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Biological nutrient removal from leachate using a pilot liquid–solid circulating fluidized bed bioreactor (LSCFB)

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ABSTRACT

Biological treatment of landfill leachate is a concern due to toxicity, high ammonia, low biodegradable organic matter concentrations, and low carbon-to-nitrogen ratio. To study the reliability and commercial viability of leachate treatment using an integrated liquid–solid circulating fluidized bed bioreactor (LSCFB), a pilot-scale LSCFB was established at the Adelaide Pollution Control Plant, London, Ontario, Canada. Anoxic and aerobic columns were used to optimize carbon and nutrient removal capability from leachate using 600 μm lava rock with a total porosity of 61%, at empty bed contact times (EBCTs) of 0.55, 0.49, and 0.41 d. The LSCFB achieved COD, nitrogen, and phosphorus removal efficiencies of 85%, 80%, and 70%, respectively at a low carbon-to-nitrogen ratio of 3:1 and nutrients loading rates of 2.15 kg COD/(m^3 d), 0.70 kg N/(m^3 d), and 0.014 kg P/(m^3 d), as compared with 60–77% COD and 70–79% nitrogen removal efficiencies achieved by upflow anaerobic sludge blanket (UASB) and moving bed bioreactor (MBBR), respectively. The LSCFB effluent characterized by ≤35 mg SBOD/L, <35 mg NH_4-N/L, <1.0 mg PO_4-P/L, and 37 mg VSS/L can easily meet sewer by-law requirements. Remarkably low yields of 0.13, 0.15, and 0.16 g VSS/g COD were observed at long biological solids retention times (SRTs) of 31, 38 and 44 d.

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1. Introduction

Landfill leachate treatment has become a major concern of the wastewater treatment industry in order to avoid the large negative environmental impact [1]. Due to release of the large recalcitrant organic molecules from the municipal solid wastes and increase of landfill leachate age, low biodegradable organic matter concentration, high COD and ammonium content, low carbon-to-nitrogen ratio, and the presence of heavy metals and toxic components pose unique challenges to biological treatment of landfill leachate [2–5]. Usually a combination of physical, chemical and biological methods is used for leachate treatment, since it is difficult to obtain satisfactory treatment efficiencies by either one of these methods alone [6–9]. Air stripping, adsorption and membrane filtration were the major physical methods used for landfill leachate treatment [10–12]. Among the chemical treatment methods used for leachate treatment, coagulation–flocculation, and chemical or electrochemical oxidation are the major ones [7,8]. Biological treatment methods used for leachate treatment are mainly aerobic, anaerobic and anoxic processes which are usually used in combination [13]. However, with ageing of landfill sites and with more stabilized leachate, as well as with more stringent discharge standards, conventional biological treatments followed by classical physicochemical methods are no longer adequate to achieve the level of purification needed to reduce the negative effects of landfill leachate on ecology and humankind [14]. There is therefore a considerable impetus to develop novel methods for biological nutrient removal from leachate in an integrated system and reduce the capital and operating cost as well as the amount of biomass produced without using any chemicals.

Among the biological processes for leachate treatment, fixed film bioprocesses offer some advantages compared to the suspended growth systems such as lower hydraulic retention time, higher biomass retention time, higher volumetric conversion rates, higher resistance to toxic agents, lower sensitivity to temperature, and less sludge production rate.

Biological leachate treatment using particulate biofilm has gained considerable interest in recent years due to more stringent regulation [3,5]. A new liquid–solid circulating fluidized bed bioreactor (LSCFB) has been developed by Nakhla and co-workers [15–19] for biological nutrient removal (BNR) and reported excellent organic, nitrogen, and phosphorus removal efficiencies of 90%, 80%, and 70%, respectively with reduced sludge yields of 0.13 g VSS/g COD employing aerobic and anoxic conditions. Although a

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Table 1
Comparison of leachate biological nutrient removal studies in terms of COD, NH_4-N, and PO_4-P removal.

Reactor type		Leachate characteristic				HRT hrs	Performance removal			Reference
		(mg COD/L)	(mg NH_4-N/L)	T (°C)	pH		COD %	NH_4-N %	PO_4-P %	
Attached static biofilm growth	TF	2000–2600	300–700	25	8.0	7.6	60	80	–	[20]
	TF	850–1350	295	19.7	8.0–8.5	4.5	52	–	–	[21]
	TF	1828 ± 190	2200	24	7.8	15.9	65 ± 6	60 ± 5	–	[4]
Attached particulate biofilm growth systems	UASB	1000–4000	1600	24	6.8–7.6	10	75	79	–	[22]
	UASB	1500–3200	500	23	7.0–7.2	16	65	70	–	[23]
	UASB	1120–3520	475	35	6.9–9.0	24	77	–	–	[24]
	MBBR	2000–3000	450–600	21	8.9–9.2	24	75	–	–	[25]
	MBBR	1740–4850	220–800	20	9.0	36	60	70	–	[26]
	P-O+MBBR	400–600	200–300	17	7.5	96	76	80	–	[27]
	P-O+FBR	1260	177	20	8.1	24	63	53	50	[28]
	FBR	1100–3800	492	30	6.5–7.8	34	82	63	–	[29]

TF: trickling filter, UASB: upflow anaerobic sludge blanket, MBBR: moving bed bioreactor, FBR: fluidized bed bioreactor, P-O: pre-ozonation.

comparative assessment of the performance of particulate biofilm growth systems (Table 1), with static biofilm growth systems clearly highlights the superiority of particulate biofilm reactors in leachate treatment at low HRTs, there are very limited studies analyzing biofilm processes for biological nitrogen removal from leachate [20–29].

Thus, the primary goal of this study is to evaluate the LSCFB performance during the treatment of high ammonia and very low carbon-to-nitrogen landfill leachate at a pilot-scale to achieve sewer use by-law requirements for City of London (Canada) characterized by 350 mg TSS/L, 300 mg BOD_5/L, 50 mg NH_4-N, and 10 mg TP/L [30]. This study also aims at evaluating the performance sensitivity to increased loading rates, reduced empty bed contact time (EBCT), and hydraulic retention time.

2. Materials and methods

A pilot-LSCFB was established to treat landfill leachate collected from the W12A Landfill in London, Ontario, Canada. The pilot-scale facility was developed based on the lab-scale experiment reported by Cui et al. [16], Patel et al. [17], and Chowdhury et al. [18].

2.1. Design and fabrication of the LSCFB

A schematic of the pilot-scale LSCFB shown in Fig. 1 was used for biological nutrient removal from landfill leachate. The details of the reactor have been presented elsewhere [19]. Table 2 shows the detailed operational conditions and reactors' design parameters of the LSCFB. When the superficial liquid velocity exceeds particle terminal settling velocity, liquids and particle move co-currently upwards to the top of the riser and are separated by the large cone-based cylindrical separator. Both the settled particles and the liquid then flow to the top of the downer by gravity. The downer was operated in a conventional fluidization regime (by recirculating the liquid from the downer liquid–solid separator) where a counter-current flow of liquid and solid is attained, as the liquid moves upward and solids downward. Due to the high abrasion in the three-phase (air, solids, and liquid) medium,

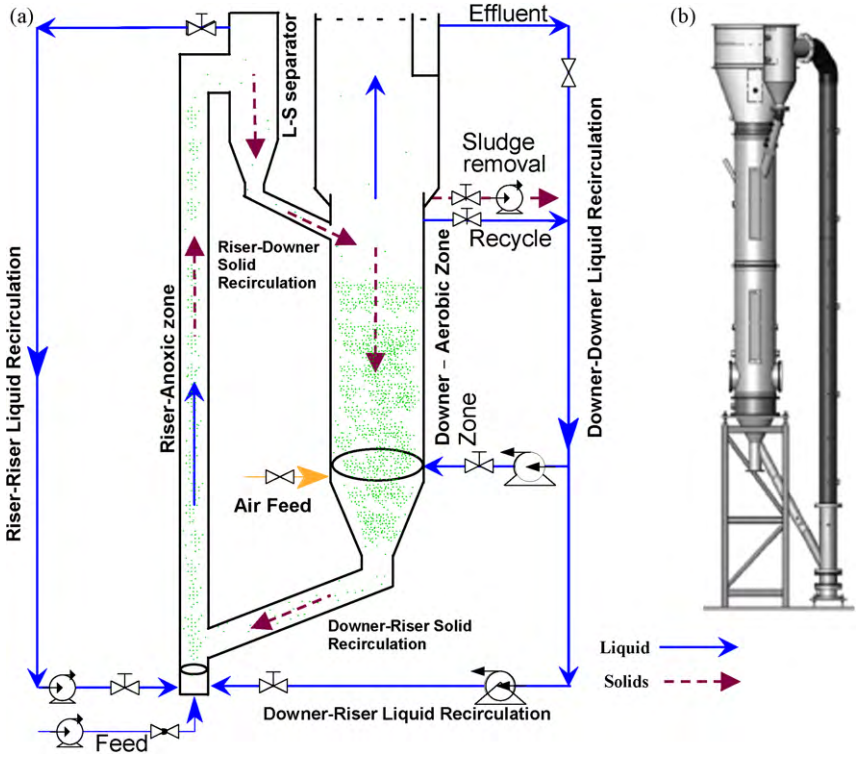

Fig. 1. (a) Schematic and (b) 2-D view of the pilot-scale LSCFB.

Table 2
Operating conditions.

		Phase I	Phase II	Phase III
Influent flow, Q_{in} (L/d)		650 ± 35	720 ± 35	864 ± 35
Average organic loading (kg COD/(m^3 d))		1.90	2.15	2.60
Average nitrogen loading (kg N/(m^3 d))		0.60	0.68	0.81
Average phosphorus loading (kg P/(m^3 d))		0.010	0.014	0.016
Riser–Riser recirculation ratio (Q_{r-r}/Q_{in})		69	62	52
Downer–Riser recirculation ratio (Q_{d-r}/Q_{in})		34	31	26
Downer–Downer recirculation ratio (Q_{d-d}/Q_{in})		77	70	58
Empty bed contact time (d)[d]	Anoxic	0.12	0.11	0.09
	Aerobic	0.43	0.38	0.32
Nominal HRT (d)[e]	Anoxic	0.08	0.07	0.06
	Aerobic	0.29	0.25	0.21
Avg. attached biomass (mg VSS/g lava rock)	Anoxic	14.57	16.30	18.70
	Aerobic	6.13	5.95	7.32
Biomass (g VSS)	Anoxic	1821.25	2037.5	2337.5
	Aerobic	2580.73	2504.95	3081.72
Food/microorganisms ratio (g COD/g VSS d)		0.18	0.20	0.21
Detachment rates (d^{-1})	Anoxic	0.117[a]	0.127	0.132
	Aerobic	0.101[a]	0.122	0.127
Estimated SRT (d)	Anoxic	18[b]	17	13
	Aerobic	26	21	18
	Overall	44[c]	38	31
Run time (d)		40	32	22

[a] Based on Eq. (1).
[b] Based on Eq. (2).
[c] Based on Eq. (3).
[d] EBCT = Vcompact/*Q*.
[e] Nominal HRT = EBCT × (1 − compact bed porosity).

the biofilm is sheared from the particles coming from the riser liquid–solid separator, thus increasing settling velocity and affecting particle recirculation back to the riser through a connecting pipe to allow continuous particle circulation in the riser column from the downer column. Thus, the riser primarily serves as an anoxic reactor where denitrification of the aerobically nitrified downer effluent is achieved. When readily biodegradable COD concentration in the influent exceeds the denitrification requirement, then anaerobic phosphorus release also occurs in the riser. The riser effluent then undergoes further organic removal and nitrification in the aerobic downer.

Lava rock particles with an average diameter of 600 μm (300–1000 μm) were used as the carrier media for biofilm attachment in the LSCFB. The particle porosity was about 33% and the total porosity (particle porosity and void between particles) was 61%. The bulk density (considering packed media filled with water) of particles was approximately 1720 kg/m^3, with a true density (the ratio of sample mass to its true volume) of 2560 kg/m^3 and a high surface area of 10,950 m^2/m^3. The LSCFB was started with 125 and 421 kg of fresh lava rock particles with corresponding compact bed volume of 80 and 277 L in the riser and the downer respectively. The amount of particles was determined considering the observed nitrification–denitrification rates of 0.14 g N/(g VSS d) and 0.62 g N/(g VSS d) respectively and attached biomass of 15–39 mg VSS/g lava rock in the lab-study [19]. The observed attached biofilm thicknesses on the aerobic and anoxic bio-particles in the pilot-study were 120 and 600 μm. The comparatively thin biofilm of the aerobic particles was mainly due to the higher abrasion and agitation generated by air, injected at the bottom of the aerobic column. The overall volume of the anoxic reactor, aerobic reactor, liquid–solid separator, and final clarifier are 0.18, 0.58, 0.06, 0.30 m^3, respectively.

2.2. Reactor start-up

The pilot-scale reactor was inoculated with enriched nitrifiers, acclimatized in the lab using return activated sludge from the Adelaide Pollution Control Plant, London, Canada, further details of the start-up are presented elsewhere [19].

2.3. Batch tests

Batch tests were conducted to examine nitrification and denitrification rates of the attached biomass of the LSCFB bio-particles. The 0.5 L batch reactors were equipped with magnetic stirrers and operated under aerobic (purging air to maintain dissolved oxygen) and anoxic (maintained airtight to avoid intrusion of oxygen from air) conditions at different initial substrates to microorganisms (S_o/X) ratios of 0.50–0.65 g COD/g VSS.

For nitrification, known amounts of ammonium chloride to affect an initial NH_4-N concentration ranging from 25 to 30 mg/L with an additional alkalinity of 250 mg/L as $CaCO_3$ was added in each sample. For the denitrification test, sodium nitrate of 20–25 mg/L as well as acetic acid of 300–400 mg/L was added as readily biodegradable carbon source. To reduce the effect of substrate mass transfer limitation into the biofilm, the biofilms were removed from 30 to 40 g media using sonication and then placed into the reactors. The S_o/X ratios were calculated based on nutrient loading rates and available attached biomass in the LSCFB. NH_4-N and NO_3-N levels were monitored for 6–7 h to determine the maximum nitrification and denitrification rates of the bio-particles.

2.4. Analytical methods

Influent, anoxic bed effluent, and final effluent samples were collected from the influent, riser top effluent, downer top effluent,

and final effluent in airtight bottles twice a week, refrigerated at 4 °C prior to analysis. Total suspended solids (TSS), volatile suspended solids (VSS), biological oxygen demand (BOD), and total Kjeldahl nitrogen (TKN) were analyzed according to the Standard Methods [31].

DO and ORP were measured using Thermo Orion (810 A+) meter, and pH-11 series pH/(mV °C) meter (Oakton, Singapore) respectively. HACH methods and testing kits (HACH Odyssey DR/2500) were used to measure total chemical oxygen demand (COD), soluble chemical oxygen demand (SCOD), and total phosphorus (TP). NH_4, NO_2, NO_3, and PO_4 were measured using ion chromatography (IC, Dionex 600, USA) equipped with CS16-HC and AS9-HC columns. Biofilm thickness of the LSCFB particles was measured using a microscope (SteREO Discovery V8, Carl Zeiss, Inc, Germany) coupled with a camera (Axio Cam HR, 13 MP, Carl Zesis, Germany), at a magnification of 80×.

Attached biomass on the support media was examined according to the Standard Methods (APHA, 1998) and expressed as mg

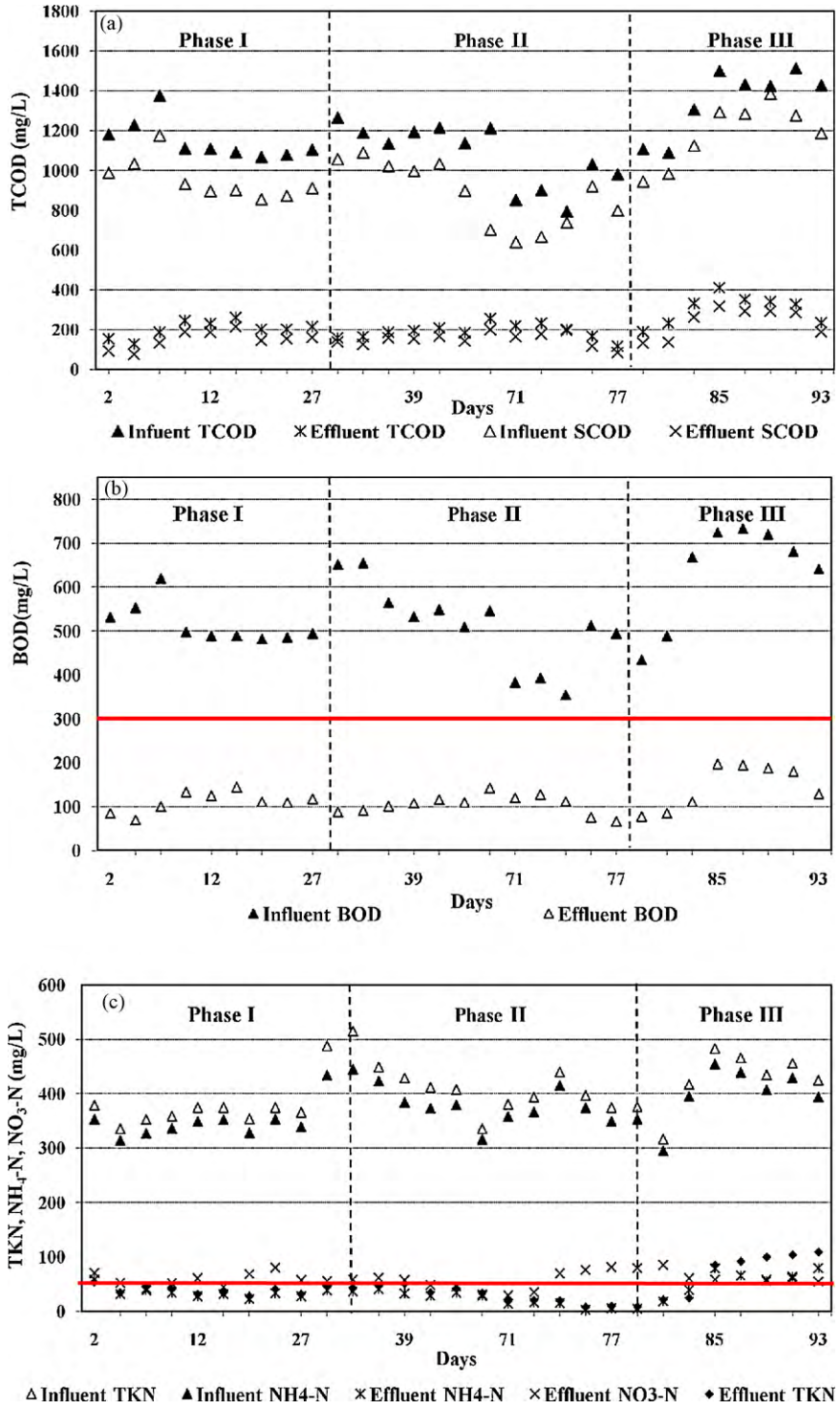

Fig. 2. Nutrient removal using the LSCFB, (a) COD removal; (b) BOD removal; (c) nitrogen removal; (d) ammonia removal; (e) total phosphorus removal, and (f) PO_4-P removal.

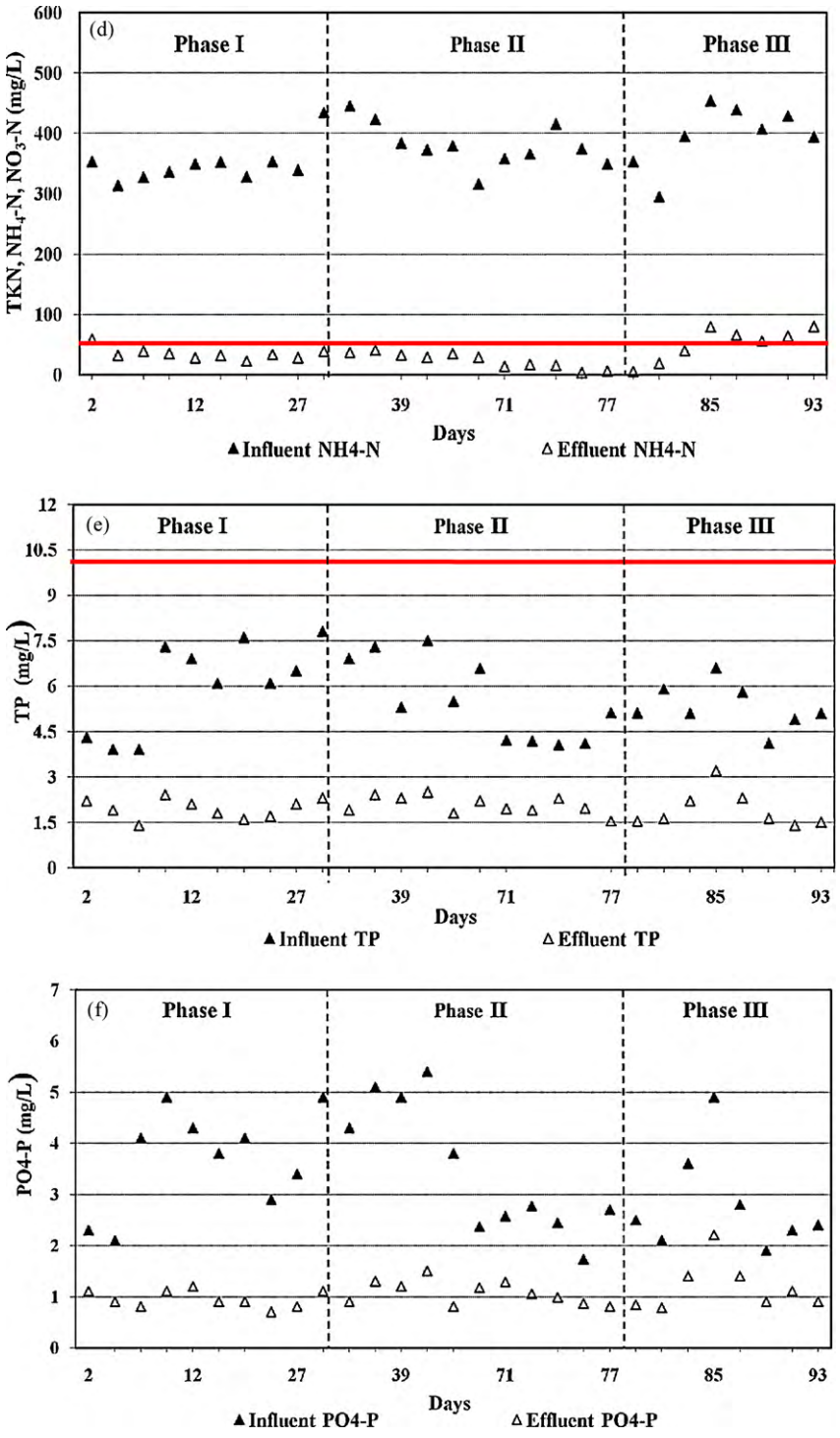

Fig. 2. (*Continued*).

VSS/g clean particles. Approximately 4–5 g bio-particles were taken from the two columns, suspended in a 50 mL vial, and sonicated for 3 h at 30 °C in an Aquasonic sonicator (Model 75HT, ETL Laboratory Testing, Inc., New York). After sonication, the VSS content of the detached biomass was measured using Standard Methods [31] and the sonicated particles were cleaned and weighted after drying at 550 °C for 1 h. The paired Student's *t*-test was conducted to determine the statistical significance of the observed differences between the experimental data at the 95% confidence level.

3. Results and discussion

In order to evaluate the system sensitivity to different loading rates, empty bed contact times (EBCTs), and hydraulic retention time, were adjusted by varying the influent flow rate from 650 L/d (phase I) to 720 L/d (phase II) and ultimately to 864 L/d (phase III). All volumetric loadings expressed in Table 2 have been calculated based on the total LSCFB volume of 0.77 m^3 comprised of 0.19 m^3 anoxic riser, and 0.58 m^3 aerobic downer. Monitoring of ORP and DO values in the downer and riser

confirmed the aerobic (nitrification) and anoxic (denitrification) processes. DO concentrations of 2–3.1 mg/L in the downer and ≤0.4 mg/L in the riser coupled with ORPs of +14 to +66 mV and −88 to −136 mV in the downer and the riser, respectively ensured proper nitrifying-denitrifying conditions in the LSCFB.

3.1. Organic removal

Three different EBCTs of 0.55, 0.49, and 0.41 d were examined to optimize the organic removal efficiency of the LSCFB. Fig. 2a shows the COD removal profile during the different phases. The raw leachate characteristics depicted in Table 3 reflect a COD:N:P ratio of 3:1:0.0155. The organic matter in the leachate was predominantly soluble with ratios of average SBOD:BOD of 0.71:1 and SCOD:COD of 0.80:1. The ratio of SBOD to SCOD of 0.4 reflects relatively low biodegradability. The pseudo-steady-state average influent and effluent characteristics, illustrated in Table 3, reflect ≥85% TCOD removal in phases I and II at EBCTs of 0.55 and 0.49 d, whereas on average, 76% of the influent COD was removed at an EBCT of 0.41 d. The decrease in EBCT affected an increase in organic loading rate (OLR) from 1.90 to 2.60 kg COD/m^3 d as influent COD concentrations were almost constant throughout the study. The BOD removal profile, shown in Fig. 2b, indicates that all the effluent BOD samples during the various phases met the sewer use by-law requirements for City of London (Canada) limit of 300 mg BOD_5/L.

Even though the influent COD concentrations were 1259 ± 77 mg/L, a significant change in effluent COD concentrations was observed with variation of OLRs. The effluent COD concentrations increased from 195 to 302 mg/L when OLR was increased from 1.90 to 2.6 kg COD/m^3 d. It is noteworthy that although effluent SBOD concentrations in all three phases were around 32–40 mg/L, effluent SCOD concentrations in phase III increased sharply from the 150 mg/L observed in phases I and II to 245 mg/L in phase III, despite constant raw leachate characteristics. This effluent SCOD increase may be attributable to nonbiodegradable soluble microbial products (SMP) since effluent SBOD and raw leachate characteristics were constant. Furthermore, as evident from Table 3, effluent VSS concentrations in phase III were about 20% higher than in phases I and II.

Effluent biomass concentrations were significantly influenced by OLRs, which increased surface growth rates and detachment coefficients. The first-order detachment rate coefficients (d^{-1}), reported in Table 2, were calculated using Eq. (1), where the total daily amount of biomass (as VSS) leaving the reactor effluent (X_1) was divided by the total amount of attached biomass (X_m) available in the reactor estimated as the product of particles in the reactor and attached biomass concentrations [32,33].

$$b' = \frac{QX_1}{MX_m} \quad (1)$$

As apparent from Table 2, the anoxic detachment rates increased from 0.127 d^{-1} in phase II to 0.132 d^{-1} in phase III. Similarly, the aerobic detachment rate increased from 0.122 d^{-1} in phase II to 0.127 d^{-1} in phase III which coupled with the increased biomass rationalize the rise in effluent VSS at higher OLRs. It is interesting to note that in all phases the LSCFB system achieved average effluent concentrations of 195–302 mg COD/L, 56–60 mg TSS/L, 37–44 mg VSS/L, 32–40 mg SBOD/L, and 83–98 mg BOD/L, well below the sewer use by-law requirements for City of London (Canada) of 350 mg TSS/L and 300 mg BOD_5/L.

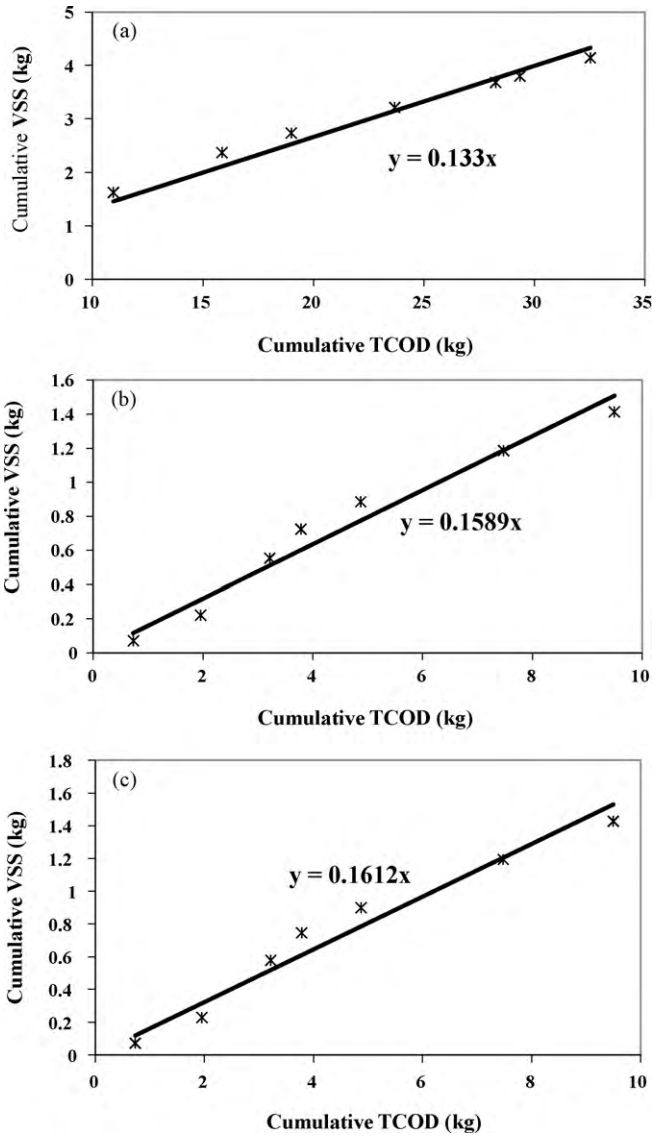

Fig. 3. Yield of process using LSCFB at (a) Phase I, (b) Phase II, and (c) Phase III.

Table 3
Influent and effluent characteristics for different phases.

Parameter	Influent[a]	Effluent[a]		
		Phase I	Phase II	Phase III
pH	7.9–8.8	6.9–7.9	7.2–8.2	7.6–8.1
Alkalinity[b]	1619 ± 52	311 ± 69	323 ± 71	296 ± 57
COD (mg/L)	1259 ± 77	195 ± 35	197 ± 46	302 ± 98
SCOD mg/L)	1025 ± 270	149 ± 39	153 ± 43	245 ± 85
NH_4-N (mg/L)	360 ± 59	34.6 ± 8.2	35.4 ± 13.1	54.7 ± 11.2
NO_3-N (mg/L)	3.1 ± 1.5	57.5 ± 10.5	59.9 ± 31.1	63.9 ± 10.3
TKN (mg/L)	392 ± 64	41 ± 8	49 ± 15	92 ± 23
PO_4-P (mg/L)	3.4 ± 1.1	1.0 ± 0.2	1.0 ± 0.2	1.2 ± 0.5
TP (mg/L)	6.2 ± 1.3	1.9 ± 0.6	1.7 ± 0.3	2.0 ± 0.6
TSS (mg/L)	263 ± 42	56 ± 5	60 ± 13	58 ± 8
VSS (mg/L)	156 ± 30	38 ± 5	37 ± 5	44 ± 8
BOD (mg/L)	565 ± 121	85 ± 16	83 ± 13	98 ± 18
SBOD (mg/L)	402 ± 83	32 ± 9	35 ± 8	40 ± 12

[a] Average ± SD.
[b] (mg $CaCO_3$/L).

3.2. Nitrogen removal

Influent nitrogenous compounds were nitrified in the downer, where DO level was 2.0 ± 0.9 mg/L and the nitrate generated in the downer was denitrified in the anoxic riser. The LSCFB demonstrated a nitrification capacity of 0.81–1.1 kg N/m^3 d, estimated considering the compacted bed volume of 0.58 m^3 in the aerobic downer

and the amount of nitrogen nitrified. Based on the compacted bed volume of 0.19 m^3 in the anoxic riser and the amount of nitrogen denitrified, the LSCFB demonstrated a denitrification capacity of 2.43–3.28 kg N/m^3 d. The LSCFB was efficient in removing nitrogen from leachate, as shown in Fig. 2c. Approximately 80% of influent nitrogen was removed at nitrogen loading rates (NLRs) of 0.60, and 0.68 kg N/m^3 d in phases I and II, respectively. The system in both phases readily achieved <50 mg NH_4-N/L based on the total bioreactor volume of 0.77 m^3. Statistical analysis of the pseudo-steady-state data (Table 3) indicates that 95% of the samples tested in phases I and II met the 50 mg NH_4-N/L limit of sewer by-law requirements for the City of London (Canada).

Even though average influent NH_4-N concentrations were 360 ± 59 mg/L throughout the study, nitrogen loading rate increased from 0.60 to 0.81 kg N/m^3 d as EBCT decreased. In phase III, statistical analysis of the pseudo-steady-state data indicates that 75% of the samples tested (Fig. 2d) did not meet the 50 mg NH_4-N/L sewer discharge limit for the City of London at a NLR of 0.81 kg N/m^3 d. Average effluent ammonia concentration increased to 54.7 mg NH_4-N/L and nitrogen removal efficiency decreased significantly to 62%. This indicates that the performance of the LSCFB is limited by nitrification, as a result of the short aerobic EBCT of 0.32 d. Thus, although the LSCFB met sewer discharge BOD and TSS requirements in all three phases, the maximum sustained loading is governed by nitrification and corresponds to a flow rate of 720 L/d, and a NLR of 0.7 kg N/m^3 d at an EBCT of 0.49 d.

The pilot-LSCFB nitrification–denitrification rates, estimated based on available anoxic-aerobic biomass and amount of nitrogen nitrified and denitrified in the system, were 0.05–0.11 g N/(g VSS d) and 0.13–0.18 g N/(g VSS d), respectively. Off-line bench scale tests conducted on the pilot-LSCFB particles specific nitrification (SNRs) and denitrification (SDNRs) rates of 0.14 g NH_4-N/(g VSS d) and 0.62 g NO_3-N/(g VSS d) are much higher than the aforementioned observed nitrification–denitrification rates in the pilot-LSCFB, due to lower carbon-to-nitrogen ratio, limited readily biodegradable carbon source, and external mass transfer resistances despite particles fluidization.

It is noteworthy that the novel LSCFB used in this study achieved 80% nitrogen removal without any pre-treatment at EBCTs of 0.55 and 0.49 d in phases I and II, respectively corresponding to NLR of 0.60 and 0.68 kg N/m^3 d, whereas overall N removal efficiency in pre-ozonation conventional fluidized bed reactor treating leachate characterized by a C/N ratio of 5:1 at NLR of 0.7 kg N/m^3 d was 60% [28].

3.3. Phosphorus removal

Approximately 70% phosphorus removal was observed using LSCFB in this study without any chemical addition as shown in Fig. 2e. Table 3 shows influent and effluent PO_4-P concentrations of 3.4 and 1.2–1.0 mg/L respectively in phases I–III. It is interesting to note that in all phases the LSCFB system achieved average effluent concentrations of 1.7–2.0 mg TP/L and 1–1.2 mg PO_4-P/L, well below the sewer use by-law requirements for City of London (Canada) of 10 mg TP/L.

The overall average phosphorus removal in the LSCFB based on the difference between influent TP and effluent soluble P varied narrowly from 5 mg/L in phase III to 5.2 mg/L in phases I and II. Thus, the overall phosphorus removal rates were 3.38 g P/d (phase I), 3.74 g P/d (phase II), and 4.32 g P/d (phase III). Based on the yields discussed later, phosphorus utilized for biomass synthesis in phases I–III were 1.92, 2.52, 2.82 g P/d, respectively. Chemical phosphorus removal by influent calcium with an average concentration of 48.7 mg Ca^{+2}/L by precipitation contributed 1.46, 1.26, and 1.5 g P/d in phases I–III, respectively, corresponding to 43%, 34%, and 35% of overall P removal in the system.

3.4. Sludge yield

Sludge yield in the pilot-scale LSCFB was calculated as the sum of the net change in attached biomass, sludge wastage, and effluent solids divided by the total COD consumed in the process. Fig. 3 shows the observed yields as linear regressions between cumulative biomass and cumulative COD removal of 0.133, 0.158, and 0.161 g VSS/g COD in PI, PII, and PIII, respectively. Reduction of the sludge yield will substantially minimize post treatment cost of the leachate sludge.

Comparison between observed yields and the estimated yields, as reported in Table 4, considering stoichiometric yield coefficients of 0.63 g COD/g COD, 0.54 g COD/g COD, and 0.24 g COD/g N for aerobic, anoxic, and nitrification, respectively [34], process SRTs, decay coefficient for heterotrophic (K_d) of 0.1 d^{-1}, decay coefficient for autotrophic (K_{dn}) of 0.08 d^{-1}, and fraction of inert biomass that remains as cell debris (f_d) of 0.15 g VSS/g VSS [35], the estimated yields of 0.11, 0.12, and 0.14 g VSS/g COD are in close agreement with the observed yields of 0.133, 0.158 and 0.161 g VSS/g COD in PI, PII, and PIII, respectively. Using Eqs. (2) and (3), overall SRT of 31–44 d and anoxic SRT of 13–18 d were calculated throughout the experiments (Table 2), where M is the weight of particles (g) and X_{anoxic} and $X_{aerobic}$ are the attached VSS (mg) per each gram media in the anoxic and aerobic column respectively. $X_{wastage}$ is the amount of VSS (mg) wasted per day, $VSS_{effluent}$ is the concentration of biomass in the effluent (mg/L) and $Q_{effluent}$ stands for the effluent flow rate (L/d).

$$SRT_{Total} = \frac{M_{aerobic}X_{aerobic} + M_{anoxic}X_{anoxic}}{Q_{effluent}VSS_{eff} + X_{wastage}} \quad (2)$$

$$SRT_{anoxic} = SRT_{Total}\frac{M_{anoxic}X_{anoxic}}{M_{aerobic}X_{aerobic} + M_{anoxic}X_{anoxic}} \quad (3)$$

It is interesting to note that the significantly lower observed yields of the LSCFB relative to activated sludge processes are attributed to its extended SRTs, anoxic COD consumption of 90%, and comparatively lower food/microorganisms (F/M) ratios of 0.18–0.21 g COD/(g VSS d) as shown in Table 2.

3.5. Overall nutrient mass balances

Table 4 presents the overall mass balances for COD, nitrogen, and alkalinity in the anoxic and aerobic column of the LSCFB. Approximately 92% of the influent COD was utilized in the anoxic column by denitrification in phases I and II as compared with 82% in phase III. Anoxic COD consumption was 644 and 719 g COD/d in phases I and II respectively. COD consumption for denitrification (3.5–3.7 mg COD/mg NO_3-N) was estimated using Eq. (4) [35], considering the observed biomass yield of 0.133–0.158 g VSS/g COD.

$$\text{COD consumption for denitrification} = \frac{2.86}{1 - 1.42 \times Y} \quad (4)$$

COD percent (%) closure has been calculated using influent and effluent COD concentrations, and COD in the mass wastage from the LSCFB system. Even though percentage COD closures are approximately 92–93% in phases I and II, COD closure in phase III is only 82%.

Table 4 shows that 183–195 g NO_3-N/d was removed in the anoxic column, which generates 652–696 g alkalinity as $CaCO_3$/d. In the aerobic column, 220–250 g NH_4-N/d was nitrified and utilized 1573–1780 g alkalinity as $CaCO_3$/d. In phase I, the estimated alkalinity loss of 921 g $CaCO_3$/d (Table 4) is about 8% higher than the 850 g $CaCO_3$/d observed experimentally (Table 3). In phase II, estimated alkalinity reduction of 1004 g $CaCO_3$/d is 7.5% higher than the 930 g $CaCO_3$/d observed experimentally while the estimated alkalinity loss for phase III of 1085 g $CaCO_3$/d is only 5% lower than the measured 1143 g $CaCO_3$/d.

Table 4
Overall mass balance.

		Phase I	Phase II	Phase III
COD removed (g COD/d)		721.5[e]	796.3	876.1
Anoxic COD consumed (g COD/d)		644[f]	719.2	723
COD-Biomass (g COD/d)		136.3[g]	178.7	199
N-Nitrification (g N/d)		220.3[h]	237.9	249.4
N-Denitrification (g N/d)		182.6[i]	194.8	194.9
Alkalinity$_{anoxic}$ (g $CaCO_3$/d)		−651.8[j]	−695.4	−695.8
Alkalinity $_{aerobic}$ (g $CaCO_3$/d)		1573[k]	1699	1781
Solids retention time (d)	Anoxic	18	17	13
	Aerobic	26	21	18
k_d[l] for heterotrophic (d^{-1})		0.1	0.1	0.1
k_{dn}[m] for autotrophic (d^{-1})		0.08	0.08	0.08
f_d[n] (g VSS/g VSS)		0.15	0.15	0.15
Heterotrophic biomass production (g VSS/d)		110.9[a]	127.1	142.7
Autotrophic biomass production (g VSS/d)		15.9[b]	18.9	21.1
Estimated yield (g VSS/g COD)		0.11[c]	0.12	0.14
Observed yield (g VSS/g COD)		0.133	0.158	0.161
% COD closure		96%[d]	98%	85%

[a] Heterotrophic biomass production = $[Y/(1+k_d SRT_{anoxic})(1+f_d k_d SRT_{anoxic})] \times$ Anoxic $COD_{consumed}$ (g/d).
[b] Autotrophic biomass production = $[Y_n/(1+k_{dn} SRT_{aerobic})(1+f_d k_{dn} SRT_{aerobic})] \times$ N-Nitrification (g/d).
[c] Estimated yield = $(Y_{anx} COD_{anx} + Y_{aer} COD_{aer})/(COD_{anx} + COD_{aer})$.
[d] % COD closure = (Anoxic COD consumed + COD − Biomass)/$TCOD_{ln}$.
[e] COD removed = $(TCOD_{in}$ (g/L) − $SCOD_{eff}$ (g/L)) × Q_{in} (L/d).
[f] Anoxic COD consumed = [(N-Denitrification (g/d)) × 2.86/(1 − 1.42Y_{obs})].
[g] COD-biomass = $COD_{removed} \times 1.42 Y_{obs}$.
[h] N-Nitrification = $(TKN_{in}$ (g/L) − TKN_{eff} (g/L)) × Q_{in} (L/d) − N_{sludge} (g/d).
[i] N-Denitrification = N-Nitrification (g/d) − (NO_{3eff} (g/L) × Q_{in} (L/d)).
[j] Alkalinity generated in the anoxic column = (−) N-Denitrification × 3.57.
[k] Alkalinity consumed in the aerobic column = N-Nitrification × 7.14.
[l] Endogenous decay coefficient for heterotrophic bacteria.
[m] Endogenous decay coefficient for autotrophic bacteria.
[n] Cell debris (f_d).

4. Conclusions

The LSCFB proved to be a reliable integrated technology for biological nutrient removal from landfill leachate at a low carbon-to-nitrogen ratio of 3:1. The system was operated at loading rates of 1.90–2.60 kg COD/(m^3 d), 0.60–0.81 kg N/(m^3 d), and 0.010–0.016 kg P/(m^3 d) to optimize the loading. The system efficiently removed nutrients at flow rate of 720 L/d corresponding to an EBCT of 0.49 d and loading rate of 2.15 kg COD/m^3 d, 0.68 kg N/m^3 d, and 0.014 kg P/m^3 d.

The LSCFB removed approximately 85% organic, 80% nitrogen, and 70% phosphorus at nutrients loading rates of 2.15 kg COD/(m^3 d), 0.68 kg N/(m^3 d), and 0.014 kg P/(m^3 d). LSCFB effluent characterized by ≤35 mg SBOD/L, <35 mg NH_4-N/L, <1.0 mg PO_4-P/L, and 37 mg VSS/L easily met the sewer by-law criteria for City of London (Canada) without using any chemicals for phosphorus removal. Remarkably low yields of 0.13, 0.15, and 0.16 gVSS/gCOD were observed at long biological solids retention time (SRT) of 31–44 d. Overall mass balances indicated COD closures of 96%, 98%, and 85% in phases I–III, respectively, and alkalinity mass balances closed within 5–8%, confirming data reliability.

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