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ORGANIC LOAD REMOVED BY BIOMASS IMMOBILIZED IN CERAMIC CARRIERS

Activated sludge was immobilized in two ceramic carriers differing in internal structure. Volumetric loading rate (VLR) of the carriers varied from 6.5 to 48.8 g COD/dm^3·d and from 5.4 to 16.6 g COD/dm^3·d for reactor I and for reactor II, respectively. The efficiency of organic compounds removal (expressed as COD) by immobilized biomass ranged from 85.2 to 93.8% for reactor I and from 62.9 to 87.1% for reactor II. Organic load removed by cellular oxidation, denitrification, biomass production and intracellular storage was estimated based on VLR. It was proved that organic load removed due to biomass synthesis only slightly affected COD removal by immobilized biomass. In reactor I, an intracellular storage in immobilized biomass had a great influence on the COD removal, and in reactor II the proportion of particular processes in the removal of organic compounds was similar.

1. INTRODUCTION

In the reactors with an increased biomass concentration, as a result of its immobilization, the efficiency of organic compounds' removal from wastewater is high. ROSENBERGER et al. [1] studied aerobic treatment of municipal wastewater in hollow fibre membrane bioreactor at VLR of 1.1–1.7 kg COD/m^3·d and they found that the removal of COD was 95%. JEFFERSON et al. [2] investigated BOD_5 removal in membrane bioreactor at VLR of 0.005–0.11 kg BOD_5/m^3·d, in membrane aeration bioreactor at VLR of 0.22–1.6 kg BOD_5/m^3·d and in biologically aerated filter at VLR of 0.45–7.0 kg BOD_5/m^3·d and they obtained: 100%, 75% and 84%, efficiencies of BOD_5 removal, respectively. YAMAMOTO and WIN [3] reported that in sequencing batch membrane reactor at VLR of 3, 5 and 10 kg COD/m^3·d, the efficiency of COD removal ranged between 93.7 and 96.3%. CHUI et al. [4] proved 95% efficiency of COD removal at VLR of 5 kg COD/m^3·d in upflow fixed bed filter. PANKHANIA et al. [5] achieved 86% COD removal in hollow fibre membrane bioreactor at the highest VLR of 8.94 kg COD/m^3·d. STROHWALD and ROSS [6] obtained the efficiency of

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COD removal ranging from of 96 to 99% in membrane bioreactor at VLR of 15 kg COD/m^3·d.

According to literature data the efficiencies of organic compounds removal depend on reactor loading, provided that the proportion of biomass production, cellular oxidation, denitrification or intracellular storage in this process are not taken into account. When a dependence of VLR on the efficiency of particular processes of COD removal by immobilized biomass is found, this will make possible to optimize the removal of organic compounds in reactor with high biomass concentration, especially excess sludge production.

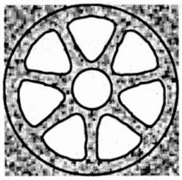
2. MATERIALS AND METHODS

2.1. CHARACTERISTICS OF CARRIERS

Activated sludge was immobilized in two porous ceramic cylinder-shaped carriers. The carriers differed in internal structure, number of internal channels, the size of internal surface and total volume (table 1). Pore diameter varied from 4 to 6 μm and material porosity, from 35 to 40%. Both carriers were made from aluminium oxide (Al_2O_3), titanium oxide (TiO_2) and zirconium oxide (ZrO_2).

Table 1

Characteristics of porous carriers

Carrier	Cross-section	External diameter [mm]	Length [mm]	Internal surface [m^2]	Total volume [dm^3]
I		10	1200	0.04	0.094
II		25	1178	0.20	0.578

2.2. COLONIZATION PROCEDURE

The activated sludge derived from the sequencing batch reactor was the source of inoculum. It was thickened to the concentration of about 23 g TSS/dm^3. Circulation of the activated sludge in the reactors for 24 h made the immobilization. The initial loading of carriers amounted to 24.5 g TSS/dm^3 (carrier I) and 18.2 g TSS/dm^3 (carrier II).

2.3. CHARACTERISTICS OF THE REACTORS

Each carrier with immobilized biomass was the stationary filling of the reactor. Carrier I and carrier II were put in reactor I and in reactor II, respectively. Both bioreactors worked under aerobic conditions. Reactor I and reactor II were supplied with about 50 dm^3 of air per 1 h and about 120 dm^3 of air per 1 h, respectively, in order to maintain the oxygen concentration of 2 mg O_2/dm^3. The experiment was carried out at the temperature of 20 °C. The scheme of reactor and the description of wastewater flow have been given earlier [7].

2.4. CHARACTERISTICS OF WASTEWATER

Municipal wastewater taken directly from a sink basin was used in the research. Average content of organic compounds, nitrogen compounds and total suspended solids is presented in table 2.

Table 2

Chemical characteristics of wastewater

Parameter	Unit	Mean value
COD	g O_2/m^3	337.6
COD soluble	g O_2/m^3	118.0
Volatile acids	g CH_3COOH/m^3	85.4
Kjeldahl nitrogen	g TKN/m^3	47.4
Ammonium nitrogen	g $N–NH_4/m^3$	27.0
Total suspended solids	g TSS/m^3	236.4

2.5. ORGANIZATION OF EXPERIMENT

The studies were carried out at the volumetric loading rates (VLR) of the carrier ranging from 6.5 to 48.8 g $COD/dm^3\cdot d$ for reactor I and at VLR from 5.4 to 16.6 g $COD/dm^3\cdot d$ for reactor II. An increase in VLR above 16.6 g $COD/dm^3\cdot d$ in reactor II limited nitrification. Table 3 presents volumetric loading rates (VLR) and surface loading rates (SLR) for both carriers.

Table 3

Scheme of research

	Reactor	I				II		
SLR	[g $COD/m^2\cdot d$]	15.3	18.8	48.8	114.6	15.6	16.8	47.9
VLR	[g $COD/dm^3\cdot d$]	6.5	8.0	20.8	48.8	5.4	5.8	16.6

The experiment at each VLR value was carried out for about 2 weeks after biomass adaptation. Each point in the figures represents an arithmetical average value of all the values obtained for this time.

2.6. ANALYTICAL METHODS

Wastewater was assayed for the concentration of organic compounds (expressed as COD and COD soluble), volatile acids, Kjeldahl nitrogen, ammonium nitrogen and total suspended solids according to Polish Standards.

The respirometric activity of immobilized biomass was measured by OxiTop method. The excess sludge in the effluent was analyzed. In order to determine the substrate respiration, the samples of biomass, raw wastewater and thiourea as a nitrification inhibitor were transferred to measuring vessels. The organic loading rate of the biomass was constant and amounted to 0.25 g COD/g TSS·d (similarly to that reported by VAN BENTHUM et al. [8]).

3. RESULTS AND DISCUSSION

In reactor I, volumetric loading rate (VLR) of three-channelled carrier increased from 6.5 to 48.8 g COD/dm^3·d. Organic load removed by immobilized biomass (Q_{rem}) increased almost 8-fold: from 0.5 to 3.9 g/d. The efficiency of COD removal varied from 85.2 to 93.8%. In reactor II, VLR of eight-channelled carrier increased from 5.4 to 16.6 g COD/dm^3·d. The effectiveness of COD removal ranged from 62.9 to 87.1%. Q_{rem} increased 2.7-fold: from 2.0 to 5.4 g/d.

It was proved that from reactors with biomass immobilized in ceramic carriers organic compounds are removed due to cellular oxidation, biomass synthesis, denitrification and intracellular accumulation of organic substances.

Organic load removed by cellular oxidation was calculated according to the following formula:

$$Q_{ox} = (L_0 \cdot q) - Q_{syn} \quad \text{[g/d]}, \tag{1}$$

where:

L_0 – total concentration of oxygen used for oxidizing organic compounds in wastewater, determined by respirometric measurements [g O_2/m^3],

q – flow rate of wastewater [m^3/d],

Q_{syn} – organic load used for biomass synthesis [g/d].

Organic load removed by cellular oxidation (Q_{ox}) in reactor I assumed similar values ranging from 0.08 to 0.14 g/d regardless of VLR examined (figure 1a). It was simultaneously proved that the share of cellular respiration in total load removed (Q_{rem}) by immobilized biomass under aerobic conditions in reactor I decreased along with an increase in VLR and varied from 24% at VLR of 6.5 g COD/dm^3·d to 3% at VLR of 48.8 g COD/dm^3·d. In reactor II, along with an increase in VLR, Q_{ox} increased from 0.81 to 1.71 g/d. The contribution of cellular oxidation in COD removal in reactor II increased slightly, i.e. from 32% at VLR of 5.4 g COD/dm^3·d to 34% at VLR of 16.6 g COD/dm^3·d (figure 1b).

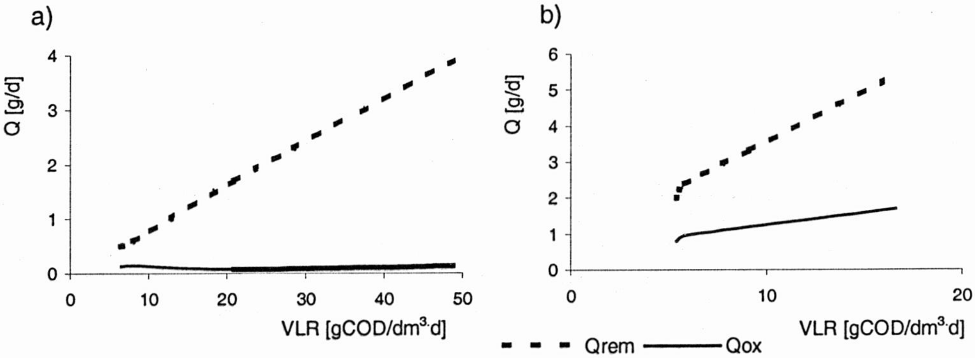


Fig. 1. Organic load removed by cellular oxidation versus VLR in reactors I (a) and II (b)

In conventional activated sludge systems, about 1/3 of organic compounds is assumed to be oxidized by microorganisms in order to produce energy. JEFFERSON et al. [2] and WITZIG et al. [9] claimed that in the systems of high biomass concentration, bacteria utilized the substrate being supplied mainly for maintaining their metabolism. Our studies show that in reactors with biomass immobilized in porous carriers, especially in reactor I, cellular oxidation did not influence significantly the removal of organic compounds (figure 1a).

Microorganisms of immobilized activated sludge utilized a part of organic compounds for reduction of oxidized nitrogen being produced during nitrification.

Organic load removed by denitrification was calculated according to the following formula (2):

$$Q_{den} = C_{Nred} \cdot 2.6 \cdot q \quad [g/d], \tag{2}$$

where:

C_{Nred} – concentration of nitrogen removed in denitrification [g N–NO_3^-/m^3],

2.6 – amount of organic compounds used for reduction of 1 g of oxidized nitrogen [10] [g COD/g N–NO_3^-],

q – flow rate of wastewater [m^3/d].

In reactor I, almost 8-fold increase (from 0.12 to 0.52 g/d (figure 2a)) in organic load removed corresponded to 4.3-fold increase in organic load used for denitrification (Q_{den}). The proportion of Q_{den} in total load removed decreased from 22% at VLR of

6.5 g COD/dm^3·d to 12% at VLR of 48.8 g COD/dm^3·d. At VLR between 20.8 and 48.8 g COD/dm^3·d organic load removed by nitrate respiration exceeded the load removed by oxygen respiration. Under conditions of high VLR in internal layers of immobilized biomass, anoxic zones could have been formed which changed a microbial metabolism.

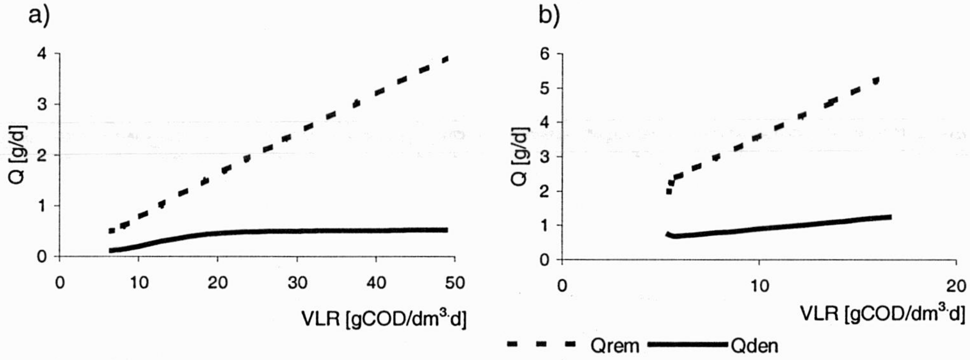


Fig. 2. Organic load removed by denitrification (Q_{den}) versus VLR in reactors I (a) and II (b)

For reactor II at 2.7-fold increase in total load removed (Q_{rem}), organic load used for nitrate reduction (Q_{den}) increased 1.7-fold: from 0.75 to 1.25 g/d (figure 2b). The contribution of Q_{den} to Q_{rem} declined from 30% at VLR of 5.4 g COD/dm^3·d to 25% at VLR of 16.6 g COD/dm^3·d.

Organic load used for biomass synthesis was calculated according to the following formula:

$$Q_{syn} = Y \cdot (\mathrm{COD_i} - \mathrm{COD_e}) \cdot q \cdot 0.8 \quad \text{[g/d]}, \tag{3}$$

where:

Y – sludge yield [g TSS/g COD],

$\mathrm{COD_i}$ – organic compounds in influent [g COD/m^3],

$\mathrm{COD_e}$ – organic compounds in effluent [g COD/m^3],

q – flow rate of wastewater [m^3/d],

0.8 – COD concentration corresponding with 1 g TSS [g COD/g TSS].

In both reactors, the uptake of organic compounds from wastewater for biomass production was low. In reactor I, along with an increase in VLR from 6.5 to 48.8 g COD/dm^3·d, organic load necessary for biomass synthesis (Q_{syn}) increased from 0.07 to 0.28 g/d (figure 3a). The contribution of Q_{syn} to total load removed decreased from 13% at VLR of 6.5 g COD/dm^3·d to 6% at VLR of 48.8 g COD/dm^3·d.

In reactor II, along with an increase in VLR from 5.4 to 16.6 g COD/dm^3·d, Q_{syn} grew up slightly from 0.44 to 0.53 g/d, whereas its proportion in total load removed declined from 18% to 11% (figure 3b).

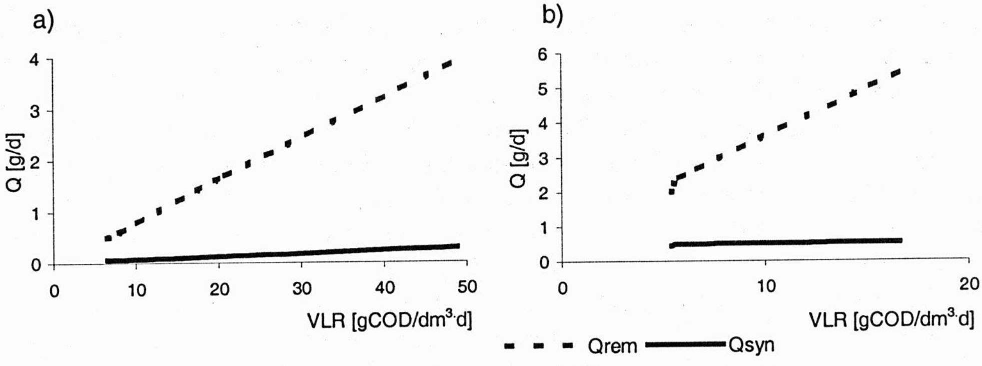


Fig. 3. Organic load used for biomass synthesis versus VLR in reactors I (a) and II (b)

Many authors claimed that at high biomass concentration and at long solids' retention time (SRT), biomass production is limited. WANG et al. [11] proved that in the reactor with high concentration of biomass there was much less excess sludge because of longer food-chains. Too small amount of substrate in comparison with the amount of microorganisms could have been the reason of small uptake of organic compounds for sludge production in reactors of high biomass concentration. GANDER et al. [12] and CHIEMCHAISRI and YAMAMOTO [13] claimed that the higher the biomass concentration, the lower the food/microorganisms (F/M) ratio. In such conditions, the production of excess sludge is limited. Only if substrate is supplied in excess, bacteria are able to grow [2], [9]. According to ROSENBERGER et al. [1], low F/M ratio means a limited amount of substrate per unit biomass, which leads to competition among the microorganisms and results in decreasing of the net sludge production.

The interest in the methods allowing us to decrease the volume of the excess sludge has been rapidly growing. There are some experimental data on the excess sludge decrease or prevention. YOON [14] examined a membrane bioreactor–sludge disintegration system for zero excess sludge production. KIM et al. [15] introduced excess mechanical shear caused by high-flow rate pumps reducing the sludge yield in a cross-flow membrane bioreactor.

Low values of sludge yield obtained in our research (from 0.066 to 0.175 g TSS/g COD) are similar to literature data. In reactors with immobilized biomass, the excess sludge production amounts to 0.094 g MLSS/g COD [16] and 0.2–0.3 g TSS/g COD [17].

According to literature on the subject the biomass production decreases (by 4–10% according to BEUN et al. [18] and by 6% according to VAN AALST-VAN LEEUWEN et al. [19]) during polyhydroxybutyrate (PHB) accumulation. The studies of BEUN et al. [20] showed that about 70% of acetate taken was used for PHB synthesis and the remaining amount was necessary for growth processes under aerobic and anoxic conditions. In our research, it was assumed that organic compounds from wastewater not removed by cellular oxidation, denitrification and sludge production were accumulated by immobilized biomass as stored materials. In reactor I, an organic load accumulated (Q_{acc}) increased from 0.22 to 3.38 g/d along with an increase in Q_{rem} from 0.5 to 3.9 g/d (figure 4a). The contribution of Q_{acc} to total load removed increased from 41% at VLR of 6.5 g COD/dm^3·d to 78% at VLR of 48.8 g COD/dm^3·d. These results did not confirm the studies by DIONISI et al. [21], who had shown in their anoxic batch tests that as organic load increased, the polyhydroxyalkanoate (PHA) storage capability of mixed cultures decreased.

In reactor II, the proportion of intracellular storage was lower. An initial increase in VLR from 5.4 to 5.8 g COD/dm^3·d caused an increase in load accumulated from 0.49 to 1.19 g/d. Along with a further increase in VLR to 16.6 g COD/dm^3·d, a slow increase in Q_{acc} to 1.49 g/d was observed (figure 4b). The contribution of Q_{acc} to Q_{rem} increased from 20% at VLR of 5.4 g COD/dm^3·d to 30 % at VLR of 16.6 g COD/dm^3·d.

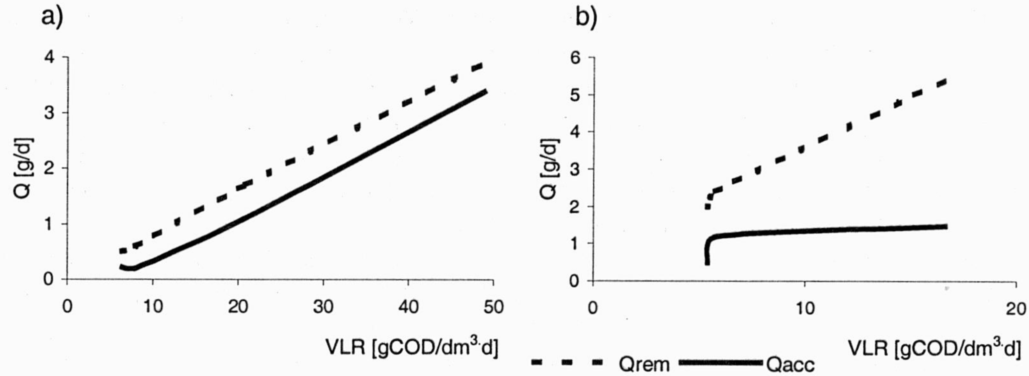


Fig. 4. Organic load accumulated intracellularly (Q_{acc}) versus VLR in reactors I (a) and II (b)

The figures show that intracellular storage has the highest significance in organic compounds removal by biomass immobilized in three-channelled reactor I, whereas in eight-channelled reactor II the proportion of particular processes in COD removal was similar. According to PICIOREANU et al. [22] the carrier structure has an essential significance during biodegradation by immobilized microorganisms, because an increase in the distance of substrate and oxygen diffusion are responsible for a decrease in the effectiveness of mass transport. The carriers used in our research differed in an internal surface and in the proportion of internal channels in total volume. Internal channels occupied about 50% of carrier I and about 44% of carrier II. This feature could have influenced different environmental conditions of immobilized biomass, and thereby the efficiency of particular processes in the removal of organic compounds.

4. CONCLUSIONS

1. In reactor I, the amount of an organic load oxidized did not depend on VLR and remained on the similar level (from 0.08 to 0.14 g/d) along with an increase in VLR (from 6.5 to 48.8 g COD/dm^3·d). In reactor II, an oxidized load increased about 2-fold, from 5.4 to 16.6 g COD/dm^3·d, with an increase in VLR.

2. In reactor I, at VLR between 20.8 and 48.8 g COD/dm^3·d organic load consumed for nitrate respiration exceeded the load removed by oxygen respiration.

3. It was proved that sludge production in reactors with biomass immobilized in porous ceramic carriers was limited. In reactor I, along with an increase, from 0.5 to 3.9 g/d, in total organic load removed, the organic load used for biomass production increased from 0.07 to 0.28 g/d. In reactor II, an increase, from 2.0 to 5.4 g/d, in total organic load removed corresponded to an increase, from 0.44 to 0.53 g/d, in load removed by biomass synthesis.

4. In reactor I, organic load accumulated by biomass increased considerably from 0.22 to 3.38 g/d by an increase in VLR.

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USUWANIE ŁADUNKU ZWIĄZKÓW ORGANICZNYCH PRZEZ BIOMASĘ IMMOBILIZOWANĄ W NOŚNIKACH CERAMICZNYCH

Osad czynny był immobilizowany w dwóch ceramicznych nośnikach różniących się strukturą wewnętrzną. Obciążenie objętości nośników ładunkiem związków organicznych (VLR) w reaktorze I zmieniano w zakresie od 6,5 do 48,8 g ChZT/dm^3·d, a w rekatorze II – w zakresie od 5,4 do 16,6 g ChZT/dm^3·d. Sprawność usuwania związków organicznych (ChZT) przez biomasę immobilizowaną w badanym zakresie obciążeń wyniosła 85,2–93,8% w reaktorze I oraz 62,9–87,1% w reaktorze II. Oszacowano ładunek związków organicznych usunięty w wyniku utleniania komórkowego, denitryfikacji, produkcji biomasy i wewnątrzkomórkowego magazynowania przez biomasę immobilizowaną w zależności od VRL. Wykazano, że ładunek usunięty w wyniku produkcji biomasy miał niewielki udział w usuwaniu związków organicznych przez biomasę immobilizowaną. W reaktorze I istotny udział w usuwaniu ChZT miało magazynowanie substancji zapasowych w biomasie immobilizowanej. Natomiast w reaktorze II udział poszczególnych procesów jednostkowych w usuwaniu związków organicznych był zbliżony.