Integrated biological (anaerobic–aerobic) and physico-chemical treatment of baker's yeast wastewater

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Abstract The UASB reactor (35 °C) was quite efficient for removal of bulk COD (52–74%) from simulated (on the basis of cultivation medium from the first separation process) general effluent of baker's yeast production (the average organic loading rates varied from 8.1 to 16 g COD/l/d). The aerobic-anoxic biofilter (19–23 °C) can be used for removal of remaining BOD and ammonia from anaerobic effluents; however, it suffered from COD-deficiency to fulfil denitrification requirements. To balance COD/N ratio, some bypass (~10%) of anaerobically untreated general effluent should be added to the biofilter feed. The application of iron (III)-, aluminium- or calcium-induced coagulation for post-treatment of aerobic-anoxic effluents can fulfil the limits for discharge to sewerage (even for colour mainly exerted by hardly biodegradable melanoidins), however, the required amounts of coagulants were relatively high.

Keywords Aerobic-anoxic biofilter; baker's yeast wastewater; iron coagulation; melanoidins; UASB reactor

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Introduction

Baker's yeast industry represents a substantial threat for environment in Russia due to the large volume of wastewater generated (56 Mm^3/year) and its high contamination potential (Kalyuzhnyi *et al.*, 2003). The general effluent from typical Russian yeast factory usually contains 7–12 g COD/l, 0.5–11 g/l total N and sulphate as well a significant amount of recalcitrant for biodegradation and highly coloured melanoidin and phenolic substances (Koshel *et al.*, 1992; Kalyuzhnyi *et al.*, 2003). Since land disposal of such contaminated wastewater is banned in Russia, currently many yeast factories are faced with heavy trade-effluent charges because a majority of local municipal sewage treatment plants insist on pre-treatment of such effluents before discharge into their sewerage. The objective of this paper was to develop a lab-scale technology for treatment of simulated (on the basis of cultivation medium from the first separation process, CM-1S) general effluent of baker's yeast factory to meet the limits for discharge of treated wastewater into municipal sewerage. The most troublesome limits in this case are the following (mg/l, except colour): COD – 800; SO_4^{2-} – 500; total N – 100; N-NH_3 – 50; P–PO_4^{3-} – 3.5; colour – optical density <0.1 at dominant wavelength. As a first treatment step, the UASB reactor operating at 35 °C was applied for the elimination of the major part of COD and concomitant sulphate reduction. In a subsequent step, the biofilter operating in alternative aerobic-anoxic regime at ~19–23 °C was used for the removal of remaining BOD and nitrogen. Finally, coagulation with Fe, Al and Ca was tested to fulfil the limits on COD, total nitrogen, PO_4^{3-} and colour.

Materials and methods

Wastewater. A general effluent of yeast factory was simulated by tap water dilution (in 2–3 times) of CM-1S representing the major (~30% of total volume wastewater produced) and the strongest stream from such factories (Koshel *et al*., 1992). Some characteristics of CM-1S taken from Moscow baker's yeast factory during February–March, 2003 and used in this study are presented in Table 1.

Laboratory reactors. Details of UASB reactor and aerobic-anoxic biofilter used here are described previously (Gladchenko *et al*., 2004). The UASB reactor was kept in the thermostat (35 ± 1 °C) and was seeded with granular sludge (66.5 g VSS, specific aceticlastic activity −0.3 g COD/g VSS/day) from the full-scale EGSB reactor treating brewery wastewater (Efes-Moscow). The biofilter operated at 19–23 °C with attached nitrifying-denitrifying biomass formed during the previous research (Gladchenko *et al*., 2004) was directly used for treatment of anaerobic effluents in this study.

Coagulation assays. They were performed with 200 ml of biofilter effluent in a laboratory glass under continuous stirring and pH control. Addition of coagulant ($FeCl_3 \cdot 6H_2O$, $AlCl_3$ or CaO) was carried out under 200 rpm, then stirring intensity was reduced to 40 rpm to complete a flocculation process during which pH was maintained at 7.2–7.5 for Fe and Al as well as at 8.0–8.5 for Ca., The percentage of sludge formed and the sludge volume index (SVI) was determined after 30 min settling. To enhance coagulation, polyelectrolyte Praestol 650 BC (Stockhausen, Germany) was tested at concentrations 5–78 mg/l

Analyses. Sampling of treated wastewater for analysis was usually started after 3 hydraulic retention times (HRT) after change of working regime to ensure reactors operation in quasi steady-state conditions. All analyses were performed by *Standard Methods* (1995) or as described previously (Gladchenko *et al*., 2004). Statistical analysis of data was done using Microsoft Excel.

Results and discussion

UASB reactor performance

In the preliminary experiments, it was found that the simulated general effluent was quite biodegradable in anaerobic conditions (>80% on COD basis). Some results of the mesophilic UASB treatment (35 °C) of this effluent under quasi-steady state operation are shown in Figure 1. It can be seen that a stepwise increase of organic loading rate (OLR) from 8.1 to 16 g COD/l/d led to a decrease of total COD removal from 74 to 52% (Figure 1a). These results are in accordance with literature data on anaerobic treatment of baker's yeast wastewater (Van Der Merwe and Britz, 1993; Van Der Merwe-Botha

Table 1 Range of variation of some characteristics of the CM-1S (average values from 5 samplings are given in brackets)

COD_{tot}, g/l	COD_{SS}, g/l	COD_{col}, g/l	COD_{sol}, g/l	pH
20.3–31.1 (25.7)	0.95–2.93 (1.94)	0.82–1.57 (1.20)	18.5–26.6 (22.6)	4.01–4.99 (4.50)
Total N, mg/l	N-NH_3, mg/l	Total P, mg/l	P-PO_4, mg/l	SO_4, mg/l
1,075–1,651 (1,363)	235–450 (342)	13–78 (46)	6–32 (19)	1,245–2,267 (1,756)
Phenolic compounds, mg/l	Dominant wavelength, nm	Colour purity, %	Colour luminance, %	OD_{580}
713–1,167 (940)	580	48.0–52.8 (50.4)	46.2–50.2 (48.2)	0.76–0.88 (0.82)

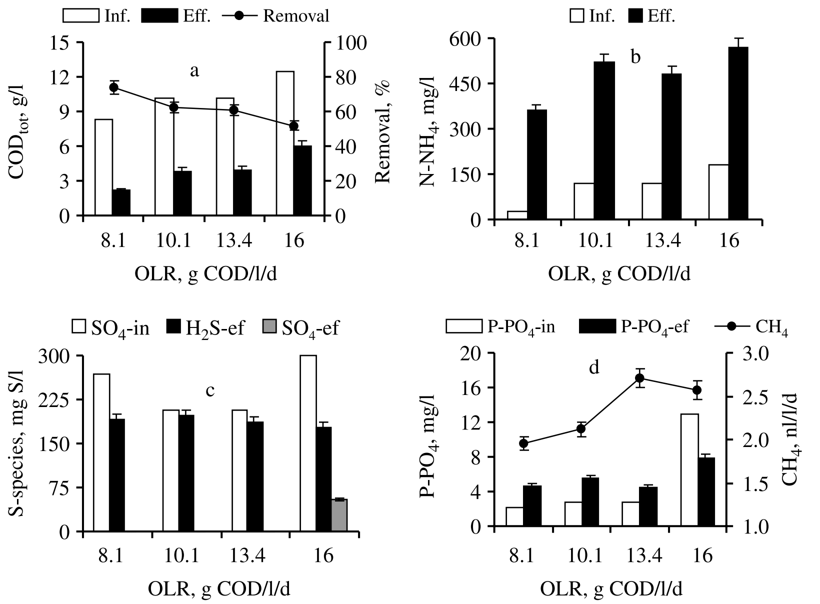

Figure 1 Performance of the UASB reactor treating the simulated general effluent of yeast factory: a) influent and effluent total COD and its removal; b) influent and effluent ammonia; c) influent and effluent sulphate and effluent sulphide; d) influent and effluent phosphate and specific methane production

and Britz, 1997; Inanc *et al.*, 1999; Radrigan *et al.*, 2002; Kalyuzhnyi *et al.*, 2003). Only traces of VFA were detected in the effluents (data not shown). However, such exhaustion of easily biodegradable COD in the anaerobic effluents might create COD deficiency problems for subsequent biological nitrogen removal. In spite of acidic influent pH fed, the effluent pH was close to 8 as a result of VFA consumption and mineralisation of nitrogenous species to ammonia (Figure 1b). The specific methane production was around or higher (Figure 1d) the theoretically expected values taking into account the observed COD removal and concomitant sulphate reduction (Figure 1c). The observed higher methane production can be attributed to the presence of betaine in the influents, which is not measured in the COD analysis (Radrigan *et al.*, 2002). The concentrations of phosphate increased (except OLR of 16 g COD/l/d) in the effluents (Figure 1d) due to mineralisation of phosphoric species. On the contrary, a development of biological sulphate reduction led to an almost complete disappearance of sulphate in the UASB reactor (Figure 1c). The latter is almost quantitatively recovered as soluble sulphide (Figure 1c). The observed sulphide concentrations seem to be non-inhibitory for anaerobic sludge, which was a concern for some other studies (Lo and Liao, 1990; Lo *et al.*, 1990). The concentration of phenolic compounds and colour almost did not change (data not shown) showing that phenols and substances responsible for colour are persistent in anaerobic conditions.

Performance of alternative aerobic-anoxic biofilter

During direct treatment of UASB effluents in biofilter (after optimisation of durations of aerobic and anoxic phases which were 25 and 35 min, respectively), the following results were obtained (Figure 2, run 1). It is seen that the average total COD and ammonia removals accounted for 68% and 94%, respectively. However, the effluent nitrate concentrations were relatively high (207 mg N/l, on average) that was related with COD deficiency to have a stable denitrification – some part of incoming COD (~1.15 g/l, Table 4, run 1) was non-biodegradable in neither aerobic nor anoxic conditions.

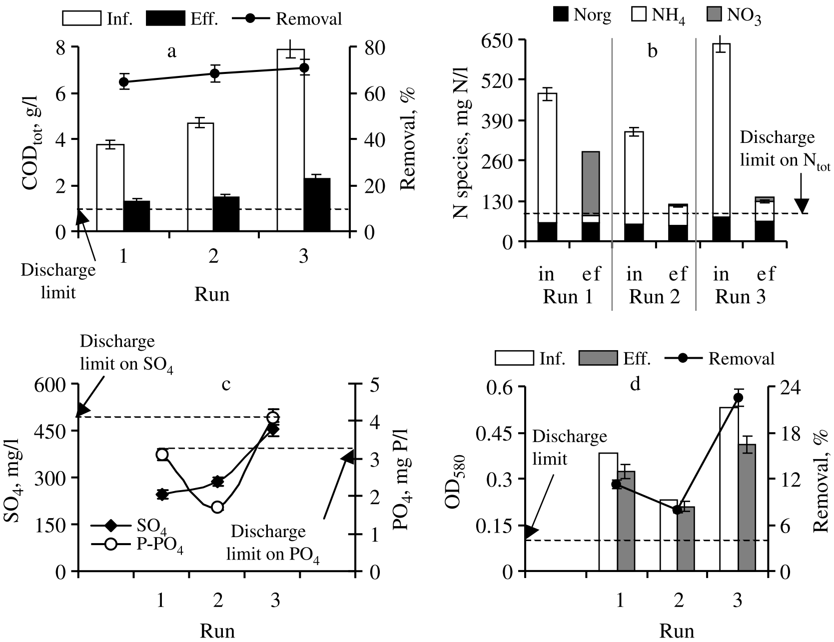

Figure 2 Performance of the aerobic-anoxic biofilter treating the UASB effluents (during runs 2–3, 10% of anaerobically untreated wastewater was added to the feed to balance COD/N ratio for denitrification): a) influent and effluent total COD and its removal; b) influent and effluent nitrogen species; c) effluent sulphate and phosphate; d) influent and effluent OD_{580} and its removal

To balance COD/N ratio, 10% of anaerobically untreated general effluent was added to the biofilter feed during runs 2–3 (durations of aerobic and anoxic phases were 35–40 and 25–20 min, respectively). This led to a substantial decrease of nitrate but some increase of ammonia in aerobic effluents (Figure 2b, runs 2–3). It seems that it is hardly possible to reach a lower level of ammonia in the effluent due to an immanent drawback of this relatively simple biofilter construction where wastewater filling and effluent withdrawal were performed simultaneously in a CSTR regime. The better performance can be expected under disruption of filling and withdrawal phases in the biofilter as in sequencing batch biofilm reactor (SBBR) constructions. Though during runs 2–3 the total inorganic nitrogen concentrations were around 70 mg N/l, the aerobic effluents also contained significant concentrations (52–65 mg N/l) of organic nitrogen (seems to be hardly biodegradable) resulting in total nitrogen concentrations above 120 mg N/l (Figure 2b), i.e., higher than discharge limit to sewerage (100 mg N/l). The total COD concentrations during runs 2–3 were close to the biodegradability limit of the baker's yeast wastewater but higher (Figure 2a) than the discharge limit to sewerage (800 mg/l). Sulphate and phosphate concentrations in the biofilter effluents (Figure 2c) were below or close to the discharge limits − 500 mg/l and 3.5 mg P/l, respectively. In spite of 63% removal of phenolic compounds during aerobic-anoxic stage (data not shown), colour removal accounted for only 8–23% (Figure 2d). This is in accordance with our own (Gladchenko *et al.*, 2004) and literature data (Francisca Kalavathi *et al.*, 2001) that the visible colour is mainly associated with the other substances than phenolic compounds namely, with persistent to biodegradation melanoidins.

Performance of iron coagulation step

Preliminary study (Gladchenko *et al.*, 2004) on the application of iron coagulation for post-treatment of biofilter effluents showed that all targeted parameters (total COD and nitrogen, phosphate, ammonia and colour) decreased with increasing acting Fe concentrations and the discharge limits are already achievable under iron concentrations around 200 mg/l. In order to further optimise an iron coagulation step, an influence of polyelectrolyte (PE) addition was researched (Figure 3). It is seen that the addition of PE has a positive influence on total COD and especially on colour removals (Figure 3a) as well as on quality of sludge formed (Figure 3b). Taking into account a relatively high cost of PE, further experiments were carried out with PE concentration of 10 mg/l.

From Table 2, it is seen that though all discharge limits can be ultimately met only under iron concentration of 275 mg/l, reasonable results (only total COD exceeds a discharge limit (800 mg/l)) were already observed under Fe concentration of 193 mg/l (+10 mg/l PE) (Table 2). The sludge formed under these conditions was reasonably voluminous (SVI = 418 ml/g TSS) and had 49% of VSS content (Table 2). Further increase of Fe added led to a decrease of VSS content of sludge and to a decrease of residual iron in treated water (Table 2). Since there is a discharge limit for Fe (3 mg/l) in Russia, which is difficult to meet, the coagulation step was further researched with Al and Ca limits for which are much less strict.

Performance of aluminium coagulation step

From Tables 3–4, it is seen that the PE addition had a slight influence on performance of Al coagulation. All the discharge limits can be ultimately met under Al concentration of around 540 mg/l (Tables 3–4) though the reasonable results (only total COD slightly exceeds a discharge limit) were already observed under Al concentration of 372 mg/l (+10 mg/l PE) especially on colour removal and the SVI of sludge formed (Table 4). Moreover, half of the colour was removed even at Al concentration of 193 mg/l (+10 mg/l PE) (Table 4). However, the sludge volume is too large (Tables 3–4) and this might create problems for its dewatering and disposal.

Performance of calcium coagulation step

The PE addition also did not have a significant influence on performance of Ca coagulation (Tables 5–6). Though Ca was not able to fulfil a COD limit (800 mg/l) even at its highest concentration applied, this coagulant was quite efficient for colour removal and the formed sludges had low SVIs (Tables 5–6). Taking into account a low cost of CaO, this may also be an option for post-treatment of anaerobic-anoxic effluents.

Comparative coagulation studies with Fe, Al and Ca showed that the latter coagulant may be considered as an option for post-treatment of aerobic-anoxic effluents taking into account non-strict limits for this ion (compared to Fe) for discharge into sewerage and relatively low volume of sludge generated (compared to Al). However, generally coagulation seems to be an expensive step taking into account expenses for chemicals and sludge disposal. Thus, there is a need for development of cheaper alternatives for

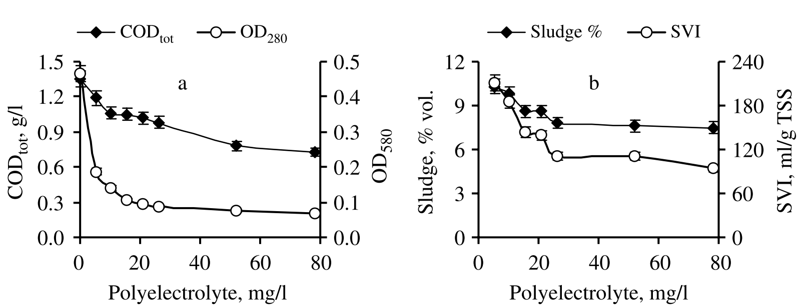

Figure 3 Influence of polyeletrolyte addition on performance of iron coagulation step (98 mg/l Fe): a) total COD and colour decrease; b) sludge percentage and SVI

Table 2 Performance of iron coagulation step with addition of 10 mg/l PE

Parameters	Acting Fe concentration, mg/l					
	0	98	193	275	375	465
COD_{tot}, mg/l	1,810	1,390	1,050	800	710	630
Phenols, mg/l	122	87	68	60	53	47
$P\text{-}PO_4$, mg/l	1.79	0.04	Traces	Traces	Traces	Traces
N_{tot}, mg/l	121.1	99.5	75.0	66.1	58.2	54.7
$N\text{-}NH_3$, mg/l	61.3	54.8	49.5	49.0	45.0	42.1
$N\text{-}NO_3$, mg/l	8.0	6.9	6.5	6.2	6.0	5.8
N_{org}, mg/l	51.9	33.2	19.0	10.9	7.2	6.8
Residual Fe_{tot}, mg/l	0	51.6	20.9	11.0	5.5	4.7
OD_{580}	0.219	0.184	0.108	0.074	0.07	0.066
Dominant wavelength, nm	578	580	578	577	577	577
Purity, %	29.4	25.3	19.1	16.5	15.9	15.3
Luminance, %	76.1	77.3	86.2	89.5	90.0	90.5
Sludge percentage, % vol.	–	45.0	46.4	49.6	51.6	54.5
SVI, ml/g TSS	–	777	418	316	285	260
Sludge VSS/TSS, %	–	48.6	46.3	41.6	37.4	32.9

Table 3 Performance of aluminium coagulation step without addition of PE

Parameters	Acting Al concentration, mg/l					
	0	195	375	545	702	850
COD_{tot}, mg/l	1,810	1,040	900	780	760	720
Phenols, mg/l	122	79	67	55	53	49
$P\text{-}PO_4$, mg/l	1.79	0.14	Traces	Traces	Traces	Traces
N_{tot}, mg/l	121.1	89.6	78.1	69.9	63.2	61.2
$N\text{-}NH_3$, mg/l	61.3	60.8	58.6	56.3	52.9	52.1
$N\text{-}NO_3$, mg/l	8.0	7.4	7.0	6.8	6.4	6.0
N_{org}, mg/l	51.9	21.4	12.5	6.8	3.9	3.1
OD_{580}	0.219	0.138	0.122	0.078	0.062	0.052
Dominant wavelength, nm	578	577	575	575	577	578
Purity, %	29.4	19.7	15.3	15.9	13.5	14.1
Luminance, %	76.1	83.8	86.4	86.1	92.5	91.5
Sludge percentage, % vol.	–	90.7	92.1	93.5	94	93.9
SVI, ml/g TSS	–	501	342	220	179	169
Sludge VSS/TSS, %	–	51.2	54.0	47.1	38.4	51.9

Table 4 Performance of aluminium coagulation step with addition of 10 mg/l PE

Parameters	Acting Al concentration, mg/l					
	0	193	372	540	697	845
COD_{tot}, mg/l	1,810	1,000	830	760	720	700
Phenols, mg/l	122	71	56	49	48	45
$P\text{-}PO_4$, mg/l	1.79	Traces	Traces	Traces	Traces	Traces
N_{tot}, mg/l	121.1	88.0	75.5	65.8	62.1	59.6
$N\text{-}NH_3$, mg/l	61.3	59.5	49.5	48.4	47.1	45.5
$N\text{-}NO_3$, mg/l	8.0	7.3	7.0	6.8	6.4	6.0
N_{org}, mg/l	51.9	21.2	19.5	10.6	8.6	8.1
OD_{580}	0.219	0.112	0.070	0.062	0.061	0.056
Dominant wavelength, nm	578	578	577	577	577	577
Purity, %	29.4	20	14.7	14.4	14.4	13.5
Luminance, %	76.1	85.5	90.7	91.2	91.2	92.1
Sludge percentage, % vol.	–	93.8	93.7	93.5	93.4	93.6
SVI, ml/g TSS	–	509	322	228	176	155
Sludge VSS/TSS, %	–	40.0	78.9	42.3	35.3	39.9

Table 5 Performance of calcium coagulation step without addition of PE

Parameters	Acting Ca concentration, mg/l				
	0	1463	1790	2102	2689
COD_{tot}, mg/l	1,810	1,620	1,490	1,390	1,150
Phenols, mg/l	122	58	49	49	47
$P\text{-}PO_4$, mg/l	1.79	Traces	Traces	Traces	Traces
N_{tot}, mg/l	121.1	90.2	61.1	59.0	54.8
$N\text{-}NH_3$, mg/l	61.3	56.5	52.2	49.4	47.8
$N\text{-}NO_3$, mg/l	8.0	7.5	6.9	6.5	6.0
N_{org}, mg/l	51.9	26.2	2.2	3.1	1.0
OD_{580}	0.219	0.062	0.052	0.05	0.046
Dominant wavelength, nm	578	575	575	575	575
Purity, %	29.4	15.3	15.0	13.5	11.2
Luminance, %	76.1	91.1	91.9	92.5	93.8
Sludge percentage, % vol.	–	98.8	32.2	36.4	37.0
SVI, ml/g TSS	–	402	118	116	118
Sludge VSS/TSS, %	–	54.6	38.9	29.2	13.0

Table 6 Performance of calcium coagulation step with addition of 10 mg/l PE

Parameters	Acting Ca concentration, mg/l				
	0	1451	1776	2083	2667
COD_{tot}, mg/l	1,810	1,600	1,400	1,300	1,090
Phenols, mg/l	122	58	48	45	45
$P\text{-}PO_4$, mg/l	1.79	Traces	Traces	Traces	Traces
N_{tot}, mg/l	121.1	87.9	60.2	56.5	52.7
$N\text{-}NH_3$, mg/l	61.3	54.2	51.4	47.7	44.7
$N\text{-}NO_3$, mg/l	8.0	7.4	6.9	6.5	6.0
N_{org}, mg/l	51.9	26.3	2.9	2.3	2.0
OD_{580}	0.219	0.054	0.048	0.046	0.042
Dominant wavelength, nm	578	575	575	575	573
Purity, %	29.4	14.1	13.2	13.2	10.0
Luminance, %	76.1	92.0	92.8	92.9	94.4
Sludge percentage, % vol.	–	98.0	29.1	34.7	35.3
SVI, ml/g TSS	–	388	109	112	115
Sludge VSS/TSS, %	–	47.0	36.9	27.3	8.0

*after 30 min of settling

decolourisation and organic nitrogen removal of aerobic-anoxic effluents, e.g., application of cyanobacteria, which are able to degrade melanoidins (Francisca Kalavathi *et al.*, 2001).

Conclusions

The UASB reactor was quite efficient for removal of bulk COD (52–74%) from simulated general effluent of baker's yeast production.

The aerobic-anoxic biofilter can be used for removal of remaining BOD and ammonia from anaerobic effluents; however, it suffered from COD-deficiency to fulfil denitrification requirements. To balance COD/N ratio, some bypass of raw wastewater should be added to the biofilter feed.

The application of coagulation for post-treatment of aerobic-anoxic effluents can fulfil the discharge limits to the sewer (even for colour exerted by hardly biodegradable melanoidins); however, the required amount of inorganic coagulants were relatively high.

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