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Investigation of different schemes for anaerobic treatment of food industry wastes in Estonia

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Abstract. During the last 5 years, four types of wastewaters from the food industry (yeast, cheese whey, distillery, vegetable oil) with different technological schemes of anaerobic mesophilic digestion (one or two stages) and different types of reactors (contact process, anaerobic filter, fixed bed filter with plastic media, UASB reactor, and SBR) were investigated. On the basis of the results, the main technological schemes in Estonia and the main types of reactors with main parameters for local treatment of the investigated industrial wastewater were recommended.

Key words: anaerobic, cheese whey, distillery, food industry, vegetable oil, UASB, yeast.

INTRODUCTION

Anaerobic wastewater treatment technologies are used throughout the world for effective treatment of a wide variety of industrial wastewaters, in particular to wastewaters from the food industry. The food industry is one of the major contributors of wastewater pollution. There are 70 small food processing enterprises in Estonia; some with very low flow rates. Some enterprises pump their wastewaters to municipal WWTPs, others have their own treatment plants. In many cases municipal WWTPs are rather old and inefficient. The quality of wastewater varies according to the branch of industry and mill type, but all wastewaters from food industries contain easily biodegradable organic matter. Most effluents are also rich in phosphorus and nitrogen, mostly originating from raw materials or products, but some also from washing.

The average wastewater concentrations from the food industry in Estonia are: biological oxygen demand (BOD_7) – 1177 mg L^{-1}, suspended solids (SS) –

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261 mg L^{-1}, total phosphorus (P_{tot}) – 19.1 mg L^{-1}, total nitrogen (N_{tot}) – 57.9 mg L^{-1}. The ratio BOD : N : P is 100 : 4.9 : 1.6.

The temperature of wastewaters from the food industry is higher than that of municipal wastewaters. Wastewaters from the food industry contain proteins, fats, lactose, etc. in high concentrations. Full utilization of all wastes on spot and their reuse at the manufactures are naturally the best methods for most food industry enterprises. However, these technologies are rather complicated and expensive to use in small enterprises. A biological waste treatment may be a good alternative in such cases.

In Estonia, aerobic processes are used mainly for municipal and industrial wastewater treatment. However, the wastes of food industries are categorized as medium strength organic wastewater, requiring a large amount of energy for aeration. Besides, a large amount of waste sludge is generated from these aerobic processes. On the other hand, anaerobic treatment technologies are used throughout the world for effective treatment of a wide variety of industrial wastewaters. The main advantages of the anaerobic treatment are low production of biological excess sludge, high treatment efficiency, low capital costs, no oxygen requirement, methane production (potential source of energy), low nutrient requirement [1]. A comparison of anaerobic and aerobic processes is shown in Fig. 1.

Anaerobic digestion is a complex biological process consisting of biodegradation of organic liquid or solid waste with biogas productions, mainly CH_4 and CO_2. Anaerobic digestion consists of four phases – hydrolysis, fermentation, acetogenesis, and methanogenesis. The IWA Anaerobic Digestion Model No 1 [2] differs from the classic four-phase scheme by an additional separate extracellular (partly non-biological) disintegration phase.

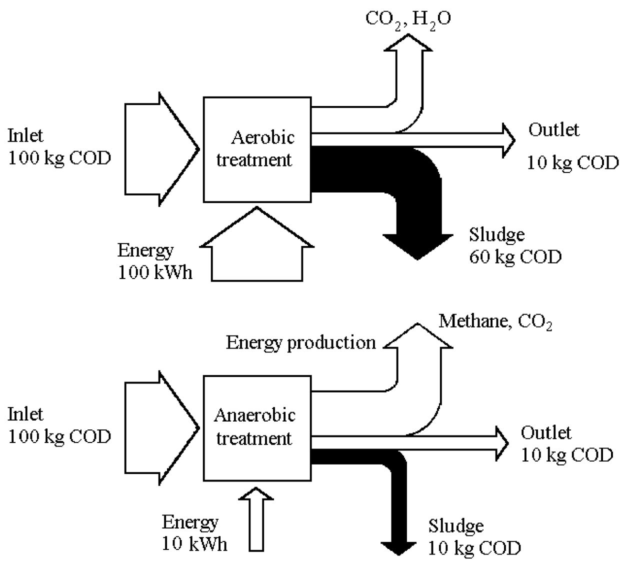

Fig. 1. Comparison of anaerobic and aerobic processes.

In anaerobic processes two important goals are achieved simultaneously: removal of organic matter and of sulphates (yeast industry wastewater). However, a high sulphate content can lead to destabilization of the process due to hydrogen sulphate formation [3]. Sulphate reducing bacteria interact competitively with other anaerobic bacteria involved in methanogenesis, resulting in the formation of H_2S rather than methane. On the other hand, despite the noted difficulties, anaerobic digestion has been successfully applied to a variety of sulphate-rich wastewaters both in laboratory and full-scale plants [4, 5] (see Fig. 2).

Table 1 summarizes the main parameters of the anaerobic treatment processes for wastewaters of the food industry [6–11].

One or two reactors (stages) can be used for the anaerobic digestion process. Separation of phases enables a selection of optimal conditions for both processes – (hydrolysis and methanogenesis) acid genesis/fermentation and acetogenesis/ methanogenesis. As known, methanogens are more active in the phase-separated set-up than in the single-phase system [5]. As fermentation proceeds at a much greater speed than acetogenesis/methanogenesis, the former is carried out in acidic conditions in a separate reactor.

The main aim of this study was to establish the application possibility and expected maximum efficiency of the anaerobic treatment process for food industry wastewater in Estonia by using reactors of different type.

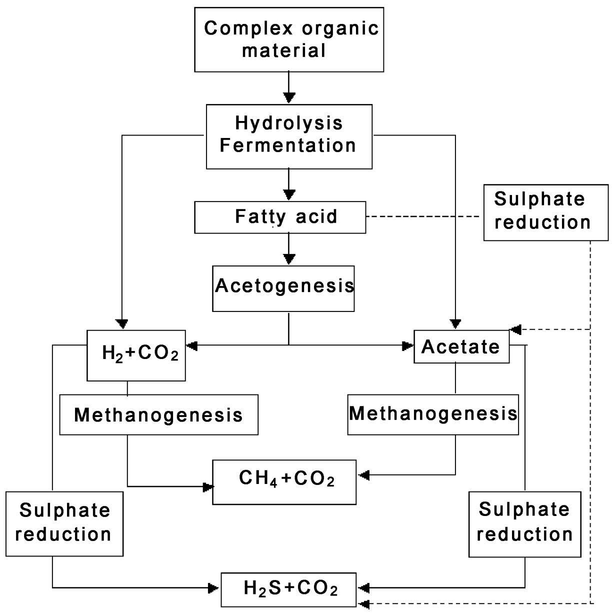

Fig. 2. Anaerobic treatment of sulphate containing wastewater [12].

Table 1. Main parameters for wastewater treatment from the food industry using anaerobic digestion processes

Industry	Type of the reactor[a]	Wastewater concentration, mgCOD L^{-1}	Load, kgCOD m^{-3} day^{-1}	HRT[b], h	COD removal, %
Beer	UASB	1 300–4 600	1.4–14.9	5.6–9	75–80
Starch	H	45 000	4	228	97
	AF	4 500	10.8	10	80
	UASB	10 000	15	18	90–95
Potatoes	AF	8 000	8	24–26	80–93
	H	7 500	11.6	16.3	70
Dairies	FB	28 000	7	24	80
	H	1 600	2	20	70
	UASB	3 000–33 000	12	65	85
Cheese	FB	3 200	22	2.4	70
	AF	40 000–70 000	8–15.6	96–120	82–85
	H	3 600	216	85	90
	UASB	3 000–4 500	3.5–15	6–8.2	92–95
Vegetable oil					
Olive mill	FB	40 000–47 100	–	5–50	87–94
Sunflower	–	21 320	–	8–15	48–62

[a] UASB – upflow anaerobic sludge blanket, H – hybrid, AF – anaerobic filter, FB – fixed bed processes.
[b] HRT – hydraulic retention time.
– No data.

MATERIALS AND METHODS

Anaerobic mesophilic (36 ± 1 °C) treatment of highly concentrated wastewater of the food industry was studied at a laboratory-scale plant. The experimental plant consisted of five-litre (total volume) reactors, a sedimentation tank, a feed tank, and a gas collection tank (Fig. 3). An electric heating mat wrapped around the external wall of the reactor maintained temperature.

The Standard Methods for Water and Wastewater Examination [13] were used to measure BOD_7, COD, SS, N_{tot}, P_{tot}, dry matter, alkalinity, and volatile fatty acids (VFA) of the wastewater and effluent. Flow rates, biogas production rate, temperature, and the effluent pH were measured daily.

The chemical characteristics of the studied wastewater are shown in Table 2.

As the efficiency of a high-load anaerobic treatment process is mainly determined by the start-up of the reactor, special attention was paid to the procedure. The temperature was kept at +36 ± 1 °C. Sludge seed for the reactors originated from the anaerobic digestions of Tallinn WWTP. The sludge was a mixture (3 : 1) of primary (dry solids 5.2%) and activated sludge (dry solids 0.5%). The seed sludge volume was 25% of the volume of the reactor. The wastewater dose was increased step-by-step, according to the reactor's pH and

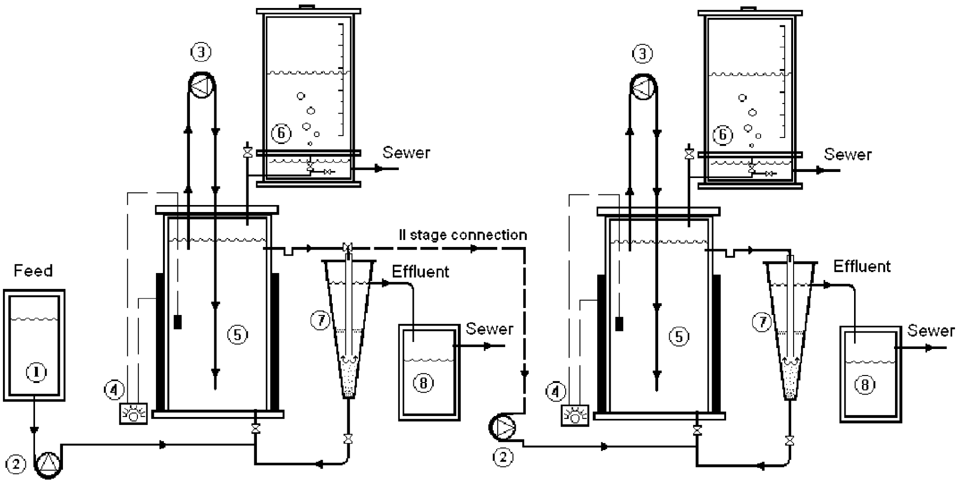

Fig. 3. Scheme of the experimental plant. 1 – feed tank, 2 – feed pump, 3 – circulation pump, 4 – temperature control, 5 – anaerobic reactor (working volume 4.5 L), 6 – gas collection tank, 7 – sedimentation tank, 8 – effluent tank.

Table 2. Chemical characteristics of the studied wastewaters by industry

Concentration of pollutants, mg L^{-1}	Cheese	Distillery	Yeast	Vegetable oil
BOD_7	35 500–46 000	24 000–27 000	7 700–8 700	–
COD	60 300–66 700	49 000–53 000	8 900–27 000	6 700–11 000
Dry matter	57 000–71 000	39 000–42 000	152 000–408 000	–
Suspendid solids	4 100–10 000	–	–	–
N_{tot}	–	975–1 320	798–1 260	35.6–85
P_{tot}	–	613–690	26–53	12.6–23.3
SO_4	–	–	2 640–5 000	–
Alkalinity, mEq L^{-1}	404–3 280	–	2.0–2.6	–
pH	3.8–6.3	5.2–7.6	~6.0	6.5

– No data.

hydraulic retention time. For the start-up of the laboratory-scale reactor under mesophilic conditions with the unadapted sludge as the inoculum a period of up to 3 months was needed. After a satisfactory start-up, the reactor was operated until a steady-state performance was reached as indicated by the constant gas production rate and effluent COD concentration.

RESULTS AND DISCUSSION

Cheese whey [14, 15]

Two schemes of the single-stage anaerobic reactor (contact process and UASB reactor) were studied.

Contact process

The hydraulic retention time (HRT) was reduced from 60 to up to 7 days and the effluent of COD 4.7 g L^{-1} was achieved. The sludge load was 4.3–18.3 kgCOD m^{-3} d^{-1} and the gas production was 0.28–0.59 L $kg^{-1}COD_{removal}$. COD removal was up to 83% (Fig. 4). The gas produced was composed of 76% methane, 20% carbon dioxide, and 4% nitrogen.

UASB

The HRT was reduced from 12 to up to 2.5 days and the effluent of COD 4.6 g L^{-1} was achieved. The sludge load was 0.5–9.0 kgCOD m^{-3} d^{-1} and the gas production was 0.20–18.5 L d^{-1} (Fig. 5). The gas produced was composed of 78% methane, 20% carbon dioxide, and 2% nitrogen. The degradation of organic matter was up to 98%. The UASB reactor was very effective for removing the biodegradable organic matter, but not for removing phosphate and ammonia. The effluent phosphorus and ammonia concentrations increased from 38.5 to 79 mgP_{tot} L^{-1} and from 190 to 638 mgN_{tot} L^{-1} during the experiments.

The UASB reactor proved to be a very reliable unit throughout the year (Fig. 6). No problems occurred with restarting the UASB reactor after a standstill over a period of some weeks.

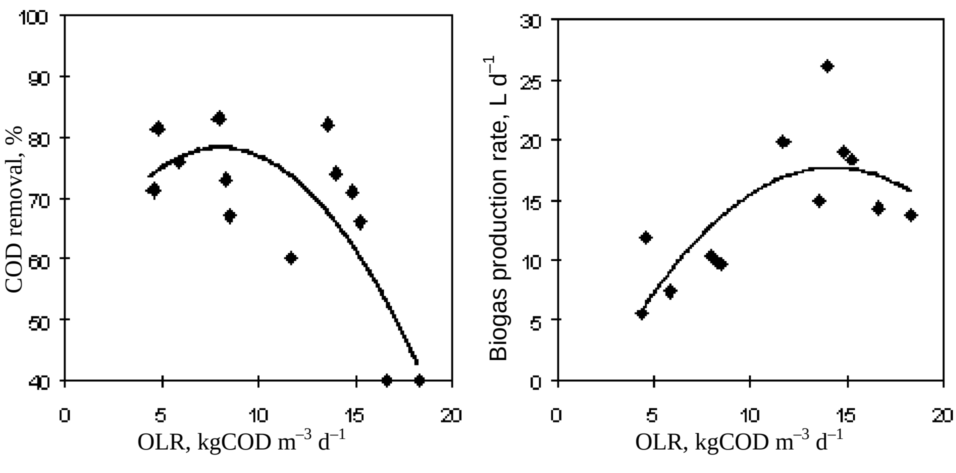

Fig. 4. Dependence of COD removal and biogas production on the organic loading rate (OLR).

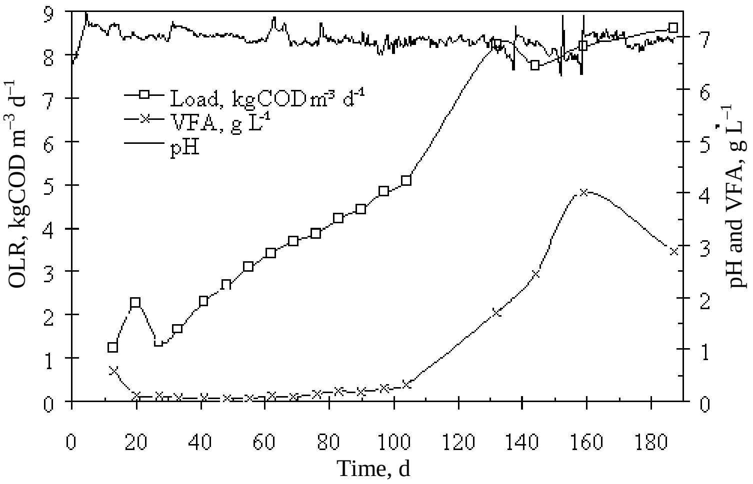

Fig. 5. Changes in the OLR, pH, VFA, and alkalinity in time.

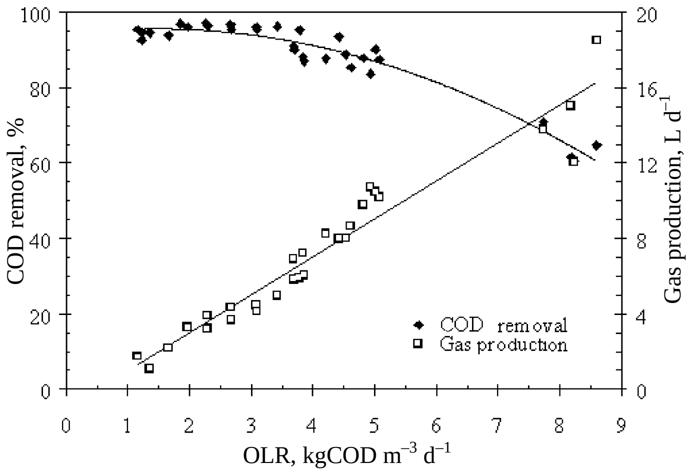

Fig. 6. COD removal and biogas production depending on OLR.

The laboratory-scale investigation demonstrated that the UASB reactor is highly effective for COD removal and energy recovery (via produced biogas) when treating cheese waste. The most important problem was to prevent washout of the active microbial biomass. Recirculation from the sedimentation tank to the anaerobic reactor was used to solve this problem.

Yeast [16, 17]

A two-stage system with an AF in the first stage and a UASB reactor in the second stage and a single-stage system with SBR were studied.

Two-stage system

Experiments were conducted with an HRT of 5 to 16 days and OLR of 0.6 to 4.3 kgCOD m^{-3} d^{-1} in the first stage and 9 to 15 days and 0.1 to 1.4 kgCOD m^{-3} d^{-1} in the second stage. The COD removal efficiency was 87% and 70% in the first and the second stage, respectively. The sulphate removal efficiency was 98%, of which up to 91% was removed (converted to sulphides) in the first reactor (Fig. 7). The content of H_2S in biogas was 2.8%.

Experiments showed that a high pH value together with high sulphide concentrations inhibits the growth of methanogenes and leads to a decrease in the biogas production.

Anaerobic treatment is considered as a feasible treatment method for sulphate-rich wastewaters. It was shown that sulphate reduction, as well as methanogenesis, took place predominantly in the first stage of the two-stage digestion scheme. In the case of the two-stage scheme the total sulphate removal was 98%, and COD removal was up to 88%.

Anaerobic single-stage sequence batch reactor (SBR) [16]

The anaerobic SBR worked on fixed cycles of 24 h made up of 23 h of reaction–agitation, 0.5–0.7 h of rest for settling, and 0.3 h for filling and drawing. The COD removal of up to 82%, sulphate removal of 99%, methane concentration of up to 60%, CO_2 up to 35%, H_2S up to 2.7%, and OLR optimal 7.7 kgCOD m^{-3} d^{-1} were received (Fig. 8). The sludge concentration was 13–15 g total solids. The main problem was that a long-time exploitation of the reactor led to decreasing purification efficiency as a result of the formation of insoluble sediment (presumably of $CaCO_3$ and $Ca_3(PO_4)_2$) on the bottom of the reactor. For successful application of SBR it is necessary to find a way to remove the inorganic precipitate from the reactor.

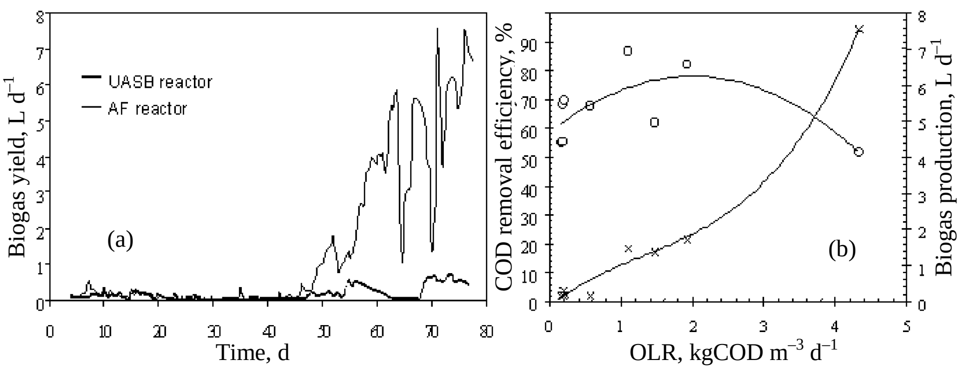

Fig. 7. (a) Biogas production in the first stage (AF) and in the second stage (UASB) and (b) COD removal efficiency and biogas production as a function of OLR in AF: ○ – COD removal, × – biogas production.

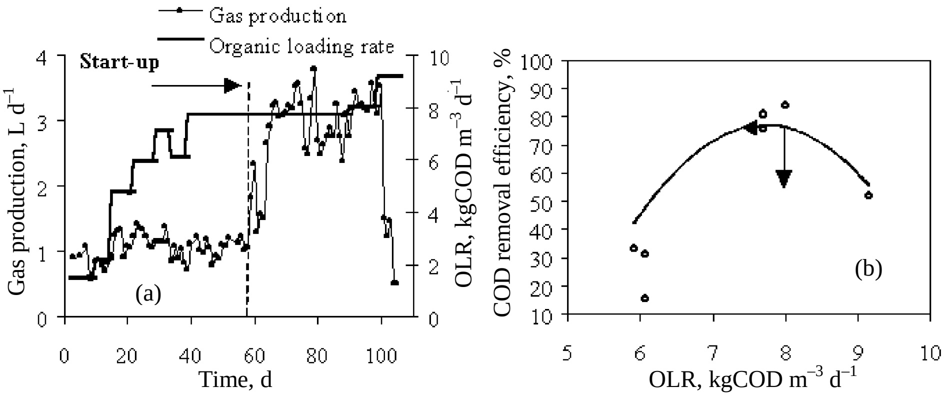

Fig. 8. (a) Biogas production and OLR during the experiment and (b) relationship between COD removal and OLR.

The results of the study carried out demonstrated that the anaerobic sequencing batch reactor (ASBR) is suitable and effective for anaerobic degradation of sulphate-rich wastewaters from baker's yeast production. Biomass scaling and fast accumulation of inorganic compounds were detected during the experiment.

Distillery [18]

A two-stage system with an AF as the first stage and a UASB reactor as the second stage were studied. According to the local distillery technology, dry solids were removed with centrifugation at 1500 rpm during 15 min.

Two-stage system

Experiments were conducted with the HRT of 10–19 days, OLR 2.5–5.1 kgCOD m^{-3} d^{-1} in the first stage and with the HRT of 20–39 days, OLR 0.6–2.5 kgCOD m^{-3} d^{-1} in the second stage. The COD removal efficiency was 54% and 93% in the first and the second stage, respectively (Fig. 9). The acidogenic reactor provided satisfactory conversion of initial COD to VFA, averaging 20.5%.

The used two-stage set-up is suitable for anaerobic digestion of distillery waste, enabling better conditions for the methanogenic phase. Control of acidogenesis in the first stage ensures greater stability of methanogenesis in the second stage. The optimum conditions recommended for stable work of the reactor are: for the acidogenic stage organic loading 2.5–3.5 kgCOD m^{-3} d^{-1} at pH 6.0 and for the methanogenic stage organic loading 1–2 kgCOD m^{-3} d^{-1} at pH 7.6.

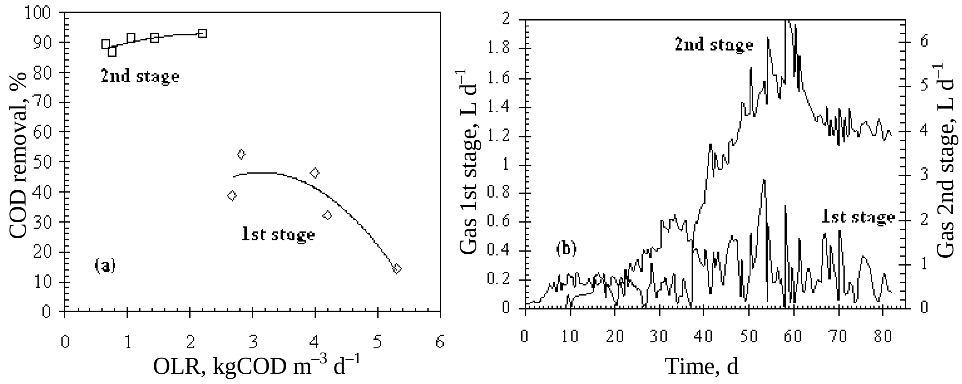

Fig. 9. (a) COD removal efficiency depending on OLR and (b) biogas production during the experiment.

Vegetable oil

First experiments were carried out with single-stage processes – first as AF and secondly as FB. The second experiments were carried out with the two-stage process – both stages were operated as a fixed bed filter.

Single-stage system

The sludge load was 0.1–1.4 kgCOD m^{-3} d^{-1} in the first anaerobic filter and 0.1–2.2 kgCOD m^{-3} d^{-1} in the fixed bed filter. The HRT changed from 80 up to 12 days in the scheme with the fixed bed filter and from 90 up to 7 days in the scheme with the filter. The highest volume of biogas production (180 L kg added COD^{-1} d^{-1} in the first reactor and 220 L kg added COD^{-1} d^{-1} in the second reactor) and the best results with COD removal were received from the fixed bed filter (Figs 10 and 11). The methane content was 55%.

Two-stage system

Experiments were conducted with the HRT of 1–1.5 days, OLR 6–9 kgCOD m^{-3} d^{-1} in the first stage and 3–4 days at ORL 1.6–2 kgCOD m^{-3} d^{-1} in the second stage. The total volume of biogas production was 340 L kg added COD^{-1} d^{-1} (Fig. 12). The methane content was 55%. COD removal of up to 85% was achieved.

The investigated parameters of the anaerobic treatment processes are shown in Table 3.

A comparison of data presented in Table 3 with the literature data for various anaerobic treatment systems of food industry wastewater (see Table 1) indicated that these results are among the best in terms of treatment efficiencies and significantly surpass the other treatment system previously described on the basis of the OLR achieved.

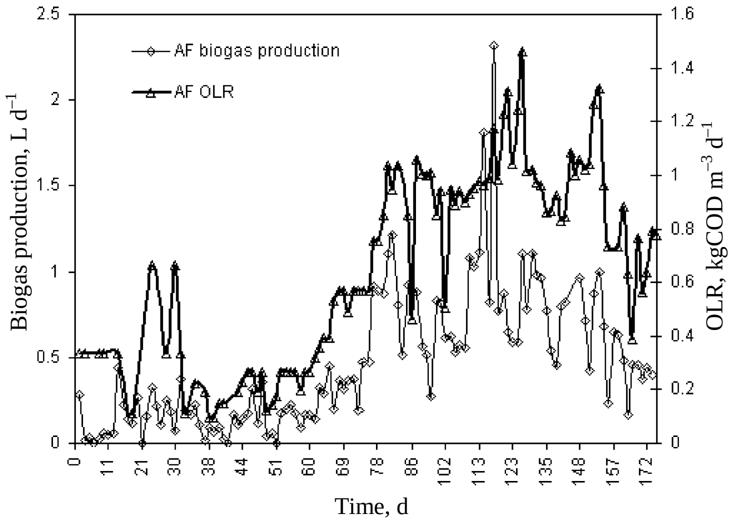

Fig. 10. Biogas production and OLR changes in time in the scheme with a filter.

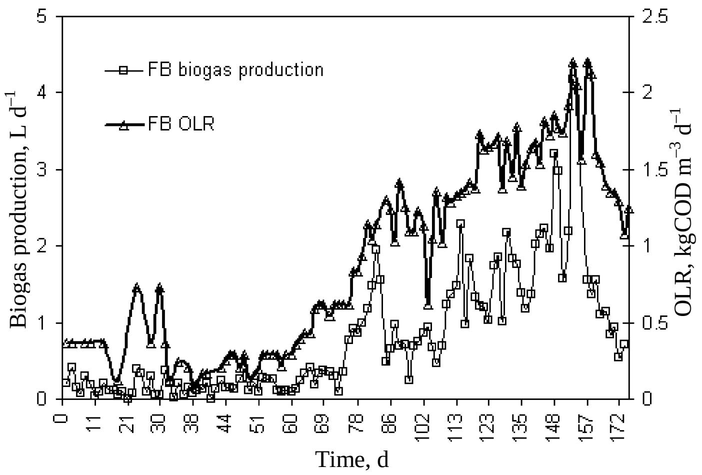

Fig. 11. Biogas production and OLR changes in time in the scheme with a fixed bed filter.

The main results of our investigation and recommended type of reactors for different types of food industry wastewaters are presented in Table 4 and Fig. 13.

As shown in Tables 3 and 4 and Fig. 13, the UASB reactor may be recommended for the treatment of all types of wastes in the food industry. The main problem is proper granular sludge and its immobilization. Therefore, additional investigations are necessary.

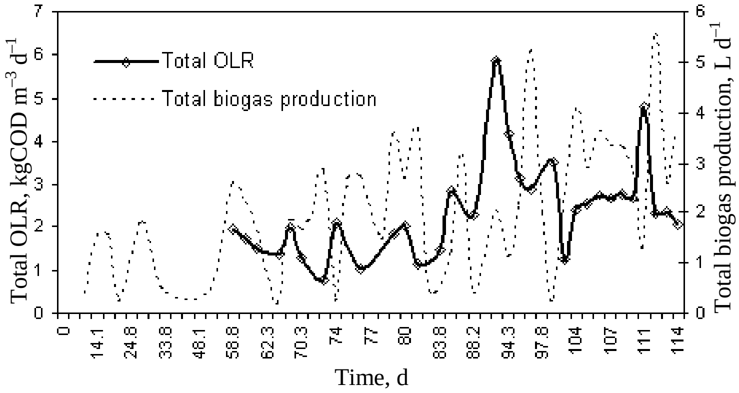

Fig. 12. OLR and biogas production in time.

Table 3. The main investigated parameters of the anaerobic treatment process

Reactor type	Origin of wastewater	HRT, days	Sulphate removal, %	Load, kgCOD m^{-3} d^{-1}	COD removal, %	Biogas production
Contact process	Cheese whey[a]	5–10	–	4.32–18.28	40–83	0.28–0.59 L kg^{-1} $COD_{removal}$
UASB	Cheese whey[a]	2.5–12	–	0.5–16	58–98	0.212–0.814 L kg^{-1} $COD_{removal}$
AF	Yeast[b]	5–16	91	0.6–4.3	52–87	7.5 L d^{-1}
UASB	Yeast[b]	9–15	–	0.1–1.4	50–70	0.6 L d^{-1}
SBR	Yeast[a]	1	99	7–8	82	3.85 L d^{-1}
AF	Distillery[b]	10–19	–	2.5–5.1	54	7.0 L d^{-1}
UASB	Distillery[b]	20–39	–	0.6–2.5	93	
AF	Vegetable oil[a]	80–12	–	0.1–1.4	85	180 L added $kgCOD^{-1}$ d^{-1}
FB	Vegetable oil[a]	90–7	–	0.1–2.2	85	220 L added $kgCOD^{-1}$ d^{-1}
FB	Vegetable oil[b]	1–1.5	–	6–9	85	340 L added $kgCOD^{-1}$ d^{-1}
FB	Vegetable oil[b]	3–4	–	1.6–2	–	

[a] One-stage system.
[b] Two-stage system.
– No data.

The recommended OLR for 85% COD removal in the UASB reactor were: 5.3 kgCOD m^{-3} d^{-1} for cheese whey, 3.5 kgCOD m^{-3} d^{-1} for yeast, and 1.5 kgCOD m^{-3} d^{-1} for distillery wastewaters.

Table 4. Recommended types of reactors for anaerobic treatment of food industry wastewaters according to the present results

Type of industry	Contact process	UASB	AF	FB	SBR
Cheese whey	o[a]	+[a]	–	–	–
Distillery	–	o[b]	o[b]	–	–
Yeast	–	o[b]	o[b]	–	o[a]
Vegetable oil	o[a]	–	–	+[a]	–

+ Recommended; o medium; – not investigated.
[a] One-stage system.
[b] Two-stage system.

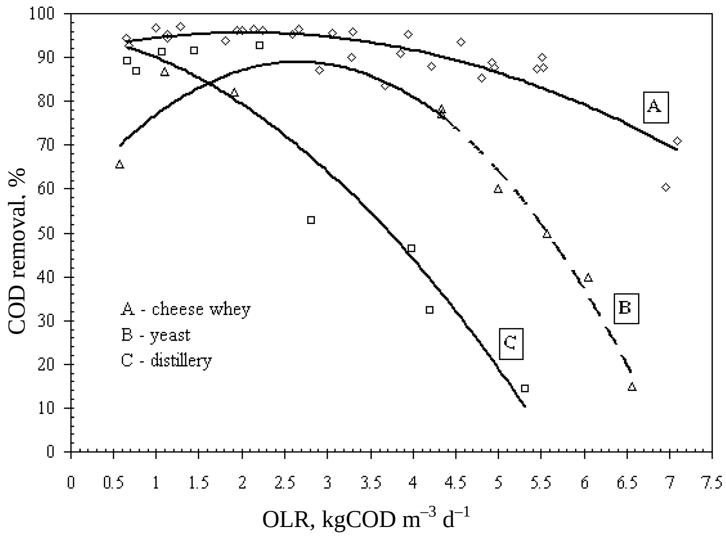

Fig. 13. COD removal versus OLR in the UASB reactor for different wastewaters.

CONCLUSIONS

The anaerobic process can be useful for effective treatment of a wide variety of industrial wastewaters. For the start-up of the laboratory-scale reactor under mesophilic conditions with the unadapted sludge as the inoculums a period of up to 3 months was needed.

The UASB reactor was quite efficient for the removal of COD (90–98%) from cheese whey (the average OLR varied from 5 to 7 kgCOD m^{-3} d^{-1}). The SBR can be used for the removal of COD (75–82%) and sulphate (up to 99%) for wastewaters of baker yeast industries (OLR 7.7 kgCOD m^{-3} d^{-1}).

The two-stage anaerobic mesophilic treatment was efficient for the removal of COD (up to 90%) from distillery wastewater. AF (OLR 2–4 kgCOD m^{-3} d^{-1}) can be used as a first stage and UASB reactor (OLR 1–2 kgCOD m^{-3} d^{-1}) as a second stage.

The FB with a special surface of plastic media 180 m^2 m^{-3} can be used for the removal of COD (up to 85%) from vegetable oil wastewater (OLR 0.1–2.2 kgCOD m^{-3} d^{-1}).

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Eesti toiduainetööstuse reovee käitluse uuringud erinevate anaeroobsete puhastustehnoloogiatega

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TTÜ Keskkonnatehnika Instituudis on viimase viie aasta jooksul uuritud pärmi-, juustu-, piirituse- ja taimeõlitööstuse reovee anaeroobset mesofiilset degradatsiooniprotsessi temperatuurirežiimil. On uuritud nii ühe- kui ka kaheastmelist tehnoloogilist skeemi erinevate reaktoritüüpidega (kontaktprotsess, anaeroobne filter, kandekihiga täidisreaktor, UASB-tehnoloogia, SBR). Erinevat tüüpi reovete käitluseks on esitatud optimaalsed tehnoloogilised parameetrid.