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NITRIFICATION IN A VERTICALLY MOVING BIOFILM SYSTEM

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ABSTRACT

A laboratory continuous feed biofilm reactor, comprising a bulk fluid reactor, a biofilm plastic module, a feed tank, pneumatic devices and controls, was operated for a total period of 257 days, including seeding time, to treat domestic-strength synthetic wastewater under increasing ammonium nitrogen ($\text{NH}_4^+\text{-N}$) loading rates, ranging from $0.17 \pm 0.01 \text{ kg m}^{-3} \text{ d}^{-1}$ ($0.71 \pm 0.06 \text{ g m}^{-2} \text{ d}^{-1}$) to $0.70 \pm 0.02 \text{ kg m}^{-3} \text{ d}^{-1}$ ($2.9 \pm 0.1 \text{ g m}^{-2} \text{ d}^{-1}$). The biofilm plastic module was moved vertically in and out of the wastewater in continuous cycles. The maximum $\text{NH}_4^+\text{-N}$ removal rate was reached during the maximum loading phase, when a $\text{NH}_4^+\text{-N}$ loading rate of $0.70 \pm 0.02 \text{ kg m}^{-3} \text{ d}^{-1}$ ($2.9 \pm 0.1 \text{ g m}^{-2} \text{ d}^{-1}$) was applied to the system. During this loading period, the average $\text{NH}_4^+\text{-N}$ removal rate was $0.30 \pm 0.10 \text{ kg m}^{-3} \text{ d}^{-1}$ ($1.30 \pm 0.40 \text{ g m}^{-2} \text{ d}^{-1}$).

Keywords: Biological nitrogen removal; vertically moving biofilm system; wastewater treatment.

Abbreviations: VMBS, vertically moving biofilm system.

1. INTRODUCTION

Ammonium nitrogen ($\text{NH}_4^+\text{-N}$) in aquatic environments is becoming an increasing concern for environmental protection bodies and the general public. Free ammonia is toxic to fish and $\text{NH}_4^+\text{-N}$ can be used by microorganisms leading to the depletion of dissolved oxygen (DO) in receiving waters. Nitrogen - as a nutrient for aquatic plants - may contribute to eutrophication, leading to algal blooms and deterioration of water quality in lakes. Attached and suspended growth systems such as continuously moving biofilm reactors (Rodgers and Burke, 2002), sequencing batch biofilm reactors (SBBRs) (Rodgers et al., 2004), trickling filters (Kuai et al., 1999) and activated sludge systems (Gao et al., 2004) have shown good potential for biological nitrogen removal.

Rodgers and Burke (2002) used a continuously moving biofilm reactor for the treatment of high strength wastewater. The system comprised six reactors in series: one anaerobic, one anoxic and four aerobic reactors. In the anaerobic and anoxic reactors, plastic modules of specific surface area $240 \text{ m}^2 \text{ m}^{-3}$ moved up and down but were always submerged in the wastewater, whereas, in the aerobic reactors, the plastic modules moved vertically up and down, in and out of the wastewater. To facilitate carbon and nitrogen removal, wastewater was returned from the fourth aerobic tank to the anoxic tank, giving a $\text{NH}_4^+\text{-N}$ loading rate of approximately $0.17 \text{ kg m}^{-3} \text{ d}^{-1}$ on the first aerobic reactor. The maximum $\text{NH}_4^+\text{-N}$ removal rate was recorded in the second aerobic reactor and was $1.86 \text{ g NH}_4^+\text{-N m}^{-2} \text{ d}^{-1}$ on a substratum surface basis and $0.12 \text{ kg NH}_4^+\text{-N m}^{-3} \text{ d}^{-1}$ on a bulk fluid volume basis.

The removal of nutrients using a SBBR, comprising feeding, aerobic, anaerobic and settlement phases, has also been investigated. Rodgers et al. (2004) operated a laboratory vertically moving SBBR, with a total chemical oxygen demand (COD_T) and $\text{NH}_4^+\text{-N}$ loading rate of $0.7 \text{ kg COD}_T \text{ m}^{-3} \text{ d}^{-1}$ and $0.034 \text{ kg NH}_4^+\text{-N m}^{-3} \text{ d}^{-1}$, respectively, and measured an average $\text{NH}_4^+\text{-N}$ conversion rate of $0.025 \text{ kg m}^{-3} \text{ d}^{-1}$ (74% removal). $\text{NH}_4^+\text{-N}$ conversion rates of over 97% were measured by Cho et al. (2001) using plastic porous media (specific area = $50\text{-}130 \text{ m}^2 \text{ m}^{-3}$) in a 24-hour cycle SBBR loaded at organic loading rates of 0.3 to 0.6 $\text{kg COD}_T \text{ m}^{-3} \text{ d}^{-1}$. Di Iaconi et al. (2002) also used a plastic porous media (specific area = $50\text{-}130 \text{ m}^2 \text{ m}^{-3}$) in an

upflow SBBR, aerated by a mechanical aerator, to treat tannery wastewater at an organic loading rate varying from 2.1 to 3 kg COD_T m⁻³ d⁻¹ and measured NH₄⁺-N removal rates in excess of 98%.

Trickling filtration systems have also been used to treat domestic effluent with good success. Kuai et al. (1999) used a semi-continuously loaded trickling filter, comprising charcoal with an average particle diameter less than 2 cm, to treat high strength domestic wastewater, following primary sedimentation and decantation. Under organic loading rates of between 698 and 1035 g COD_T m⁻² d⁻¹ (expressed in terms of filter surface area), maximum removal rates of COD_T and NH₄⁺-N were 98% and 93%, respectively, and NH₄⁺-N removal rates of between 0.25 kg m⁻³ d⁻¹ and 0.3 kg m⁻³ d⁻¹ were measured.

The aim of this study was to examine the performance of a vertically moving biofilm system (VMBS) in the treatment of domestic-strength synthetic wastewater under increased NH₄⁺-N loading rates.

2. MATERIALS AND METHODS

The VMBS unit used in this study, based on a design after Rodgers (1999) and located within a temperature-controlled room at 10°C to simulate yearly average Irish water temperatures, comprised a bulk fluid reactor, a biofilm plastic module, a synthetic wastewater feed tank, a peristaltic pump and pneumatic devices with pneumatic controls (Figure 1). The biofilm plastic module was moved vertically in and out of the bulk fluid in continuous cycles and the reactor tank was constantly loaded with synthetic wastewater.

[Figure 1 here]

The reactor tank, was 0.55 m in height and tapered slightly from an internal plan dimension of 0.28 m x 0.34 m at the top to 0.28 m x 0.295 m at the base. The height of the outlet pipe in the reactor tank was 0.33 m from the bottom of the tank and the bulk fluid volume was 25.8 L. The outlet pipe from the reactor tank had a diameter of 0.032 m.

In the reactor tank, a module of dense BIOdek (Munters, UK) filter media, constructed from polyethylene sheets with corrugations at 30° to the horizontal, and with dimensions 0.3 m by 0.195 m in plan and 0.26m deep, was moved vertically in and out of the wastewater in cycles, using a pneumatic piston, limit switches and timers. The specific surface area of the media was 410 m² m⁻³, giving a module area of 6.24 m². The module was supported in a stainless steel frame that was connected to the pneumatic piston. The piston was powered by a compressed air system and travelled a vertical distance of 0.4 m. The dipping cycle of the module was: 5 seconds in the air, 2 seconds travelling down, 4 seconds in the water and 3 seconds travelling up. As a result, the module had an overall motion of 4.3 cycles per minute.

The study had 3 phases, in which the synthetic wastewater constituents of Phases 2 and 3 were double those of Phases 1 and 2, respectively (Table 1). The module was seeded for a period of 160 days at NH₄⁺-N and COD_T loading rates of 0.08±0.01 kg m⁻³ d⁻¹ (0.34±0.03 g m⁻² d⁻¹) and 0.3±0.02 kg m⁻³ d⁻¹ (1.2±0.1 g m⁻² d⁻¹), respectively, to ensure a biofilm had developed on the module. The NH₄⁺-N loading rates detailed in this study are approximately 2, 4, and 10 times the original NH₄⁺-N loading rate, and all values are reported when COD effluent concentration showed little variation with respect to time. The total study duration (including seeding time) was 257 days. The synthetic feed, with constituents tabulated in Table 1, was made up each day in the laboratory to provide the substrate for the biofilm microorganisms. The contents of the feed tank were continuously mixed with two small circulating pumps. The feed, along with dilution tap water, was pumped into the reactor at a combined rate of 144 L d⁻¹ using peristaltic pumps. The average nutrient concentrations entering the reactor for each study phase are tabulated in Table 2.

During the three phases of the study, the NH₄⁺-N loading rate was increased from 0.17±0.01 kg NH₄⁺-N m⁻³ d⁻¹ to 0.70±0 kg NH₄⁺-N m⁻³ d⁻¹ on a bulk fluid volume basis and 0.71±0.06 g NH₄⁺-N m⁻² d⁻¹ to 2.9±0.1 g NH₄⁺-N m⁻² d⁻¹ on a substratum surface basis, with an equivalent increase in the organic loading rate from 0.36±0.03 kg COD_T m⁻³ d⁻¹ (1.5±0.11 g COD_T m⁻² d⁻¹) to 1.0±0 kg COD_T m⁻³ d⁻¹ (4.0±0.1 g COD_T m⁻² d⁻¹), based on the bulk fluid volume in the reactor.

The water quality parameters measured were: $\text{NH}_4^+\text{-N}$ (ammonia-selective electrode method), COD_T and filtered COD (COD_F) (closed reflux, titrimetric method), total $\text{PO}_4\text{-P}$ ($\text{PO}_4\text{-P}_T$) and filtered $\text{PO}_4\text{-P}$ ($\text{PO}_4\text{-P}_F$) (ascorbic acid method), suspended solids (SS) (total suspended solids dried at 103-105°C), and volatile suspended solids (fixed and volatile suspended solids ignited at 550°C). The plastic module was weighed over time and samples of biofilm were taken from the top, bottom and side of the module and tested for dry solids concentration. All water quality parameters were tested in accordance with the Standard Methods (APHA-AWWA-WEF, 1995).

3. RESULTS AND DISCUSSION

3.1 Phase 1

In Phase 1, under $\text{NH}_4^+\text{-N}$ and COD_T loading rates of $0.17\pm 0.01 \text{ kg m}^{-3} \text{ d}^{-1}$ ($0.71\pm 0.06 \text{ g m}^{-2} \text{ d}^{-1}$) and $0.36\pm 0.03 \text{ kg m}^{-3} \text{ d}^{-1}$ ($1.5\pm 0.11 \text{ g m}^{-2} \text{ d}^{-1}$), respectively, a $\text{NH}_4^+\text{-N}$ conversion rate of $0.16\pm 0.01 \text{ kg m}^{-3} \text{ d}^{-1}$ ($0.65\pm 0.06 \text{ g m}^{-2} \text{ d}^{-1}$) was measured; the $\text{NH}_4^+\text{-N}$ was reduced from an average influent $\text{NH}_4^+\text{-N}$ concentration of $30\pm 3 \text{ mg L}^{-1}$ to an average effluent concentration of $3\pm 1 \text{ mg L}^{-1}$ (Table 2), giving a 91% reduction in $\text{NH}_4^+\text{-N}$; this was less than the reduction rate of 98%, measured by Di Iaconi et al. (2002) in a lab-scale SBBR operated at 20°C at an organic loading rate varying from 2.1 to 3 $\text{kg COD}_T \text{ m}^{-3} \text{ d}^{-1}$. The COD_T and COD_F concentrations in the effluent were $25\pm 3 \text{ mg L}^{-1}$ and $21\pm 2 \text{ mg L}^{-1}$, respectively. SS were also reduced during this phase; an average SS concentration of $16\pm 2 \text{ mg L}^{-1}$ was measured in the effluent.

3.2 Phase 2

During Phase 2, the $\text{NH}_4^+\text{-N}$ and COD_T loading rates were increased to $0.3\pm 0 \text{ kg NH}_4^+\text{-N m}^{-3} \text{ d}^{-1}$ ($1.4\pm 0.2 \text{ g m}^{-2} \text{ d}^{-1}$) and $0.6 \text{ kg m}^{-3} \text{ d}^{-1}$ ($2.3\pm 0.2 \text{ g m}^{-2} \text{ d}^{-1}$), respectively. The COD_T removal rate increased to 76% and the $\text{NH}_4^+\text{-N}$ conversion rate increased to $0.2 \text{ kg m}^{-3} \text{ d}^{-1}$ ($0.9\pm 0.2 \text{ g m}^{-2} \text{ d}^{-1}$).

3.3 Phase 3

During Phase 3, the performance of the system continued to improve; increased COD removal and $\text{NH}_4^+\text{-N}$ conversion rates were measured during this phase (Figure 2). Under $\text{NH}_4^+\text{-N}$ and COD_T loading rates of $0.7 \text{ kg m}^{-3} \text{ d}^{-1}$ ($2.9 \pm 0.1 \text{ g m}^{-2} \text{ d}^{-1}$) and $1.0 \text{ kg m}^{-3} \text{ d}^{-1}$ ($4.0 \pm 0.1 \text{ g m}^{-2} \text{ d}^{-1}$), respectively, the average effluent $\text{NH}_4^+\text{-N}$ conversion rate rose to $0.3 \pm 0.1 \text{ kg m}^{-3} \text{ d}^{-1}$ ($1.3 \pm 0.4 \text{ g m}^{-2} \text{ d}^{-1}$). The effluent $\text{NH}_4^+\text{-N}$ concentration was $69 \pm 16 \text{ mg L}^{-1}$, giving a 44% removal, and COD_T removal rates of 92% were measured. Although the areal $\text{NH}_4^+\text{-N}$ conversion rates measured in this study do not reach the levels of Rodgers and Burke (2002), where a maximum $\text{NH}_4^+\text{-N}$ conversion rate of $1.86 \text{ g NH}_4^+\text{-N m}^{-2} \text{ d}^{-1}$ was measured, they do compare favourably against other studies. In a 3-stage RBC system, Gupta (1999) measured $\text{NH}_4^+\text{-N}$ conversion rates of $0.47 \text{ g NH}_4^+\text{-N m}^{-3} \text{ d}^{-1}$ and $1.1 \text{ g NH}_4^+\text{-N m}^{-3} \text{ d}^{-1}$ at loading rates of $0.69 \text{ g NH}_4^+\text{-N m}^{-3} \text{ d}^{-1}$ and $2.09 \text{ g NH}_4^+\text{-N m}^{-3} \text{ d}^{-1}$, respectively.

[Figure 2 here]

3.4 Module mass

During the experiment, no clogging occurred in the plastic module. At the end of Phases 1, 2, and 3, the module mass was 2120 g, 2874 g, and 3596 g, respectively, giving an average mass increase of $0.61 \text{ g m}^{-2} \text{ d}^{-1}$, $3.36 \text{ g m}^{-2} \text{ d}^{-1}$, and $3.99 \text{ g m}^{-2} \text{ d}^{-1}$ during each phase (Figure 3). The increased biofilm mass during each phase of the study contributed to the rise in the carbonaceous oxidation efficiency; COD_T removals rose from 61% at the end of Phase 1 to 92% at the end of Phase 3. The vertical movement of the biofilm module also supplied oxygen and prevented clogging of the module. At the end of the study, samples of the biofilm were removed from the module and tested. The average thickness of the biofilm was 0.32 mm and the average moisture content was 94.5%. The total solids content of the biofilm was 65.7 g L^{-1} , which contained 46 g L^{-1} (69%) volatile solids and 19.8 g L^{-1} inert solids; this solids concentration is about 10 times greater than that present in an activated sludge system.

[Figure 3 here]

4. CONCLUSIONS

In this study, the VMBS unit had good nitrification and carbonaceous oxidation rates. The maximum NH_4^+ -N and organic loading rates that produced maximum NH_4^+ -N conversion and carbonaceous oxidation from the system occurred during Phase 3, when NH_4^+ -N and organic loading rates of $0.7 \text{ kg } \text{NH}_4^+\text{-N m}^{-3} \text{ d}^{-1}$ ($2.9 \pm 0.1 \text{ g m}^{-2} \text{ d}^{-1}$) and $1.0 \text{ kg COD}_T \text{ m}^{-3} \text{ d}^{-1}$ ($4.0 \pm 0.1 \text{ g m}^{-2} \text{ d}^{-1}$) were applied to the reactor. During this phase, the average NH_4^+ -N conversion rate was $0.3 \pm 0.1 \text{ kg m}^{-3} \text{ d}^{-1}$ and 92% of the total organic carbon substrate was utilised, producing an average effluent COD_T concentration of $13 \pm 2 \text{ mg L}^{-1}$, which was much less than the Urban Waste Water Treatment Directive (EU, 1991) value of 125 mg L^{-1} . The mean effluent SS concentration was always below 20 mg L^{-1} . The maximum NH_4^+ -N removal rate measured in this study compares favourably against the NH_4^+ -N removal obtained in continuously moving biofilm reactors, SBBRs, and trickling filters. Even though the specific surface area of the media was $410 \text{ m}^2 \text{ m}^{-3}$, the module never clogged. This was due to the continuous vertical movement of the module into and out of the wastewater. The VMBS unit was simple to construct and operate and required little maintenance.

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LIST OF FIGURES

Figure 1. Schematic of the vertically moving biofilm system (VMBS) used in this study.

Figure 2. NH_4^+ -N conversion rates measured in this study.

Figure 3. The mass increase of the module during the laboratory VMBS study.

Table 1. Chemical composition of the synthetic wastewater^a used in each phase.

Chemical	Amount (g)		
	Phase 1	Phase 2	Phase 3
Days of operation	26	37	34
Urea	21.4	42.8	85.6
NH ₄ Cl	42.6	85.2	170.4
Na ₂ HPO ₄ .12H ₂ O	71.0	142.0	284.0
KHCO ₃	35.6	71.2	142.4
NaHCO ₃	92.4	184.8	369.6
MgSO ₄ .7H ₂ O	35.6	71.2	142.4
CaCl ₂ .6H ₂ O	2.1	4.3	8.6
MnSO ₄ .H ₂ O	1.4	2.8	5.7
FeSO ₄ .7H ₂ O	1.4	2.8	5.7
Bentonite	28.4	56.8	113.6

^a The synthetic wastewater was made up to a total volume of 28.8 L.

Table 2. Average nutrient concentrations (\pm standard deviation) entering the VMBS for nitrification reactor tank for each study phase.

Phase	Location	Loading period (d)	NH ₄ ⁺ -N loading rates ^a		COD loading rate		Concentration (mg L ⁻¹)				NH ₄ ⁺ -N conversion rate		COD _T removal rate	
			kg m ⁻³ d ⁻¹	g m ⁻² d ⁻¹	kg m ⁻³ d ⁻¹	NH ₄ ⁺ -N DO	COD _T	COD _F	SS	pH	g m ⁻² d ⁻¹	kg m ⁻³ d ⁻¹	kg m ⁻³ d ⁻¹	
1	Feed tank	26	0.17 (0.01)	0.71 (0.06)	0.36 (0.03)	30 (3)	2.5 (0.4)	64 (5)	49 (5)	72 (7)		0.65 (0.06)	0.16 (0.01)	0.22 (0.14)
	Reactor tank				3 (1)	5.2 (0.5)	25 (3)	21 (2)	16 (2)	7.0 (0.2)				
	% removal				91	-	61	57	78	-				
2	Feed tank	37	0.30 (0.04)	1.4 (0.2)	0.6 (0)	62 (8)	2.5 (0.2)	99 (7)	79 (8)	144 (46)		0.90 (0.20)	0.20 (0.05)	0.4 (0)
	Reactor tank				22 (7)	4.4 (0.3)	24 (3)	21 (3)	17 (5)	7.2 (0.2)				
	% removal				65	-	76	73	88	-				
3	Feed tank	34	0.70 (0.02)	2.9 (0.1)	1.0 (0)	124 (4)	4.5 (0.1)	172 (3)	139 (7)	187 (18)		1.30 (0.40)	0.30 (0.10)	0.9 (0)
	Reactor tank				69 (16)	4.5 (0.3)	13 (2)	10 (1)	12 (2)	7.7 (0.2)				
	% removal				44	-	92	93	94	-				

^a NH₄⁺-N loading rates based on a module surface area of 6.24 m² in the reactor tank with a bulk fluid volume of 25.8 L loaded at 144 L d⁻¹

Figure 1. Rodgers et al. (2005). Nitrification in a vertically moving biofilm system.

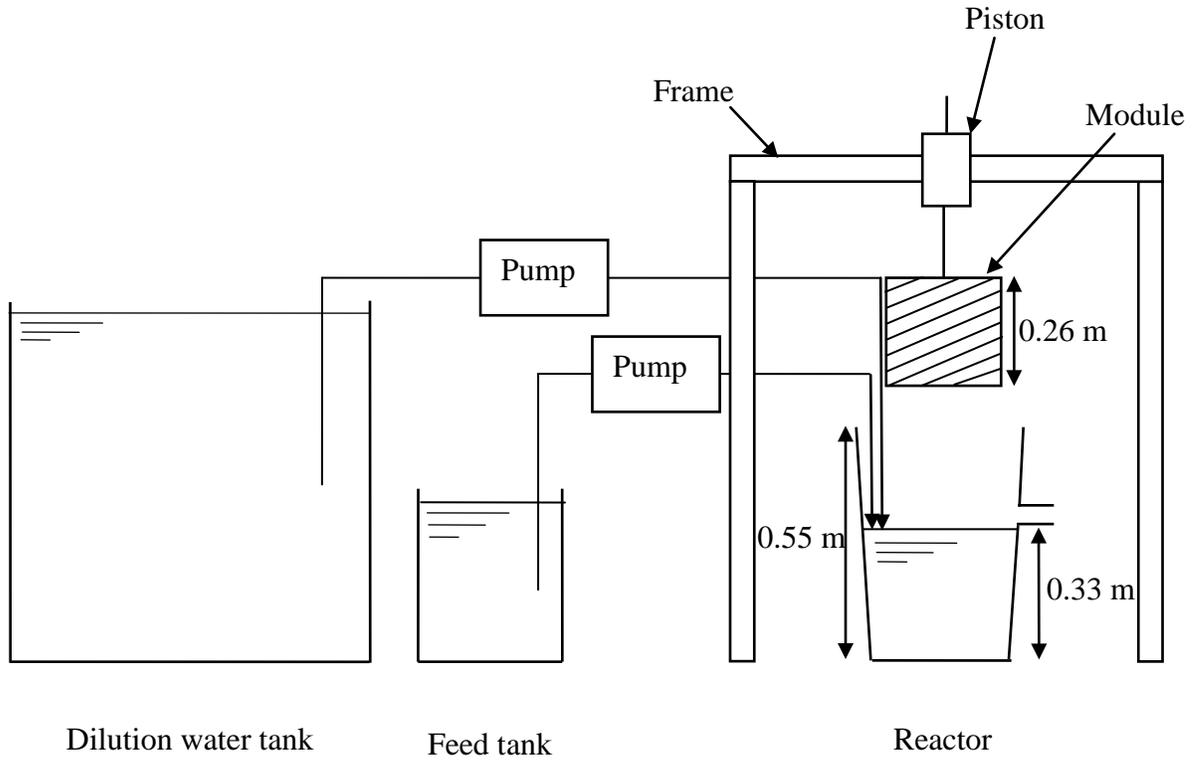


Figure 2. Rodgers et al. (2005). Nitrification in a vertically moving biofilm system.

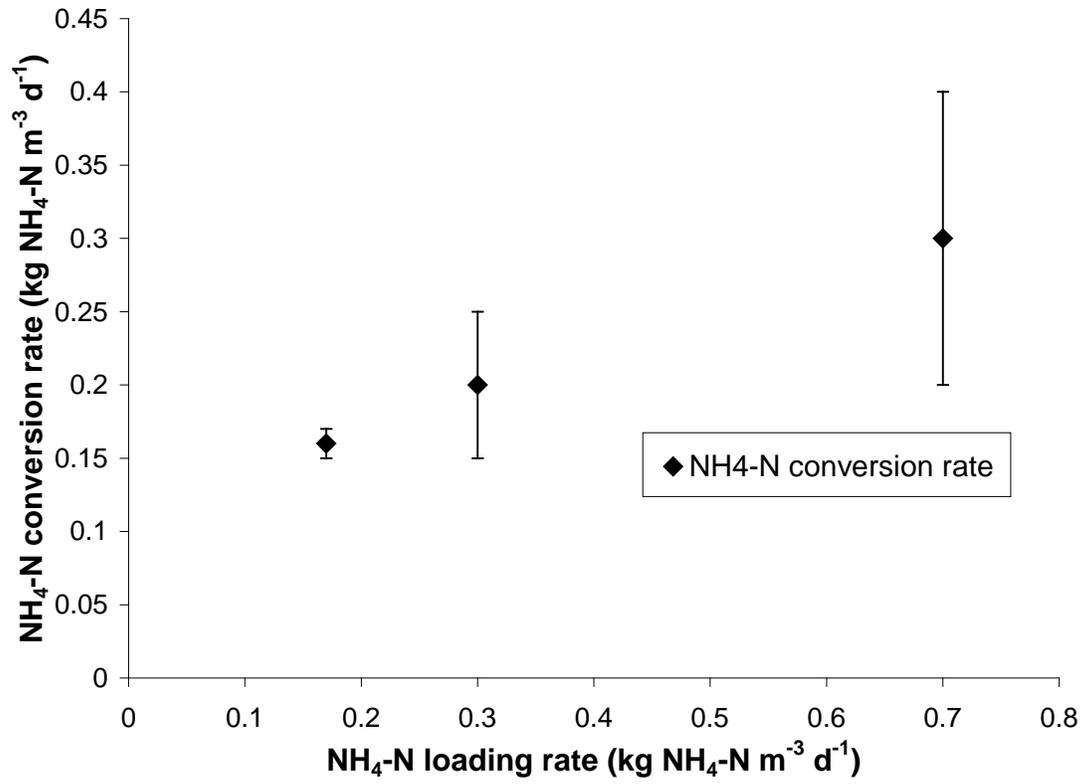


Figure 3. Rodgers et al. (2005). Nitrification in a vertically moving biofilm system.

