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NITRIFICATION IN TERTIARY TRICKLING FILTERS FOLLOWED BY DEEP-BED FILTERS

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Abstract—Based on 20 months of pilot experiments, tertiary plastic media trickling filters have shown to be a feasible and cost-saving solution for the enlargement of existing treatment plants for nitrification. The influence of several process variables such as hydraulic load, media characteristics, NH_4-load, concentration fluctuations, suspended solids, organic nutrients and biomass grazing on nitrification activity was evaluated. From performance analysis along the trickling filter depth, basic design informations were obtained. In addition to suspended solids removal, subsequent deep-bed filtration proved to be an excellent final treatment to further reduce and stabilize effluent ammonia and nitrite residuals.

Key words—nitrification, trickling filter, plastic media, ammonia, nitrite, hydraulic load, recirculation, biomass grazing, cooling effect, oxygen transfer, start-up, process stability, deep-bed filtration, nitrifying filter

INTRODUCTION

In recent years, the majority of the Swiss population has been connected to sewage treatment plants designed primarily to reduce BOD- and phosphorous loads. The sewage is treated mainly by activated sludge plants allowing usually no or only partial nitrification in summer.

To keep the ammonium concentrations well within the required standard for river waters (0.5 mg $NH_3 + NH_4^+$-N l^{-1}), full nitrification, for several river basins with dense population and relatively small receiving waters, will be necessary. It may be estimated that 35–45% of the Swiss population should be served by nitrifying plants.

In most cases, nitrification has to be integrated into existing activated sludge plants. Possible alternatives for upgrading existing plants are

—extension of the existing aeration and sedimentation tank volume in a one- or two-stage activated sludge process

—addition of a tertiary trickling filter to the existing treatment facilities.

Since nitrification as a tertiary treatment step produces only small amounts of surplus sludge, the advantage of the trickling filter alternative is, that no additional clarifier is required, leading to considerably lower investment costs. If low suspended solids concentrations have to be attained, the trickling filter effluent may be directly treated in subsequent deep-bed filters.

Up until now, nitrification in trickling filters as tertiary treatment has rarely been used in European practice. Therefore, only little information on design and operating experience is available. Results on tertiary nitrification by trickling filters have been published by the U.S.EPA (1973), Bruce *et al.* (1975), Brown and Caldwell (1975), Norris *et al.* (1980) and Wilderer *et al.* (1980).

In order to provide design guides to the practical engineer, a 20-month pilot study with plastic media trickling filters was conducted at EAWAG's experimental sewage treatment facilities.

In this paper, trickling filter and deep-bed filter performance data under different operating conditions and the basic design data are presented. In a different paper by Gujer and Boller (1986) this information is compared to a theoretical trickling filter model for tertiary nitrification which may serve as a guide for practical trickling filter design.

PILOT PLANTS

Wastewater, drawn from the main sewer of the City of Zurich was treated in pilot scale primary sedimentation and an activated sludge plant at a rate of 150 $m^3 d^{-1}$. The activated sludge age was maintained at about one day in order to avoid nitrification. Ferric chloride addition to the aeration tank served for phosphorus removal. The treated wastewater was delivered to two trickling filters with an i.d. of 0.90 m and a packing height of 6.75 m. The trickling filters, either operated in parallel or in series were filled with a corrugated plastic sheet packing with a specific surface of 230 $m^2 m^{-3}$. Flow rates were between 28 and 90 $m^3 d^{-1}$ including recirculation.

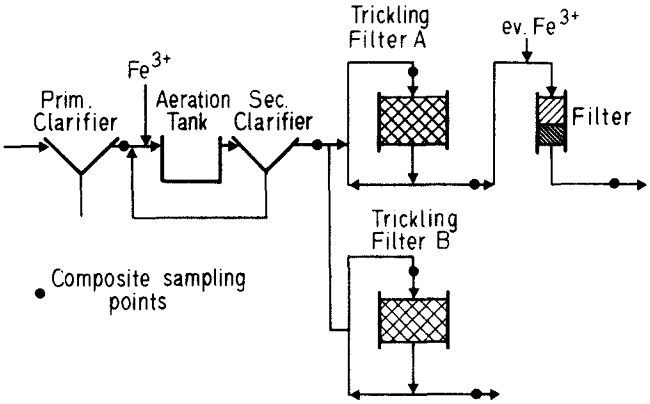

Fig. 1. Pilot plant facilities for tertiary nitrification in trickling filters followed by deep-bed filters.

The plastic media was packed in a way, that wall effects were minimized.

Composite samples from in- and effluent of the different process steps as well as grab samples from different depths of the trickling filter were taken. Pieces of biomass support media could be removed and visually inspected at several depths.

During part of the trickling filter experiments, the nitrified effluent was further treated by a dual media deep-bed pilot filter with 0.19 m dia at a filtration rate of 10 m h^{-1}. The filter contained 0.3 m quartz sand as lower media and 1.05 m expanded slate as top layer.

A schematic diagram of the process facilities is shown in Fig. 1. Figure 2 indicates in more detail hydraulic flow scheme and sampling points of the trickling filters.

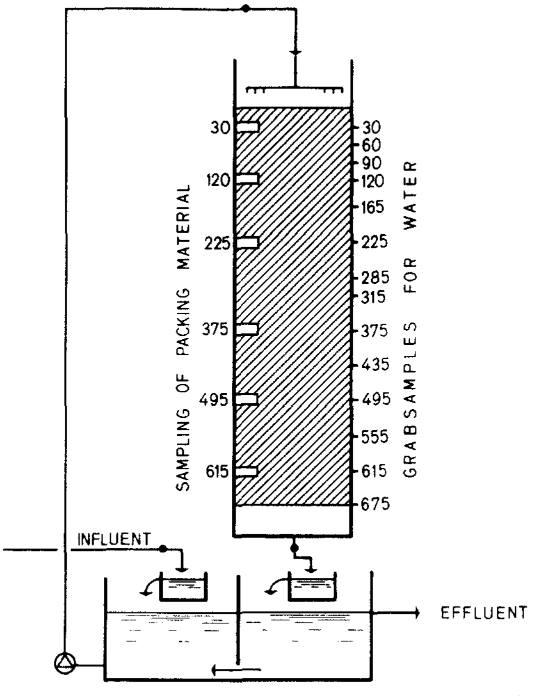

Fig. 2. Hydraulic flow scheme and sampling points for the pilot scale tertiary trickling filters. ● indicates composite sampling points.

Another pilot trickling filter with 1.60 m dia and a packing depth of 3.90 m was operated on a full-scale treatment plant with conventional primary sedimentation and high-load activated sludge treatment. In this pilot plant, four different trickling filter packings were tested in parallel with respect to nitrification and operating performance.

RESULTS OF TRICKLING FILTER NITRIFICATION

Operating conditions

Within the 20 months of experiments, five different periods were distinguished in which the influence of different process variables was tested.

In a first period, start-up of nitrification at low NH_4-loads was observed. In a second experimental phase, the influence of a preceeding deep-bed filter at mean NH_4-loads was tested with the aim of removing heterotrophic organisms from the trickling filter inlet. In this way it was hoped to create more favourable conditions for a dense nitrifier population on the media surface. Higher nitrification rates and hence smaller trickling filter volume were expected advantages of this process combination.

After a start-up period of 2 months, nitrification performance was disturbed by severe biomass grazing. Cause and effect of biomass predation will be discussed later. The operating conditions of the subsequent experimental periods were therefore directed towards reduction of grazing organisms in the trickling filters. The following measures were taken into account and their effect on nitrification performance was observed over periods of at least 3 months under constant operating conditions. In period 3,

—trickling filter A was operated without recirculation in order to prevent re-inoculation of grazing organisms and

—trickling filter B was run at high hydraulic load to avoid dry places on the media which promote

Table 1. Process conditions for tertiary trickling filter nitrification experiments

Period	No. of days	Trickling filter	Process arrangement	Hydraulic load* incl. recirculation ($m^3 m^{-2} h^{-1}$)	Recirculation ratio R/Q	Mean† NH_4-load (gNH_4-N $m^{-2} d^{-1}$)
1	67	A	low NH_4-load	2.0	1	0.11
		B	low NH_4-load TF after filtration	2.0	1	0.09
2	117	A	mean NH_4-load	3.0	0.5	0.35
		B	mean NH_4-load TF after filtration	3.0	0.5	0.39
3	106	A	high NH_4-load	3.0	0	0.52
		B	high NH_4-load high hydr. load	6.0	1	0.54
4	151	A	high NH_4-load interrupting air-flow	3.0	0	0.82
		B	high NH_4-load 10% prim. effl.	3.0	0	0.80
5	87	A	design conditons	4.0	1	0.42

*(Wastewater flow + recirculation)/cross sectional area.

†Mean NH_4-load/internal surface area of the media.

egg-deposition of trickling filter flies and subsequent growth of grazing fly larvaes.

In a fourth experimental period, conditions were changed such that

—in trickling filter A the air flow was periodically interrupted to create unfavourable anaerobic conditions for predating organisms and

—trickling filter B was fed with a mixture of secondary effluent and 10% primary effluent in order to increase heterotrophic biomass production and hence decrease grazing on nitrifying organisms.

Finally, period 5 served as a control experiment operating under the most favourable conditions determined from the results of the preceeding periods.

Details on the operating conditions and duration of the different experimental periods are summarized in Table 1.

Nitrification performance of tertiary trickling filters

Summary of experimental results. Nitrification performance and sludge production data for the different experimental periods are summarized in Table 2. From the data records of 250 24-h composite samples, some conclusions are drawn in this overview section. Special aspects of the experiments are described in more detail in subsequent parts of the paper.

To start nitrification in the pilot trickling filters, nitrifying activated sludge was dosed to the plant inlet. The sludge was partly captured on the support media and after two weeks of operation, full nitrification at low NH_4-loads was obtained in both trickling filters. With increasing operation time, the activated sludge flocs were washed out or mineralized and replaced by a thin layer of biomass, unevenly distributed over the plastic media surface.

During the first 2 months, a slightly better nitrification performance was observed in trickling filter B with preceeding filtration as compared to trickling filter A (see Table 2).

After this period, however, increased NH_4-break throughs indicated a considerable loss in process stability. Inspection of the trickling filter media revealed the presence of excessive amounts of biomass grazing organisms. The effect of these organisms was documented by a series of NH_4-profiles along the filter depth and by counting the concentration of predators on the support media (see next section).

Together with an increase of the NH_4-load from 0.1 to nearly 0.4 g NH_4–N $m^{-2} d^{-1}$ and the hydraulic load from 2 to 3 m h^{-1} in the second period, biomass grazing and NH_4-overloading caused a period of rather unstable performance. But under the influence of higher hydraulic loads ($\geq 3 m h^{-1}$), the concentrations of grazing organisms decreased within 5 weeks.

No sudden nitrification break-downs were observed in the course of subsequent experiments.

After changing nutrient and operating conditions from period 2 to 3 and period 3 to 4, an adaptation period of 4–5 weeks in winter and 3–4 weeks in summer was observed until full nitrification was reached again. During the entire experimental period an increase of average nitrification rates from 0.2 to finally 0.7 g NH_4–N $m^{-2} d^{-1}$ was reached. The latter values in period 4 seem to be an upper limit since maximum nitrification capacity (not NH_4-limiting conditions) was close to the observed rates.

Although satisfactory ammonia-N removal efficiency was obtained within a few weeks, the biomass took a longer time to reach equilibrium after changing the prevailing nutrient and operating conditions. When changing operating conditions from one period to another, 3 months were necessary to attain steady state solids production. Therefore solids production data in Table 2 may not reflect in all periods the situation under steady operating conditions. It may be concluded, that the development of a stable and effective nitrifying biofilm is a longterm process, taking months until maximum efficiency is achieved.

Table 2. Nitrification performance and sludge production data under different experimental conditions

Period	Trickling filter	Effluent pH	Water temp. (°C)	NH_4-load (gNH_4–N m^{-2} d^{-1})	Nitrification rate (gNH_4–N m^{-2} d^{-1})	NH_4-removal rate (%)	Effluent conc. ammonia (gNH_4–N m^{-3})	Effluent conc. nitrite (gNO_2–N m^{-3})	Solids production (gTSS m^{-2} d^{-1})	Effluent conc. suspended solids (gTSS m^{-3})
1	TF A	8.1	9.0	0.11	0.08	89.7	0.72	0.11	−0.091	9.3
	TF B	8.2	9.0	0.09	0.07	93.6	0.37	0.07	0.024	7.6
2	TF A	7.9	9.5	0.35	0.22	77.6	2.52	0.23	−0.076	11.8
	TF B	7.9	9.5	0.39	0.23	75.7	3.07	0.23	0.100	8.8
3	TF A	7.8	18.0	0.52	0.46	88.0	1.34	0.53	0.119	14.8
	TF B	7.9	18.0	0.54	0.46	93.5	0.76	0.56	0.211	18.2
4	TF A	7.6	13.2	0.82	0.73	88.4	2.05	0.57	0.035	13.9
	TF B	7.8	12.5	0.80	0.69	87.2	2.21	0.47	−0.300	20.0
5	TF A	7.7	10.6	0.42	0.39	96.0	0.54	0.10	0.047	13.4

In all cases without addition of primary effluent, solids production rates were in the order of 0.03–0.2 g TSS m^{-2} d^{-1} which only increased suspended solids concentrations in the effluent by 2–3 mg TSS l^{-1}. Such an increase also follows from heterotrophic and autotrophic yield calculations based on activated sludge data.

In the last experimental period 5, all information gained from the preceeding experiments was used to determine operating conditions for full and stable nitrification. For period 5 the hydraulic load was kept at 4 m h^{-1} in order to guarantee complete wetting of the media surface and an NH_4-load for the total surface of 0.4 g NH_4–N m^{-2} d^{-1} seemed to be appropriate for a safe design under winter conditions. A recirculation ratio of 1 was necessary to fulfill both criteria. As indicated by a series of 20 composite samples at the end of period 5, summarized in Table 3, a 96% reduction of NH_4 and consistent low NH_4– and NO_2–residuals were achieved.

The data of period 5 allow an interesting comparison with period 2 under similar operating and temperature conditions (see Table 2). Nitrification rates and effluent quality show a considerable increase in performance over 1 yr of continuous operation. It may be concluded, that pilot experiments with tertiary trickling filters must last for more than 1 yr in order to be representative for a longterm application. If a new plant is brought into operation, the first year may not yield the expected performance. In places with marked seasonal load variations (tourism), tertiary trickling filters should not be applied, because the approach to a new steady state may require several weeks to months.

Influence of biomass grazing. Since the production of biomass in a tertiary trickling filter is small, massive growth of biomass grazing organisms may influence nitrification performance considerably. In our experiments enormous concentrations of the trickling filter fly larvae (*Psychodidae* spp) and of worms (*Naididae* spp) were observed. At certain periods, concentrations of fly larvae of up to 26,000 m^{-2} support media and up to 15,000 worms m^{-2} were counted. The worms were found on places with well developed biomass whereas the fly larvae preferred the nearly blank media surface. The presence of worms certainly affected the level of nitrification rates, but did not cause serious fluctuations in performance since they grew continuously with the biofilm and grazing reached some kind of equilibrium with biomass growth. However, trickling filter fly larvae showed sudden invasions and within a few days nitrification was stopped completely as is demonstrated by the NH_4-profiles in Fig. 3 under normal operating conditions and during heavy grazing by fly larvae.

Inspection of the support media with a specific surface of 230 m^2 m^{-3} showed, that at hydraulic loads of about 2 m h^{-1} only a thin waterfilm developed, leaving dry spots and places where the imago flies

Table 3. Nitrification performance data in period 5 under "design conditions"

	Secondary effluent		Trickling filter inflow incl. recirculation		Trickling filter effluent	
	mean	80% freq.	mean	80% freq.	mean	80% freq.
NH_4–N ($mg\,l^{-1}$)	13.57	15.73	6.77	7.86	0.54	0.83
NO_2–N ($mg\,l^{-1}$)	0.20	0.27	0.23	0.31	0.10	0.20
NO_3–N ($mg\,l^{-1}$)	3.32	4.15	11.56	15.01	17.67	20.69
TSS ($mg\,l^{-1}$)	10.7	13.2	12.6	14.8	13.4	15.2
Worms (l^{-1})	3	8	23	46	30	66
TOC ($mg\,l^{-1}$)	12.6	15.0	—	—	12.3	15.0
DOC ($mg\,l^{-1}$)	7.6	9.1	—	—	6.3	8.9
pH —	7.5	7.8	7.6	7.8	7.7	8.8
Alkalinity (m-equiv l^{-1})	4.20	4.66	—	—	1.85	2.80
Temperature air (°C)	—	—	5.5	10.0	—	—
water (°C)	—	—	11.1	12.4	10.6	12.3

could deposit the eggs. Increased hydraulic load was therefore used as one measure to control invasions of the trickling filter fly. In all subsequent experiments the hydraulic load was 3 m h^{-1} and higher, with the result that the concentrations of larvae decreased to negligible amounts and no further nitrification breakdown was observed.

Influence of hydraulic load and recirculation. In period 3 of the experiment, the two trickling filters were operated in parallel at the same NH_4-load of 0.6 g NH_4–N $m^{-2}\,d^{-1}$ under different hydraulic conditions. Trickling filter A was operated without recirculation at 3 m h^{-1} and trickling filter B with a recirculation ratio of 1 at a mean hydraulic load of 6 m h^{-1}. The water to trickling filter B was dosed intermittently, simulating a rotary distributor system.

As may be seen in Table 2 nitrification rates were nearly the same in both trickling filters. Due to a more homogeneous distribution of the wastewater at high hydraulic load, nitrification in the top section of trickling filter B was faster (see Fig. 12) leading to a slightly better performance with respect to effluent quality and process stability. Typical NH_4-profiles along the depth are drawn in Fig. 4.

Considering only nitrification efficiency, recirculation does not bring any savings in reactor volume. However, recirculation is usually required to maintain hydraulic loads of about 3 m h^{-1} at relatively low design NH_4-loads in the order of 0.4 g NH_4–N $m^{-2}\,d^{-1}$.

Influence of organic nutrients. With an average of 7.5 mg DOC l^{-1} the content of organic substances in the secondary effluent was low, within the trickling filter a further reduction of 1.5 mg DOC l^{-1} was measured leading to a heterotrophic biomass growth in the order of 1–2 mg TSS l^{-1}. The low organic load allowed nitrification to start right at the top of the media packing. In period 4, trickling filter A was run parallel to trickling filter B at the same NH_4–load of 0.8 g NH_4–N m^{-2} d^{-1}. The hydraulic load was 3 m h^{-1} in both trickling filters and no recirculation was applied. The idea of creating anaerobic conditions by interruption of the air flow in trickling filter A was abandoned after a few experiments. In fact, part of the predators were washed out during anaerobiosis, but restart of full nitrification took 1–2 days which was considered to be too long. During the major part of period 4, trickling filter A was therefore operated under normal conditions.

To the inflow of trickling filter B primary effluent was added at 10% of the total flow in order to

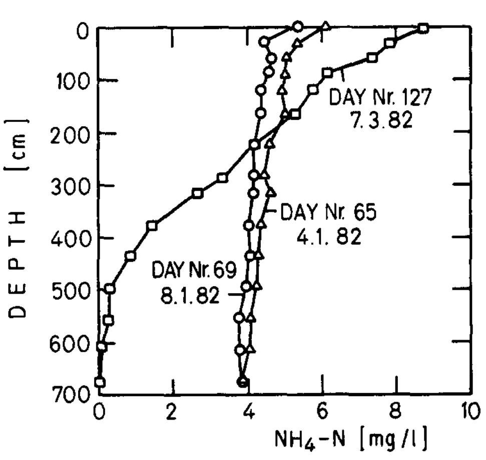

Fig. 3. Ammonia concentration profiles in pilot scale trickling filter during a massive invasion of trickling filter fly larvae (predation) on days 65 and 69 and during normal operation on day 127.

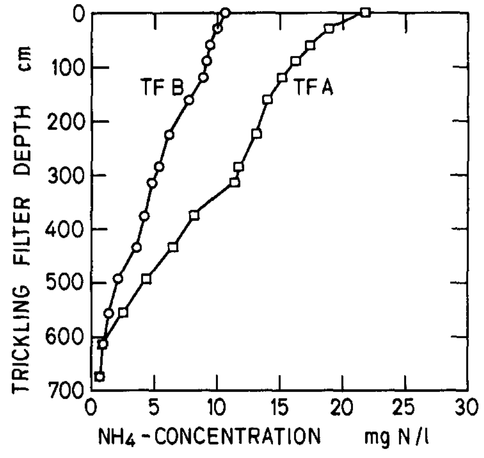

Fig. 4. Typical NH_4-profiles at an NH_4-load of 0.45 g NH_4–N m^{-2} d^{-1} in trickling filter A (3 m h^{-1}, recirculation = 0) and in trickling filter B (6 m h^{-1}, recirculation = 1). Inlet concn 22 mg NH_4–N l^{-1} and 11 mg NH_4–N l^{-1} respectively.

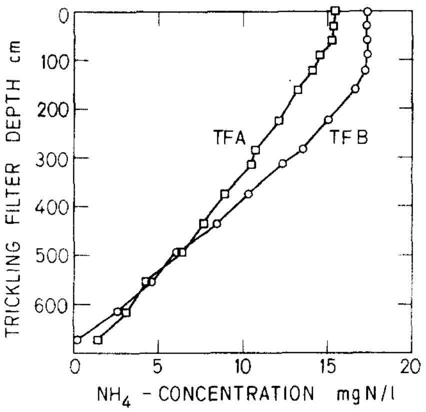

Fig. 5. Typical NH_4-profiles at an NH_4-load of 0.8 g NH_4-N m^{-2} d^{-1} in trickling filter A (normal operation at 3 m h^{-1}) and trickling filter B (10% primary effluent, 3 m h^{-1}).

promote biomasss production and hence reduce grazing on nitrifying organisms.

Comparing nitrification efficiency of the two trickling filters, a slightly better performance of trickling filter A (normal operation) was obtained. Looking at nitrification along the trickling filter depth, a considerable difference of the NH_4-profile pattern is evident. Two typical profiles are shown in Fig. 5. In trickling filter B the nitrifying biofilm present was partly covered by heterotrophic organisms and by adsorbed suspended solids from primary effluent. Therefore, trickling filter B did not nitrify over the top 1.2 m, but showed higher nitrification rates at the lower end due to an increased supply of NH_4 in this section.

Addition of primary effluent increased sludge production and as a consequence suspended solids concentrations in the effluent rose beyond standard requirements up to 20–30 mg TSS l^{-1}. Furthermore, suspended solids were captured in the top section leading to a partial clogging of the media.

Influence of media characteristics. In a pilot trickling filter of 1.6 m dia four different media were tested in parallel. For an experimental period of 1 yr, start-up of nitrification and nitrification efficiency were investigated. Media characteristics are summarized in Table 4.

The hydraulic load was 4 m h^{-1} throughout the entire experimental period. Media height was 3.9 m allowing only for partial nitrification. After one yr of continuous operation, the nitrification rates in the four media were compared. NH_4-measurements were carried out during a summer period at water temperatures of 17–20°C. In Table 5 the nitrification rates with respect to reactor volume and internal media surface are calculated. If volume specific rates are compared to media specific surface Fig. 6 is obtained. The results show a clear advantage of the corrugated plastic sheets over the random packed media. Considering, however, that only half of the plastic saddles may be wetted, the saddles would perform equal to the Flocor plastic sheets compared on the base of specific media surface.

Table 5. Volume specific and surface specific nitrification rates of four different trickling filter media at 17–20°C

Media	Volume specific nitrification rate ($g NH_4$-N m^{-3} d^{-1})	Surface specific nitrification rate ($g NH_4$-N m^{-3} d^{-1})
Volcanic rock	67	0.67
Plastic saddles	163	0.68
Plastic sheets (Flocor)	139	1.54
Plastic sheets (Plasdek)	286	1.19

Furthermore, the clogging behaviour of the different media was observed during a period of high effluent suspended solids concentrations originating from the preceeding activated sludge plant. During sludge wash-out from the secondary clarifier all media were clogged except the plastic sheets with low specific surface (Flocor). The duration of clogging lasted nearly the entire investigation in the volcanic rock media whereas the others recovered within 6 weeks and started to nitrify at satisfactory rates.

Comparing only the corrugated plastic media, nitrification rates seem to be more or less proportional to the internal surface. The larger the internal surface, however, the more the media is subject to clogging by sludge flocs from the preceeding treatment step. Therefore a corrugated plastic media with a specific surface in the order of 150–200 m^2 m^{-3} is considered to be best suited for tertiary nitrifying biofilters.

Information from profile analysis

By measuring NH_4, NO_2, NO_3, O_2, pH, temperature and alkalinity as a function of trickling filter depth, the effect of various process parameters on nitrification performance could be followed within the reactor. From NH_4-profiles, nitrification rates were calculated serving as a base for design considerations and input information for theoretical model calculations.

Table 4. Characteristics of tested trickling filter media

	Packing	Specific surface (m^2 m^{-3})	Surface characteristics	Wetting characteristics
Volcanic rock	random	100	porous, rough	full, dry spots
Plastic saddles	random	240	PVC, very smooth	only upper side (1/2 surface)
Corrugated plastic sheets (Flocor)	ordered	90	PVC, smooth	full
Corrugated plastic sheets (Plasdek)	ordered	230	PVC, smooth	full at hydr. load > 3m h^{-1}

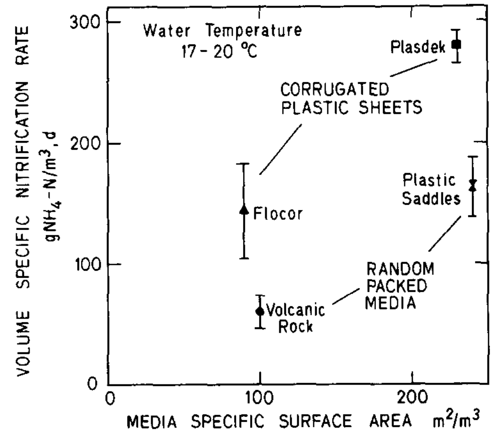

Fig. 6. Volume specific nitrification rates of four different trickling filter media.

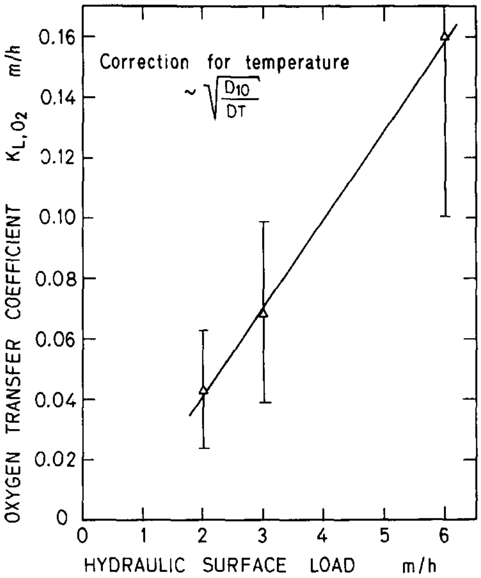

Fig. 7. Gas transfer coefficient as a function of the hydraulic load for a corrugated plastic sheet media with a specific surface of 230 m^2 m^{-3}.

Oxygen transfer rates. From the nitrification reaction it is well known, that 4.3 mg O_2 are consumed for the oxidation of 1 mg NH_4–N. Knowing the reduction of NH_4 from profile analysis, the respiration rates in each section of the trickling filter can be calculated. Respiration rates and measured O_2-profiles allow the determination of the oxygen transfer rates of the tested support media with the help of the following O_2-mass balance

$$\frac{Q}{A}\frac{dc}{dx} = K_{L,O_2}a\,(c_s - c(x)) - r_{O_2}\cdot a \qquad (1)$$

where

Q = flow rate, [$m^3\,h^{-1}$]
A = cross sectional area, [m^2]
$\frac{dc}{dx}$ = O_2-gradient across a depth element
K_{L,O_2} = gas transfer coefficient, [$m\,h^{-1}$]
a = specific surface of the media, [$m^2\,m^{-3}$]
c_s = oxygen saturation concentration, [$g\,m^{-3}$]
$c(x)$ = oxygen concentration at depth x, [$g\,m^{-3}$]
r_{O_2} = specific respiration rate, [$g\,O_2\,m^{-2}\,h^{-1}$].

Approximating dc/dx by $\Delta c/\Delta x$ from O_2-profiles, the gas transfer coefficients in Fig. 7 were obtained at different hydraulic loads. The temperature influence was corrected by the diffusion correction factor $\sqrt{D_{10}/D_T}$. From the calculated $K_{L,O_2}a$-values it may be concluded, that even at low oxygen concentrations in the inlet, no O_2-transfer problems will arise. The height of a transfer unit for liquid-side controlled oxygen transfer only amounts to 0.20 m.

Nutrient limitations. From biofilm theories it is known that nitrification depends on ammonium concentration in the low concentration ranges ($<$3–5 mg NH_4–N l^{-1}) and follows a zero order rate equation at higher NH_4-concentrations at which oxygen diffusion is the rate determining step. In a normally operating trickling filter, the top sections with higher NH_4-concentrations will therefore nitrify at a constant rate whereas the lower sections, where effluent quality is approached, will show a steady decrease of the nitrification rate.

By dosing NH_4 to the trickling filter inflow, conditions may be created in which all layers operate under O_2-limitation at constant rates, thus giving the maximum nitrification capacity of a trickling filter under the prevailing conditions. In a trickling filter with a homogeneous biomass activity throughout the total depth, typical NH_4–profile patterns at high and low inlet concentrations are formed. Figure 8 shows two examples after an operating time of 1 year with a well developed biomass.

Under practical conditions, the lower parts of a trickling filter will only be loaded with NH_4 during part of a day due to diurnal NH_4-fluctuations in the wastewater. NH_4-concentration profiles will therefore vary according to load-variations. In Fig. 9, the time certain concentration profiles will be exceeded during a day at a large sewage treatment plant is

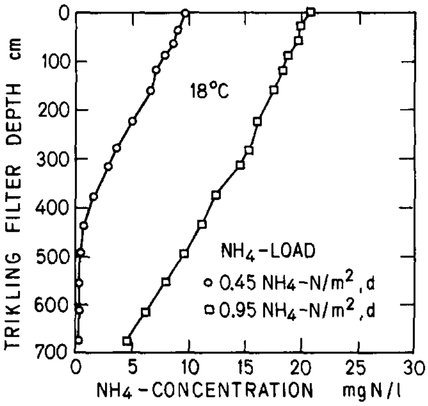

Fig. 8. Typical NH_4-profiles at low and high NH_4-load during a period with well developed biomass.

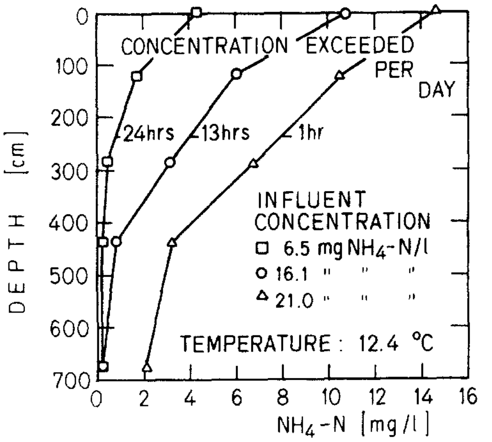

Fig. 9. Diurnal variation of ammonia concentration profiles with indication of daily duration of concentrations exceeding indicated values. NH_4-profiles during a period with inhomogeneous nitrification activity with depth.

indicated. NH_4-fluctuations cause smaller biomass growth at the lower end leading to an inhomogeneous distribution of the biofilm and hence to a decrease of maximum nitrification rates with depth. The slowdown of biomass activity is clearly visible in the NH_4-profiles in Fig. 9 which show a curved profile pattern indicating a steady decrease of the nitrification rates. In the design and operation of tertiary trickling filters, it is therefore important to minimize diurnal load variations. Digester supernatant should be recycled during periods of low NH_4-load since it may add 10–20% of the daily load.

Design information. From the NH_4-profiles it was possible to calculate the nitrification rates along the depth under the process conditions tested. The nitrification rates over four sections of the trickling filter height were evaluated. All rates are corrected for temperature by the following equation

$$r_{NH_4,10^\circ C} = r_{NH_4,T^\circ C} \cdot \exp[k_T(10^\circ - T^\circ)] \qquad (2)$$

where

$\left.\begin{matrix} r_{NH_4,10^\circ C} \\ r_{NH_4,T^\circ C} \end{matrix}\right\}$ nitrification rate at 10°C and T°C respectively [g NH_4–N m^{-2} d^{-1}]

T°C = water temperature under experimental conditions

$k_T = 0.044^\circ C^{-1}$ according to Gujer and Boller (1986).

In Fig. 10 the nitrification rate functions of the second period are shown. They indicate the inhomogeneous distribution of biomass by a strong decrease of the maximum rate from the top to the lowest section. A more homogeneous biomass activity and a higher nitrification capacity could be reached during period 3 at summer conditions as may be seen from Fig. 11.

Considering only the nitrification rates under O_2-limiting conditions (profiles with NH_4-effluent concentration >5 mg NH_4–N l^{-1}), the maximum nitrification capacity of the trickling filter can be determined. The results for the different experimental periods are shown in Fig. 12 as a function of trickling filter depth. The distribution of maximum nitrification activity with depth is important information which is used for further design calculations as demonstrated by Gujer and Boller (1986). The increase of nitrification rates and the development towards more homogeneous activity throughout phase 2–4 is clearly visible. The lower rates in the first section of trickling filter A in phase 4 is due to a change of the distributor system.

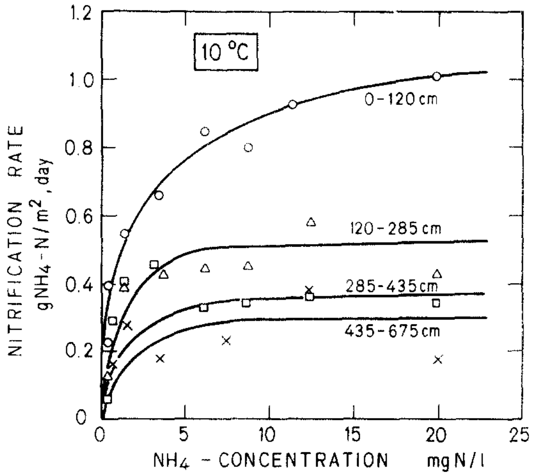

Fig. 10. Nitrification rate as a function of the NH_4-effluent concentration for four different sections of the trickling filter height during period 2 with inhomogeneous biomass activity.

Operating trickling filters in series

The inhomogeneous distribution of biomass activity in a trickling filter may be overcome by operating two trickling filters in series instead of parallel. In

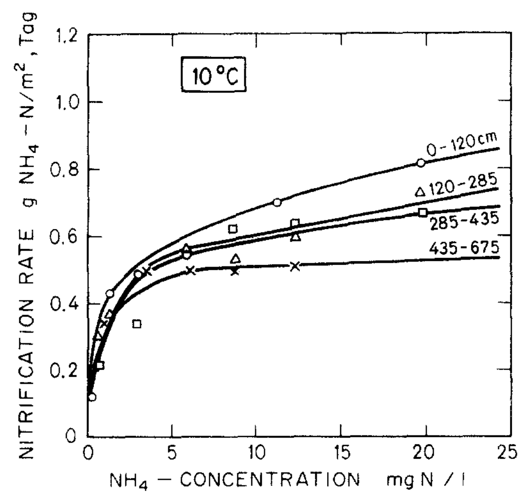

Fig. 11. Nitrification rate as a function of the effluent NH_4-concentration for four different sections of the trickling filter height during period 3 with more homogeneous biomass activity.

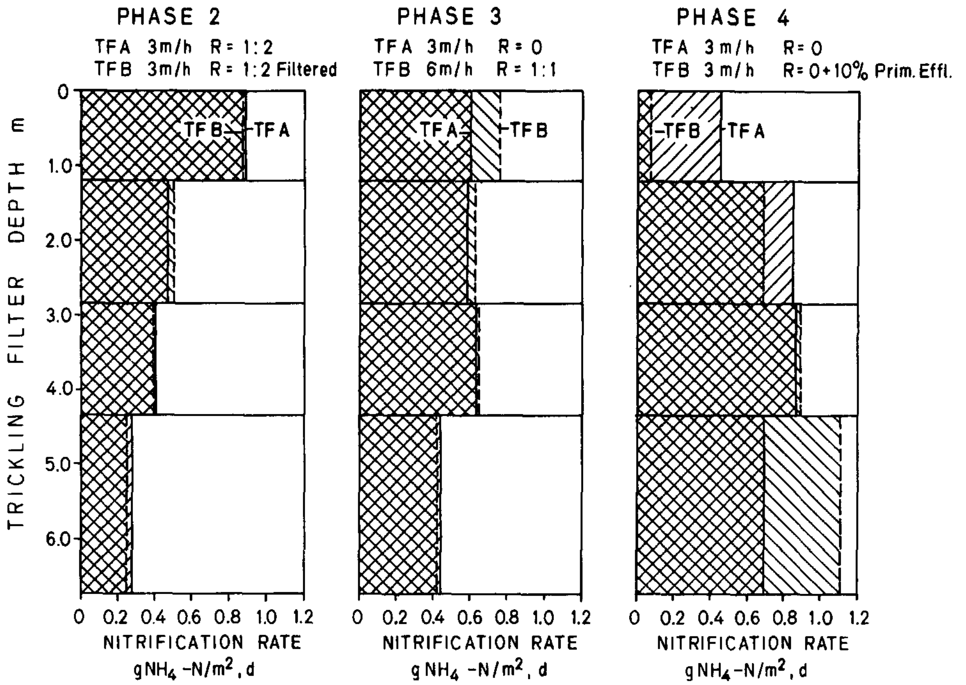

Fig. 12. Maximum nitrification rates (O_2-limited) in function of trickling filter depth for experimental periods 2, 3 and 4.

intervals of some days the order of the two reactors is inversed leading to a uniform development of the biomass in both reactors according to their average NH_4-load. Since most nitrifying trickling filter designs require recirculation, two step trickling filters do not require more pumping energy at equal hydraulic load than the operation of two trickling filters in parallel.

To test the feasibility of serial operation, experiments were carried out in which several periods with and without NH_4 containing wastewater followed each other. To simulate a worse case for the second trickling filter, fully nitrified effluent without NH_4 was dosed. The decrease of nitrification activity with time was measured by dosing NH_4 during profile measurements. In order to test the behaviour of a trickling filter after flow inversion, NH_4 containing wastewater was fed again and the restart of nitrification observed. The results shown in Fig. 13 indicate, that a severe nitrification break-down takes place after a starving period of about 10 days and another 10 days are required to regain the level of former nitrification

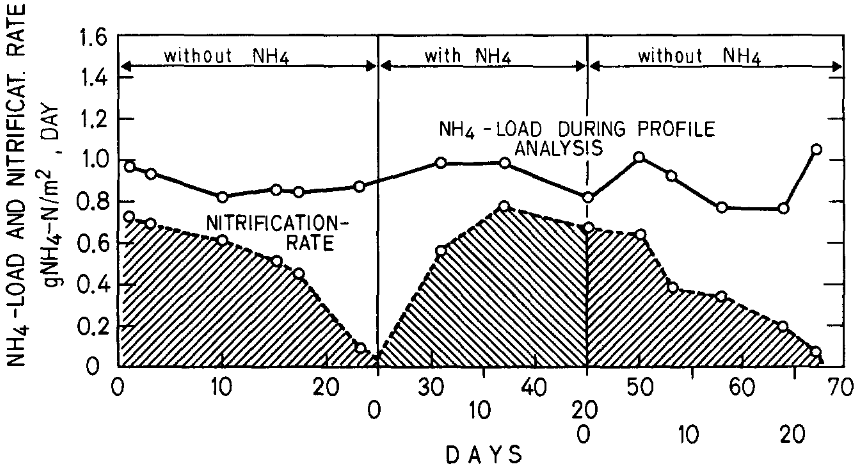

Fig. 13. Nitrification rates during "starving" and "start-up" periods simulating extreme situation of trickling filters in series when run in an alternating mode.

rates when NH_4 is dosed. It may be concluded, that the nitrification capacity of two trickling filters in series will be maintained at a high level, if the flow is inversed within periods of less than approx. 10 days.

DEEP-BED FILTER NITRIFICATION AS FINAL TREATMENT

If low suspended solid standards are required, the tertiary trickling filter effluent may be directly treated by some kind of filter. Deep-bed filters are especially suited for the purpose because of the possibility of further nitrification in the low concentration range. Eventual breakthroughs of NH_4 and NO_2 during peakload hours may thus be prevented. Since the trickling filter effluent is nearly saturated with oxygen and contains nitrifying organisms in ample amounts, conditions for nitrification in deep-beds are favourable.

To investigate the nitrification capacity and the influence of backwashing and chemical conditioning on nitrification in deep-beds, filtration experiments were carried out with a dual-media filter specified in Table 6. Profile analysis of NH_4, NO_2, O_2, TSS and head loss at a constant filtration rate of $10\,m\,h^{-1}$ enabled detailed performance qualification.

Considering the NH_4- and O_2-profiles, two different cases with respect to nutrient limitation may be distinguished.

(1) The trickling filter effluent contains only small amounts of NH_4. The oxygen present will not be totally consumed for nitrification.

(2) In the case NH_4-concentrations are high, the oxygen is used up completely limiting the extent of nitrification to the oxygen equivalent contained in the inflow to the filter. In this case maximum nitrification capacity of a deep-bed filter is reached.

NH_4- and O_2-profiles of the discussed cases are shown in Fig. 14.

From the results of several filter runs under different NH_4-loads, maximum nitrification capacity may be obtained by plotting NH_4-effluent vs NH_4-inflow concentrations. Figure 15 indicates, that approx. $1.7\,mg\;NH_4\text{-}N\,l^{-1}$ may be nitrified by a deep-bed filter.

Since the trickling filter effluent contained $7\text{–}8\,mg\,O_2\,l^{-1}$, the result is in agreement with the stoichiometric oxygen consumption resulting from the nitrification reaction.

To elucidate the question, whether the nitrifying biomass is part of a permanent biofilm on the filter grains or is just captured by the floc entrappment during filtration, oxygen profiles were analysed immediately before and after backwashing and during the filter run. As can be seen in Fig. 16 oxygen consumption is constant throughout the whole filter run, indicating that nitrification is performed by organisms on the filter media surface. Expanded slate samples were taken out from the freshly backwashed filter bed and oxygen uptake was measured in a respirometer after addition of NH_4. The respiration rates confirmed that the nitrifiers are not removed during intense air/water backwash and therefore maximum nitrification capacity can be maintained constant over the total filter run.

Table 6. Specification of the dual-media filter

Filter media	Grain size (mm)	Layer thickness (cm)
Expanded slate	2–4	105
Quartz sand	0.8–1.2	30

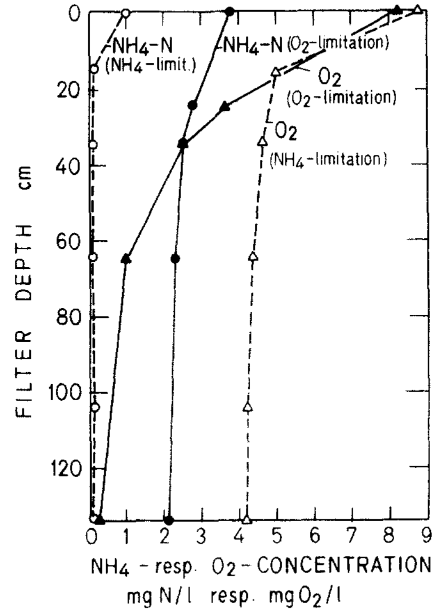

Fig. 14. Ammonia and oxygen profiles at NH_4- and O_2-limiting conditions in a deep-bed filter.

In Switzerland deep-bed filters are often applied for advanced phosphorus removal. This application necessitates the addition of precipitating agents as Fe- or Al-salts to the filter inlet. In further filtration

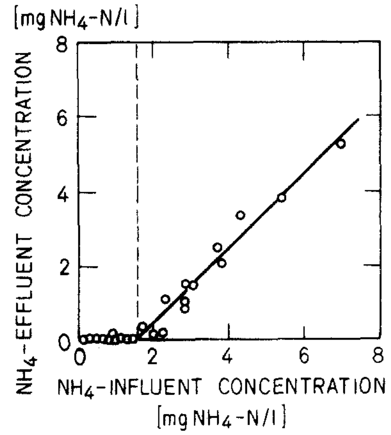

Fig. 15. Correlation between influent and effluent ammonia concentration in a nitrifying dual media filter after a tertiary trickling filter. Above a removal of $1.7\,mg\;NH_4\text{-}N\;l^{-1}$ nitrification becomes O_2-limited.

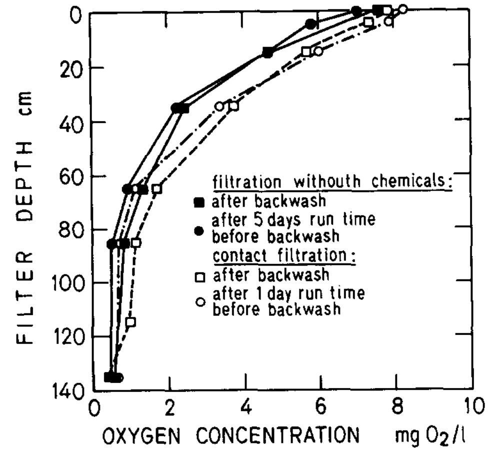

Fig. 16. Oxygen profiles in a nitrifying deep-bed filter immediately before and after backwash. Nitrification rates are not reduced by backwashing.

experiments it was tested, whether the freshly precipitated metalhydroxophosphate-complexes cover the active biomass on the filter grains and thus hinder nitrification. Comparing again oxygen consumption profiles of filter runs with and without chemical precipitation, no significant difference could be observed. The respective profiles are also shown in Fig. 16.

Under all tested conditions nitrification rates are high enough to consume all oxygen in the top 0.60–0.80 m of the filter bed. In Table 7, volume and surface specific nitrification rates are calculated for the first 0.35 m of expanded slate assuming a specific surface of 2500 $m^2 m^{-3}$. The difference between runs with and without addition of ferric chloride is statistically not significant.

The results reveal that a deep-bed filter following tertiary nitrification with trickling filter may act as a suspended solids and phosphorus removal process as well as an advanced nitrification step. Since nitrification takes place in the first 0.80 m of the filter, it does not affect design considerations of deep-bed contact filters with a bed depth usually in the order of 1.20–2.00 m and hydraulic loads of 8–12 $m h^{-1}$.

To confirm the experimental finding, water quality data under normal operating conditions were collected over 8 continuous days. The results are presented in Table 8. Run time length up to an available head of 2.6 m water column amounted to 120 h without and 25 h with the addition of 2.5 mg Fe (III) l^{-1}.

Table 7. Volume and surface specific nitrification rates in the top 0.35 m of a filter bed under winter conditions. Mean and standard deviation from 10 filter runs each with and without addition of 3 mg Fe(III) l^{-1}

	Without chemicals		Contact filtration	
	Mean	SD	Mean	SD
Volume specific nitr. rate ($g NH_4$-N $m^{-3} d^{-1}$)	770	110	883	259
Surface specific nitr. rate ($g NH_4$-N $m^{-2} d^{-1}$)	0.31	0.04	0.35	0.10

Table 8. Nitrification performance of a dual-media filter subsequent to a tertiary trickling filter

	Filter inflow	Filter effluent
NH_4-N mg l^{-1}	1.08	0.25
NO_2-N mg l^{-1}	0.27	0.07
NO_3-N mg l^{-1}	16.76	17.61
TSS mg l^{-1}	17	2.4
Worms l^{-1}	26	0
pH	7.6	7.3

CONCLUSIONS

Plastic media trickling filters following conventional mechanical–biological wastewater treatment are especially suited for nitrification in existing large treatment plants where ammonia-load fluctuations are not too high. Low solids production allows direct discharge without the need for additional clarifier volume. Specific surface of the media in the order of 150–200 $m^2 m^{-3}$, hydraulic loads higher than 2 $m h^{-1}$ and design loads of approx. 0.4 g NH_4-N $M^{-2} d^{-1}$ are favourable conditions for full nitrification (<2 mg NH_4-N l^{-1}) at winter conditions (water temp. 10°C). In summer, nitrite may be the limiting parameter for process design. NH_4-load fluctuations usually cause an inhomogeneous distribution of biomass along the trickling filter depth, decreasing the ability to fully nitrify peak-loads. This tendency may be overcome by running trickling filters in series in an alternating mode. Process stability of nitrifying trickling filters have shown to be equal to activated sludge performance.

Subsequent removal of the effluent suspended solids by deep-bed filters leads to a further reduction and stabilization of NH_4- and NO_2-residuals. With the oxygen present in the trickling filter effluent a maximum nitrification capacity of 1.7 mg NH_4-N l^{-1} can be expected. Neither intense air/water backwash nor chemical dosing for contact filtration reduce nitrification activity. Residual nitrification does not need any change in the design of conventional deep-bed filters.

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