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Impacts of temperature and nitrifying community on nitrification kinetics in a moving-bed biofilm reactor treating polluted raw water

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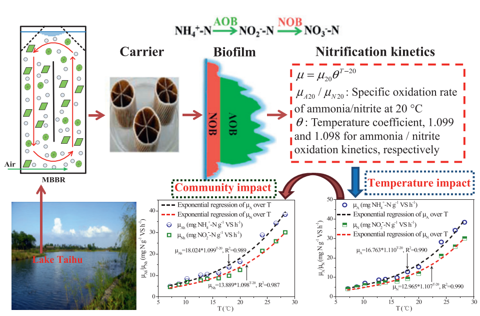
HIGHLIGHTS

- Nitrification kinetics was studied in a MBBR treating polluted raw water.
- Temperature and nitrifying community impacts on nitrification kinetics were focused.
- Temperature impact was affected by severe inhibition of temperature below 5.0 °C.
- Variation in nitrifying community influenced temperature impacts on nitrification.
- Temp. coeffi. were 1.099 and 1.098, respectively, for NH_3/NO_2^- oxidation kinetics.

GRAPHICAL ABSTRACT



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ABSTRACT

Although nitrification kinetics have been widely studied in wastewater treatment systems to optimize the design and operation of the nitrification process, more information is still needed to fully understand the kinetics of moving-bed biofilm reactors (MBBRs) used for biological pretreatment of low ammonia concentration polluted raw water. In this study, nitrification kinetics of a pilot-scale MBBR treating polluted raw water were studied while focusing on the impacts of temperature and the nitrifying community. Nitrification batch tests were conducted with an initial ammonia concentration of 2.0 mg L^{-1} and varying raw water temperatures of 2.8–28.3 °C. The oxidation rates of ammonia and nitrite increased with temperature, although the biomass concentrations decreased from 348.7 to 188.9 mg VS L^{-1} as temperature increased from 16.1 to 28.3 °C. The specific ammonia and nitrite oxidation rates were also highly dependent on temperature. Because of severe inhibition at temperatures below 5.0 °C, the temperature impacts were calibrated by eliminating the kinetic data measured below 5.0 °C. Moreover, the variations in functional microorganisms for AOB (*β-Proteobacterial AOB*) and NOB (*Nitrobacter* spp.) were normalized for the modified nitrification kinetics. Thus, the final temperature coefficients were 1.099 and 1.098 for ammonia and nitrite oxidation kinetics, respectively, demonstrating the temperature impacts on nitrification kinetics in MBBRs treating polluted raw water.

1. Introduction

Discharges of industrial and domestic wastewater often lead to serious deterioration of surface water quality in many developing countries. In China, the concentrations of ammonia in some polluted surface water bodies have reached 2 mg L^{-1} or more [1], presenting difficult challenges for chlorine disinfection during drinking water treatment. Pre-chlorination is commonly used to remove ammonia from polluted raw water. However, this process has several disadvantages, including increased process costs associated with increased chlorine dosage, difficult process control due

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to variable ammonia concentrations, formation of harmful disinfection by-products, chlorine-related tastes and odors [2,3] and regrowth of nitrifying bacteria in drinking water distribution systems owing to the decay of chloramine formed during prechlorination [4,5]. Accordingly, removal of ammonia from polluted raw water in an efficient way while avoiding health risks associated with the formation of harmful by-products poses great challenges to water pretreatments.

Rittmann and Huck [6] found that ammonia in polluted raw water could be efficiently removed by biological pretreatments, thus minimizing the formation of disinfection by-products, which can be accomplished in biofilm processes [3,7,8]. The moving-bed biofilm reactor (MBBR) was developed for wastewater treatment about 30 years ago [9,10]. Such reactors are filled with suspended carriers, which move and circulate while providing an attachable surface for slow-growing microorganisms such as nitrifying bacteria. These reactors enable operation in continuous mode without backwashing or sludge return [9,10]. Ammonia removal from polluted raw water was recently successfully achieved in MBBRs [11,12].

Nitrifying bacteria are sensitive to temperature [13,14], which makes temperature a key influencing ammonia removal rates in MBBR systems [12,15]. The dependence of nitrification kinetics on temperature has been widely investigated in the past several decades with the purpose of optimizing the design and operation of nitrification reactors for ammonia removal. For suspended growth systems, Painter and Loveless [16] reported a temperature coefficient θ of 1.076, which described the dependence of the biological reaction rate on temperature. Similar values were also reported by Barnes and Bliss [17] in the temperature range of 5–30 °C. The temperature impacts on nitrification rate were found to be lower than expected in fixed-film biofilters designed for ammonia removal in recirculating aquaculture production systems. When oxygen is limited, the decrease in saturated dissolved oxygen (DO) concentration as temperature increases results in a negative temperature impact on the nitrification rate [18]. For MBBR systems treating wastewater, the ratio of oxygen to ammonia is lower than 2 g O_2 g^{-1} NH_4^+—N, which is defined as an oxygen limiting condition [19]. Ødegaard and Rusten [20] studied the impacts of temperature on nitrification kinetics under such oxygen limiting conditions and found that there was no significant increase in ammonia removal rates at higher temperature. However, for MBBR systems treating secondary effluent from a municipal wastewater treatment plant, Salvetti et al. [15] found that the actual biological temperature coefficient, θ, ranged from 1.086 to 1.109 (an average value of 1.098) under ammonia limiting conditions (the oxygen to ammonia ratio is above 5.0 g O_2 g^{-1} NH_4^+—N), while under oxygen limiting conditions it ranged from 1.023 to 1.081 (average value = 1.058).

There is little information available about the impacts of temperature on nitrification kinetics in MBBRs used to treat polluted raw water. In such MBBRs, the low ammonia concentration of 0.2–2.0 mg L^{-1} [1] but high DO concentration of 6.5–14.4 mg L^{-1} contribute to the high oxygen to ammonia ratio, which is always above 5.0 g O_2 g^{-1} NH_4^+—N, signifying ammonia limiting conditions [15]. In addition, variations in the nitrifying community structure of MBBRs might influence the nitrification kinetics; however, this aspect has not been thoroughly investigated [15,20].

In this study, the temperature impacts on kinetic behaviors of ammonia and nitrite oxidation under ammonia limiting conditions were investigated in MBBRs being used to treat polluted raw water, as expressed by the van't Hoff–Arrhenius equation. The nitrite oxidation kinetics is valuable for understanding NO_2^-—N conversions in such MBBRs, and was therefore evaluated in this study. Fluorescent in situ hybridization (FISH) revealed that the nitrifying community structure varied during a kinetic study [12]; therefore, it was taken into account to eliminate its influence on nitrification kinetics. To exclude disturbances caused by ammonia concentration and hydraulic conditions [21,22], this study was conducted in a pilot-scale MBBR via batch tests under a consistent ammonia concentration of 2.0 mg L^{-1} and aeration rate of 0.8 m^3 h^{-1}.

2. Materials and methods

2.1. A pilot-scale MBBR configuration and operation

A pilot-scale MBBR with an effective volume of 4.4 m^3 (1.1 × 1.0 × 4.25 m) was constructed at the Chongshan water treatment plant, which is located next to Lake Taihu (Wuxi, China). The cuboid MBBR was fabricated from steel and divided into two chambers by a separating plate with a 4.0 m^3 working chamber and a 0.4 m^3 settling chamber, as shown in Zhang et al. [12]. A center baffle (2.8 m in length, 1.0 m in width) was then installed in the working chamber to allow the carriers to circulate around the entire tank without accumulating in the corners. The MBBR was operated in continuous mode at ambient temperature to treat raw water from Lake Taihu from May 2010 to June 2011.

The MBBR was filled with suspended plastic bio-carriers (Yuhuan Water Treatment Group Co., Yuhuan, China) that had a density slightly below 1.0 g cm^{-3}, enabling the carriers to be suspended and move in the reactor. The carrier was made of polyethylene and consisted of a small oblique cylinder 25 mm in height and 20 mm in diameter with a 60° inclination angle. The carrier also had longitudinal fins that protruded on the outside and three crossed sheets inside to divide the cylinder into six sectors [12]. The carriers were retained in the MBBR by a sieve (with 10 mm holes) placed at the outlet of the working chamber. Because the biofilm mainly grows on the protected internal area of the cylinder [19], the effective specific surface area of the carriers was determined to be 230 m^2 m^{-3}. The fraction of the effective working volume occupied by the carriers was determined to be 50%, as suggested by Salvetti et al. [15].

Aeration was provided by a perforated pipe connected to a roots blower (HC-301S, B-Tohin Machine Co., Jiangsu, China) that was placed on one side of the bottom of the working chamber [12]. In addition to providing good oxygen transfer into the bulk solution, the air bubbles generated by the aeration also enabled the movement and circulation of the carriers in the reactor, preventing the formation of stagnant areas. The DO concentration was varied from 6.5–14.4 mg O_2 L^{-1} during the operational period. In addition, the hydraulic retention time was adjusted by regulating the flow rate of the influent using a glass rotameter (LZB-80, SHKQ Co., China). The air–water ratio was set at desired values by adjusting an air vortex flow meter (KQ-LUGB, SHKQ Co., China).

The entire operation was divided into six runs according to the changes in environmental factors and operational parameters, as shown in Zhang et al. [12].

2.2. Nitrification batch experiments

Nitrification batch experiments were performed at ambient temperatures of 2.8 °C, 3.4 °C, 4.1 °C, 7.2 °C, 8.8 °C, 10.3 °C, 12.8 °C, 14 °C, 16.1 °C, 18.0 °C, 20.0 °C, 24.1 °C, 26.6 °C and 28.3 °C in the MBBR (Table 1). During the batch tests, the introduction of influent to the MBBR was stopped by turning off the influent pump, while the air flux was maintained at the same value as that applied during continuous operation. At the start of the batch test, NH_4Cl solution was added to the MBBR to increase the bulk NH_4^+—N concentration by 2.0 mg L^{-1}. The pH values were maintained at approximately 7.5 by adding 0.1 M NaOH or 0.1 M HCl to avoid alkalinity limitation during the nitrification process. Liquid