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Biotechnology

Second, Completely Revised Edition

Edited by H.-J. Rehm and G. Reed
in cooperation with A. Pühler and P. Stadler

Volume 11a: Environmental Processes I
Volume Editor: J. Winter

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Contents of Volume 11a

1999, XVI, 598 pages, hardcover, DM 545,00
ISBN 3-527-28321-8

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17 Submerged Fixed-Bed Reactors

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1 Process Definition

Biological treatment by means of sessile microorganisms is mainly based on the natural characteristic of many types of bacteria and protozoa to colonize on surfaces. Biofilm operation is also the oldest form of bioprocessing (BISHOP and KINNER, 1986). An overview of this phenomenon is given in Chapter 4, this volume.

Due to the more stringent requirement for wastewater treatment and the increased demand for space saving and low-maintenance processes, approximately 10 years ago, biofilm processes or so-called "fixed-bed reactors" began to be used more and more frequently for wastewater treatment. In wastewater engineering, the term "fixed-bed reactor" in accordance with the German Standard DIN 4045, is defined as being a "reservoir containing substrata colonized by microorganisms which cause biochemical degradation processes". Since these processes take place as a result of biofilm activity they are also called "biofilm reactors" in European Standard EN 1085. Within this group, submerged fixed-bed reactors can be more closely defined as "permanently submerged surfaces with a regular structure and a theoretical percentage of available void space of over 85%".

Fig. 1 shows the different categories of biofilm processes, including the submerged fixed-bed reactor referred to by SEYFRIED (1997).

This chapter deals exclusively with fixed-bed reactors of the "submerged" type in accordance with the above categorization.

Fig. 2 illustrates the submerged fixed-bed principle in wastewater engineering. The reactors comprise aerators (usually membrane-type tubular aerators), which are installed under the substratum to introduce the oxygen and circulate the water, and the submerged fixed bed itself, which is fixed in the reactor.

If denitrification is required, the necessary forced flow can be produced either by means of agitators or, alternatively, by nozzles. As a matter of principle, there is no sludge recircu-

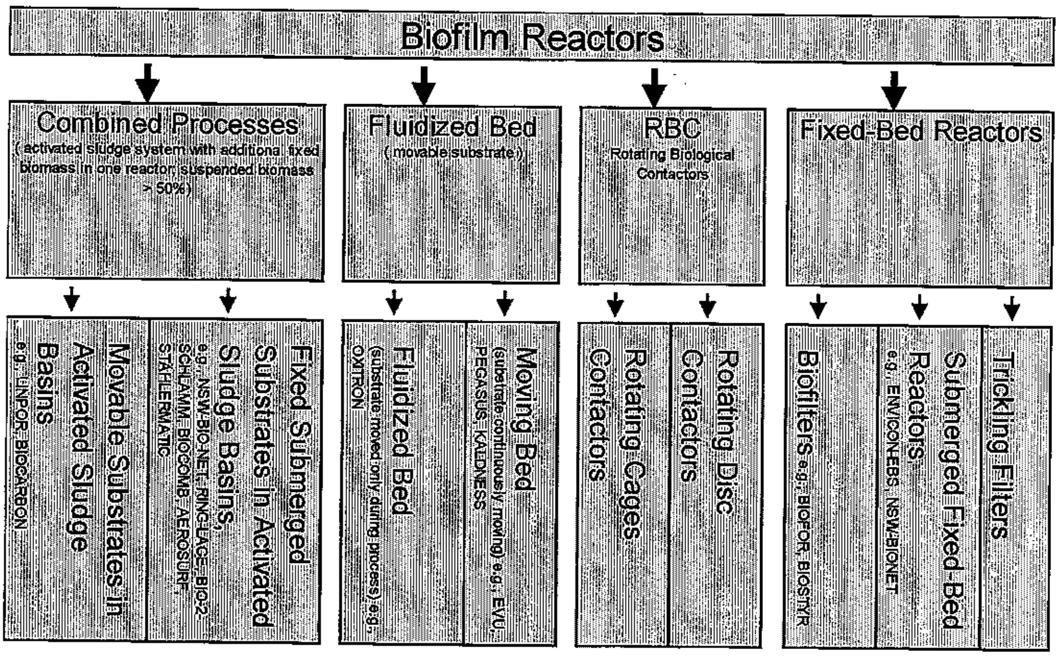

Fig. 1. Biofilm reactors.

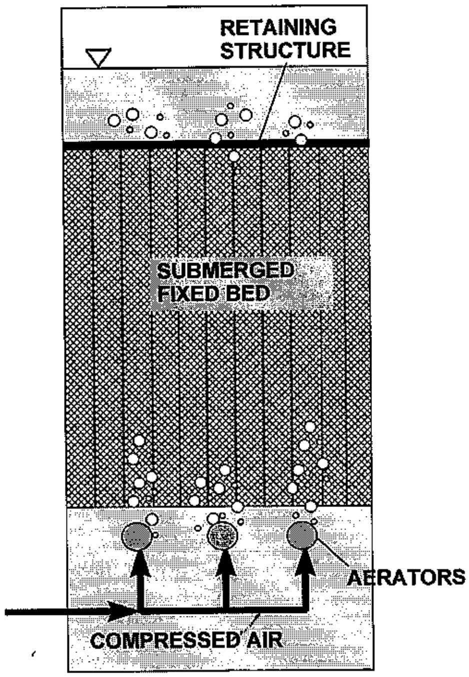

Fig. 2. Submerged fixed-bed reactor.

lation. Surplus sludge is sedimented in a secondary sedimentation tank and subsequently disposed of.

Considering the question of the ideal field of application there are at least three significant advantages offered by biofilm processes in general – and submerged fixed-bed reactors in particular – in contrast to the activated sludge process, namely:

- low space requirement,
- low maintenance costs in terms of personnel and time,
- high flexibility *vis à vis* load surges.

Operational experience has shown that either compactness or low maintenance costs can be achieved. Biofilm processes either have large specific surfaces and high volumetric degradation efficiency, but require a higher degree of maintenance ("biofilters"), or they are very rugged and require little maintenance, but more space. As far as its requirements in terms of volume and retention times are concerned, the submerged fixed-bed reactor of the type described here is more closely related to the activated sludge process than to biofilters. The higher costs involved in installing the fixed-bed reactor are compensated for by a distinctly lower space requirement and the absence of sludge recirculation to control the biomass. Therefore, it is, generally speaking, ideal for

- the complete, decentralized biological treatment of domestic wastewater from 4 to approximately 8,000 PE (population equivalents), as well as of specific commercial and industrial effluents;
- the pretreatment of highly polluted industrial effluents (prior to, e.g., an activated sludge process);
- final treatment, e.g., in the form of a nitrification stage.

Several examples of ideal cases of application are given at the end of this chapter.

2 Application of Submerged Fixed-Bed Reactors

As can be seen from Fig. 2, the process comprises three variable components:

- substratum (carrier, fixed-bed),
- aerators,
- reactor volume/design.

All three have a decisive influence on the degradation efficiency and must be aligned with each other in a manner appropriate to the effluent to be treated. Since sludge cannot be recirculated with this process, once the plant has been constructed, little can be done to influence degradation efficiency, since the biomass cannot be set to a specific value. Only aeration intensity can be adjusted and/or the effluent can be recirculated. For this reason, all factors must be taken into account in the planning stage and be carefully considered in relation to each other.

2.1 The Substratum

The suitable substratum for the specific case of application is of particular importance for this process. The submerged fixed-bed reactor operates with block-like structures in the form of plastic grids or laminated plastic sheets, the specific surfaces of which range between 100 and 400 $m^2 m^{-3}$.

Carrier materials of this type are formed from, e.g., extruded HDPE grids (ENVICON, NSW) like the BIOPAC® shown in Fig. 3, or laminated PVC sheets (MUNTERS, RICHTER). The substrata are usually installed in uniformly distributed blocks above the aerators and are held firmly between the supporting and the retaining structure. It is particularly important that, when densely colonized, the substratum still allows a high rate of flow. This not only ensures that flow resistance is kept to a minimum, but also prevention of blockages. Intensive mixing of the gas and water phases, as well as optimum contact with the biofilm, is achieved and air pockets are prevented while, simultaneously, oxygen is utilized to an optimum degree (ATV, 1996).

Substrata may have a smooth or rough surface structure. Smooth surfaces may retain complex biofilms less efficiently than fissured, rough surfaces, because they offer fewer opportunities for the biofilm to adhere and the smoother the substratum the higher the danger that portions of the biofilm will become detached as a result of the turbulence and cause blockages at other points. Therefore, in the case of high flow rates, particularly when these are characterized by surges, special attention should be paid to the micro-roughness of the substratum (VAN LOOSDRECHT et al., 1995).

It must also be borne in mind that material- and production-related release agents or pigments in the substratum material may inhibit the growth of the biofilm. A longer conditioning time is needed before growth develops on materials of this type; they are often avoided for a prolonged period by particularly sensitive bacteria such as nitrificants. The physical and biological interactions occurring between bacteria and surfaces have been treated thoroughly by BERKELEY et al. (1980). Technical aspects, such as break resistance and resistance to physical forces, e.g., pressure, must also be taken into account when choosing substrata for installation in larger-scale reactors.

Inert materials, such as polyethylene, have neutral properties and can, in principle, be considered suitable for biological processes, as is recommended by the German ATV (ATV, 1996).

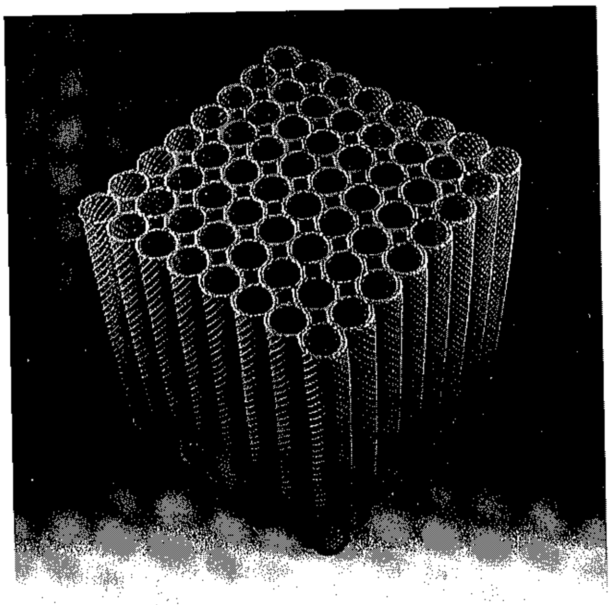

Fig. 3. BIOPAC® (ENVICON, Germany): extruded grid substratum.

Fig. 4 shows a substratum optimally covered with a mushroom-type biofilm as described in Fig. 6.

The fixed-bed substratum must be held down by means of a retaining structure to prevent it from floating. The substratum carrying the biofilm rests on a supporting structure. The weight of the biofilm can be calculated according to Tab. 2. Low-loaded biofilms weigh between 70 and 150 kg m^{-3}, whereas high-loaded biofilms and such with filamentous components may weigh up to 350 kg m^{-3}. The weight of the substratum ranges from 40 to 80 kg m^{-3}, depending on type, material, and specific surface. Experience gained to date has shown that the stack height should not exceed 4 m. The ideal stack height depends on the stability of the substratum and on the degree to which water can be circulated in the reactor.

The majority of biofilm reactors (biofilters, trickling filters) are designed on the basis of the space loading (kg BOD_5 m^{-3} fixed-bed volume d^{-1}). The conventional design of submerged fixed-bed reactors, which is based solely on the potentially available substratum surface (growth surface), is derived from the rotating disc contactor. However, in the case of this system, the increase in size of the surface originally available is solely biofilm-related so that, mathematically, at the most, the organic load on the surface is reduced, and the design is without risk. The design of grid-type substrata blocks of the submerged fixed-bed reactor is also based on the product-specific potential growth surface. At the same time, however, it must be borne in mind that the active surface initially increases due to the growth of the furry biofilm. In case of an inadequate forced flow, overloading, or the selection of a too high

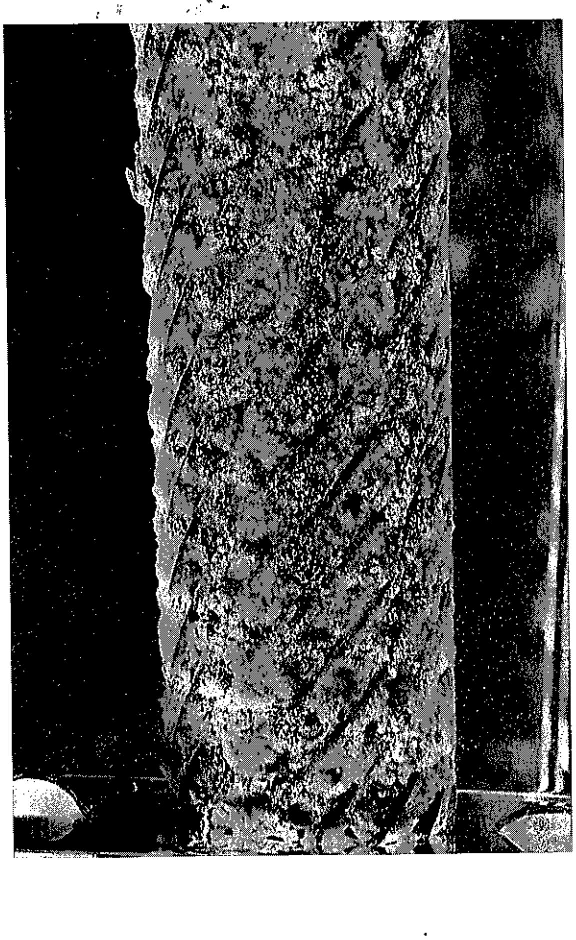

Fig. 4. Mushroom-type biofilm on HDPE grid (BIOPAC®).

specific surface, it can decrease again due to overgrowth on the substratum structure. In such cases only a reduced surface is available, so that the surface load is far higher than originally calculated. If this is not taken into consideration, breakdown can occur as a result of overloading. The microorganisms then typically react by increasing the number of suspended cells. This results in distinct turbidity combined with high effluent values. Simultaneously, the oxygen supply to the biofilm is reduced due to the smaller surface area, resulting in anaerobic processes and the release of organic acids.

It is, therefore, extremely important to base the choice of the submerged fixed bed and, thus, the specific surface, on the load to be expected and, in addition, to take the fixed bed-related space loading (kg BOD_5 m^{-3} fixed-bed volumel d^{-1}) into consideration as a design aid. Tab. 1 should be of assistance in this regard.

In cascaded plants, it is quite possible to install substrata with increasing specific surfaces along the flow path in different basins.

Fig. 5 shows a possible relationship between space loading and degradation efficiency, determined in a laboratory-scale plant (V = 60 L) with domestic wastewater.

2.2 Aeration

Aeration is normally effected by means of uniformly distributed fine-bubble membrane-type tubular aerators. It is important that the secondary biological sludge which is detached from the fixed bed as a result of the forced flow is constantly kept floating and is thus conveyed to the secondary sedimentation stage. An inadequate or wrongly directed forced flow, e.g., due to the installation of inappropriate aerators (disc aerators) or an unfavorable reactor design, leads to uncontrollable sludge deposits in the fixed-bed reactor (BISHOP and KINNER, 1986).

The aeration of submerged fixed-bed reactors according to this method fulfills two tasks of equal importance. On one hand, the aera-

Tab. 1. Relationship between BOD Load and Specific Surface of the Substratum

BOD Load	Specific Surface of the Substratum (m^2 m^{-3})
Low (nitrification)	≥200
Medium	~150
High	~100

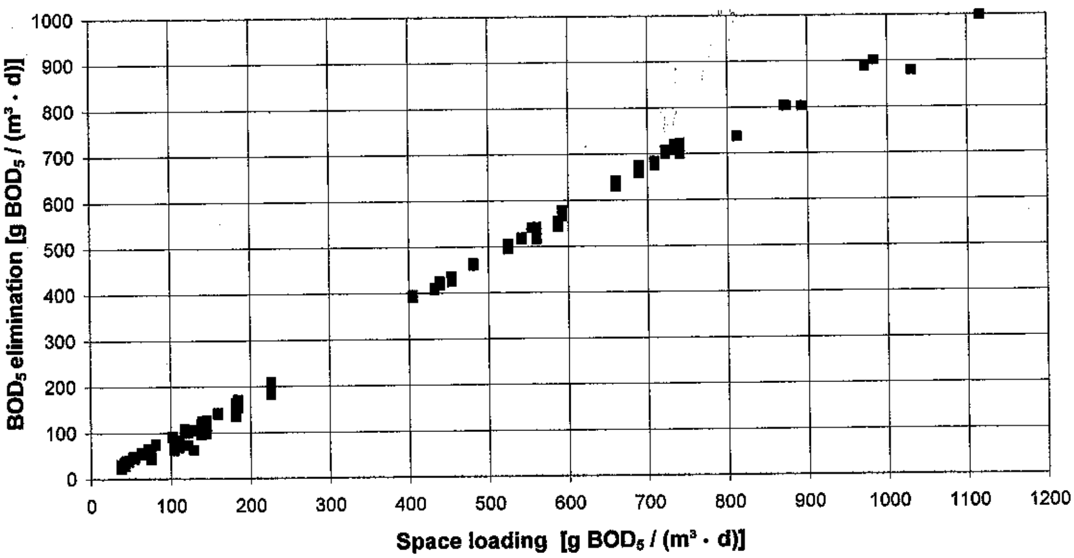

Fig. 5. BOD elimination as a function of space loading.

tors introduce the atmospheric oxygen needed for biological metabolism and, on the other hand, they generate the flow needed to ensure that the fixed-bed reactor does not become blocked. At the same time, the fixed-bed reactor acts as a flow barrier. The coarser the grid, the greater the similarity of flow to that of a completely mixed basin. Depending on the specific surface of the substratum, between 5 $Nm^3 h^{-1} m^{-2}$ and 15 $Nm^3 h^{-1} m^{-2}$ air must be introduced. According to SCHLEGEL (1988), oxygen input is intensified by the fixed bed due to the fact that large bubbles burst and the retention time of the bubbles is longer. Therefore, it is in principle very easy to retrofit existing activated sludge plants with an increase of the density of aerators and without a changing of the reactor geometry.

It has proved practical for reasons of cost to minimize aeration in everyday operation after a short start-up phase. In this context, the energy input for plants can be considerably reduced if, instead of continuous aeration, intermittent aeration is chosen. Preference should be given to short intervals. In addition, in low-load periods, e.g., during the night, oxygen input can be further reduced provided that on the basis of measurements the plant will not become anaerobic and the minimum requirements will be met. Particularly in the case of high-loaded plants, supplementary flushing by means of a higher oxygen input at regular intervals can increase the stability of the process and have a positive effect on the clarity of the effluent.

2.3 Reactor Volume/Design

It is known that the hydraulic regime can strongly influence the system (BISHOP and KINNER, 1986). The overall hydraulic mode may be complete mix, plug flow, or some hybrid of the two as in cascade reactors. When designing submerged fixed-bed reactors, not only the substratum, but also the reactor geometry must be aligned to the organic fixed-bed load for the specific application. Since the thickness and structure of the biofilm is influenced to a high degree by the concentration of biodegradable substances, the degree of dilution, which is a function of the volume of the basin, is a determining factor. Under no circumstances should an attempt be made to balance out high concentrations in small reactors by choosing a substratum with a particularly high specific surface. Another aspect to be considered is the technical flow control of the biofilm. This, together with stability factors, limits the maximum height of the fixed bed to approximately 4 m.

It is in principle possible to install fixed beds in all types of conventional basins. In this respect, the most important question to be clarified is whether a completely mixed basin, a plug flow basin, or a cascaded reactor offers the ideal solution. This depends on the boundary conditions.

In the case of municipal wastewater, the usual treatment objective is optimum carbon removal with simultaneous nitrification. To achieve this, fixed-bed reactors are usually loaded with 4–6 g $BOD_5 m^{-2} d^{-1}$.

In order to effect nitrogen removal as reliably as possible, it must be taken into account that load surges can have a negative influence on nitrification and that the water flowing in, particularly in the case of the mixed system, has widely fluctuating properties. In such cases, it is recommended to divide the reactors into several cascades. This results in a higher fixed-bed load in the first cascades and a lower load in the last cascades. This effect allows a higher mean loading of the plant with simultaneous maximum stability of the biological degradation.

As in the trickling filter process, where the different stages of biological degradation take place along a vertical axis (WANNER and GUJER, 1984), the division of the basin into 3–6 cascades has a positive effect on the biological efficiency, leading to a horizontal segmentation of different biocenotic areas. This results in greater operational reliability and an increased degradation rate. A reactor of this type responds very flexibly to hydraulic and organic load surges. This enables the surge loads typical for combined water systems to be balanced out to a high degree.

Higher fixed-bed loads are primarily used for pretreatment, e.g., that of industrial effluents. In this context, it must be borne in mind that even easily biodegradable substances can have an inhibiting effect on microbes if a certain concentration limit is exceeded. A good example is sugar, which is certainly very easily biodegradable, but in high concentrations is a conservation agent (candied fruits, jam). If an industrial effluent contains a component which, due to its concentration, has an inhibiting effect, it must be ensured that this critical value is not exceeded in the reactor. The reactor must be designed with a correspondingly large volume.

3 Development and Structure of Biofilms in Submerged Fixed-Bed Reactors

The colonization processes which take place on a substratum have already been described in Chapter 4, this volume.

Numerous experts, such as those referred to by IAWQ (1993), TOETTRUP et al. (1993), BOLLER et al. (1993), BISHOP and KINNER (1986) and MOSER (1985), prefer thin biofilms (<100 μm) for aerobic applications. Although high degradation rates have been achieved with this technique even with considerably thicker biofilms, i.e., up to 1,500 μm. However, viewed under a microscope, the biofilms are so fluffy and fissured and (LEWANDOWSKI et al., 1994; HAMILTON and CHARACKLIS, 1989) a far larger surface is created than in the case of thin biofilms, and nutrients rarely have to penetrate the substratum deeper than 200 μm. The biofilm – liquid film interface, however, is not smooth or uniform (BISHOP and KINNER, 1986). It seems very logical that, with this type of process, a minimum quantity of biomass is needed, i.e., in the order of that required in the case of activated sludge systems. There is a close relationship between the organic load and the biomass, as is shown in Tab. 2. The organic proportion of the sludge is approximately 65–85%. Porosity increases enormously with increasing biofilm thickness, due to the formation of typical filaments, as can be seen in Fig. 6.

This behavior ensures that there is an adequate nutrient gradient even in thick biofilms so that sensitive processes, such as nitrification, are not inhibited. In parallel to this, a substantial increase in the biofilm surface is achieved, which is reflected in both the adsorption potency and the degradation efficiency. The experience gained with the fixed-bed reactor technique described here has shown that, in practice, thicker biofilms can also be used successfully without a risk of damage to the plant. Fig. 7 is a microscopic image of a *Zoogloea*-type biofilm.

The biofilms can be described as "natural populations" because natural selection occurs and determines which organisms can survive (MOSER, 1985).

There are generally three types of organisms composing the biofilm as known from other systems: bacteria, protozoa, and metazoa. The role of each group is described by MOSER (1985).

The biofilms on permanently submerged surfaces differ in some points from those in the case of trickling filters and rotary disc contactors. There have been observed no Psychodidae or other insects, because these have rare

Tab. 2. Relationship of the Biofilm Thickness as a Function of the Load

B_F	B_L	W	Application
<3	1.5	0.015	nitrification and complete carbon elimination
3–6	1–4	0.017	nitrification and simultaneous carbon elimination
6–12	4–10	0.02	carbon elimination with partial nitrification
12–30	10–20	0.03	carbon elimination

B_F: BOD_5 load (g BOD_5 m^{-2} d^{-1})
B_L: thickness of biofilm or length of biofilm filaments (mm)
W: weight factor (kN m^{-2}) according to Deutscher Normenausschuß Wasserwesen, 1989

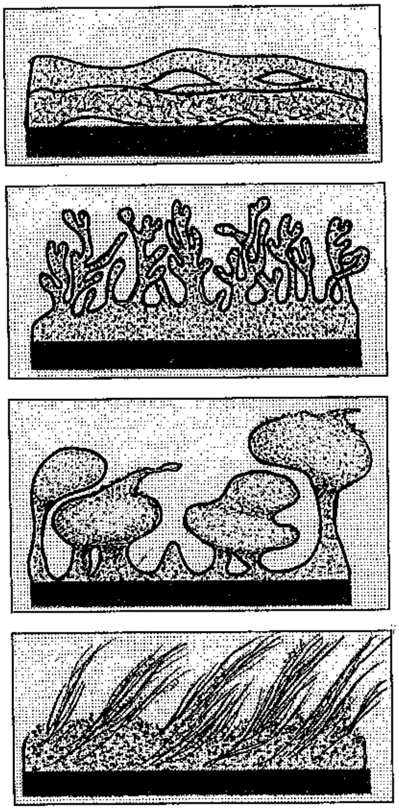

Fig. 6. Types of bacterial biofilm occurring on submerged surfaces.

opportunity of depositing their eggs. Very large colonies of Peritricha are typical in submerged fixed-bed domestic wastewater treatment plants due to the moderate turbulence and the constant supply of oxygen and bacteria. *Carchesium*, *Zoothamnium*, *Epistylis*, *Opercularia*, and *Vorticella*, in particular, often stabilize the biofilm with the skeleton of their stalks. Some species of filamentous bacteria or fungi may also play the same role. These filaments are surrounded by a bacterial community connected by extracellular polymeric substances (EPS). The surface of the biofilm is the habitat of other protozoa, chiefly the grazing species, as well as of rotifers (*Rotaria*, *Cephalobdella*) and worms (*Nais*, *Chaetogaster*, Tubificidae, Nematoda sp.), which feed on the bacterial matrix, thus, loosening it. Similar biocenotic communities have been described for the rotating biological contactor (RBC) by BISHOP and KINNER (1986) and for activated sludge systems by CURDS and COCKBURN (1970).

Although these organisms remove a portion of the sludge, only in rare cases do they have a damaging effect on the biofilm and are rather to be seen as positive due to the reduction of the sludge and the loosening effect. An increase in load and number of non-aeration intervals has been found helpful when these organisms occur in masses. The bacteria grow in the submerged biofilm in a variety of forms, the most significant of which are shown in Fig. 6. Mixed forms frequently occur. Among the factors which determine the growth form and biofilm structure are the species of bacteria, the degree of turbulence, and the compositon of the wastewater (Fig. 6). Tab. 2 provides an overview of the biofilm thickness to be ex-

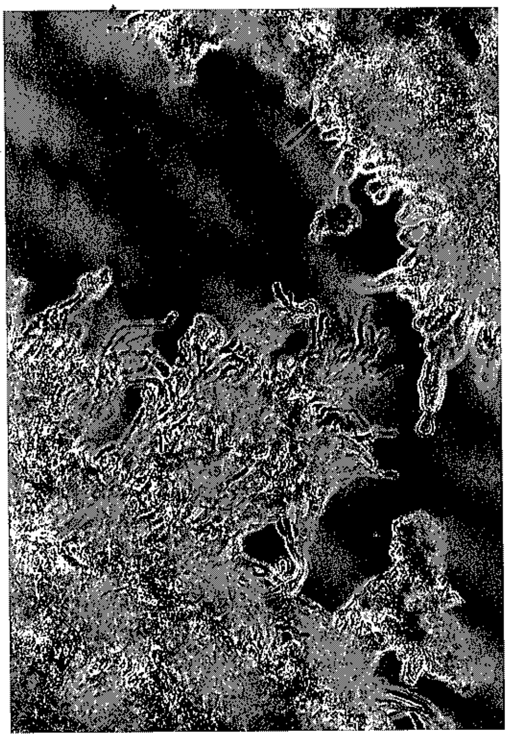

Fig. 7. Microscopic photograph of a *Zoogloea*-type biofilm.

pected as a function of the load, and applies to the turbulences usual in the case of aeration without back-washing.

The surplus sludge production of the submerged biofilms is influenced to a high degree by the preset fixed-bed load. As a rule, sludge production is considerably lower than in the case of an activated sludge process with the same load. In municipal plants with 4–6 BOD_5 m^{-2} d^{-1} and cascades, it is usually between 0.01 and 0.1 kg MLVSS per kg BOD_5 eliminated. In industrial high-load plants with 20–30 g BOD_5 sludge production in the order of 0.6 kg MLVSS per kg BOD_5 m^{-2} d^{-1} eliminated has been measured (SCHLEGEL, 1998). At the same time, it could be shown that the sludge quantity can be distinctly reduced as a result of pretreatment in a fixed-bed reactor. Considering the microbiological and ecological aspects, this can probably primarily be attributed to

- sludge removal by macro-invertebrates (Rotaria, worms),
- the lower separation rate of sessile bacteria (AUDIC et al., 1984),
- the reduced selection rate of fast-growing bacteria to the benefit of slower-growing species (HAMILTON and CHARACKLIS, 1989),
- further mineralization due to the high oxygen content (ABBASSI et al., 1996).

4 Examples of Practical Applications

Practical application ranges from three-compartment septic tanks to large-scale plants with several thousands of cubic meters of fixed beds in correspondingly dimensioned concrete basins.

Apart from the domestic and industrial applications described in the following examples, fixed-bed reactors can also be used for any type of biodegradable sewage. In this connection, all types of fixed-bed reactors can be employed, not only for pretreatment, in the form of high-load units, and for complete biological treatment, but also in the form of a downstream unit to achieve more advanced treatment objectives.

4.1 Domestic Wastewater

An important aspect of the *in situ* treatment of wastewater in both centralized and decentralized plants is that fixed-bed reactors can be adapted to all types of wastewater profile, which makes them an ideal solution when looking towards the future. There are special problems connected with small, decentralized wastewater treatment plants, such as inhomogeneous influent patterns, extreme sensitivity to temperature, and a lack of maintenance personnel. For the decentralized treatment of the wastewater from 4 to 1,000 PE, in particular, there is a need for systems such as fixed-bed reactors, which require little maintenance and are very easily controlled.

With fixed-bed reactors designed for approximately 4–6 g BOD_5 m^{-2} d^{-1}, carbon and nitrogen can be simultaneously eliminated without difficulty. A reduction in the COD of 90% and in the BOD_5 of 95% is possible. Ammonium-N is normally nitrified to over 95% ($t > 12°C$), (BOD load $< 4\ g\ m^{-2}\ d^{-1}$).

Reactors with a sessile biomass have been found to be ideal for nitrification purposes. As early as 1988, SCHLEGEL published the operating results of a fixed-bed nitrification plant which showed that approximately 1.5 g $NH_4{-}N\ m^{-2}\ d^{-1}$ can be reliably nitrified. Results of studies published in Munich in 1991 (Technische Universität München, 1991) and observations of fluidized beds by KUGEL and HELLFEIER in 1995 verify that systems with sessile nitrificants respond to fluctuating loads and low temperatures in an exceptionally stable manner. High denitrification rates can be achieved with intermittent aeration, the recirculation of water containing nitrates, or the addition of carbon from an external source. When compared with other types of plants, the surface-related degradation efficiency must be taken into account. With continuous aeration and thick biofilms, simultaneous denitrification is about 40% due to the partially anoxic conditions within the biofilm layers. It is possible to achieve 70% nitrogen elimination with a recirculation of only 100%, and to adhere to the limit of 18 mg L^{-1} total N recommended for domestic wastewater treated in much larger plants (SCHULZ et al., 1998).

Simultaneous phosphorus removal of 20–50% is also frequently achieved, as has been confirmed not only by internal measurements but also by a study carried out by the Institute of Technology in Munich in 1991 (Technische Universität München, 1991). Purely biological phosphorus elimination is probably not possible due to the absence of sludge recirculation and the necessary alteration between aerobic and anaerobic conditions. However, simultaneous P eliminaton has been observed in a large number of plants. Further research is required to describe the reasons for this. Possibly crystallization of phosphate compounds plays a role, because crystalline structures frequently occur in biofilms.

Fig. 8 illustrates the ENVICON 3K PLUS as an example of very small fixed-bed reactors (4 to 200 PE) in three-compartment septic tanks. Fig. 9 shows a mobile container-type wastewater treatment plant based on the submerged fixed-bed reactor principle.

4.2 Industrial Applications

The submerged fixed-bed reactor technique is applied successfully in the treatment of many different types of industrial effluents, e.g.: toluene-polluted groundwater, effluents from latex and tenside processing, from fish, juice, and beer processing, from the beverage industry and from textile and carpet production, as well as from the production of amides and aromatics. The submerged fixed-bed process is suitable for the treatment of all types of biodegradable wastewaters, even if the COD:BOD ratio is poor, or there are fluctuations in the influent. The microbiological reason for this suitability is the agglomeration of specific slow-growing sessile specialized microorganisms. A few possible applications are described in the following sections.

4.2.1 A Submerged Fixed-Bed Reactor as a Pretreatment Stage – Effluent from a Vegetable and Ice-Cream Processing Plant

A wastewater treatment plant, designed for 25,000 PE, needed a more efficient method to pretreat the large volumes of effluent produced by an industrial-scale vegetable and ice-cream processing plant. To achieve this and to improve nitrification, the wastewater treatment plant would have had to expand its capacity to approximately 30,000 PE. A cost analysis showed that in this case the installation of a fixed-bed reactor would cost 50% less than a conventional expansion of the existing activated sludge plant. Fig. 10 shows the degree of COD elimination as a result of the fixed-bed reactor referred to by SCHLEGEL (1998).

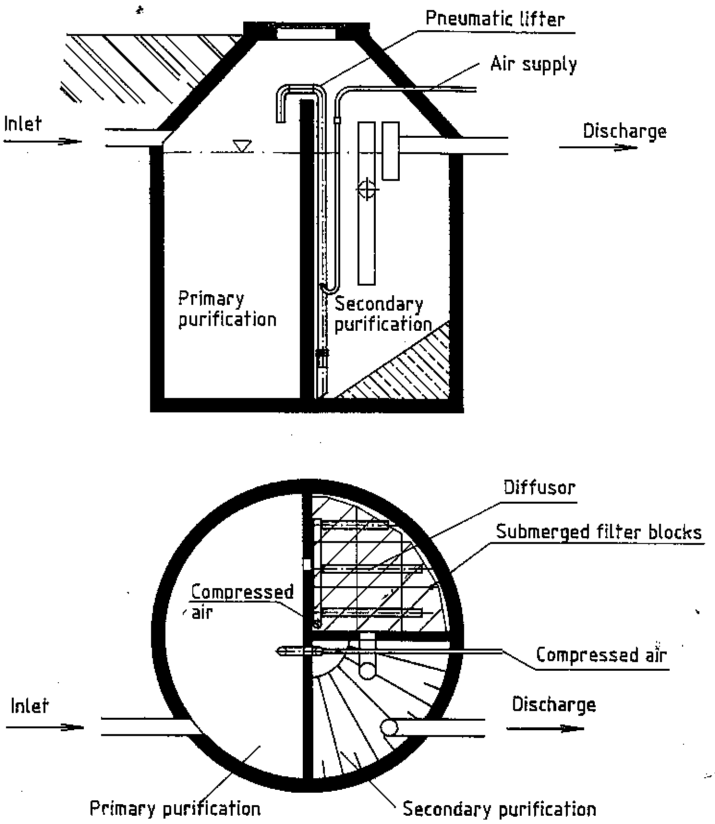

Fig. 8. ENVICON 3K PLUS in a three-compartment septic tank.

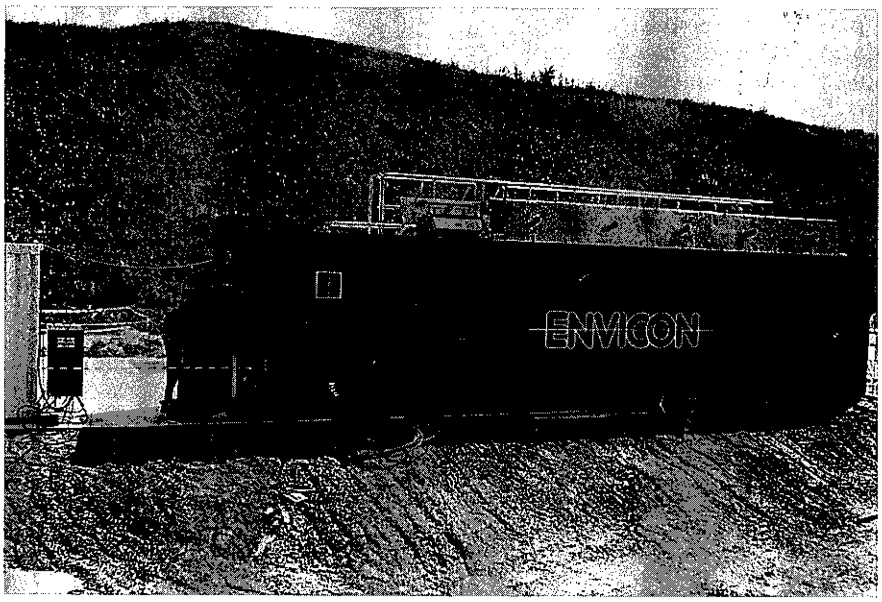

Fig. 9. A container-type wastewater treatment plant.

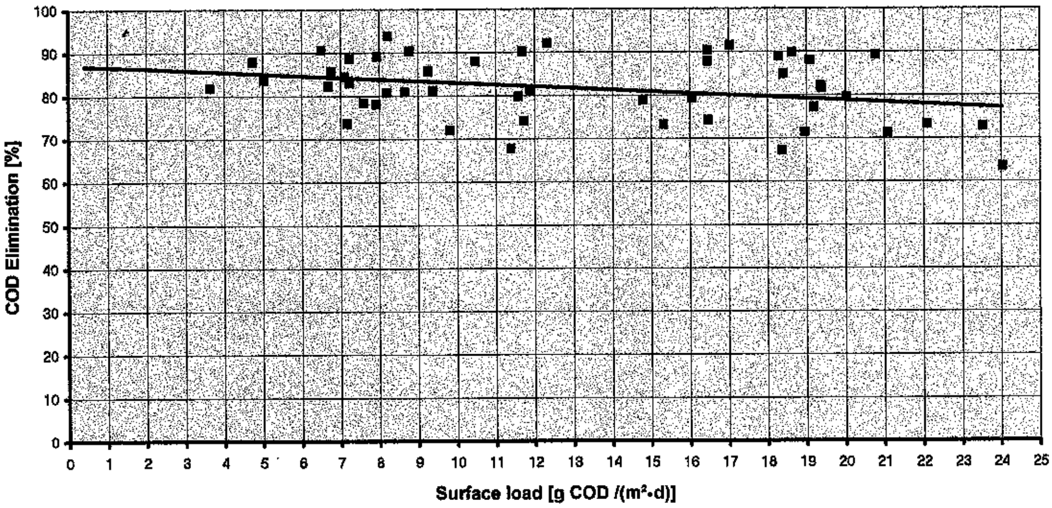

Fig. 10. COD elimination in the effluent from a vegetable and ice-cream processing plant as pretreatment stage.

4.2.2 A Fixed-Bed Reactor as the Sole Biological Treatment Stage Presented by the Example of a Detergent and Cosmetics Production Plant

A plant required a completely biological solution for the treatment of tenside-polluted effluents from the production of detergents, cleansing agents, and cosmetics. It was decided to install a fixed-bed reactor with the following key data:

- primary sedimentation area 3.5 m^3
- fixed-bed area 6.5 m^3
- secondary sedimentation area 3.5 m^3
- fixed-bed surface 975 m^2

The COD in the influent of the reactor was about 5,000 mg L^{-1}, and tensides approximately 2,000 mg L^{-1} (methylene blue active substances, MBAS). Antispumin was continuously metered in to reduce foam formation.

Fig. 11 shows the COD and tenside (MBAS) elimination efficiency of the fixed-bed reactor. From this, it is clear that using fixed-bed technology complete biological treatment of industrial effluents of these types is possible with low maintenance. In this case, sludge production was only a fraction of that in an activated sludge plant with the same load.

4.2.3 A Fixed-Bed Reactor as the Final Treatment Stage Presented by the Example of a Slaughterhouse

The slaughterhouse had a physicochemical wastewater treatment plant with grease trap, flotation tank, and proteolysis, as well as a decanter, in order to pretreat the effluent produced when slaughtering pigs and cattle, prior to discharge into the sewerage system. The highly concentrated effluent conveyed to the physico-chemical plant was found to have a COD between 4,600 and 6,700 mg L^{-1}. The effluent flowing out of the decanter and conveyed without sedimentation to the biological treatment unit still had a residual COD content between 1,200 and 3,000 mg L^{-1} and had to be reduced to COD values <800 mg L^{-1}. The fixed-bed reactor installed corresponded to that described in Sect. 4.2.2. The BOD_5 load exceeded 12 g m^{-2} d^{-1}. Phosphorus was metered in to compensate for nutrients. On the average more than 80% of the COD in the influent of the fixed-bed reactor was eliminated. Fig. 12 shows that the BOD_5 value aimed at was achieved over the entire period.

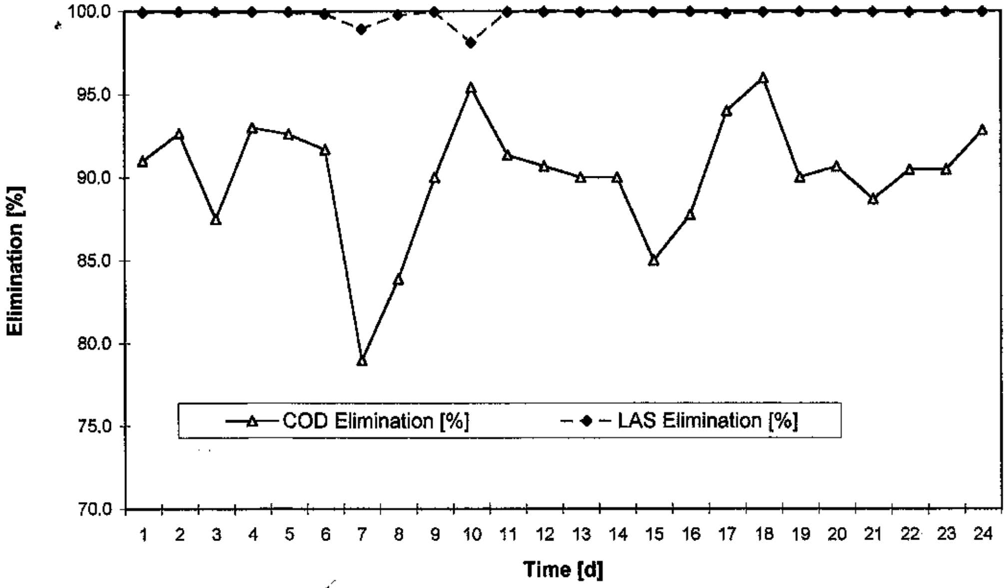

Fig. 11. COD and tenside elimination in the effluent from a detergent and cosmetics production plant.

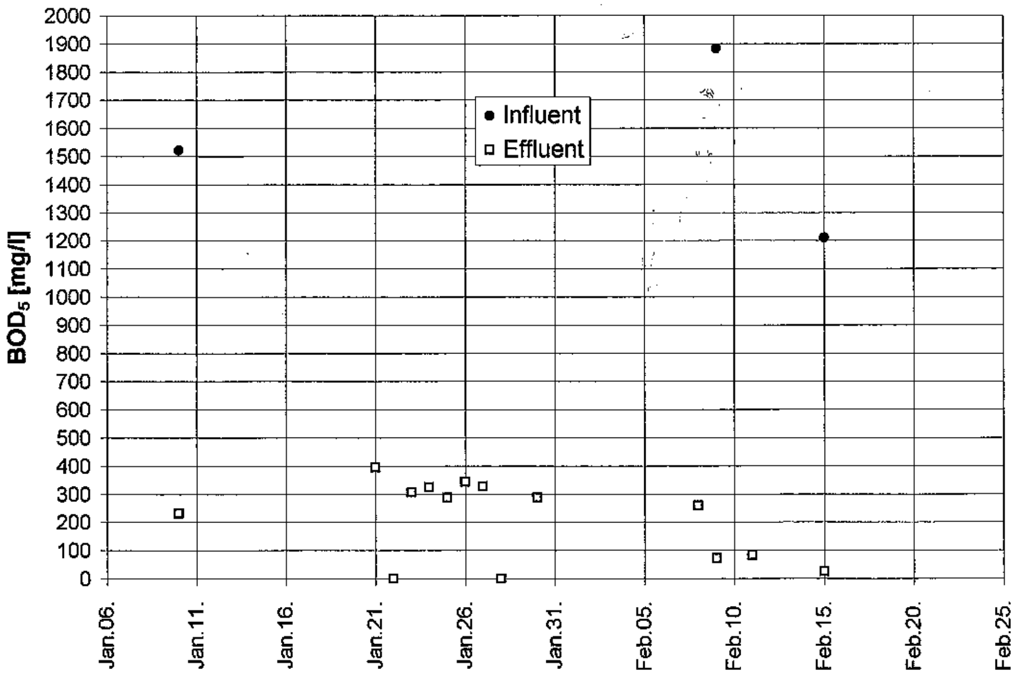

Fig. 12. Final treatment of effluent from a slaughterhouse with a submerged fixed-bed reactor.

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