Aus dem Institut für Technologie und Biosystemtechnik

Michael Sievers
Ulrich Jahnz
Klaus-Dieter Vorlop
Sven Schäfer
Marc Schlieker

Significant reduction of energy consumption for sewage treatment by using LentiKat encapsulated nitrifying bacteria

Published in: Landbauforschung Völkenrode Sonderheft 241, pp. 81-86

Braunschweig
Bundesforschungsanstalt für Landwirtschaft (FAL)
2002

Significant reduction of energy consumption for sewage treatment by using LentiKat® encapsulated nitrifying bacteria

Michael Sievers[1], Sven Schäfer[1], Ulrich Jahnz[2], Marc Schlieker[3], and Klaus-Dieter Vorlop[3]

Abstract

Bacteria from an external fermentation were employed in entrapped form to specifically increase the nitrification rate in nitrifying waste water treatment plants. For maximum biological and mechanical stability a matrix consisting of polyvinyl alcohol (PVA) was chosen. Stable hydrogels were obtained by room-temperature gelation according to the LentiKat® method. Waste water from a municipal waste water treatment plant was used directly for the lab-scale set-up and the parameters ammonia, nitrate and COD were measured regularly. The set-up was run with different parameters over a period of 650 days. A specific volumetric nitrate production rate of approx. 25 to 30 mg/(L·h) was achieved at maximum nitrification. The residence time was between 30 and 60 minutes which is ten times shorter compared to conventional methods. For real waste water treatment plants this means a significant reduction in size for the nitrification reactors. The COD consumption showed values between 10 and 50 % due to specific nitrification. The remaining COD is available for the subsequent denitrification step. The LentiKats® showed no deterioration over the complete time span.

Keywords: Nitrification, immobilisation, LentiKats®, energy

1 Introduction

1.1 Situation regarding WWTPs

Stringent environmental regulations regarding effluent nitrogen concentration of wastewater treatment plants (WWTPs) were established in many countries in the last decade. Moreover, the growth of the population mostly requires upgrading of existing sewage treatment plants. Therefore, to achieve complete nitrogen removal in a conventional single-sludge WWTP, a significant increase of the reaction volume compared to chemical oxygen demand (COD) removal has been commonly established.

Presently, new solutions for cost-effective nitrogen removal are necessary both for less investment and lower operational costs to ensure sustainable wastewater treatment not only in highly industrialised but also well developed countries. One possibility for a new process at WWTPs is the use of nitrifying microorganisms encapsulated in LentiKats®.

1.2 Encapsulated nitrifiers

The advantages of the use of encapsulated microorganisms compared to conventional systems are as follows:

1. It is possible to nitrify with much less water hydraulic retention time due to the high concentration of encapsulated organisms and their high activity.
2. The high age of the sludge, which is necessary in single sludge systems to ensure complete nitrification due to the low growth of nitrifying microorganisms could be reduced. Therefore, the additional aeration for endogenous respiration, which increases with the sludge age, could be reduced substantially.
3. A more selective nitrification process with less biological oxygen demand (BOD) reduction due to at this stage unwanted heterotrophic microorganisms becomes possible. As a result, post denitrification can be done with the internal use of organic compounds.
4. The internal recycling of nitrified wastewater as commonly established for pre-de-nitrification processes is not always necessary with respect to waste water concentration of carbon ions and capacity to equalise alkalinity.

2 Operations for sewage treatment

A typical flow scheme of a sewage treatment plant is shown in Figure 1. The sewage is treated firstly by mechanical processes such as sieving and primary settling, and secondly by biological processes. The mechanical processes eliminate suspended particles of

---

[1] Michael Sievers and Sven Schäfer, CUTEC-Institut GmbH (Clausthal Environmental Technology Institute), Leibnizstraße 21, 38678 Clausthal-Zellerfeld, Germany

[2] Ulrich Jahnz, geniaLab Biotechnologie GmbH, Bundesallee 50, 38116 Braunschweig, Germany

[3] Marc Schlieker and Klaus-Dieter Vorlop, Institute of Technology and Biosystems Engineering, Federal Agricultural Research Centre (FAL), Bundesallee 50, 38116 Braunschweig, Germany

raw wastewater while the biological processes mainly eliminate dissolved nitrogen and organic compounds of raw wastewater. Sludge would be produced in these processes. This sludge is commonly treated through anaerobic digestion and sludge de-watering.

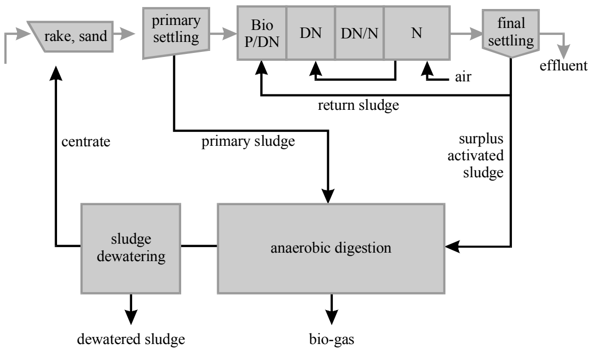

Figure 1:
Mass-flow scheme in a waste water treatment plant

2.1 Cost for waster water treatment

A typical distribution of operational costs is shown in Figure 2. It is obvious that energy consumption plays a substantial role in operational costs. Moreover, more than 65 % of overall energy consumption is needed for the biological processes and mainly for the aeration of biological processes.

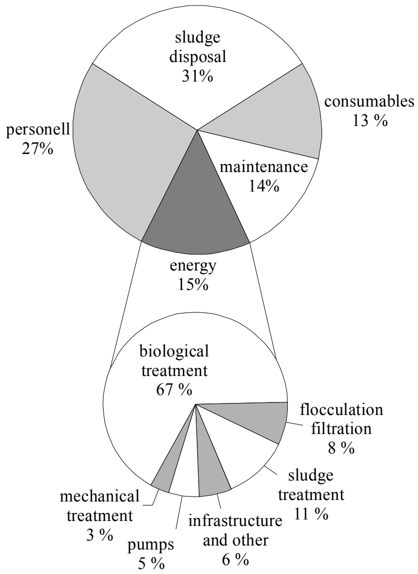

Figure 2:
Distribution of cost arising in a WWTP

2.2 Cost optimisation

Therefore, optimisation of aeration and oxygen supply could lead to a substantial reduction of energy consumption at WWTPs, but the minimum of oxygen consumption is limited to the amount of ammonia, BOD (biological oxygen demand) and COD (chemical oxygen demand), which has to be oxidised. Optimisation of energy consumption itself on WWTP could be done in two ways:

1. The operation of WWTPs could be optimised via analysis of the energy consumption and certain methods of saving energy. This potential is not the subject of this paper and it has to be dealt with carefully, because of the need to treat wastewater efficiently today and even more so in the future.
2. Further energy-savings could only be realised by altering the process configuration itself. The main approach is to optimise the biological processes, for which 70 to 80 % of the energy is used for air supply.

2.3 Sludge age and air supply

For example, the potential of energy reduction would be explained on the basis of published results on aeration experiments at domestic WWTPs. The specific oxygen consumption related to the BOD in raw wastewater is one key parameter to evaluate the energy consumption for aeration. Some data published by wastewater treatment plant operators and the organisation "Abwassertechnische Vereinigung" (ATV) are listed in Table 1 for different sludge ages. It is obvious that up to 46 % of energy for BOD oxidation could be saved just by reducing the sludge age from 25 to 4 days.

Table 1:
Specific oxygen consumption in kg O_2 per kg of BOD for different sludge ages in single sludge WWTPs

sludge age	10°C	15°C	20°C
4 days	0.81–0.83	0.89–0.94	0.97–1.05
8 days	0.97–1.05	1.05–1.20	1.13–1.35
25 days	1.21–1.55	1.26–1.60	1.31–1.60

This different oxygen consumption is caused by two main effects:

a) The oxygen consumption for endogenous respiration would be decreased for lower sludge ages.
b) The BOD of raw wastewater would be less oxidised into carbon dioxide but more into additional bio-mass. The latter has the potential for higher bio-gas production during anaerobic digestion of sludge.

3 Nitrogen elimination at WWTPs

The nitrogen to be removed from raw waste water is commonly ammonia, which can be decomposed conventionally by the following two-step overall reaction scheme:

nitrification:
$NH_4^+ + 2\ O_2 \rightarrow NO_2^- + 2\ H_2O + 2\ H^+$ and
$NO_2^- + 0.5\ O_2 \rightarrow NO_3^-$

denitrification:
$5\ CH_3COOH + 8\ NO_3^- \rightarrow 10\ CO_2 + 6\ H_2O + 8\ OH^-$

The formula for the denitrification step is shown for the case of acetic acid as carbon source. For nitrification, dissolved oxygen is relevant and therefore aeration is essential (aerobic conditions). For denitrification, solute oxygen must be avoided (anoxic conditions), otherwise denitrification will not occur due to the fact that the affinity of the electrons donated by acetic acid is much higher to molecular oxygen than to nitrate.

The electron donator, usually a carbon source, is substantially only present in raw wastewater, but not in the nitrified wastewater. To reduce nitrate of nitrified wastewater with the internal utilisation of raw wastewater carbon source three possible processes for nitrogen elimination have been established:

a) pre-denitrification
b) post-denitrification
c) simultaneous denitrification.

The first process implies a re-circulation of wastewater containing nitrate back from the nitrification to the denitrification step at the inlet of the biological basin. The effluent of such processes would always contain nitrate, the amount depending on the level of concentration and the re-circulation rate. Treatment of wastewater containing high nitrogen concentrations would need a high re-circulation rate to fulfil regulations for the effluent.

The post denitrification has the advantage of making possible an almost complete nitrogen removal through the optimisation of every single process step of the treatment process. The main disadvantage of this process is the low level of carbon sources in the nitrified wastewater and external carbon sources are commonly needed for substantial denitrification. Moreover, additional BOD compared to BOD of raw wastewater has to be oxidised, leading to more sludge and a less cost-effective process.

For the simultaneous denitrification, nitrification and denitrification would take place in the same reactor by alternating aerobic and anaerobic conditions through different aeration modes or zones.

The limitation of the growth of the nitrifying organisms, especially at lower temperatures, is common to all processes. To avoid washing out of nitrifiers compared to the faster growing heterotrophs, the need for a higher age of the sludge arises resulting in a low rate of denitrification and higher expenses for aeration needed for endogen respiration.

4 Nitrification by encapsulated nitrifiers

4.1 Demands for the encapsulation

Nitrification rates can be increased by specifically favouring those bacteria responsible for the biological oxidation of ammonia, namely *Nitrosomonas spec.* and *Nitrobacter spec.* These bacteria can be encapsulated for this purpose within a matrix. The microscopic bacteria become manageable by macroscopic means. The matrix used for this immobilisation procedure has to fulfil the following demands:

1. It must be permeable for the nutrients required by the microorganisms but it must hold back the enclosed bacteria effectively at the same time.
2. The material itself and the methods necessary to make a stable matrix must not harm the microorganisms irreversibly.
3. Since nitrification is a process mainly carried out by growing cells, the matrix must be flexible enough to allow the formation of colonies within the inner volume.
4. The material must be stable under the conditions of a WWTP, i.e., they must have resistance against mechanical forces and must also be resistant against biological degradation.
5. The resulting matrix particles must be small enough to prevent limitation effects resulting from means of diffusion which are too long.

A hydrogel on the basis of poylvinyl alcohol (PVA) meets all of these requirements. Different methods are known to produce stable hydrogels from PVA, but only the method of room-temperature gelation by controlled partial drying provides conditions mild enough to ensure good survival rates for susceptible nitrifiers. Due to their shape, the resulting particles are called LentiKats®.

4.2 Preparation of LentiKats®

For preparation of LentiKats® ready-to-use LentiKat®Liquid solution (geniaLab, Braunschweig, Germany) is mixed with a highly active fermentation broth of externally cultivated nitrifiers and small droplets are floored on a suitable surface. When these droplets are exposed to air, the water starts to evaporate and thus leads to enhanced formation of hydrogen bonds. Once the hydrogel is stable enough, it is re-swollen in a stabilising solution.

The particles formed by this procedure combine the advantages of both large and small beads as can be seen from Figure 3: On the one hand, they measure about 3 to 4 mm in diameter and can be retained by established sieve technology or rapidly by settling. On the other hand, they are only 200 to 400 µm thick and thus cause hardly any diffusional limitations to the enclosed biocatalysts (Jahnz et al., 2001).

LentiKats® were successfully used for the immobilisation of microorganisms like *clostridia* (Wittlich et al., 1998) and *Oenococcus sp.* (Durieux et al., 2000) and also enzymes (Gröger et al., 2001). Initial results for the process of nitrification were also obtained in the past (Jekel et al., 1998) but those experiments were done with artificial media and not with real waste water as described in the present work.

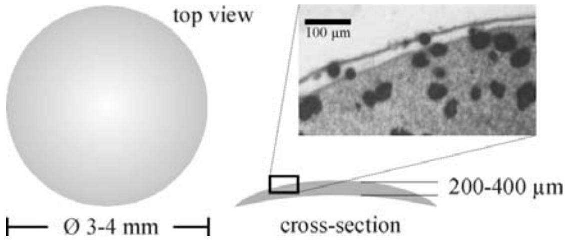

Figure 3:
Schematic view and image of a LentiKat® and microscopic view of nitrifier colonies within the hydrogel

5 Nitrogen elimination process with LentiKats®

The flow scheme of the lab-scaled process using LentiKats® is shown in Figure 4. The elimination of nitrogen is achieved by a post-de-nitrification process.

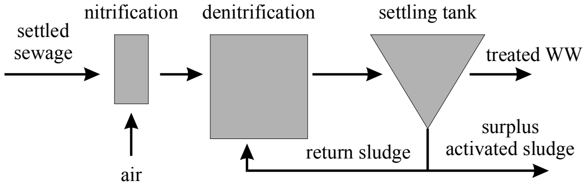

Figure 4:
Flow scheme of the laboratory set-up

A selective nitrification in the first stage of the process increases the efficiency of the process, which is catalysed by encapsulated nitrifying micro-organisms. Minimisation of BOD-removal in this stage by low concentration of heterotrophic micro-organisms is needed to ensure complete de-nitrification at the second stage by using the original BOD as an electron-donator. To minimise BOD removal in the first stage, no thickened sludge from clarifier would be cycled back to this stage. Therefore, this process should be called “pre-nitrification” instead of post-de-nitrification.

6 Experimental

Continuously driven lab scale experiments have been carried out with municipal wastewater. The volume of the reactors were 2.8 L and 9 L for the first and second stage, respectively. The wastewater was collected twice a week from a WWTP after primary settling and fed to the system via a continuously stirred tank of 1,000 L volume. The first reactor was filled with 800 g of LentiKats® equal to 1.5 L. This reactor for nitrification was continuously stirred and aerated. During the selected period of day 500 to day 650, the volumetric flow rate was about 120 L per day, which is equivalent to a hydraulic retention time in the first reactor of 34 minutes.

The main experimental parameters are shown in Table 2. The probes were collected as a spot check once a day. The flow rate of the inflow was measured by an inductive flow-meter, the pH with the instrument pH 91 and the electrode SenTix 50, dissolved oxygen and temperature with Oxi 96 and the electrode EO 96 (all equipment WTW, Germany). Different vessel tests were used to measure ammonia, nitrate and nitrite (MERCK, Darmstadt, Germany) and COD (HACH, Colorado, US). Dilution of 1:10 with demineralised water was done as necessary. After analysis, the probes from the last month were kept frozen to render possible reanalysis.

Table 2:
Main experimental results

	min	max	average
		inflow	
pH	6.88	8.45	7.5
NH_4^+, mg/L	1	191	46.3
COD, mg/L	9	278	74.6
		nitrification	
pH	5.2	8.4	6.9
NH_4^+, mg/L	0	75	11.5
NO_3^-, mg/L	14	58	30.8
NO_2^-, mg/L	0	5	1.8
COD, mg/L	7	121	53.2

7 Results

As shown in Figure 5, a nearly complete nitrification of ammonia to nitrate has been established with an average volumetric reaction rate of about 45 mg nitrogen per litre reaction volume and hour. The hydraulic retention time was always at approx. 30 or 60 minutes. This is approx. 10 times lower than the conventional adjusted hydraulic retention times in aeration zones of sewage treatment plants.

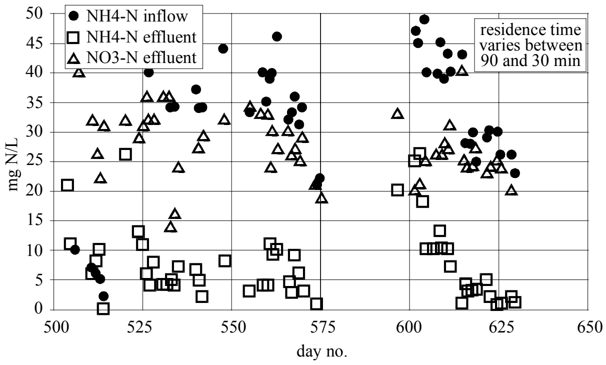

Figure 5:
Nitrification of ammonia

This figure also implies that nitrification could always be stable within a period of two years at present. Many disturbances, including an interruption of the treatment process have taken place, but never destructed the LentiKats®. Moreover, full treatment efficiency was in most cases reached at the next sampling period a day later. The high ammonia effluent at days 600 to 610 shows that maximum nitrification rate was reached with a specific volumetric nitrate production rate of approx. 25 to 30 mg/(L·h).

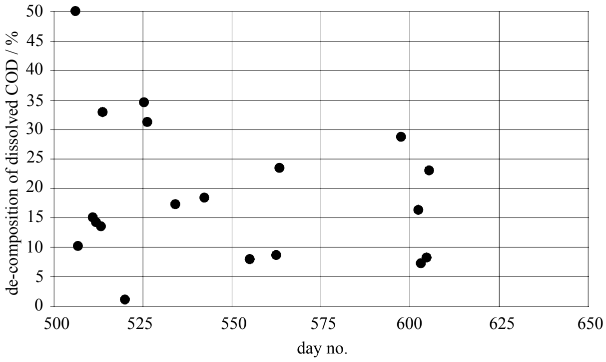

Figure 6:
Elimination of COD

To evaluate the COD elimination in this stage, the soluble COD was measured in influent and effluent. Figure 6 shows the COD degradation efficiency, which is between 10 and 50 %. Further optimisation is necessary to reduce COD degradation. However, this COD reduction does not include most of the particular COD and it is well known, that firstly a BOD uptake in heterotrophic microorganisms could take place, especially at high loading rates, and secondly, this BOD is usable for de-nitrification. Earlier experiments with acetic acid as BOD have shown that it is possible to fulfil a low dissolved COD-reduction of about 30 %.

8 Conclusions

Continuous lab scale experiments with encapsulated nitrifying microorganisms have shown a complete nitrification for more than 650 days. During that period, the nitrification operated stably, whether the denitrification was respective to the reactor design and operation due to the occurrence of floating sludge during that period.

The evaluation of lab results shows that it is possible to ensure complete nitrification by encapsulated nitrifiers with a hydraulic retention time of 0.5 hours, which is approx. 10 times lower than the the model sewage plant for the equivalent 100,000 people. Based on a flow rate of 24,500 m^3 per day, a nitrification reactor of 580 m^3 volume compared to common 5,000 to 7,000 m^3 has been calculated. However, this result has to be confirmed at pilot scale under realistic sewage treatment conditions onsite. It is expected that the efficiency of the process would decrease, but otherwise, there is also a high potential for optimisation of LentiKats® with much higher maximum reaction rates.

The results show also that the proposed process of de-nitrification after nitrification with LentiKats® would be possible due to low COD removal efficiency of 10 to 50 % in the nitrification reactor. This enables the internal use of wastewater's carbon sources for de-nitrification. However, the denitrification process has to be optimised with regard to kinetic study and avoidance of sludge flotation in final clarifier.

The energy consumption for aeration could be reduced substantially based on published results for different sludge ages for specific oxygen consumption for degradation of organic compounds. The reduction of the sludge age from 20 to less than 4 days would enable an energy reduction of 30 to 50 %. This needs to be investigated in pilot scale experiments.

References

Durieux A, Nicolay X, Simon J-P (2000), Continuous malolactic fermentation by *Oenococcus oeni* entrapped in LentiKats®, Biotechnol Lett 22(21):1679-1684

Gröger H, Capan E, Barthuber A, Vorlop K-D (2001) Asymmetric synthesis of an (R)-cyanohydrin using enzymes entrapped in lens-shaped gels. Organic Letters 3(13):1969-1972

Jekel M, Buhr A, Willke T, Vorlop K-D (1998) Immobilization of Biocatalysts in LentiKats®. Chem Eng Technol 21 (3):275-278

Jahnz U, Wittlich P, Pruesse, U, Vorlop K-D (2001), New matrices and bioencapsulation processes. In: Focus on Biotechnology Vol. 4, Hofmann M and Anne J (eds), Kluver Academic Publishers, Dordrecht, pp. 293-307

Wittlich P, Reimann C, Willke T, Vorlop K-D (1998), Bioconversion of raw-glycerol to 1,3-propanediol by immobilized bacteria. Biospektrum (special edition), p. 128