Biological nitrogen removal with three different SBBR

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Abstract In order to compare the performance of biofilms growing on different support media, three reactors were fed with municipal wastewater from the city of Garching, Germany, and operated under the sequencing batch procedure. The support media tested have the commercial names of Kaldnes, polyethylene special support for moving bed reactors with approximate diameter of 12 mm; Liapor, ceramic spheres with diameters between 4 and 6 mm; Linpor, plastic foam cut in cubes of 15 mm. The bench-top reactors were tested for COD, TSS and ammonia nitrogen removal. During 452 days runs with organic loads between 0.5 and 8.0 gCOD/m^2·d were tested. Thin biofilms (Kaldnes and Liapor) perform better for COD and ammonia removal under lower organic loading values ($<$ 2.5 gCOD/m^2·d). For organic loads over 3.0 gCOD/m^2·d, the reactor packed with Linpor (thick biofilm) showed a better COD and ammonia nitrogen removal than the other two. Linpor achieved the highest NOx-N production reaching values between 15 and 20 mg/l. For low organic loading rates Linpor and Liapor present similar average NOx-N concentrations. Kaldnes shows the lowest concentrations throughout the whole experimental period. The difference between ammonia nitrogen removal and NOx-N generation is simultaneous denitrification inside the deep biofilms. The average mean cellular retention times were 5.4 days for Liapor, 10.0 days for Kaldnes and 22.9 days for Linpor. This is the reason why Linpor achieved complete nitrification even with higher organic loads.

Keywords Biofilm; denitrification; diffusion; nitrification; packed-bed reactors

Introduction

It has been shown that simultaneous nitrification and denitrification occurs during aeration due to anoxic zones in biofilms (Garzón-Zúñiga and González Martínez, 1996; Arnz *et al.*, 2001; Gieseke *et al.*, 2002). Some authors mention the probable formation of micro niches with anoxic conditions in the deep layers of biofilms where denitrifying bacteria take advantage of nitrates coming from the superior layers where nitrifying activity is observed (Pastorelli *et al.*, 1997; Helness and Odegaard, 1999). To study the activity of thin and thick biofilms during the simultaneous removal of organic substances and inorganic nitrogen compounds from municipal wastewater, the performance of three laboratory sequencing batch biofilm reactors (SBBR) was analysed.

Method

Three different commercial biofilm support media were selected and used to pack three sequencing fixed-bed batch reactors. These biofilm support media have been used for the treatment of different wastewater types with positive results. Every one of the three reactors was packed with different support material. Table 1 presents the main characteristics of the biofilm support media. Three pilot reactors, fed with the municipal wastewater of the city of Garching, Germany, were operated for a period of 452 days. The reactors were made of Plexiglas 19 cm in diameter and 110 cm height (Figure 1). Its dimensions and influent conditions are given in Table 2 and 3, respectively. They were operated under the sequencing batch procedure with 8-hour cycles: 30 min fill, 120 min anaerobic,

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Table 1 Characteristics of the support media

Parameter	Kaldnes®	Liapor®	Linpor®
Size (mm)	10 × 7	4–8	15 × 15 × 15
Specific surface area (m^2/m^3)	500	480	270
Density (g/cm^3)	0.17	1.4	0.018
Bed height (m)	0.17–0.33	0.16–0.33	0.32–0.52
Apparent porosity (%)	44	38	58
Total surface area (m^2)	2.7–8.3	2.7–8.1	2.7–3.9

300 min aerobic, 30 min draw. A heat exchanger was necessary to keep the temperature in the reactor approximately at 25 °C. The reactors were equipped with four sample ports to take samples of the biofilm support material. Backwashing was performed every 48 hours. Every cycle 100% of the water was replaced with fresh wastewater.

During the 452 days of the experimental procedures the organic load was varied between 0.5 and 8.0 gCOD/m^2·d. Periodical sampling of influent and effluent was made for COD, suspended and volatile solids, inorganic nitrogen compounds and Kjeldahl-Nitrogen. Table 4 shows the overall operation conditions of the three reactors.

Total nitrogen balance

For the balance nitrogen is considered in both organic and inorganic (ammonia, nitrites and nitrates) forms. The balance is represented by Equation 1 (Nikolavcic *et al.*, 2000; Zwerger *et al.*, 2000).

$$(Q \times TN)_{\text{influent}} - (Q \times TN)_{\text{effluent}} = (Q \times TN)_{\text{backwashing}} + N_2\uparrow \qquad (1)$$

where

TN Total nitrogen, g/m^3 (sum of nitrate, ammonia and organic nitrogen in dissolved and suspended forms)

Q Wastewater flow, m^3/day

$N_2\uparrow$ Molecular nitrogen produced by denitrification, gTN/day

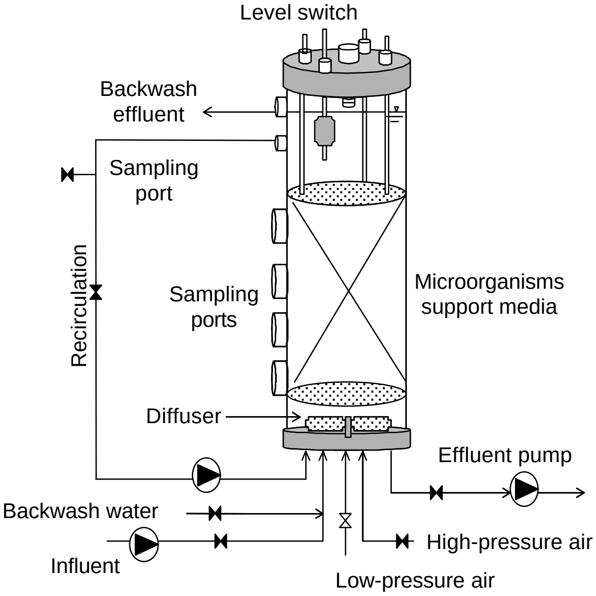

Figure 1 Schematic representation of the laboratory scale SBBR

Table 2 Reactor main characteristics

Diameter	0.19 m
Sectional area	0.028 m^2
Total volume	0.031 m^3
Water exchange volume	100%
Recirculation	0.2 m^3/h

Table 3 Mean influent concentration values

Parameter	mg/L
Total COD	214 ± 96
Dissolved COD	76 ± 26
NH_4-N	34 ± 8
Total Nitrogen	50 ± 1
PO_4-P	4 ± 1

Cycles profiles

Two representative cycles of operation were analyzed. The first one corresponds to organic loads under 2.5 gCOD/m^2·d, and the second one to organic loads over 3.0 gCOD/m^2·d.

Results

SBBR performance under an average organic load of 0.8 gDQO/m^2·d

Figure 2 shows the COD and dissolved oxygen profiles for the three reactors under an organic load of 0.8 gCOD/m^2·d. The time zero corresponds to influent concentrations. The vertical dotted line represents the end of the anaerobic reaction. The last values correspond to effluent concentrations.

COD removal. All three reactors present the same behavior. The COD decrease during the two hours of anaerobic reaction (first 120 minutes) is attributed to adsorption and biochemical transformations. Bouwer (1987) states that particles have to be adsorbed to the biofilm surface by diffusion, settling or entrapment before biochemical reactions can take place. After the anaerobic reaction is finished the COD continues decreasing until, after minute 300, a stable value is reached. In terms of COD removal it is considered that the cycle duration can be reduced to 6 hours.

The reactor packed with Kaldnes (Figure 2–A) showed total COD effluent values of 56 mg/L and 31 mg/L for dissolved COD. The reactors packed with Liapor and Linpor (Figures 2–B and 2–C, respectively) showed a similar behavior reaching total COD values in the effluent between 17 and 20 mg/L, and 15 and 16 mg/L for dissolved COD.

Table 4 Operational characteristics of the three reactors

Operation characteristics	Organic load					
	0.5–3.0 gCOD/m^2· or ·d			3.5–8.0 gCOD/m^2· or ·d		
	Liapor	Kaldnes	Linpor	Liapor	Kaldnes	Linpor
Wastewater flow, m^3/d	0.066	0.063	0.072	0.069	0.069	0.063
Bed height, m	0.33	0.33	0.52	0.16	0.17	0.32
Bed volume, m^3	0.009	0.0093	0.0148	0.005	0.0055	0.010
Total exposed area, m^2	8.3	8.1	3.9	2.7	2.7	2.7

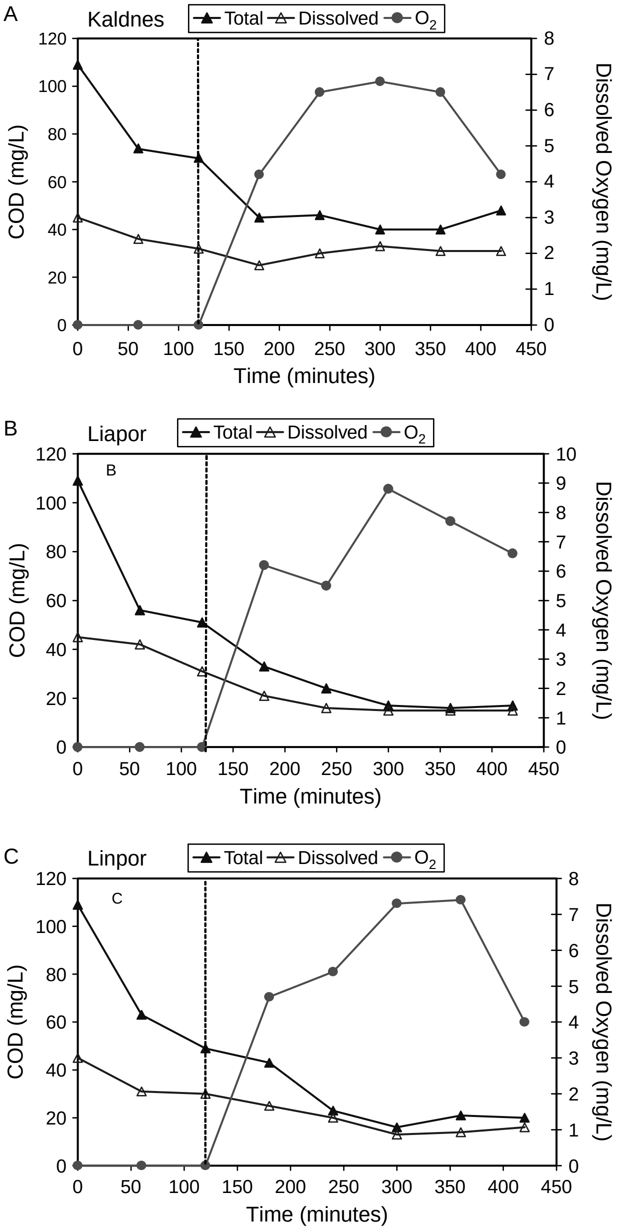

Figure 2 COD and dissolved oxygen profiles under an organic load of 0.8 gCOD/m^2·d. A) Kaldnes; B) Liapor; C) Linpor

Nitrogen removal. The pattern of the ammonia nitrogen profiles during the anaerobic phase was the same for the three reactors (Figure 3). The influent contained 22 mgNH$_4$-N/L (time zero). During the first two hours of anaerobic reaction the ammonia concentration decreased approximately to 14–27%. In previous studies it was shown that the biofilm strongly adsorbed ammonium explaining the initial reduction after filling (Nielsen, 1996; Gieseke *et al.*, 1999, 2002). Immediately after the aeration begins the activity of the nitrifiers was observed through decreasing ammonia concentration completing nitrification.

With Liapor and Linpor the nitrate concentration increased and eventually decreased at the end of the cycle. With Kaldnes the nitrite concentration increased almost till the end of the cycle. As nitrite is produced at the biofilm surface, a high concentration

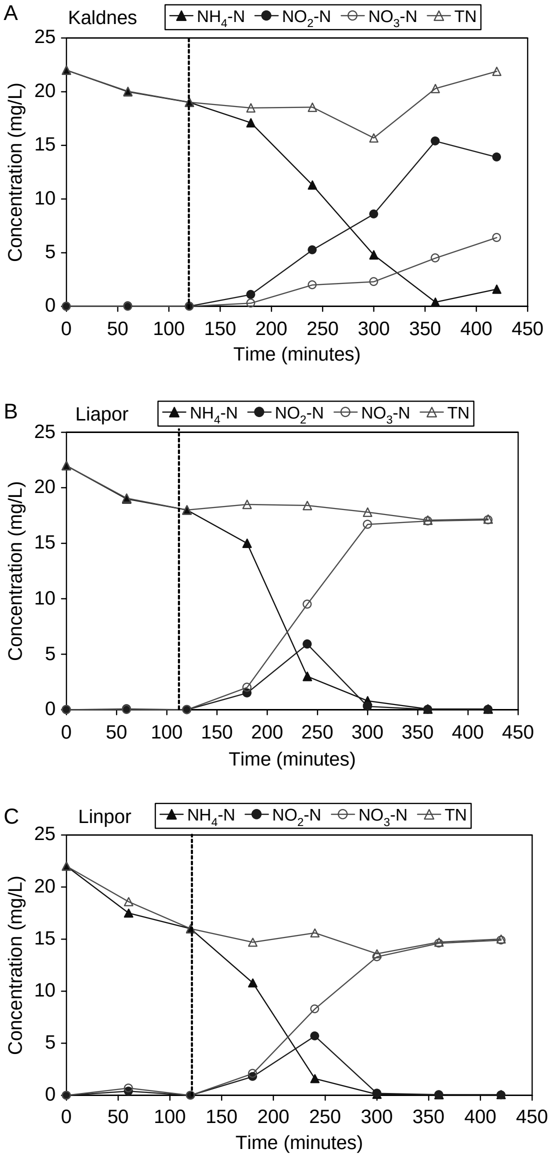

Figure 3 Ammonia, nitrite and nitrate nitrogen in the bulk liquid at an organic load of 0.8 gCOD/m^2·d. A) Kaldnes; B) Liapor; C) Linpor

gradient with an initially low nitrite concentration in the bulk fluid is induced during nitrification (Nijhof and Klapwijk, 1995). With the exception of Kaldness, nitrite was transformed in to nitrate at the end of the cycle nitrate being the sole nitrogen form detected. This situation indicates that the growing biofilm in Kaldnes presents characteristics that make difficult the diffusion into the deeper layers. The biofilm structure affects the transport of nutrients into and out of the biofilm (Beyenal and Lewandoski, 2000). When the biofilm density increases, the resistance to the diffusion increases (Cassey *et al.*, 2000).

The reactors packed with Liapor and Linpor remove the ammonia during the first three hours of aerobic reaction (300 min), indicating a strong activity of nitrifiers with the consequent presence of nitrate in the bulk liquid. The complete transformation of ammonia with the reactor packed with Kaldnes occurred after the fourth hour of aeration.

SBBR performance under an average organic load of 3.6 gCOD/m^2·d

COD removal. With a different behavior from the first experimental run, where the most important COD removal occurred during the anaerobic phase, this second experimental run showed only partial COD removal during the anaerobic phase continuing during the aerobic phase (Figure 4).

The three reactors showed similar behavior. About 35% of the total COD was removed during the anaerobic phase and about 40% during the aerobic phase. For Kaldnes and Linpor the COD decreased from 95 to 60 mg/L during the anaerobic phase.

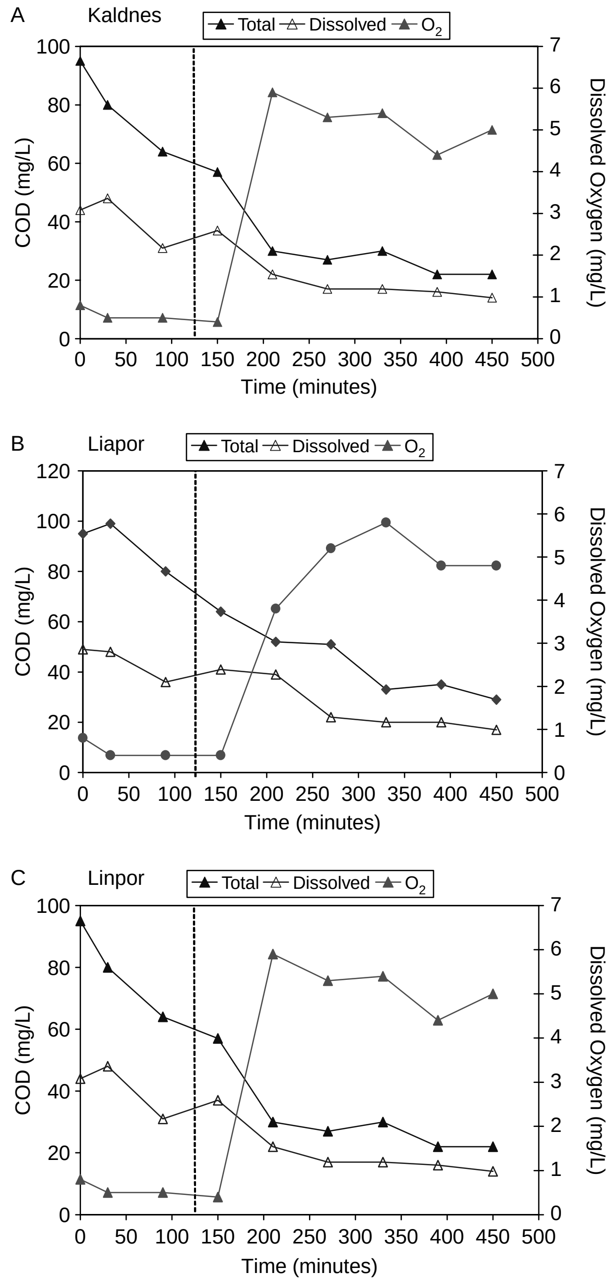

Figure 4 COD and dissolved oxygen profiles under an organic load of 3.6 gCOD/m^2·d. A) Kaldnes; B) Liapor; C) Linpor

These two reactors achieved a final total COD of 20 mg/L, while Liapor reached 30 mg/L at the end of the cycle. For the three reactors, at the end of the cycle the dissolved COD reached values slightly under 20 mg/L with Liapor showing the higher values.

Nitrogen removal. Ammonia concentration in the influent was 39 mgNH$_4$-N/L (Figure 5). At the beginning of the aerobic phase the ammonia oxidation did not begin until the biofilm was fully penetrated with oxygen (Castillo *et al.*, 1999). The oxygen requires time to diffuse through the biofilm and then the nitrifiers start their metabolism.

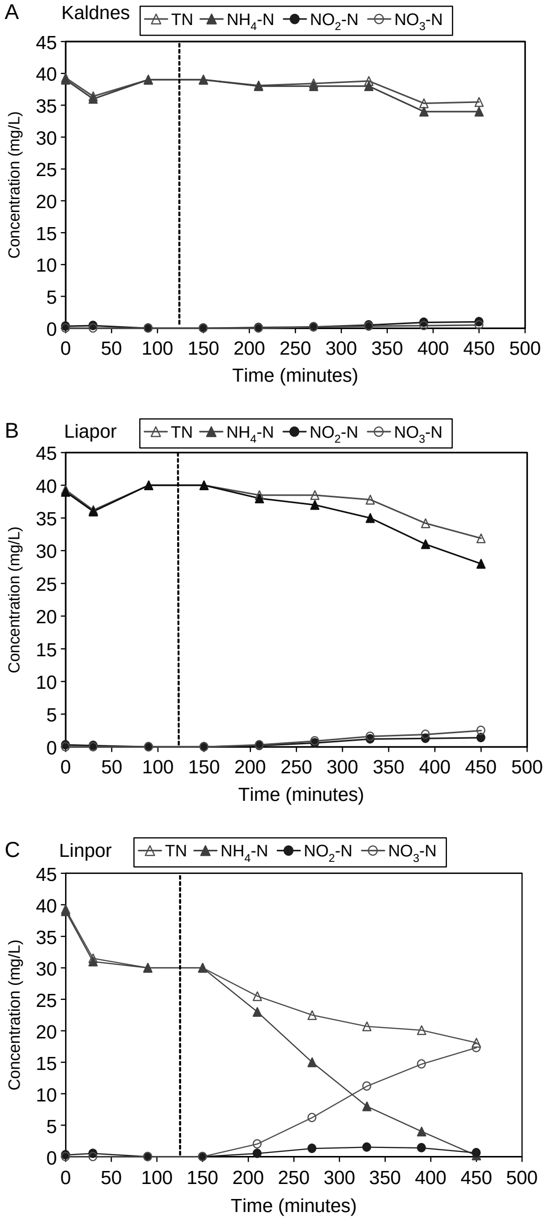

Figure 5 Ammonia, nitrite and nitrate nitrogen in the bulk liquid at an organic load of 3.6 gCOD/m^2·d. A) Kaldnes; B) Liapor; C) Linpor

The reactors packed with Kaldnes and Liapor showed a minimal nitrifying activity; the ammonia concentration showed values near the total nitrogen concentration and nitrites and nitrates showed very low concentrations (Figures 5A and B).

The reactor packed with Linpor had a better response for nitrification when the organic load increased, allowing total nitrification at the end of the cycle (Figure 5–C). In the case of Linpor, considering the ammonia concentration at the beginning of the aerobic phase (22 mgNH_4-N), the reduction in total nitrogen can only be explained when a simultaneous denitrification in the deeper layers of the biofilm is considered (Figure 5–C). Previous studies with ‘deep’ biofilms growing on Linpor and Kaldnes allow the assumption that nitrates diffuse to the regions with the lower oxygen concentration (Gieseke *et al.*, 1999; Arnz *et al.*, 2001; Falkentoff *et al.*, 2001).

Total nitrogen balance

Table 5 shows the mean values of the total nitrogen balance. The nitrogen compounds that can be used for cellular growth are included in the excess of biomass detached during the backwashing of the reactors. Molecular nitrogen (N_2) represents the amount of total nitrogen transformed during denitrification. According to Default 1 and Table 5, Linpor allows nitrification and simultaneous denitrification better than Kaldnes and Liapor at lower and higher organic loads. These last mentioned support media present better denitrification capacities at higher organic loads than at lower ones. For Linpor, denitrification occurred better at lower organic loads.

From Table 5 it is not possible to state if the increased nitrogen production during the lower organic loads depends on a better nitrification or better denitrification or both combined. The reactor packed with Liapor spheres shows the highest values of TN for backwashing indicating greater amounts of biofilm being sloughed off during this operation. Liapor presents the lowest mean cellular retention time (MCRT) with an average value of 5.4 days. The MCRT for Kaldnes is 10.0 days and for Linpor is 22.9 days. The better nitrification of Linpor at higher organic loads is then related to the higher MCRT, allowing nitrifiers to grow inside the support media under different conditions. Park and Chang (2000) reported that the amount of biomass wasted during the backwash procedure also affected nitrogen and phosphorus removal in a biofilter.

Figure 6 shows images of three support media with biofilm. Linpor allows microorganisms to grow inside the great number of pores to the deepest parts of the material allowing the highest amount of microorganisms of all three media (Figure 6–C). The microorganisms growing inside Linpor proved to be more resistant to the stress forces during backwashing and allowed greater mean cellular retention times (23 days) than the other two, giving the opportunity to the nitrifying bacteria to grow in the system without being washed during this operation.

Table 5 Total nitrogen balance (mean values) according to Equation 1

Organic load gCOD/m^2·d	Media	NT influent g/d	NT effluent g/d	NT backwashing g/d	$N_2\uparrow$ g/d
0.5–2.5	Kaldnes	7.04	6.07	0.33	0.6
	Liapor	7.04	4.97	1.22	0.8
	Linpor	6.43	1.91	0.46	4.1
3.0–8.0	Kaldnes	6.90	4.28	0.72	1.9
	Liapor	6.90	4.24	1.23	1.4
	Linpor	6.30	2.34	0.48	3.5

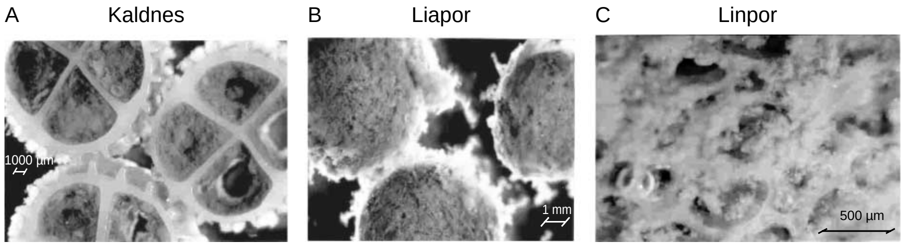

Figure 6 Media support with biofilm. Images correspond to the higher tested of organic load

Conclusions

1. All three reactors showed a more stable operation at organic loading rates under 2.0 gCOD/m^2·d. Linpor achieved higher COD removal rates at higher organic loads. Liapor showed the best performance at lower organic loads. Kaldnes showed a stable performance at medium organic load values.
2. In 95% of the experiments Linpor achieved NH_4-N removal values of over 50%. For organic loads under 2.5 gCOD/m^2·d Liapor and Kaldnes achieved high nitrification rates near 100%. For organic loads over 2.5 gCOD/m^2·d, the NH_4-N removal remained mostly under 40% without any tendency.
3. Linpor achieved the highest NOx-N production reaching values between 15 and 20 mg/l. For low organic loading rates Linpor and Liapor present similar average NOx-N concentrations. Kaldnes shows the lowest concentrations throughout the whole experimental period.
4. The explanation given to the differences between ammonia nitrogen removal and NOx-N generation is simultaneous denitrification inside the deep biofilms.
5. The average mean cellular retention times were 5.4 days for Liapor, 10.0 days for Kaldnes and 22.9 days for Linpor. This is the reason why Linpor achieved complete nitrification even with higher organic loads.

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