HYBRID SYSTEMS AND VF SYSTEMS FOR NITROGEN REMOVAL

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ABSTRACT

The paper presents the current results regarding approaches to the design of wetlands for nitrogen removal in subsurface flow wetlands. The nitrification in the vertical-flow beds (VFBs) is clearly determined by the oxygen balance in the filter. Full nitrification can only be achieved when the oxygen balance is positive. For sizing purposes equations for the calculation of oxygen demand and oxygen input are given. Critical aspects for dimensioning are mentioned.

For denitrification purposes three approaches are presented. From technical wastewater treatment plants pre-denitrification is well known. Return rates up to 200 % can be used without any hydraulic problems for the VFBs. In cases of low C/N ratios an additional application of HFBs has to be used.

Alternative pathways for nitrogen removal are discussed.

KEYWORDS

constructed wetland; denitrification; horizontal-flow bed; nitrification; subsurface flow; vertical-flow bed;

INTRODUCTION

After solving the problem of organic removal in subsurface flow wetlands (SSFW), research of the last years has concentrated on finding dimensioning criteria for removal of nutrients.

This paper presents the results of a wide range of vertical (VF) and horizontal flow (HF) plants, citing “normal” plants and “research” plants. Sizing methods for nitrification and denitrification are discussed.

The results in this paper do refer to SSFW were the filter material is sand. They do not apply to gravel nor to soil based filters. Gravel or soil filters show completely different hydraulic behaviors and therefore can not to be compared with the conditions in sand filter SSFWs.

DATABASE FOR NITRIFICATION AND DENITRIFICATION

In the last years several studies about the elimination characteristics of SSFWs have been developed. The study of Kunst & Flasche (1995) involved more than 300 plants (almost all plants < 50 p.e.) in Lower Saxonia, Germany. The results are based on the normal operational analyses. In 2000 has been done a follow up of this study by Kunst & Kasyer (2000) which led almost to the same results.

The latest study of Geller &Höner (2002) is based on the results of 62 plants. The plants were evaluated by experienced wetland specialists. Therefore the data can be considered as one of the most reliable sources available. They analyzed 62 plants of which 40 % were HFBs, 49% were VFBs and 11 % were Hybrid plants (combination VFB- HFB). The plants had a minimum size of 50 p.e and one evaluation criteria was a functioning of the plant of more than 3 years in order to guarantee realistic results.

Table 1 shows a comparison of these studies. Advanced nitrification can be observed in the case of the VFBs. The NH_4-N effluent concentration were lower or equal to 10 mg/l. The larger plants showed the lower effluent results (about 7 mg/l NH_4-N). The Ammonia effluent concentrations of the HFBs were significantly higher (22 – 36 mg NH_4-N/l), again the larger plants showed the lower concentrations. Concerning the Nitrate effluent the situation is almost reversed. The VFBs show concentrations of 21 – 65 mg NO_3-N/l, whereas the HFBs show results of 3 – 7 mg NO_3-N/l.

The conclusion is, that nitrification in HFBs is significantly lower. Whereas the elimination (denitrification) in the HFBs is much more complete than in the VFBs. The reason is a limited oxygen transfer in HFBs, while well functioning VFBs show a well aerated soil, therefore only part of the formed Nitrate is denitrified.

The removal of organic compounds is generally good, but again it can be observed that the larger plants are more effective than the smaller plants, an aspect which will be discussed later.

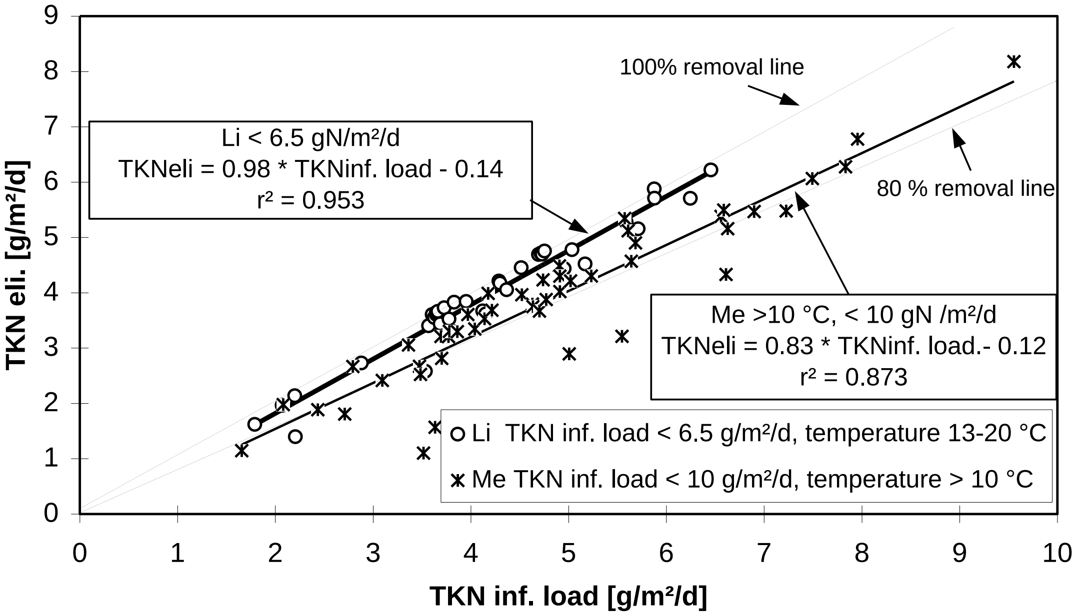
Table 1 Effluent results of HFBs and VFBs in Germany

	COD (mg/l)	NH_4-N (mg/l)	NO_3-N (mg/l)
HFBs			
Geller et al. (2002)	63	22	3
Kunst & Kasyer (2000)	90	30	5
Kunst & Flasche (1995)	103	36	7
VFBs			
Geller et al. (2002)	54	7	21
Kunst & Kasyer (2000)	70	10	40
Kunst & Flasche (1995)	69	10	65

The monitoring results showed that fully nitrification can only be achieved in VFBs. Due to their high purification capacity concerning organic load and nitrification VFBs were a kind of “top of the art” during the last years. Being operated properly the beds proved to have very high purification rates (Cooper et al., 1996; Laber et al. (1996), Platzer, 1996; Felde v. & Kunst, 1996; Bahlo, 1997). In cases where a controlled nitrification is necessary today only VFBs are used.

NITRIFICATION EXPERIMENTS IN VFBS

Concerning dimensioning nitrification in VFBs the experiences by Cooper et al. (1996) were an important starting point. They reported good nitrification results with very high ammonia loading up to 48 g NH_4-N/m²,d (three beds in rest) in tertiary treatment with BOD_5 influent concentrations below 30 mg/l. Unfortunately the experimental site was operated only a couple of years, therefore there is a lack of information about long-term performance with these loads. Based on these experiments and theoretical approaches Cooper (1998) developed a dimensioning for nitrification in VFBs. It is based on oxygen demand. A similar approach was developed by Platzer (1998a). The monitoring program carried out by him showed an almost complete nitrification using loadings below 6.5 g TKN/m²,d (figure 1, results of Liessen < 6.5 g TKN/m²,d) and guaranteeing a sufficient oxygen supply. In 95 % of the samples the effluent concentrations were below 10 mg NH_4-N/l. When using much higher concentrations but almost the same TKN loadings, nitrification was incomplete (Figure 1, results of Merzdorf > 10 °). As a result of his work he



draw the conclusion that oxygen demand and oxygen input have to be calculated in order to achieve complete nitrification. Therefore experiments concerning the Oxygen input (OI) were carried out. The experiments are described in full extension in Platzer (1998b).

Figure 1 Straight-line relationships for different TKN loading conditions at two ersearch plants: Merzdorf (Me) and Liessen (Li)

The total oxygen input (OI) has to be higher than the oxygen demand (OD). The resulting dimensioning criterion is fairly simple. It is expressed in Equation 1.

OI by diffusion + OI by convection – OD > 0 [g/d] (1)

The oxygen demand results in Equation (2)

Oxygen demand (OD) [g/d]= (0.85·0.7·CSBinf [g/d] + 4.3·TKNinf [g/d] - 0.1·2.9·TKNinf [g/d] (2)

The equation is based on a COD removal of 85 % with an oxygen consumption of 0.7 g O_2/g COD. For nitrification the OD is calculated with 4.3 g O_2/g TKN.

Recovery of oxygen from denitrification was calculated with 2.9 g O_2/g NO_3-$N_{denitrified}$ assuming a denitrification of 10%. In cases of wastewater with very low organic load this term has to be omitted. The equation has been used by a number of other authors and prooven to be a sufficient approach (concerning limitations of the assumptions see discussion of alternative nitrogen elimination below)

The oxygen input (OI) in VFBs is the sum of input by diffusion and convection.

Due to experiments the OI by diffusion is calculated with 1 g O_2/m².h, based an estimation of $3{,}5 \cdot 10^{-3}$ cm²/s for the diffusion coefficient considering a diffusion distance of 30 cm. Platzers approach to calculate the oxygen input was critically analyzed by Kayser (2003). She carried out experiments in soil columns keeping the hydraulic load the same but increasing the concentration. As the nitrification took place although the oxygen balance after Platzer was extremely negative, she draw the conclusion that the OI by convection was over estimated and the OI by diffusion heavily underestimated. Concerning the OI by diffusion I do agree with her because the diffusion distance on which was based the assumption was rated with 30 cm. As Kayser (2003) was able to show that the degradation was almost complete after 5 cm, I think the above mentioned distance or diffusion could be shortened to 5 cm. This results in an elevation of the OI by diffusion by factor 6.Unfortunately Kayser did not come to a new assumption, therefore I propose to alternate the OI by diffusion as mentioned.

OI by diffusion can not take place in a period of about 1.5 hours after each puls loading of the bed. This time of water saturation after a pulse loading has to be subtracted from the time between two pulses. Therefore the maximum input by diffusion depends on the number of loadings.

The alternated input by diffusion can be calculated with Equation 3.

OI by diffusion [g/d] = **6 [g O_2/(h·m²)] · bed area [m²]** · (24 [h] – 1.5 [h] · number of loadings) (3)

The OI by convection is calculated by the hydraulic load. For short periods of application and infiltration (< 10 min) it can be calculated that each liter of wastewater leaving the filter causes a suction of 1 liter of air into the soil. Concerning the OI by convection Luckner et al. (1998) and Kayser (2003) do not agree with Platzer. They mention that part of the air which entered the soil, leaves the soil bubbling up through the water front. This is the case, but it does not change any because the theory is based on the observation that that **each liter of wastewater <u>leaving</u> the filter causes a suction of 1 liter of air into the soil**. The theory is not related to the wastewater entering the soil. This is a very simple assumption proven by experiments shown in Platzer (1998b) and has not yet been proven to be wrong. As the air contains 300 mg O_2/l, the input by convection can be calculated easily (Equation 4)

OI by convection [g/d] = 0.3 [g O_2/l] · vol. water applied [m³/d] ·1000 [l/m³] (4)

It has to be taken into account that this equation can not be used if application and infiltration take place over longer periods of time. In this case the wastewater leaving the filter during application has to be subtracted from the total water applied. Especially in cases of light soil clogging this is an extremely aspect to be considered.

In total the role of the OI by diffusion seems to be more important than estimated.

In most cases of treating secondary municipal wastewater the oxygen input will not be the limiting factor for the nitrification in VFBs. The most critical aspect is the organic load or total solids load which could lead to soil clogging and therefore to a reduction in soil aeration, by this accelerating the clogging process (see Rustige 2003 in these proceedings)

Kayser (2003) showed clearly that the nitrification capacity normally is not the limiting factor in VFBs as well. In the above mentioned soil column tests she observed some decline in the nitrification capacity, only above 11 g NH_4-N/m²,d in a sand with low $CaCO_3$ content. This do to the lowering of the pH which inhibited the nitrification. In a soil column were she used a $CaCO_3$ rich sand, nitrification was not negatively influenced up to 43 g TKN /m²,d (Kayser 2003). Platzer postulated an upper limit for nitrification dimensioning in VFBs of 6.5 g TKN /m²,d, concerning the experiments by Kayser, the limitation should alternated to 11 g TKN /m²,d if no tests concerning the buffer capacity of the sand are carried out.

All mentioned results are valid for wastewater temperatures above 10 °C. Below this Kayser (2003) and Platzer (1998b) observed a decline due to reduced bacterial activity.

Kayser (2003) concludes that the hydraulic load in winter conditions should not exceed 80 mm/d whereas in summer conditions a medium hydraulic load can be about 130 mm/d. An important advantage of VFBs in respect to other processes is the flexibility against high hydraulic peaks. Platzer (1998) and Kayser (2003) reported no negative influence on nitrification up to hydraulic peaks of about 230 – 250 mm/d.

Usually the relevant dimensioning criterions concerning nitrification for wetlands treating municipal wastewater are the long-term loads for organic compounds and suspended solids (Platzer & Mauch 1996, Winter & Götz 2002). For further details see Rustige (2003) in these proceedings.

For Mediterranean countries it is important to mention that mild winters without periods below zero could result in a dimensioning which is closer to the mentioned summer conditions than to the winter conditions. In Brazil some plant designers build their VF plants with very high loadings but unfortunately there are no reliable analyses available.

Concerning the bed depth the results of Rustige & Platzer (2002) and Kayser (2003) prooved that 50 cm of sand are a sufficient depth. Kayser (2003) found that the elimination of organic compounds but as well the **nitrification takes place in the upper 5 cm !! of the bed**. Only under very high loading or cold temperatures the removal zone got down to 30 cm.

Some authors use k-values for nitrification purposes (Sikora et al. 1994, Hosomi et al. 1995). The use of k-values for the description of nitrification is very questionable. The ”Kickuth Equation”, developed out of the Monod kinetics, was developed for reactions of 1^{st} order. As the nitrification process in conventional wastewater treatment is usually of zero order, <u>the Equation can not be used.</u> Furthermore the extreme simplification of the Monod kinetics into one parameter has to be questioned. The k-value implies kinetic parameters (maximum growth of bacteria, yield coefficient) planning parameters (soil substrate, pore volume, bed depth) and operational parameters (temperature, oxygen supply). Therefore every plant has its ”own” k-value, which is not very helpful for dimensioning purposes.

DENITRIFICATION EXPERIMENTS IN VFBS

Denitrification in VFBs in well aerated, well funcioning VFBs is about 20 to 40 % (Laber et al. 1996, Bahlo 1997, Platzer 1998b, Rustige & Platzer 2002, Kayser 2003). Higher denitrification rates indicate a poor soil aeration and typically result in a decline of nitrification (Platzer 1998b, Rustige & Platzer 2002, Kayser 2003), later often resulting in soil clogging.

There has been a significant amount of attempts to enhance denitrification in VFBs. Besides a rather classic approach of pre-denitrification, all other attempts failed.

Pre-denitrification

Using a pre-denitrification for VFBs a sufficient contact time of wastewater and biomass of denitrifiers has to be guaranteed. In this case the pre-denitrification in VFBs can be dimensioned as the classic pre-denitrification process in activated sludge plants (Equation 5).

$$n_{DN} = 1 - 1/(1+RV) \qquad (5)$$

RV = recirculation rate in relation to the influent volume
n_{DN} = elimination rate for nitrogen

This process was tested for septic tanks by Bahlo (1997), Laber et al. (1996), Rustige (1997) and Rustige & Platzer (2002). Figure 2 shows the results of these publications concerning pre-denitrification. It can be observed that equation 5 underestimates the denitrification results in most cases. Up to a recirculation rate of 200 % the results are usually significantly higher due to the denitrification capacity of the VFBs.

Schleypen (1993) and the Bayrische Landesamt (1996) proved the applicability of ponds as a method for pre-denitrification.

In cases of high strength wastewaters concerning nitrogen, the use of a pre-denitrification is not sufficient. In this case the pre-denitrification has to be combined with an post-denitrification resulting in Hybrid systems.

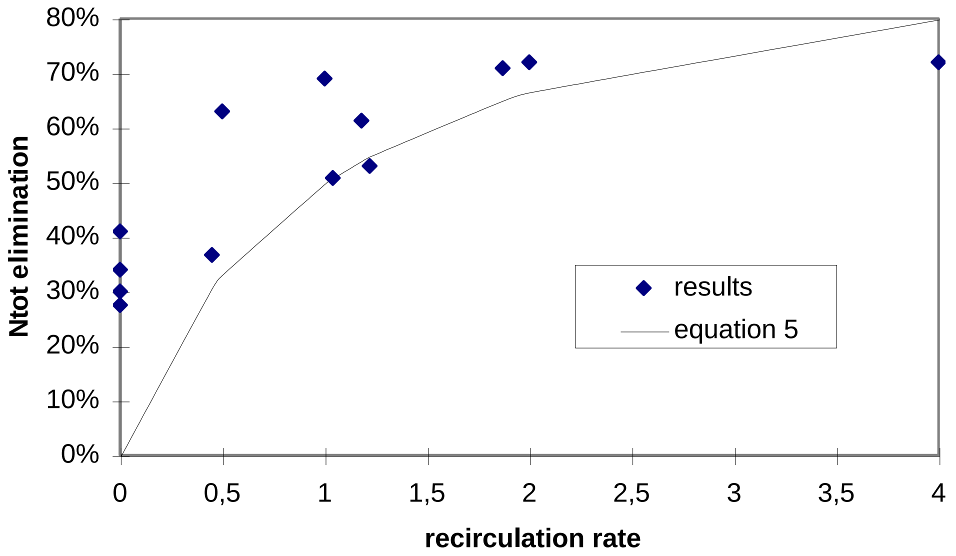


Figure 2 Recirculation rate for pre-denitrification

Failed attempts to enhance denitrification in VFBs

As there are a lot of ideas which failed but are repeated in literature over the years I will mention some of the experiments.

One of the most mentioned approaches is to dam up the lower part of a VFB in order to provoke anoxic conditions. The results by Pogade (1993), Schlegel & Mertens (1994) and Laber et al. (1996) showed that damming up the beds did not have the expected results do to the lack of a carbon source.

Some people do introduce straw during the construction phase to guarantee a carbon source until the roots have grown significantly. This approach does not work out for three reasons. First of all, even with a full established reed bed there is not enough carbon through root release to denitrify the nitrate in a well functioning VFB. Second the carbon will be released mostly in the upper part of a VFB, therefore in the well aerated part of the bed. Third, the straw will decompose rapidly not helping in the longer run.

Platzer (1998b) tried to establish operational conditions which allow to gain high denitrification rates still guaranteeing a reasonable nitrification. The idea was to overload the beds in a manor that causes light soil clogging, therefore causing reduced soil aeration, by this provoking alternative pathways of nitrification and denitrification (see below). Although this was possible for short periods, all experiments let to a severe soil clogging, needing very long resting periods to restore hydraulic conductivity. It was not able to get steady state conditions.

Another approach was the introduction a material with a high cation exchange capacity in the bed. Based on the papers of Bouwer et al. i. ex. (1980) I tried to enhance nitrification followed by denitrification by mixing in 5 % of Benotnit to the upper 30 cm of a VFB. During the first year of operation the results were very promising, achieving high nitrification rates and good denitrification. The beds did show better results than the regular sand VFBs. After the first year there was a severe decline in water conductivity resulting in reduced nitrification capacity. Even long resting periods did not restore the hydraulic capacity in a sufficient way. The experiments are summarized in Platzer (1998b).

HYBRID SYSTEMS

With rising interest in nitrogen removal there has been a growing interest in combined or hybrid systems. In these systems the advantages and disadvantages of HFB and VFB can be combined to complement each other. Some design approaches have been made using such combinations all do have advantages and disadvantages (s. table 2)

In Germany the most used combination is shown in figure 3. The basic idea of this concept is to achieve the removal of organic compounds and a nitrification in the vertical flow bed and a denitrification in the horizontal flow bed.

Post-denitrification

Platzer (1998) postulated a very simple dimensioning of post-denitrification. His results showed an elimination of 80% for nitrified nitrogen in the HFBs. These results were achieved as well at very low C/N ratios (< 0.7) (Platzer 1996).

For dimensioning purposes he proposed to use an elimination of 0.65 gN/m².d with a load of 1 gN/m².d. Therefore the $N_{nitrified}$ in g in the influent of the HFB equals the necessary area in square meters (Equation 6).

Necessary bed area [m²] = influent N_{tot}-load to the HFB [g/d] / 1 [g/(m²·d)]   (6)

Table 2 Combinations for Hybrid systems, effects and disadvantages

Var.	**Filter-combination**	**Effect**	**disadvantage**
(I)	PRE → 1. VF + 2. HF	1. nitrification and 2. denitrification and pathogen removal	possible lack of C-source in the HF
(II)	PRE → 1. VF + 2. HF	as (I) including pre-denitrifcation	possible lack of C-source in the HF
(III)	PRE → 1. VF + 2. HF	as (II) including bypass of the VF to enhance post denitrification	beside the organic C, Ammonia is introduced in the second stage
(IV)	PRE → 1. HF + 2. VF	1. carbon removal 2. nitrification	larger HF areas than in (I) necessary, very limited denitrification
(V)	PRE → 1. HF + 2. VF	As (IV) including Pre-denitrification	recirculation over the HF results in very large areas of the HF due to hydraulic limitations

Rustige & Platzer used this equation for dimensioning purposes of a plant with very high restrictions concerning total N removal. The results showed a lack of carbon leading to higher nitrate levels than expected. Due to this a raw water bypass of 25% was installed. This let to significantly lower total N concentrations (6 – 14 mg/l) without raising the organic concentrations in the effluent (DOC 26 – 30 mg/l) (Rustige & Platzer 2002). Therefore the equation 6 has to be questioned, but obviously the dimensioning offers enough security to treat even a part of the raw water. The aspect needs further research in order to minimize the area of the HFBs. Because equation 6 leads to fairly large HFBs.

In France Boutin et al. (2000) used a VFB – HFB combination as well and compared it with a double VFB (standard French system).

Another design approach was made by Johansen and Brix (1996), who used a large HFB for organic removal and partial nitrification, followed by a small VFB for nitrification. For denitrification purposes they proposed a recirculation to the HFB. This concept was built several times in Poland.

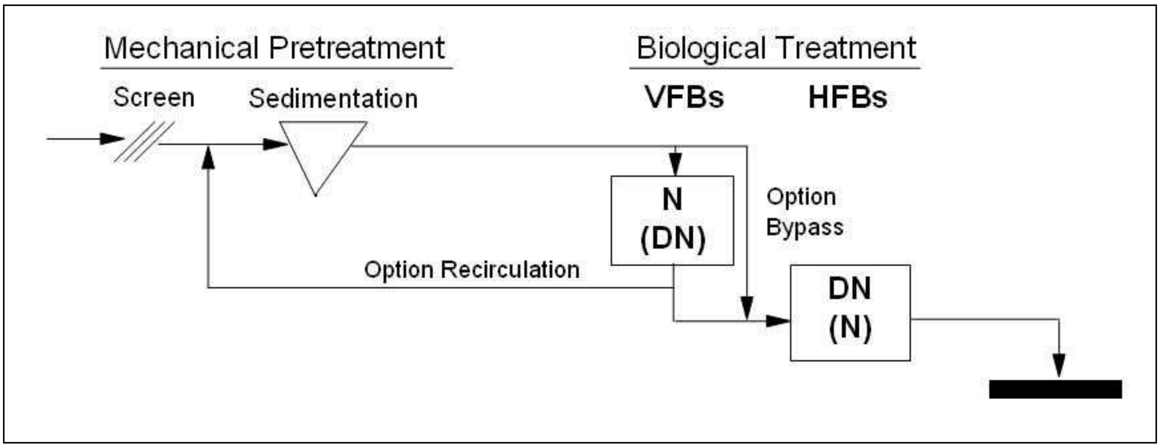


Figure 3:Flow scheme of a hybrid system

ALTERNATIVE NITROGEN TRANSFORMATIONS

Alternative nitrogen transformations have been the target of many researchers in technical wastewater treatment plants. The reason for the interest in alternative ways of nitrification and denitrification is the reduced oxygen consumption for nitrification and C consumption for denitrification. The alternative pathways concerning wetlands are discussed in Platzer (1998b).

The "normal" nitrification process is autotrophic the process needs about 4,3 g O_2/g NH_4-N. It is well known that heterotrophic nitrification exists, but under normal conditions in wastewater treatment plants the process is insignificant (Laurent 1971, Schlegel 1985, Reinheimer et al. 1988). As wetlands are extremely low loaded systems, growth conditions for heterotrophic nitrifiers are good. Hoffmann (1990, 1992) mentioned strong **heterotrophic nitrification** in his experiments. We found strong hints for heterotrophic nitrification doing a comparison of nitrification activity with or without C-source (Platzer 1998b) (s. figure 4).

Normally all nitrified N in the heterotrophic tests was denitrified as well. We observed a denitrification of about 40 %. First we thought of experimental problems as the tests were carried out under completely aerobic conditions in a shaker. Analyzing literature we found other researchers who did report the same observations. Hoffmann (1992) reported it for tests with sludge mineralization beds, Hulsbeek (1995) in regular wastewater tests. An explanation is given by Zart et al. (1996). They describe various pathways of **aerobic denitrification** which is used by bacteria under limitated Oxygen conditions, "saving" Oxygen by passing the electrons of Ammoniaoxidation not to Oxygen but to the Nitrite, the process only needs about 3,2 g O_2/ g NH_4-N. Zart et al. were able to prove that for some bacterial cultures the process continued under aerobic conditions.

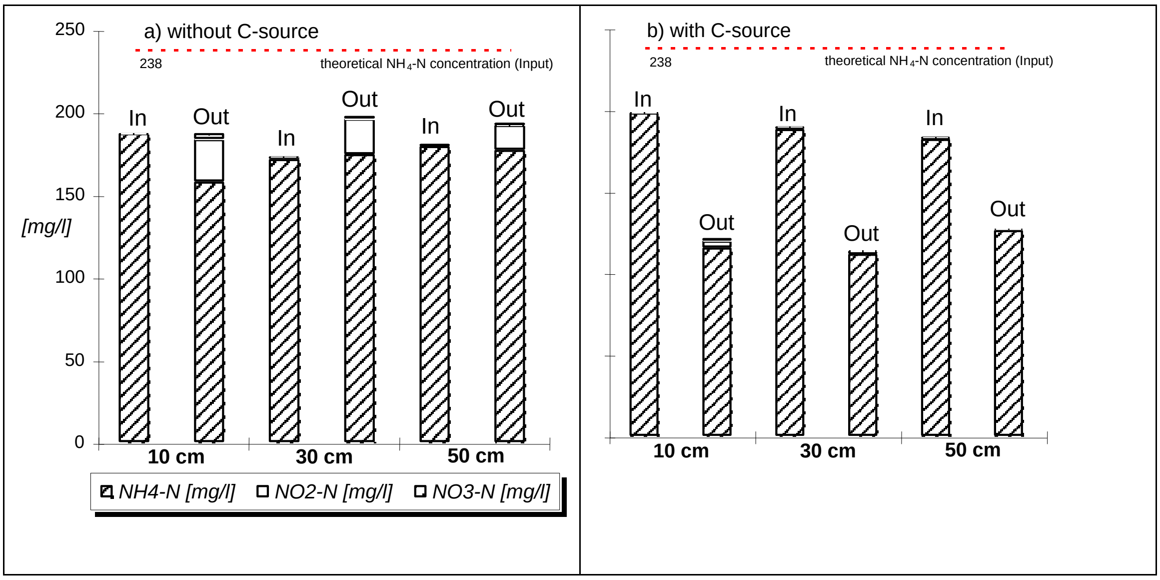


Figure 4 Massbalance of a nitrification activity experiment under a) autotrophic (without C-source) and b) heterotrophic conditions (with C-source)

The observations explain the denitrifcation in VFBs although VFB are well aerated systems. They explain as well why nitrification still takes place even though the oxygen mass balance indicates an oxygen deficit and why nitrification takes place at the same moment as organic removal.

Up to now I do not have knowledge of a study determining a balance of heterotrophic nitrifieres and alternative pathways for nitrification in VFBs and their significance for the whole nitrification process. It is a rather difficult task as CW are living systems which can not be transported to laboratory. Even than the normal fail. We had to adopt the experimental method for our purposes (Platzer 1998b). But concluding from our experiments considering the results reported in literature, I assume that the heterotrophic nitrification and alternative pathways for nitrification and denitrification play an important role in CW.

CONCLUSIONS

Summarizing the observations the situation for nitrogen transformation in CW and by summarized as follows:

- For nitrification purposes the implantation of VFBs is necessary.
- Well aerated VFBs do offer sufficient nitrification capacity when dimensioned in order to prevent soil clogging. For this purpose systems larger than 50 p.e. should always be build in four compartments in order to be able to rest one bed.
- In cases of high Ammonia concentrations the oxygen balance has to be controlled using the above mentioned equations
- VFBs are a very good possibility to upgrade small existing treatment plants which have to be adopted to nitrification, in this case the oxygen balance calculation has to be used as well.
- Up to 65 – 70% TN (total Nitrogen) removal can be obtained by doing a recirculation in to the pre-treatment.

- Other methods to improve denitrification in VFBs have not proven to be effective.
- For very high effluent standards VFBs should be used together with HFBs, the so called Hybrid systems. In dimensioning Hybrid systems it is recommendable to have a possibility to bypass the VFBs with part of the water in order to get a better carbon supply in the horizontal flow beds. A bypass of 25 % can be installed without negative influence for the effluent concentrations concerning organic compounds, on the other hand lowering significantly the TN concentrations.
- Alternative pathways for nitrification do play an important role in VFBs and HFBs. Up to now it is not possible to use this knowledge for dimensioning purposes. Therefore all dimensioning has to be done considering „normal“ nitrification and denitrification, knowing that the alternative processes give a little more security in dimensioning.

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