Sequenced anaerobic–aerobic treatment of high strength, strong nitrogenous landfill leachates

S.V. Kalyuzhnyi and M.A. Gladchenko

Department of Chemical Enzymology, Chemistry Faculty, Moscow State University, 119992 Moscow, Russia (E-mail: *svk@enz.chem.msu.ru*)

Abstract As a first step in treatment of high strength, strong nitrogenous landfill leachates (total COD – 9.66–20.56 g/l, total nitrogen 780–1,080 mg/l), the performance of laboratory UASB reactors has been investigated under sub-mesophilic (19±3 °C) and psychrophilic (10±2 °C) conditions. Under hydraulic retention time (HRT) of around 1.2 days, when the average organic loading rate (OLR) was around 8.5 g COD/l/day, the total COD removal accounted for 71% (on average) for sub-mesophilic regime. The psychrophilic treatment conducted under the average HRT of 2.44 days and the average OLR of 4.2 g COD/l/day showed an average total COD removal of 58% giving effluents more suitable for subsequent biological nitrogen removal. Both anaerobic regimes were quite efficient for elimination of heavy metals by concomitant precipitation in the form of insoluble sulphides inside the sludge. The subsequent submesophilic aerobic-anoxic treatment of submesophilic anaerobic effluents led to only 75% of total inorganic N removal due to COD deficiency for denitrification created by too efficient anaerobic step. On the contrary, psychrophilic anaerobic effluents (richer in COD compared to the submesophilic ones) were more suitable for subsequent aerobic-anoxic treatment giving the total N removal of 95 and 92% at 19 and 10 °C, respectively.

Keywords Aerobic-anoxic biofilter; denitrification; heavy metals; landfill leachate; nitrification; UASB reactor

Water Science and Technology **Vol 49 No 5–6 pp 301–312** © IWA Publishing 2004

Introduction

Above 150 million m^3 (~37.5 million tones considering a density coefficient as 0.25) of municipal solid wastes (MSW) are annually generated in Russia and more than 96% of these MSW are currently disposed of via landfilling (Kalyuzhnyi *et al.*, 2003a). Due to new legislation recently introduced in Russia, a landfill leachate containing a wide variety of organic and inorganic contaminants should be collected and treated in order to prevent dangerous environmental and health risks to surface and ground waters (Kalyuzhnyi *et al.*, 2003a). In a previous paper (Kalyuzhnyi *et al.*, 2003b), we reported about efficient COD, nitrogen and heavy metals removals using a sequenced anaerobic-aerobic treatment of diluted landfill leachates (total COD < 4 g/l; total N < 162 mg/l), which are usually produced during the winter period. The primary objective of this paper was to test this sequenced technology at the lab-scale level for treatment of high strength (COD up to 21 g/l), strong nitrogenous (total N up to 1,100 mg/l) landfill leachates. Such leachates are usually generated from the Russian landfills during warm seasons. Similarly to the previous study (Kalyuzhnyi *et al.*, 2003b), the UASB reactor was firstly applied for the elimination of the major part of biodegradable COD and concomitant precipitation of heavy metals (HM) in the form of insoluble sulphides/hydroxides inside the sludge bed. In a subsequent step, the biofilter operating in alternative aerobic-anoxic regime was used for the removal of remaining BOD and nitrogen. Both steps were investigated at 19±3 °C and 10±2 °C. The latter regime was used to evaluate a possibility of direct treatment without preliminary heating.

Table 1 Range of variation of some characteristics of the RL (mg/l) except pH (average values are given in brackets)

COD_{tot}	COD_{SS}	COD_{col}	COD_{sol}	pH
9,660–20,560 (15,110)	2,550–2,890 (2,720)	770–1,930 (1,350)	7,030–14,780 (10,905)	5.99–7.52 (6.76)
Total N	**N-NH_3**	**Total P**	**P-PO_4**	**SO_4**
780–1,080 (930)	562–882 (722)	20–51 (35)	8–16 (12)	213–355 (284)
Fe	**Zn**	**Cu**	**Pb**	**Cd**
79.2–170.4 (124.8)	2.4–28.8 (15.6)	0.096–0.168 (0.132)	0.058–0.072 (0.065)	1–6 (3.5)$\cdot 10^{-3}$

Materials and methods

Wastewater. The raw leachates (RL) were taken during April–June 2002 from the leachate collection system of the operating municipal landfill "Khmet'yevo" (Moscow province). Some characteristics of the RL used are presented in Table 1.

UASB reactors. Two laboratory UASB reactors (SM and P: rectangular cross-section 37–38 cm^2, height – 85 cm, total working volume – 2.54–2.68 l) made from transparent plastics and equipped with 6 sampling ports along the reactor height were used. The submesophilic conditions were imposed by keeping the reactor SM under ambient temperature in the laboratory (19±3 °C). Operating temperatures of 10±2 °C were maintained by placing the reactor P into refrigerator "Snaige" (Alitus, Lithuania). Reactors SM and P were seeded with submesophilic (43.6 g VSS, specific aceticlastic activity – 0.32 g COD/g VSS/day at 20 °C) and psychrophilic (28.6 g VSS, specific aceticlastic activity – 0.16 g COD/g VSS/day at 10 °C) sludges, respectively, taken from previous study of diluted landfill leachates (Kalyuzhnyi *et al.*, 2003b). To mitigate mass transfer limitations usually observed under psychrophilic conditions (Kalyuzhnyi *et al.*, 2001), a recycle of effluent was applied (recycle ratio – 2.5:1). Assessment of aceticlastic activity of the sludges used was performed under their working temperatures as described by Lettinga and Hulshof Pol (1992). Determination of anaerobic biodegradability and toxicity of the RL was conducted at 20 °C according to recommendations of Lettinga and Hulshof Pol (1992) using the same sludge as for seeding of submesophilic UASB reactor.

Aerobic-anoxic biofilter. The tubular biofilter (diameter – 5 cm, height – 55 cm) was made from transparent plastics and packed by gravel (0.5–2 cm fraction). It had a working volume of 0.7 l and functioned in alternating aerobic/anoxic regime for treatment of the anaerobic effluents. The operation scheme included a sequencing process with a one-hour cycle consisting of 4 phases. During the first unfed phase (duration – 25–41 min), air at a flow rate of 0.8 l/min was pumped through an external loop of the biofilter. Aeration was switched off throughout the second unfed phase (4–10 min) while the high recycle rate of effluent (0.125 l/min) was applied to ensure an adequate mixing and a complete consumption of resting soluble oxygen in the biofilter. During these 2 phases, nitrification and oxidation of remaining BOD proceeded. Then the feeding (this is the only period when the system was fed) was performed during 2–3 min under the same recycle rate of effluent. The third unfed phase included only mixing (by effluent recycle) and was variable (7–28 min) to close the 1 h working cycle of a programmable multi-channel timer controlled all 3 (air, recycle, feeding) pumps used. During the last 2 phases, denitrification proceeded. In the middle of the external loop of the biofilter, an electronic sensor ("Datchik", Russia) was inserted for on-line monitoring of soluble oxygen. The electric signal from this sensor was transferred to a programmable data logger system. The data were recorded every 30 s and were averaged (when necessary) over 3-min intervals. A personal computer programmed to function as a terminal emulator was used to communicate with the data logger. The attached nitrifying-denitrifying biomass formed in the biofilter during the previous research (Kalyuzhnyi *et al.*, 2003b) was directly used for treatment of anaerobic effluents in this study. The excess of sludge was periodically withdrawn by intensive backwash of biofilter. The submesophilic and psychrophilic conditions were imposed by keeping the biofilter under ambient temperature in the laboratory (19±3 °C) or inside refrigerator "Snaige" (Alitus, Lithuania) at 10 ± 2°C.

Analyses. Sampling of treated wastewater for analysis was usually started after 3 hydraulic retention times (HRT) after change of working regime for each reactor in order to ensure its operation in quasi steady-state conditions. COD was analysed spectrophotometrically using Hach tubes. The HM (Fe, Zn, Cu, Pb, Cd) in the RL, the treated effluents and the reactor sludge were analysed on a regular basis by atomic absorption spectroscopy. The samples were dried (<40 °C) and pre-treated with concentrated HNO_3 and H_2O_2 (30%), thereafter the metal content was measured from the eluate. All other analyses were performed 3–5 times per week by *Standard Methods* (1995) or as described previously (Kalyuzhnyi *et al.*, 2003b). All gas measurements were recalculated to standard conditions (1 atm, 0 °C). Statistical analysis of data was performed using Microsoft Excel.

Results and discussion

Submesophilic UASB reactor performance

In the preliminary experiments, it was found that the leachate samples used in this study were quite biodegradable in anaerobic conditions (78.9±0.9% on COD basis). Some results of the submesophilic UASB treatment of the RL under quasi-steady state operation are shown in Tables 2–4 (SM runs). It can be seen that a stepwise decrease of HRT from 3.24 to 1.2 days (organic loading rate (OLR) finally exceeded 8 g COD/l/d) led to stepwise increase of total COD removal to 71% (on average). Only traces of acetate and butyrate were detected in the effluents but propionate concentration oscillated around 0.94 g COD/l (Table 2). However, such exhaustion of easily biodegradable COD (e.g., volatile fatty acids (VFA)) in the anaerobic effluents might create COD deficiency problems for subsequent biological nitrogen removal. The effluent pH was close to 8 as a result of VFA consumption and mineralisation of nitrogenous species to ammonia (Table 2). The specific methane production was somehow below the theoretically expected values taking into account the observed COD removal (Table 2). This discrepancy can be attributed to entrapment of some part of the undigested SS by the reactor sludge bed and development of the process of biological sulphate reduction consuming some part of the COD. The latter can be witnessed by a significant drop of sulphate concentrations in the effluents compared to the influents (Table 2). The concentrations of phosphate increased in the effluents (Table 2) due to mineralisation of phosphoric species.

The submesophilic UASB reactor was quite efficient for removal of HM (Table 3) due to their concomitant precipitation/entrapment on the sludge presumably in the form of sulphides and hydroxides. The HM content (except Fe) in the anaerobically treated effluents was below the Russian limits for drinking water. The specific aceticlastic activity (20 °C) of the UASB sludge slightly decreased throughout this study from 0.3 to 0.28 g COD/g VSS/day probably due to a decrease of VSS/TSS ratio in the sludge from 0.46 to 0.3 (Table 4).

Psychrophilic UASB reactor performance

Some results of the psychrophilic treatment of the RL under quasi-steady state operation of the UASB reactor are shown in Tables 2–4 (P runs). It is seen that the effluent quality slightly deteriorated compared to the submesophilic regime (Table 2). Generally, taking into

Table 2 Operational parameters and efficiency of the UASB reactor treating the RL at 20 (SM runs) and 10 (P runs) °C (mean±standard deviation)

Parameter/run	1SM	2SM	3SM	1P	2P	3P
HRT, days	3.34±0.31	2.48±0.78	1.20±0.03	7.32±1.04	5.27±0.11	2.44±0.03
Sampling period, days	15	11	5	29	17	10
OLR, g COD/l/d	6.13±0.71	4.75±0.98	8.51±0.22	2.60±0.36	3.65±0.10	4.19±0.05
Influent COD_{tot}, g/l	19.9	9.66	10.2	19.3±0.08	19.1±0.07	10.2
Effluent COD_{tot}, g/l	9.88±0.32	3.98±0.80	2.98±0.25	9.28±1.31	8.45±1.59	4.24±0.58
Total COD removal, %	50.4±1.6	58.8±8.3	70.8±2.5	52.0±6.7	55.8±8.2	58.4±5.7
Influent Ac-COD, g/l	2.70±0.07	0.33±0.03	0.45±0.02	3.26±0.03	3.75±0.41	0.45±0.02
Effluent Ac-COD, g/l	0.17±0.03	0.08±0.04	0.04±0.01	0.22±0.01	0.19±0.06	0.65±0.46
Influent Pr-COD, g/l	3.09±0.10	0.31±0.01	0.54±0.03	2.55±0.07	3.01±0.34	0.54±0.03
Effluent Pr-COD, g/l	1.77±0.21	0.94±0.32	0.69±0.21	1.65±0.33	1.23±0.39	0.93±0.53
Influent Bu-COD, g/l	7.45±0.16	1.24±0.04	1.46±0.16	5.59±0.14	6.05±0.19	1.46±0.16
Effluent Bu-COD, g/l	3.22±1.03	Traces	Traces	2.94±0.43	3.11±0.99	0.09±0.07
Influent pH	6.03±0.07	7.52	7.52	6.0±0.09	6.0±0.05	7.52
Effluent pH	7.77±0.21	7.97±0.24	8.11±0.04	7.53±0.11	7.47±0.11	7.78±0.06
CH_4 in biogas, %	76.6±1.5	77.3±0.6	78.4±0.5	72.6±0.6	74.3±1.2	78.9±1.0
CH_4, $nl/l_{reactor}/d$	0.73±0.06	0.79±0.32	1.53±0.26	0.37±0.10	0.49±0.14	0.63±0.11
Influent $N\text{-}NH_3$, mg/l	610	822	820	576±4	579±2	822±2
Effluent $N\text{-}NH_3$, mg/l	685±44	811±66	795±9	569±6	578±13	762±11
Influent $P\text{-}PO_4$, mg/l	16.0	8.0	8.2	16.1±0.1	16.6±0.4	8.0
Effluent $P\text{-}PO_4$, mg/l	16.6±1.6	12.3±0.4	10.2±0.3	18.0±0.4	18.6±0.7	18.7±2.9
Influent SO_4, mg/l	360	213	197	355	354±6	200
Effluent SO_4, mg/l	152±8	65±5	65±8	80±5	79±7	55±8

account a need for easily biodegradable organic matter for subsequent nitrogen removal, the effluent COD characteristics were superior compared to those from submesophilic regime (Table 2) due to the presence of resting VFA (usually in the range 2–5 g COD/l). The observed specific methane production rates also showed some discrepancies with the theoretically expected ones (Table 2). Besides the reasons proposed for such discrepancy in the submesophilic regime, a supersaturation of psychrophilic effluents by dissolved methane may also be a possibility (Kalyuzhnyi *et al.*, 2001). The effluent concentrations of soluble species (ammonia, phosphate and sulphate) followed the trends observed for the submesophilic regime (Table 2). The HM removal in psychrophilic conditions was a little bit inferior but comparable with the submesophilic regime (Table 3). The accumulation of HM in the reactor was confirmed by direct measurement of HM sludge content at the start and at the end of the psychrophilic experiments (Table 4). This accumulation roughly corresponded to the HM removal from the liquid phase.

A general performance of psychrophilic and submesophilic UASB reactors may imply that the Khmet'yevo leachates can be efficiently treated without any heating in warm periods. However, some energy expenses (at least to maintain a working temperature around 10 °C) will be necessary for cold periods during a full-scale implementation of anaerobic treatment of these leachates.

Biofilter performance

Since the biomass in the biofilter was already adapted to anaerobically treated diluted landfill leachates (Kalyuzhnyi *et al.*, 2003b), the biofilter was switched (without any adaptation) on feeding with submesophilic strong nitrogenous anaerobic effluents (run SM1, Table 5), when aeration phase was 25 min, the average HRT was 3.81 days while the average OLR and ammonia loading rate (ALR) were 2.61 g COD/l/d and 172 mg N/l/d,

Table 3 HM removal by submesophilic and psychrophilic UASB reactors treating the RL under quasi-steady state operation

Parameter/Regime	Submesophilic		Psychrophilic		Russian drinking water limits
HRT, days	3.34±0.31	1.20±0.03	5.27±0.11	2.44±0.03	
Influent Fe, mg/l	170.4	79.2	170.4	79.2	
Effluent Fe, mg/l	1.3	5.9	1.6	16.0	0.3
Fe removal, %	99	93	99	80	
Influent Zn, mg/l	28.8	2.4	28.8	2.4	
Effluent Zn, mg/l	2.4	0.04	1.6	2.05	5
Zn removal, %	92	98	94	17	
Influent Cu, mg/l	0.168	0.096	0.168	0.096	
Effluent Cu, mg/l	0.048	0.02	0.043	0.06	1
Cu removal, %	71	98	74	38	
Influent Pb, mg/l	0.072	0.058	0.072	0.058	
Effluent Pb, mg/l	0.046	0.01	0.015	0.01	0.03
Pb removal, %	36	98	79	98	
Influent Cd, mg/l	0.001	0.006	0.001	0.006	
Effluent Cd, mg/l	0.0005	0.001	0.0005	0.001	0.001
Cd removal, %	50	83	50	83	

Table 4 Some sludge characteristics of submesophilic and psychrophilic UASB reactors treating the RL

Parameter/regime	Submesophilic		Psychrophilic	
	Start	End	Start	End
VSS in the reactor, g	43.6	67.1	28.6	31.2
TSS in the reactor, g	95.1	224.7	53.7	55.1
VSS/TSS, %	45.8	29.9	53.3	56.6
Aceticlastic activity, g COD/g VSS/day*	0.32	0.28	0.16	0.17
Fe content, mg/g TSS	ND	5,043	10,158	45,225
Zn content, mg/g TSS	ND	1,210	819	3,915
Cu content, mg/g TSS	ND	72.8	98.4	124.0
Pb content, mg/g TSS	ND	3.92	7.80	8.81
Cd content, mg/g TSS	ND	0.01	0.032	0.04

*Values were obtained at working temperatures – 20 and 10 °C, respectively.
ND – not determined

respectively. The average total COD removal accounted for 85% with the total COD effluent concentrations oscillating around 1.5 g COD/l (Table 5, run SM1). The efficiencies of ammonia removal and denitrification were 73 and 99% (on average) resulting in the average inorganic nitrogen removal of 72% (Table 5, run SM1). Insufficient nitrification was probably due to high COD/N ratio (15.2) of anaerobic effluent used for feeding during this run. An excess of COD leads to intensive development of heterotrophs making the reactor biofilm thick (mass transfer limitations and clogging) as well as to inhibition of autotrophic nitrifiers (Henze *et al.*, 1999).

In order to avoid such undesired phenomena, the submesophilic anaerobic effluents with lower COD/N ratio were used during run SM2 when the duration of aeration phase was increased to 40 min under the average HRT of 4.29 days giving the average OLR and ALR of 0.89 g COD/l/d and 183 mg N/l/d, respectively (Table 5). The average efficiency of ammonia removal increased (up to 90%) but the average efficiency of denitrification decreased (to 83%) compared to the corresponding values obtained during run SM1 (Table 5). The total inorganic nitrogen removal increased to 75% (on average) giving the total effluent inorganic nitrogen concentrations around 196 mg N/l (run SM2, Table 5). The elevated total nitrogen concentrations in the effluents were related with both incomplete

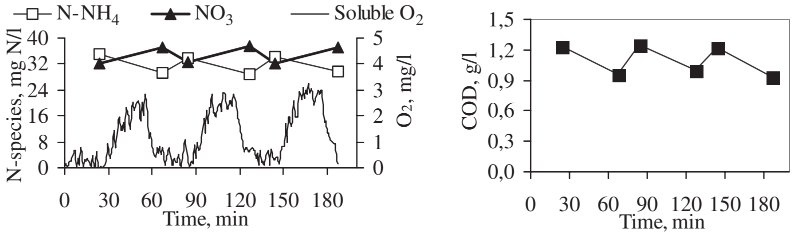

Figure 1 Dynamics of nitrogen species, soluble oxygen (left panel) and COD (right panel) concentrations during alternating operation of the biofilter (run P2, Table 5)

nitrification and COD deficiency to have a stable denitrification (COD/N ratio during run SM2 was around 5, i.e., below practically accepted value of 6 (Henze *et al.*, 1999). The possible measures to enhance nitrogen removal can include a decrease of the ALR to values below 160 mg N/l/d and balancing (if possible) a COD/N ratio.

This approach was investigated in 2 subsequent submesophilic runs where psychrophilic anaerobic effluents were used. During run SM3 (Table 5), when the diluted (2 times) effluent was fed, the average HRT was 3.47 days while the average OLR and ALR were 1.23 g COD/l/d and 121 mg N/l/d, respectively. Under duration of aeration phase of 22 min, the average total COD removal accounted for 83% with the total COD effluent concentrations oscillating around 0.7 g COD/l, (Table 5, run SM3). The efficiencies of ammonia removal and denitrification were both 97% (on average) resulting in an average inorganic nitrogen removal of 94% (Table 5, run SM3). The switch of biofilter on feeding with undiluted psychrophilic effluent (run SM4) required an increase in duration of the aeration phase (till 41 min) and HRT (till 5.1 days, on average) in order to keep the ALR around 150 mg N/l/d (Table 5). In this regime, the biofilter was able to remove 95% of total inorganic nitrogen giving an effluent with total inorganic nitrogen concentrations around 37 mg N/l. 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. Better performance can be expected under disruption of filling and withdrawal phases in the biofilter as in sequencing batch biofilm reactor (SBBR) constructions (Wilderer *et al.*, 2001).

A decrease of working temperature of the biofilter to 10 °C required a decrease of ALR because the nitrifying activity dropped substantially at these conditions (Henze *et al.*, 1999). During run P1 (Table 5), when the aeration phase lasted 25 min, while the average HRT, OLR and ALR were 5.38 days, 1.74 g COD/l/d and 109 mg N/l/d, respectively, the average total COD removal accounted for 78%, i.e., was comparable with submesophilic treatment of psychrophilic anaerobic effluents (run SM1, Table 5). However, in spite of almost complete denitrification (98% on average), the average nitrification efficiency was only 54%, giving an average total inorganic nitrogen removal of 53% (run P1, Table 5). In order to increase a nitrogen removal, the duration of the aeration phase was increased to 35 min and the average HRT was decreased to 7.1 days (run P2, Table 5) resulting in the average OLR and ALR of 0.85 g COD/l/d and 106 mg N/l/d, respectively. In this regime, the average total inorganic nitrogen removal accounted for 92% giving the total inorganic nitrogen concentrations in the effluents around 63 mg N/l from which only 30 mg N/l was represented by ammonia (run P2, Table 5). The typical dynamics of targeted pollutants and oxygen concentration inside the biofilter during 3 consecutive cycles is presented in Figure 1. Thus, the resting nitrogen concentrations were above the current national standards (10 mg N/l) for direct discharge of treated wastewater. A simple and inexpensive post-treatment step like a collection/stabilisation pond (they are usually available at the landfills) or constructed wetland will probably be

Table 5 Operational parameters and efficiency of the biofilter treating the anaerobic effluents (mean±standard deviation).

Parameter/run	SM1	SM2	SM3	SM4	P1	P2
Temperature, °C	18–22	18–22	20–22	16–19	9–11	8–12
Aeration phase, min	25	40	22	41	25	35
Mixing after aeration, min	9	10	7	4	9	8
Feeding phase, min	2	3	3	2	2	2
Mixing after feeding, min	24	7	28	13	24	15
HRT, days	3.81±0.47	4.29±0.07	3.47±0.09	5.09±0.06	5.38±0.59	7.10±0.17
Sampling period, days	9	17	16	24	17	24
Influent COD/N	15.2	4.9	10.2	7.4	16.0	7.9
OLR, g COD/l/d	2.61±0.35	0.89±0.16	1.23±0.04	1.12±0.08	1.74±0.19	0.85±0.08
Influent COD$_{tot}$, g/l	10	3.81±0.70	4.28±0.19	5.72±0.38	9.28±0.05	5.96±0.52
Effluent COD$_{tot}$, g/l	1.53±0.49	1.47±0.44	0.71±0.04	1.08±0.06	2.03±0.27	0.89±0.13
COD$_{tot}$ removal, %	84.7±4.9	63.6±5.2	83.5±0.3	80.5±1.5	78.1±3.0	86.5±1.7
Influent pH	7.74±0.23	7.71±0.09	7.8±0.05	6.9±0.1	7.47±0.04	7.41±0.10
Effluent pH	7.05±0.11	7.07±0.10	7.93±0.09	8.04±0.14	8.34±0.10	7.72±0.14
ALR, mg N-NH$_3$/l/d	172±23	183±6	121±4	151±2	109±13	106±2
Inf. N-NH$_3$, mg/l	660	784±21	420±9	771±2	579±1	752±2
Eff. N-NH$_3$, mg/l	178±25	78±9	10.8±3.0	18.8±0.9	268±23	30±1
N-NH$_3$ removal, %	73.1±3.8	90.1±1.0	97.4±0.7	97.7±0.1	53.7±3.9	96.0±0.1
Effluent N-NO$_3$, mg/l	1±1	117±14	13.7±5.8	18.0±4.5	4.3±0.4	33.1±1.5
Effluent N-NO$_2$, mg/l	Traces	1.5±1.1	0.3±0.1	0.4±0.1	2.5±1.4	0.3±0.1
*Denitrific. effic., %	99.2±0.3	83.3±2.2	96.6±1.5	97.6±0.6	97.8±0.8	95.4±0.2
Effluent total inorganic N, mg/l	182±26	196±22	28±9	37±5	275±24	63±2
#Total inorganic N removal, %	72.4±3.9	75.1±2.6	94.0±2.1	95.2±0.7	52.5±4.2	91.6±0.3
Influent P-PO$_4$, mg/l	17	14.9±5.8	10.3±1.7	18.9±0.1	18.1±0.1	18.7±0.1
Effluent P-PO$_4$, mg/l	4.6±0.8	8.1±5.4	5.9±0.8	9.8±0.5	8.0±0.2	14.9±0.3

*Calculated as: $\{1 - ([N\text{-}NO_3]_{ef} + [N\text{-}NO_2]_{ef})/([N\text{-}NH_3]_{in} - [N\text{-}NH_3]_{ef})\}*100$

#Calculated as: $\{1 - ([N\text{-}NO_3]_{ef} + [N\text{-}NH_3]_{ef} + [N\text{-}NO_2]_{ef})/([N\text{-}NH_3]_{in})\}*100$

required to ensure a safe discharge of the treated leachates (by proposed sequenced technology) to surface waters.

Conclusions

1. The UASB reactor was quite efficient for removal of bulk COD and heavy metals present in the high strength RL from Khmet'yevo landfill even during operation under submesophilic and psychrophilic conditions (10–19 °C).
2. The application of aerobic/anoxic biofilter at 10–19 °C allowed an elimination of biodegradable COD and more than 92% of inorganic nitrogen from the anaerobic effluents. However, the resting nitrogen concentrations were above the current national standards for direct discharge of treated wastewater. A simple and cheap post-treatment step like a stabilisation pond or a constructed wetland will probably be required to ensure a safe discharge of the treated leachates to surface waters.

Acknowledgements

The financial support of INCO Copernicus (contract N° ICA2-CT-2001-10001) is gratefully acknowledged. We thank "Ecotechprom" (Moscow) for delivering the landfill leachates.

References

Henze, M., Harremoës, P., LaCour Jansen, J. and Arvin, E. (1999). *Wastewater Treatment: Biological and Chemical Processes*. Springer, Heidelberg, Germany.

Kalyuzhnyi, S.V., Gladchenko, M.A., Sklyar, V.I., Kizimenko, Ye.S. and Shcherbakov, S.S. (2001). Psychrophilic one- and two-step systems for pre-treatment of winery waste water. *Wat. Sci. Tech.*, **44**(4), 23–31.

Kalyuzhnyi, S.V., Epov, A., Sormunen, K., Kettunen ,R., Rintala, J., Privalenko, V., Nozhevnikova, A., Pender S. and Colleran, E. (2003a). Evaluation of the current status of operating and closed landfills in Russia, Finland and Ireland with regard to water pollution and methane emission. *Wat. Sci. Tech.*, **48**(4), 37–44.

Kalyuzhnyi, S.V., Gladchenko, M.A., Epov, A. and Appanna, V. (2003b). COD, nitrogen and heavy metals removals using a sequenced anaerobic-aerobic treatment of landfill leachates at 10–30 °C. *Appl. Biochem. Biotechnol.*, **109,** 181–196.

Lettinga, G. and Hulshoff Pol, L.W. (1992). *Anaerobic Reactor Technology.* Wageningen Agricultural University, Wageningen, The Netherlands.

Standard Methods for the Examination of Water and Wastewater (1995). 19th edn, American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC, USA.

Wilderer, P.A., Irvine, R.L., Goronszy, M.C., Artan, N., Demoulin, G., Keller, J., Morgenroth, E., Nyhuis, G., Tanaka, K. and Torrijos M. (2001). *Sequencing batch reactor technology. IWA Scientific and Technical Report No.10*, IWA Publishing, London, UK.