and \( q_{\text{water, II}} = 5 \text{ L/(s·m²)} \) for \( t_{\text{air-water, II}} = 6 \text{ min} \), respectively), and water alone (at a strength of \( q_{\text{water, III}} = 7 \text{ L/(s·m²)} \) for \( t_{\text{water, III}} = 4 \text{ min} \)). Backwashing with air and water alternately yielded a lower filtration layer swelling ratio (approximately 10%), higher levels of biomass for biofiltration, and a longer filtration time (up to 72 hours) than backwashing with water alone.

**Ripening period of the B-IOMSNP filter under the optimal backwashing conditions**

In this study, an IOMSNP was coated in biofilm in order to reduce the ripening period of initial filtered water. Under the optimal backwashing conditions, the initial filtered water turbidity increased significantly from 0.25 NTU to 1.03 NTU within 5 minutes. After 5 minutes, the turbidity decreased to less than 1 NTU due to the residual pollutants remaining in the filter layers after backwashing. The initial filtered water did not satisfy the requirements for drinking water. The water was either drained into the sewer or returned to the raw water entrance. The filtered water turbidity of the B-IOMSNP filtration column was less than 1 NTU after 10 minutes of filtration. Thus, the water filtered in the B-IOMSNP filtration column satisfied the newly established drinking water quality standards (GB5749-2006) of China. After 30 minutes, the turbidity decreased further to less than 0.2 NTU for 72 hours.

**Filtration behaviors of B-IOMSNP under the optimal backwashing conditions**

**NH\(_4^+\) - removal efficiency and shock resistance of the B-IOMSNP**

The B-IOMSNP was capable of resisting the shock presented by a high concentration of NH\(_4^+\)-N (4 mg/L). When the NH\(_4^+\)-N concentration varied from 0.5 to 4 mg/L, the removal rate of the B-IOMSNP increased and became more stable than that of the bio-RQS (B-RQS). The removal rate of the B-IOMSNP column ranged from 88% to 96% and endured for 72 hours. The removal rate of the B-RQS column fluctuated from 60% to 82% and endured for only 16 hours. Thus, since microorganisms adhered well enough to the IOMSNP to resist shearing force, the B-IOMSNP developed in this paper could be used to effectively remove NH\(_4^+\)-N from raw water via physico-chemical adsorption and biodegradation mechanisms.

**The comparison of nitrate and nitrite concentrations in filtered water**

To understand the ammonium removal by the biomass on the surface of the IOMSNP and RQS, the nitrate and nitrite concentrations in filtered water were analyzed in the influent with 1–2 mg/L ammonia. The nitrite and nitrate concentrations after the B-IOMSNP filtration increased faster and reached greater average levels (0.62 mg/L and 3.86 mg/L respectively) than those (0.38 mg/L and 2.59 mg/L) after the B-RQS filtration. However, the average concentrations of nitrate and nitrite in the filtered water were below the regulated limits (nitrite: 1 mg/L and nitrate: 10 mg/L) for drinking water quality in China. At a higher ammonia concentration (3–4 mg/L), the average nitrite and nitrate concentrations in the filtered water were 0.82 mg/L and 7.51 mg/L from the B-IOMSNP column and 0.54 mg/L and 5.43 mg/L from the B-RQS column respectively. Therefore, B-IOMSNP demonstrated a greater ability to oxidize ammonia, probably due to the tight attachment of iron oxide particles and microorganisms.
Variations in head loss along the filtration layers

The head loss indirectly elucidated the amount of impurities captured in the filter layers, the interception capacity of the media, and the biofilm activity. Four piezometer tubes were located 25, 55, 75, and 100 cm from the top of the filtration column in different filtration layers. A head loss of 150 cm and a treated water turbidity of 0.2 NTU were achieved before the backwashing process was conducted. All of the B-IOMSNP layers played active roles in capturing pollutants under the optimum backwashing condition. The upper layer of the B-IOMSNP was developed fully, as shown by the ◆ data in Figure 3. The initial head loss of all of the filtration layers was low (<20 cm), indicating that the filter layers were highly porous with little resistance to water flow. The filtration period of the B-IOMSNP column (72 hours) yielded a treated water turbidity of less than 0.2 NTU. Within 72 hours, the upper-half layers were absorbed, and most of the pollutants had been efficiently intercepted. The remaining pollutants were trapped in the bottom-half layers. The first layer exhibited the highest amount of head loss since the microorganisms in that layer were most active due to an adequate DO concentration. The pollutants descended through the layers throughout the filtration process. As the number of intercepted impurities increased, the porosity and head loss of the B-IOMSNP decreased and increased, respectively, until reaching the established standards. In contrast, the filtration period of the B-RQS filtration column was only 16 hours under the same conditions. Only 58 cm of head loss had accumulated after the turbidity of the treated water reached the established standard, indicating that numerous pollutants had passed through the layers rather than being removed. In addition, microorganisms sloughed from the RQS easily during the water backflushing process. These results indicated that the interception capabilities of the B-IOMSNP were far greater than those of the B-RQS.

Surface morphological characteristics of the B-IOMSNP after filtration and backwashing

As shown in Figure 4, the surface morphological characteristics of the B-IOMSNP and B-RQS were different. After backwashing, the IOMSNPs were still covered with a number of microorganisms and exhibited complicated, rough, and porous structures (Figures 2(b) and 4(a)). After long periods of filtration, the B-IOMSNP intercepted and eliminated pollutants (Figure 4(c)). The surface of the B-RQS was relatively smooth after filtration and
backwashing (Figures 2(a), 4(b) and 4(d)). The low specific surface area and weak adsorption capacity of the B-RQS surface resulted in poor micro-pollutant removal efficiency. In addition, microorganisms adhered poorly to the surface of the B-RQS due to its shorter filtration time, lower levels of head loss, and slower NH$_4^+$-N removal rate. During filtration, microorganisms sloughed easily from the B-RQS and flew from the filter column. The lower levels of biomass on the surface of the B-RQS reduced its NH$_4^+$-N removal rate.

CONCLUSIONS

In this study, IOMSNP covered in biofilm was developed in order to treat ammonia-nitrogen (NH$_4^+$-N). The mixture of iron oxides and magnetite used in the IOMSNP facilitated its filtration behaviors. The specific surface area of the IOMSNP was 39 times greater than that of the RQS. Microorganisms adhered tightly to the surface of the IOMSNP. The RQS and IOMSNP exhibited biomass levels of 24.32 nmol-P/(g-sand) and 83.71 nmol-P/(g-sand), respectively.

The backwashing conditions significantly affected the porosity, biomass, microbial activity, and initial headloss filtration period of the B-IOMSNP filter. The optimum air-water backwashing conditions for B-IOMSNP were: air flushing first (strength $q_{air,1} = 7$ L·s$^{-1}$·m$^{-2}$ and time $t_{air,1} = 6$ min); then, air and water flushing together ($q_{air,1} = 7$ L·s$^{-1}$·m$^{-2}$, $q_{water,1} = 5$ L·s$^{-1}$·m$^{-2}$ and $t_{air-water,1} = 6$ min); lastly, water flushing ($q_{water,1} = 7$ L·s$^{-1}$·m$^{-2}$ and $t_{water,1} = 4$ min).

The B-IOMSNP was capable of efficiently resisting the shock elicited by high NH$_4^+$-N concentrations (4 mg/L). The ripening period of the B-IOMSNP column was equal to 30 minutes. The B-IOMSNP maintained the filtered water turbidity at values of less than 0.2 NTU for 72 hours and exhibited an NH$_4^+$-N removal rate of up to 96%. In contrast, the B-RQS exhibited a shorter filtration period (16 hours) and an NH$_4^+$-N removal rate varying from 60% to 82%. The nitrite and nitrate concentrations after the B-IOMSNP filtration increased faster and reached greater levels than those after the B-RQS filtration, which indicated for B-IOMSNP a greater ability to oxidize ammonia. Under the same backwashing conditions, the head loss of the B-IOMSNP column (132 cm) was higher than that of the B-RQS (58 cm). Due to their physico-chemical adsorption and biodegradation capabilities, the B-IOMSNP layers captured more pollutants than the B-RQS layers.

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