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Comparative modeling of biological nutrient removal from landfill leachate using a circulating fluidized bed bioreactor (CFBBR)

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ABSTRACT

Steady state operational data from a pilot scale circulating fluidized bed bioreactor (CFBBR) during biological treatment of landfill leachate, at empty bed contact times (EBCTs) of 0.49, and 0.41 d and volumetric nutrients loading rates of 2.2–2.6 kg COD/(m^3 d), 0.7–0.8 kg N/(m^3 d), and 0.014–0.016 kg P/(m^3 d), was used to calibrate and compare developed process models in BioWin® and AQUIFAS®. BioWin® and AQUIFAS® were both capable of predicting most of the performance parameters such as effluent TKN, NH_4-N, NO_3-N, TP, PO_4-P, TSS, and VSS with an average percentage error (APE) of 0–20%. BioWin® underpredicted the effluent BOD and SBOD values for various runs by 80% while AQUIFAS® predicted effluent BOD and SBOD with an APE of 50%. Although both calibrated models, confirmed the advantages of the CFBBR technology in treating the leachate of high volumetric loading and low biomass yields due to the long solid retention time (SRT), both BioWin® and AQUIFAS® predicted the total biomass and SRT of CFBBR based on active biomass only, whereas in the CFBBR runs both active as well as inactive biomass accumulated.

1. Introduction

Landfill leachate is very complex due to large recalcitrant organic molecules, long leachate age, low biodegradable organics concentration, high COD and ammonium content, low carbon to nitrogen ratio, and the presence of heavy metals and toxic components [1–4]. Compared to conventional physical, chemical, and biological treatment processes for industrial wastewater, the circulating integrated fluidized bed bioreactor (CFBBR) system has numerous advantages including small footprint with elimination of clarifiers, high biomass retention resulting in long solid residence times (SRTs) and relatively short hydraulic retention times (HRTs), enhanced mass transfer, and lower sludge production rate.

An extensive pilot-scale investigation of the patented CFBBR for biological nutrient removal (BNR) from municipal wastewater and landfill leachate has been reported by Nakhla and coworkers [5,6]. The CFBBR employs attached microbial films resulting from biodegradation of both organics and nutrients within an integrated system comprising an anoxic column in a fast fluidization regime and an aerobic column in a conventional fluidization regime. This new promising patented technology combines the compactness and efficiency of a fixed-film process with excellent organics, nitrogen, and phosphorus removal efficiencies of 85%, 80%, and 70%, respectively, and reduced sludge yields of 0.15 g VSS/g COD as compared with 60–70% COD and 70–74% nitrogen removal efficiencies achieved by upflow anaerobic sludge blanket (UASB) and moving bed bioreactor (MBBR), respectively [7–12].

Several mathematical mixed culture biofilm models have been published and presented over the past 20 years [13,14]. These models vary in complexity from simple analytical models to multi and three-dimensional (3D) dynamic models in order to solve the mass balance differential equations between the biofilm and various particulate and dissolved components of microbial cells, extracellular polymeric substance, organic and inorganic particles, nutrients, electron acceptors, and electron donors as a function of transport and transformation processes [13]. For the specific purpose of engineering design and analysis, a balance between the simplified and complex mechanistic approach is required. One-dimensional (1-D) fully dynamic and steady-state simulation models are widely used to simulate the full-scale wastewater treatment plant (WWTP) such as the stratified dynamic multi-species model introduced and implemented in the AQUASIM software [13,15–18] and Activated Sludge Models (ASM1, ASM2, ASM2d, ASM3) introduced by International Water Association (IWA) [19]. The IWA model is available in several user-friendly forms, the most common of which are the Simba® (Ifak GmbH, Magdeburg, Germany), ASIM® (EAWAG, Switzerland), EFOR® (DHI Inc., Denmark), BioWin® (Envirosim Associates Ltd., Burlington, ON), GPS-X® (Hydromantis Inc.,

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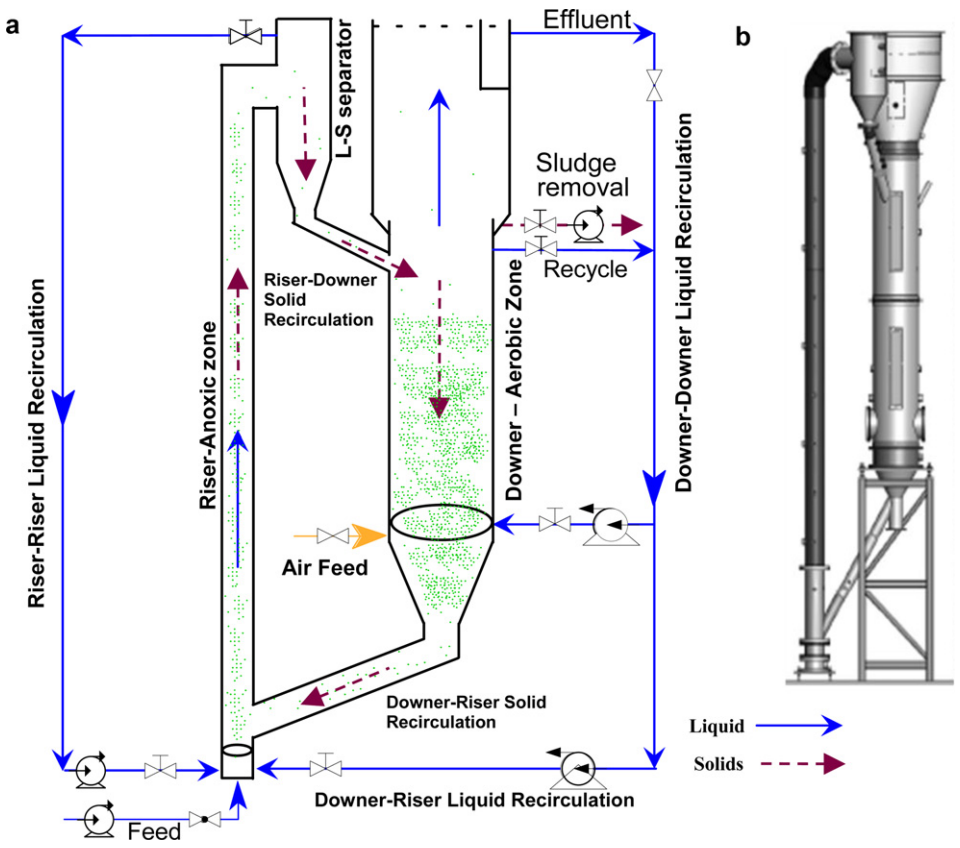

Fig. 1. (a) Schematic and (b) 2-D view of the pilot-scale CFBBR.

Hamilton, ON), AQUIFAS® (Aquaregen, Mountain View, CA), Pro-2D® (CH2 M HILL, Inc., Colorado, US), STOAT® (WRc, Wiltshire, England), and WEST® (Mostforwater, Belgium). However, Simba®, ASIM®, and EFOR® are only developed for the suspended growth municipal wastewater treatment plants while BioWin®, GPS-X®, AQUIFAS®, Pro-2D®, STOAT®, and WEST® are developed for both suspended and attached growth systems.

BioWin® and AQUIFAS® developed a fixed film model and successfully simulated the integrated fixed-film activated sludge (IFAS) process, moving bed biofilm reactor (MBBR), and biological aerated filter (BAF) systems for municipal wastewater treatment plants using a wide range of BOD loadings and biofilm thicknesses [20–25]. The developed models improved the accuracy of diffusional models by evaluating results against semi-empirical data based on experimental measurements from different full-scale WWTPs. For example, fluxes and thicknesses computed by biofilm diffusional modeling can be corrected based on the experimental measurements.

In a fluidized bed bioreactor, simulating the effective volume of the reactor (expanded bed) as a function of biofilm thickness and recirculation flows is challenging due to the complex hydrodynamics involving changing biofilm thicknesses, varying detachment and attrition rates whereas in the IFAS and MBBR detachment and attrition effects are minimal. Moreover, the characteristics of wastewater have a considerable effect on the growth rate of attached biomass and biofilm thickness. Particularly, in case of landfill leachate with C/N ratio of 3:1, total chemical oxygen demand to violate suspended solids (TCOD/VSS) ratio of 8:1 and total biochemical demand to total chemical oxygen demand (TBOD/TCOD) of 0.44, simulation of biological nutrient removal using fluidized bed bioreactors is challenging as a result of biodegradable carbon limitation and biofilm growth limitations. However, none of the aforementioned softwares is designed to model fluidized bed bioreactors as a function of effective volume of the reactor, biofilm thickness limitation, and recirculation flows. In addition, the comprehensive literature review using web of Science® and Google Scholar®, as a search engines, with a keywords of landfill leachate; biological nutrient treatment; and modeling demonstrated that no models are readily available that can accurately predict biological nutrient removal from landfill leachate in a biofilm systems.

Thus, comparative modeling of CFBBR system treating landfill leachate was performed using calibrated BioWin® and AQUIFAS ® softwares. The primary goal of this study was to develop a model to simulate the CFBBR system during the treatment of landfill leachate. In addition to evaluating and comparing the CFBBR performance using both commercially available simulation models during the treatment of a high ammonia and very low carbon to nitrogen landfill leachate. This study also aimed at evaluating the biofilm and biomass prediction in the anoxic and aerobic columns and verifying the calibrated models by increasing the loading rates, reducing the empty bed contact time (EBCT), and decreasing the hydraulic retention time.

2. Materials and methods

2.1. Liquid–solid circulating fluidized bed bioreactor

Experiments were conducted in a pilot-scale CFBBR with an anoxic compartment (riser) followed by aerobic compartment (downer) and recirculation lines between downer and riser as shown in Fig. 1 to treat landfill leachate collected from the W12A Landfill in London, Ontario, Canada. Table 1 illustrates the leachate, characterized predominantly by a carbon to nitrogen ratio of 3:1, TCOD/VSS ratio of 8:1 and TBOD/TCOD of 0.44.

Table 1
Influent and effluent characteristics for different phases.

Parameter	Experimental influent characteristics[a]	BioWin® model influent characteristics[b]	Effluent[a]	
			Phase I	Phase II
pH	7.9–8.8	8.40	7.2–8.2	7.6–8.1
Alkalinity[b]	1619 ± 52	1619	323 ± 71	296 ± 57
COD (mg/L)	1259 ± 77	1300	197 ± 46	302 ± 98
SCOD (mg/L)	1025 ± 27	1058	153 ± 43	245 ± 85
NH_4-N (mg/L)	360 ± 59	349	35.4 ± 13.1	54.7 ± 11.2
NO_3-N (mg/L)	3.1 ± 1.5	3.1	59.9 ± 31.1	63.9 ± 10.3
TKN (mg/L)	392 ± 64	392	49 ± 15	92 ± 23
PO_4-P (mg/L)	3.4 ± 1.1	3.8	1.0 ± 0.2	1.2 ± 0.5
TP (mg/L)	6.2 ± 1.3	7	1.7 ± 0.3	2.0 ± 0.6
TSS (mg L)	263 ± 42	270	60 ± 13	58 ± 8
VSS (mg/L)	156 ± 30	163	37 ± 5	44 ± 8
BOD (mg/L)	565 ± 121	687[c]	83 ± 13	98 ± 18
SBOD (mg/L)	402 ± 83	684[c]	35 ± 8	40 ± 12

[a] Average ± SD of a number of samples 8–12 with a frequency of a sample every 4 d.
[b] mg $CaCO_3$/L.
[c] Higher than the experimental data due to the BioWin® influent specifier limitations.

The pilot-scale facility was developed based on the lab-scale experiments reported by Cui et al. [26], Patel et al. [27], and Chowdhury et al. [28]. Table 2 shows the detailed operational conditions and reactor design parameters of the CFBBR; further details of the reactor and operational conditions are presented elsewhere [6,28].

Lava rock particles with an average diameter of 600 μm (300–1000 μm) were used as the carrier media for biofilm attachment in the CFBBR. The particle porosity was about 33% and the total porosity (particle porosity and voids between particles) was 61%. The bulk density (considering packed media filled with water) of particles was approximately 1720 kg/m^3, with true density (the ratio of sample mass to its true volume) of 2560 kg/m^3 and a high specific surface area of 10,950 m^2/m^3. The CFBBR was started with 125 and 421 kg of fresh lava rock particles with the corresponding compact bed volumes of 80 L 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 [28,29]. The observed attached biofilm thicknesses on the aerobic and anoxic bioparticles 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 were 0.19, 0.58, 0.06, and 0.30 m^3, respectively. 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, with further startup details presented elsewhere [28,29].

Table 2
Operating conditions.

	Phase I	Phase II
Influent flow, Q_{in} (L/d)	720 ± 35	864 ± 35
Average organic loading (kg COD/(m^3 d))	2.15	2.60
Average nitrogen loading (kg N/(m^3 d))	0.68	0.81
Average phosphorus loading (kg P/(m^3 d))	0.014	0.016
Riser–riser recirculation ratio (Q_{r-r}/Q_{in})	62	52
Downer–riser recirculation ratio (Q_{d-r}/Q_{in})	31	26
Downer–downer recirculation ratio (Q_{d-d}/Q_{in})	70	58
Empty bed contact time (d)[a]		
Anoxic	0.11	0.09
Aerobic	0.38	0.32
Nominal HRT (d)[b]		
Anoxic	0.07	0.06
Aerobic	0.25	0.21
Avg. attached biomass (mg VSS/g lava rock)		
Anoxic	16.3	18.7
Aerobic	5.9	7.3
Biomass (g VSS)		
Anoxic	2037.5	2337.5
Aerobic	2504.9	3081.7
Food/microorganisms ratio (g COD/g VSS d)	0.20	0.21
Detachment rates (d^{-1})		
Anoxic	0.127[c]	0.132
Aerobic	0.122[c]	0.127
Estimated SRT (d)		
Anoxic	17[d]	13
Aerobic	21	18
Overall	38[e]	31

[a] EBCT = Vcompact/Q.
[b] Nominal HRT = EBCT × (1 − compact bed porosity).
[c] Detachment rates (b') = $\frac{QX_1}{MX_m}$.
[d] $SRT_{anoxic} = SRT_{Total} \frac{M_{anoxic}X_{anoxic}}{M_{aerobic}X_{aerobic}+M_{anoxic}X_{anoxic}}$.
[e] $SRT_{Total} = \frac{M_{aerobic}X_{aerobic}+M_{anoxic}X_{anoxic}}{Q_{effluent}VSS_{eff}+X_{wastage}}$.

2.2. Analytical methods

Influent, anoxic bed effluent, and final effluent samples were collected in airtight bottles twice a week, and refrigerated at 4 °C prior to analysis. Total suspended solids (TSS), volatile suspended solids (VSS), 5 d biological oxygen demand (BOD), and total Kjeldahl nitrogen (TKN) were analyzed according to the Standard Methods [30].

Dissolved oxygen (DO) in the CFBBR downer was measured using Thermo Orion (810 A+) meter. HACH methods and testing kits (HACH Odyssey DR/2500) were used to measure TCOD, 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. The biofilm thickness of the CFBBR 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 Standard Methods (APHA, 1998) and expressed as mg VSS/g clean particles. Approximately 4–5 g bioparticles were taken from each of the two columns, suspended in a 50 mL vial, and sonicated for 3 h at 30 °C in an Aquasonic sonicator (Model 75HT, ETL Lab-

Table 3
Carbonaceous and nutrient fraction estimated for wastewater and assumed for landfill leachate in BioWin®.

Fraction (abbreviation)	Unit	Default[a]	Input[b]
Readily biodegradable (F_{bs})	g COD/g TCOD	0.16	0.694[c]
Acetate (F_{ac})	g COD/g rbCOD	0.15	0.15
Non-colloidal slowly biodegradable (F_{xsp})	g COD/g sbCOD	0.75	0.05[d]
Unbiodegradable soluble (F_{us})	g COD/g TCOD	0.05	0.12[e]
Unbiodegradable particulate (F_{up})	g COD/g TCOD	0.13	0.185[f]
Ammonia (F_{na})	g NH_3-N/g TKN	0.66	0.89[g]
Particulate organic nitrogen (F_{nox})	g N/g Organic N	0.5	0.25[h]
Soluble unbiodegradable TKN (F_{nus})	g N/g TKN	0.02	0.02
N:COD ratio for unbiodegradable part. COD (F_{upN})	g N/g COD	0.035	0.035
Phosphate (F_{PO_4})	g PO_4-P/g TP	0.5	0.548[i]
P:COD ratio for influent unbiodegradable part. COD (F_{upP})	g P/g COD	0.011	0.011
Non-poly-P heterotrophs (FZ_{bh})	g COD/g TCOD	0.0001	0.0001
Anoxic methanol utilizers (FZ_{bm})	g COD/g TCOD	0.0001	0.0001
Ammonia oxidizers (FZ_{aob})	g COD/g TCOD	0.0001	0.0001
Nitrite oxidizers (FZ_{nob})	g COD/g TCOD	0.0001	0.0001
Anaerobic ammonia oxidizers (FZ_{amob})	g COD/g TCOD	0.0001	0.0001
PAOs (FZ_{bp})	g COD/g TCOD	0.0001	0.0001
Propionic acetogens (FZ_{bpa})	g COD/g TCOD	0.0001	0.0001
Acetoclastic methanogens (FZ_{bam})	g COD/g TCOD	0.0001	0.0001
H_2-utilizing methanogens (FZ_{bhm})	g COD/g TCOD	0.0001	0.0001

[a] Default of municipal wastewater fractions.
[b] Calibrated using the experimental data.
[c] Fraction of TCOD which is readily biodegradable [(soluble readily biodegradable complex COD (S_{bsc}) + soluble readily biodegradable volatile fatty acid COD (S_{bsa}))/TCOD].
[d] Fraction of slowly biodegradable influent COD which is particulate [slowly biodegradable particulate COD (X_{sp})/(slowly biodegradable colloidal COD (X_{sc}) + slowly biodegradable particulate COD (X_{sp}))].
[e] Fraction of TCOD which is soluble unbiodegradable [$SCOD_{eff}/TCOD_{inf}$].
[f] Fraction of TCOD which is particulate unbiodegradable [calibrated using the influent specifier associated with the model and equal to $(1 - F_{bs} - F_{us})$].
[g] Fraction of influent TKN which is ammonia.
[h] Fraction of influent biodegradable organic nitrogen which is particulate.
[i] Fraction of influent TP which is phosphate.

oratory Testing, Inc., New York). After sonication, the VSS content of the detached biomass was measured using Standard Methods [30] and the sonicated particles were cleaned and weighted after drying at 550 °C for 1 h. The paired student *t*-test was conducted to determine the statistical significance of the observed differences between the experimental data at the 95% confidence level.

3. Modeling and simulation

The experimental results of the pilot-scale CFBBR were modeled and calibrated using BioWin® (3.0) software developed by Envirosim Associates Ltd. (Burlington, ON, Canada) and AQUIFAS® (AQUANET) software developed by Aquaregen (Mountain View, CA, US). Modeling of particulate attached growth systems using both softwares for simulation of the complex interactions that occur in the anoxic riser and aerobic downer biofilm reactors [19] was based on general Activated Sludge Models, i.e. ASM1, ASM2d, and ASM 3 [31–33].

3.1. Modeling using BioWin®

BioWin® is developed to model biofilm systems as 1-D fully dynamic and steady-state simulations using a wide range of BOD loading, biomass, and biofilm thickness evaluated against semi-empirical data based on experimental measurements from a full-scale WWTPs. The influent characteristics of the landfill leachate, simulated using the influent specifier associated with BioWin® revealed the carbonaceous and nutrient fractions summarized in Tables 1 and 3 illustrating the simulated landfill leachate characterization compared to the experimental leachate characterization confirm the validity of the specification of various organic and nutrient fractions (Table 3) as reflected by the close agreement between all water quality parameters of COD and BOD. It must be asserted that BioWin® model is COD based and calculates TSS, VSS, and BOD (total and soluble) based on the specification of unbiodegradable particulate and non-colloidal slowly biodegradable fractions, which are not readily measured. In order to account for the much higher soluble fraction of the organic matter in the landfill leachate relative to typical municipal wastewater using the influent specifier, unbiodegradable particulate (F_{up}) and non-colloidal slowly biodegradable (Fxsp) were adjusted to 0.185 g COD/g TCOD and 0.05 g COD/gsb COD, respectively. It is noteworthy to mention that the adjusted parameters were out of the typical range considered for municipal wastewater in BioWin®. As depicted in Table 4, the various kinetic parameters for autotrophs and heterotrophs used in all modeling runs were set to default values.

3.2. Modeling using AQUIFAS®

AQUIFAS® is developed to model fixed film process using semi-empirical equations and a 2-dimensional biofilm model [20–22]. The model equations are based on the kinetics of COD uptake, nitrification, denitrification, and biological phosphorus removal by biofilm carrier particles, as measured under different substrate conditions within the length of a biological reactor. The equations incorporate Monod kinetics with mass flux to simulate the variation in substrate uptake rates, as a result of changes in external substrate concentrations, and associated changes in the biofilm thickness and fraction of nitrifiers in the biofilm that develop in a different cell reactors. The detailed model equations are presented elsewhere [20–22].

The biofilm diffusion model breaks the biofilm into 12 layers and a stagnant liquid layer. COD, DO, biomass, nitrogen, and phosphors fluxes from a concentric layer to the next deeper layer are the net uptake and release in the layer and the flux from the concentric outer layer to this layer. This model adopted the model equations and stoichiometric relationships used in AQUIFAS® to compute the substrate uptake and biomass generation in each layer of the biofilms. The model sums up the substrate uptake and biomass generation over the 12 default model layers to compute the substrate and biomass flux for the biofilm in each cell of the reactor. Multipli-

Table 4
Kinetic parameters used for landfill leachate in BioWin®.

Name [unit]	Default	Input[a]	Arrhenius
Ammonia-oxidizing bacteria (AOB)			
Max. spec. growth rate [1/d]	0.90	0.90	1.072
Substrate (NH_4) half sat. [mg N/L]	0.70	0.70	1.00
Aerobic decay rate [1/d]	0.17	0.17	1.029
Anoxic/anaerobic decay rate [1/d]	0.08	0.08	1.029
$KiHNO_2$ [mmol/L]	0.005	0.005	1.00
Nitrite-oxidizing bacteria (NOB)			
Max. spec. growth rate [1/d]	0.70	0.70	1.06
Substrate (NO_2) half sat. [mg N/L]	0.10	0.10	1.00
Aerobic decay rate [1/d]	0.17	0.17	1.029
Anoxic/anaerobic decay rate [1/d]	0.08	0.08	1.029
$KiNH_3$ [mmol/L]	0.075	0.075	1.00
Ordinary heterotrophic organisms (OHOs)			
Max. spec. growth rate [1/d]	3.20	3.20	1.029
Substrate half sat. [mg COD/L]	5.00	5.00	1.00
Anoxic growth factor	0.50	0.50	1.00
Aerobic decay [1/d]	0.62	0.62	1.029
Anoxic/anaerobic decay [1/d]	0.30	0.30	1.029
Hydrolysis rate (AS) [1/d]	2.10	2.10	1.029
Hydrolysis half sat. (AS)	0.06	0.06	1.00
Anoxic hydrolysis factor	0.28	0.28	1.00
Anaerobic hydrolysis factor	0.50	0.50	1.00
Adsorption rate of colloids [L/(mg COD d)]	0.80	0.80	1.029
Ammonification rate [L/(mg N d)]	0.04	0.04	1.029
Assimilative nitrate/nitrite reduction [1/d]	0.50	0.50	1.00
Fermentation rate [1/d]	3.20	3.20	1.029
Fermentation half sat. [mg COD/L]	5.00	5.00	1.00
Anaerobic growth factor (AS)	0.125	0.125	1.00
Hydrolysis rate (AD) [1/d]	0.10	0.10	1.05
Hydrolysis half sat. (AD) [mg COD/L]	0.15	0.15	1.00

[a] Calibrated using the experimental data.

cation of substrate and biomass flux with the surface area in each cell gives the uptake for the cell. Unlikely BioWin® which requires detailed fractionation of COD as described in Table 3, AQUIFAS® input was limited to the typical composite parameters, i.e. BOD (total and soluble), COD (total and soluble), TSS, VSS, TN (total and soluble), and TP.

3.3. Model implementation and calibration

The CFBBR was modeled using basic reactors available in BioWin® and AQUIFAS®, i.e. influent, unaerated media bioreactor, aerated media bioreactor, nitrate recirculation, clarifiers, effluent, and sludge wastage effluent as shown in Fig. 2. The riser was simulated using two media bioreactors followed by three aerated media bioreactors as a downer and a solid–liquid separator to collect the excess biomass from the system. The influent enters into the riser with a downer–riser liquid and nitrate recirculation collected from the last downer of aerated reactor. The combined fluid flows from riser to the downer. Finally, the effluent from the downer goes to the downer solid–liquid separator, shown as a clarifier, with the provision for sludge wastage. The cross sectional area of anoxic and aerobic reactors was considered equal to the actual cross sectional area of the column in the pilot-scale. To ensure proper nitrifying-denitrifying conditions in the CFBBR, the DO set points in the anoxic riser and aerobic downer are similar to those measured onsite of 0.4 mg/L and 2–3.1 mg/L, respectively.

Lava rock particles with an average size of 600 μm were used as a carrier media in both the anoxic and aerobic reactor. The maximum possible surface area (SSA_{max}) in the anoxic and aerobic reactors was calculated considering zero void ratio and biofilm thickness of 500 μm and 120 μm diameter and a bare lava rock particles of 600 μm diameter as 3750 m^2/m^3 and 7060 m^2/m^3, respectively. Considering bed porosity, spherical lava rock particles occupy 44% of the total reactor volume at 100% fill, translating into a possible surface area for the anoxic and aerobic reactors of 2100 m^2/m^3 and 3950 m^2/m^3, respectively. Thus, the total surface area of the carrier media for the entire anoxic and aerobic reactors considering the compact bed was 166 m^2 (2100 $m^2/m^3 \times 0.11$ d ($EBCT_{Ano}$ in Table 2) $\times$ 0.72 m^3/d) and 1080 m^2 (3950 $m^2/m^3 \times 0.38$ d ($EBCT_{Aer}$ in Table 2) $\times$ 0.72 m^3/d), respectively.

Table 5
Calibrated BioWin® parameters.

Parameters	Reactor	Default values	Used values[a]
Detachment rate (g/m^3 d)	Anoxic 1	8×10^4	8×10^4
	Anoxic 2	8×10^4	8×10^4
	Aerobic 1	8×10^4	2×10^6
	Aerobic 2	8×10^4	1.8×10^6
	Aerobic 3	8×10^4	1.8×10^6

[a] Calibrated using the experimental data.

In order to simulate the fluidization regime of CFBBR system and the change of biofilm thickness, the shear factor was calibrated separately in each reactor with respect to expanded fluidized bed by a detachment rate coefficient in BioWin® model and hydrodynamic shear factor (G) in AQUIFAS® as shown in Tables 5 and 6. It is interesting to note that the properties and the weight of the carrier media such as roughness, porosity, and chemical adsorption in BioWin® and AQUIFAS® models are not explicitly defined but implicitly as SSA, % fill, and biofilm volume fraction (BVF).

4. Results and discussion

The CFBBR was tested and evaluated at two different loading rates, empty bed contact times (EBCTs), and hydraulic retention time by adjusting the influent flow rate from 720 L/d (phase I) and 864 L/d (phase II). All volumetric loadings expressed in Table 2 have been calculated based on the total CFBBR volume of 0.77 m^3 comprised of 0.19 m^3 anoxic riser, and 0.58 m^3 aerobic downer. The models were first calibrated with phase I data and then validated for phase II.

4.1. CFBBR performance

Two different EBCTs of 0.49 and 0.41 d were examined to optimize the organic removal efficiency of the CFBBR. The raw leachate characteristics depicted in Table 1 reflect a COD:N:P ratio of 3:1:0.0155. The CFBBR had to meet sewer use by-law criteria of 350 mg TSS/L, 300 mg BOD_5/L, 50 mg NH_4-N, and 10 mg TP/L [34]. The CFBBR 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 2.2–2.6 kg COD/(m^3 d), 0.68–0.81 kg N/(m^3 d), and 0.014–0.016 kg P/(m^3 d). The system efficiently removed nutrients at a 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 CFBBR 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), as

Table 6
Calibrated AQUIFAS® parameters.

Parameters	Reactor	Default values	Used values[a]
Hydrodynamic shear coefficient (G)	Anoxic 1	0–5	0.2
	Anoxic 2	0–5	0.2
	Aerobic 1	0–5	4
	Aerobic 2	0–5	3
	Aerobic 3	0–5	3

[a] Calibrated using the experimental data.

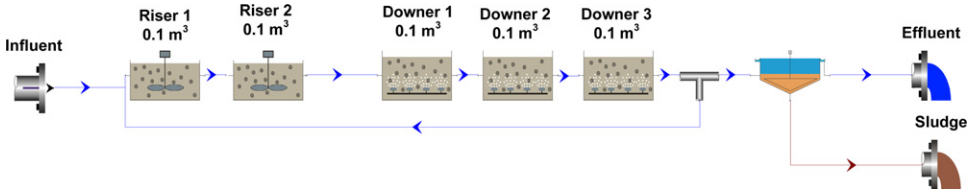

Fig. 2. BioWin® and AQUIFAS® schematic flow diagram of CFBBR model.

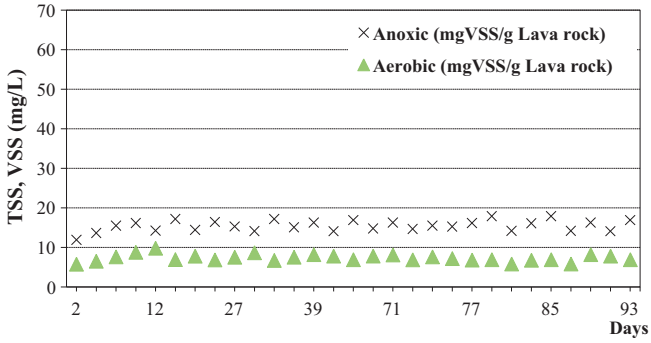

Fig. 3. Temporal variation of attached biomass in the anoxic and aerobic reactors.

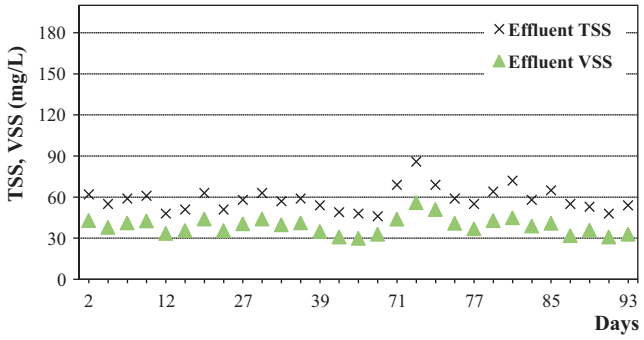

Fig. 4. Temporal variation of the CFBBR effluent VSS concentrations.

compared with 60–70% COD and 70–74% nitrogen removal efficiencies achieved by upflow anaerobic sludge blanket (UASB) and moving bed bioreactor (MBBR), respectively [7–12]. The CFBBR 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, as shown in Table 1, sufficiently met sewer use by-law requirements for the City of London (Canada) without using any chemicals for phosphorus removal. Remarkably low yields of 0.15 and 0.16 g VSS/g COD were observed at long biological solids retention time (SRT) of 31–38 d. Overall mass balances indicated COD closures of 96% and 85% in phases I and II, respectively, and alkalinity mass balances closed within 5–8%, confirming data reliability. In order to ensure attainment of the steady-state conditions in the system, the suspended and attached biomass in the aerobic and anoxic columns were measured. As depicted in Fig. 3, the coefficient of variation (COV) for attached biomass in the aerobic and anoxic columns during this study are 9% and 11%, respectively. Although it is arguable that suspended VSS concentrations varied more widely, as reflected by COV of 13% and 18% (Fig. 4), this process is indeed a fixed-film system and 99.99% of the biomass inventory in the system is in the form of attached biomass. Therefore, the attached biomass and biomass activity remained constant during the study, reflecting attainment of steady-state conditions.

4.2. Model calibration

The models were calibrated with the experimental data at the optimum loading rate of the pilot-scale CFBBR of 2.2 kg COD/(m^3 d), 0.68 kg N/(m^3 d), and 0.014 kg P/(m^3 d) corresponding to 720 L/d and were subsequently validated using the other set of experimental data at the higher loading rate of 2.6 kg COD/(m^3 d), 0.81 kg N/(m^3 d), and 0.016 kg P/(m^3 d). The simulations were started with the default values of the model which were later adjusted to match the observed pilot-scale CFBBR results. Table 5 shows the parameters adjusted during BioWin® calibration. Considering the effect of the perforated coarse bubble distributor in the aerobic reactor and its low oxygen transfer efficiency, the detachment rate was used to maintain the biofilm thickness as observed in the pilot-scale CFBBR system. Moreover, the percentage of the reactor occupied by the media was adjusted to simulate the changes in the expanded bed bioreactor. In AQUIFAS®, the

Table 7
Experimental and simulated effluent quality.

Parameter	Influent[a]	Phase I			Phase II		
		Simulated		Exp.[a]	Simulated		Exp.[a]
		BioWin	AQUIFAS		BioWin	AQUIFAS	
pH	7.9–8.8	7	–	7.2–8.2	7.2	–	7.6–8.1
Alkalinity[b]	1619 ± 52	311	338	323 ± 71	323	338	296 ± 57
COD (mg/L)	1259 ± 77	236	174	197 ± 46	235	203	302 ± 98
SCOD (mg/L)	1025 ± 27	169	128	153 ± 43	169	166	245 ± 85
NH_4-N (mg/L)	360 ± 59	33.7	35.9	35.4 ± 13.1	54.7	56.3	54.7 ± 11.2
NO_3-N (mg/L)	3.1 ± 1.5	61.1	69.4	59.9 ± 31.1	58.4	57.5	63.9 ± 10.3
TKN (mg/L)	392 ± 64	46.4	36.5	49 ± 15	67.3	69.8	92 ± 23
PO_4-P (mg/L)	3.4 ± 1.1	0.8	0.9	1.0 ± 0.2	1	1	1.2 ± 0.5
TP (mg/L)	6.2 ± 1.3	1.5	1.6	1.7 ± 0.3	1.8	1.8	2.0 ± 0.6
TSS (mg L)	263 ± 42	60	62	60 ± 13	58	62	58 ± 8
VSS (mg/L)	156 ± 30	45	45	37 ± 5	44	50	44 ± 8
BOD (mg/L)	565 ± 121	19	40	83 ± 13	20	45	98 ± 18
SBOD (mg/L)	402 ± 83	1	18	35 ± 8	1.3	19	40 ± 12

[a] Average ± SD of a number of samples 8–12 with a frequency of a sample every 4 d.
[b] mg $CaCO_3$/L.

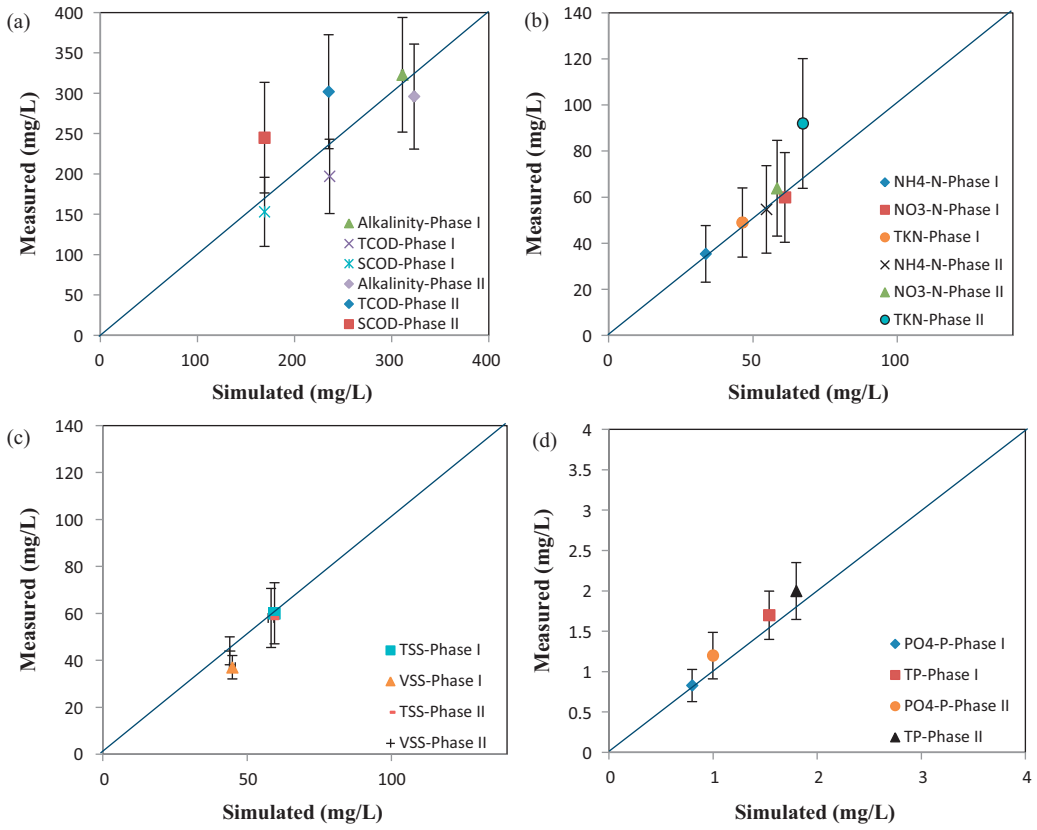

Fig. 5. Comparison between predicted and measured parameters for phases I and II with BioWin®.

hydrodynamic shear coefficient and the BVF defined as the fraction of liquid tank volume displaced by biofilm, were adjusted to simulate additional turbulence in fluidized beds as shown in Table 6. It is noteworthy to mention that the percentage of the reactor fill ratio used by BioWin® considered the volume of reactor occupied by clean media only while the BVF ratio used by AQUIFAS® considers only the biofilm attached to the lava rock media.

4.3. Steady-state CFBBR model

The steady-state CFBBR models using BioWin® and AQUIFAS® were focused on various aspects of process performance, i.e. reactor effluent characteristics, nutrient removal rates, biofilm thickness, total biomass in the reactor, and process yields as well as the COD uptake, nitrification, and denitrification rates.

4.3.1. BioWin® model

Table 7 shows a comparison between model prediction and experimental data for both phases using BioWin®. In phase I, the model predicted effluent NH_4-N of 33.7 mg/L, NO_3-N of 61.1 mg/L, and TKN of 46.6 mg/L compared well to observed NH_4-N of 35.4 ± 13.1 mg/L, NO_3-N of 59.9 ± 31.1 mg/L, and TKN of 49 ± 15 mg/L, in the pilot-scale CFBBR system while in phase II the model predicted effluent NH_4-N of 54.7 mg/L, NO_3-N of 58.4 mg/L, and TKN of 67.3 mg/L closely matched observed NH_4-N of 54.7 ± 11.2 mg/L, NO_3-N of 63.9 ± 10.3 mg/L, and TKN of 92 ± 23 mg/L. As described in Table 7, the average percentage error (APE) in phase I, calculated as the summation of the absolute difference between the experimental and predicted values divided by the experimental values, averaged over the number of data points, revealed that the discrepancy between predicted and measured final effluent alkalinity, SCOD, NH_4-N, NO_3-N, TKN, TP, PO_4-P, and TSS was 1–10%. Comparatively, a higher APE of 20% was observed between simulated and measured final effluent TCOD and VSS in phase I. In phase II, the BioWin® model overpredicted SCOD, TKN, and PO_4-P by 20% while the other final effluent characteristics were in agreement with the experimental data. Furthermore, while the model overpredicted the final effluent VSS in phase I by 20%, it predicted the effluent VSS accurately in phase II reflecting lack of systematic prediction errors. Due lack of consideration of soluble microbial products (SMPs), the model significantly underpredicted the effluent BOD and SBOD in both phases by APE of 77% and 97%, respectively. However, predicted model results were within the range of the average plus or minus standard deviation of the effluent characteristics as shown in Fig. 5. The model accurately predicted effluent soluble nutrients. The APE for the effluent in both phases with respect to SCOD, ammonia, nitrates, and orthophosphates were 20%, 5%, 6%, and 9%, respectively. In general, the predicted effluent characteristics by BioWin® model in both phases were in good agreement (APE < 22%) with the experimental but the effluent BOD and SBOD were underpredicted for various runs by 77–97%.

4.3.2. AQUIFAS® model

Comparison between model prediction and experimental data using AQUIFAS® (Table 7) shows the discrepancy of 1–13% between predicted and measured final effluent alkalinity, TCOD, NH_4-N, NO_3-N, TP, PO_4-P, and TSS, while a higher APE of 21% was observed between simulated and measured final effluent SCOD and VSS. In phase I, the model predicted effluent NH_4-N of 35.9 mg/L and NO_3-N of 69.4 mg/L compared to measured NH_4-N of 35.4 ± 13.1 mg/L and NO_3-N of 59.9 ± 31.1 mg/L, while in phase II the model predicted effluent NH_4-N of 56.3 mg/L and NO_3-N of 57.5 mg/L matched NH_4-N of 54.7 ± 11.2 mg/L and NO_3-N of 63.9 ± 10.3 mg/L.

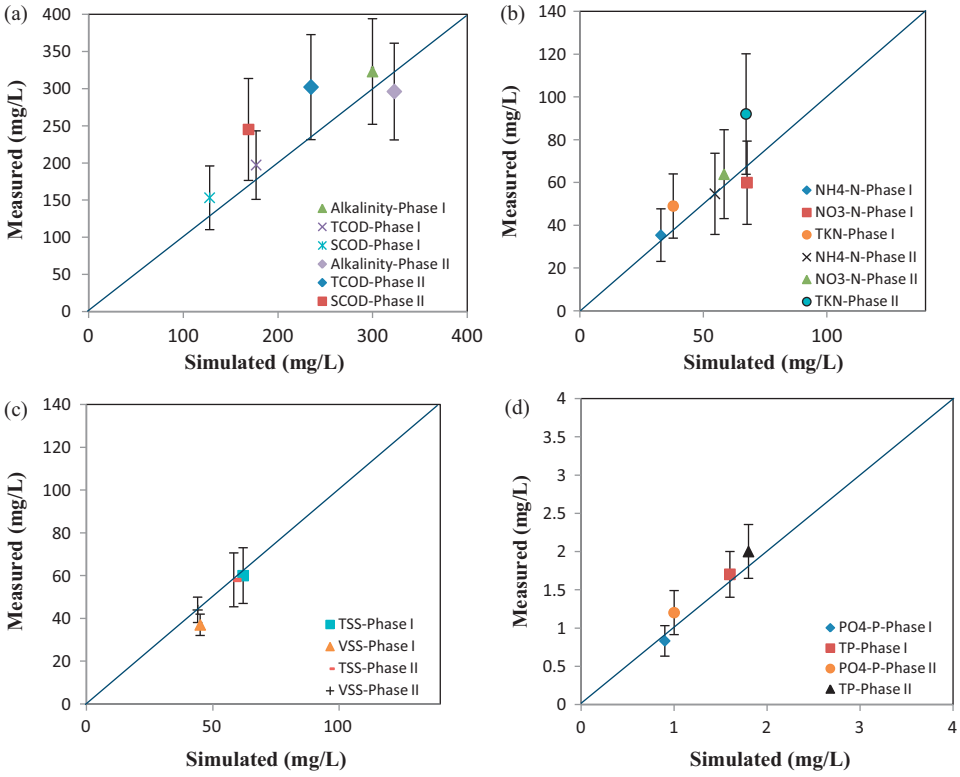

Fig. 6. Comparison between predicted and measured parameters for phases I and II with AQUIFAS®.

In both phases, the model underpredicted final effluent TKN with an APE of 24%. Moreover, the AQUIFAS ® model in phase I predicted TCOD and SCOD within APE of 10% and 16%, respectively, whereas in phase II, underpredicted TCOD and SCOD by 32% APE, reflecting lack of systematic prediction errors. Furthermore, the AQUIFAS® predictions for BOD and SBOD in both phases were more accurate than BioWin® with an APE of 50%. Model-predictions were within the range of the average plus or minus standard deviation of the effluent characteristics as shown in Fig. 6. In general, the AQUIFAS® model-predictions for all effluent characteristics (excluding BOD), in both phases were in good agreement (APE < 19%) with the experimental data but the BOD and SBOD were under-predicted for various runs by 50%.

The high discrepancy between the predicted and experimental BOD values by both the models may be due to soluble microbial products (SMPs) in the effluent. In fixed-film wastewater systems with longer sludge retention times, the effluent soluble BOD is predominantly more than effluent SBOD in suspended growth systems as a result of release of SMPs. None of the ASM models accounts for SMPs which is not really substantial in short SRT systems such as activated sludge but maybe important in long SRT systems such as CFBBR [35].

4.4. Simulated biomass yield

Biomass yield in the pilot-scale CFBBR 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 was 0.15 and 0.16 g VSS/g COD in phases I and II, respectively, with overall sludge production of 146 g VSS/d and 164 g VSS/d. BioWin® predicted that 32 g VSS/d and 32.4 g VSS/d biomass were lost in the effluent of CFBBR system with an overall sludge wastage of 175 g VSS/d and 213 g VSS/d in phases I and II, respectively. Considering the aerobic and anoxic nutrient mass removal rates, the mean cell residence time, decay coefficient, and the simulated COD removal of 888 g COD/d and 1063 g COD/d in phases I and II, the simulated biomass yields with BioWin® were calculated as 0.23 g VSS/g COD and 0.24 g VSS/g COD in phases I and II, respectively, which are approximately 50% higher than those observed experimentally.

As reported in Table 8, for AQUIFAS®, considering the effluent biomass of 32 g VSS/d and 46 g VSS/d and sludge production of 132 g VSS/d and 133 g VSS/d with a COD removal of 930 g COD/d and 1109 g COD/d in phases I and II, respectively, leads to a simulated biomass yield of 0.17 g VSS/g COD and 0.16 g VSS/g COD in phases

Table 8
Simulated results and measured parameters for nutrient removal rates.

Parameter	Phase I			Phase II		
	Simulated		Exp.[a]	Simulated		Exp.[a]
	BioWin	AQUIFAS		BioWin	AQUIFAS	
Anoxic COD consumption (kg/d)	0.83	0.70	0.71 ± 0.05	0.97	0.77	0.72 ± 0.05
Aerobic COD consumption (kg/d)	0.08	0.18	0.08 ± 0.05	0.10	0.29	0.15 ± 0.05
Yield (g VSS/g COD)	0.23	0.17	0.16 ± 0.04	0.24	0.16	0.16 ± 0.02
Anoxic N removal (kg/d)	0.24	0.24	0.24 ± 0.05	0.27	0.27	0.25 ± 0.06
Aerobic N removal (kg/d)	0.20	0.18	0.19 ± 0.04	0.23	0.21	0.19 ± 0.04

[a] Average ± SD of a number of samples 8–12 with a frequency of a sample every 4 d.

I and II, respectively, approximately 6% (on average) higher than experimental. AQUIFAS® biomass yields were thus much closer to the observed yields than BioWin®.

Although the predicted aerobic and anoxic attached biomass thicknesses of 160–200 and 500–580 μm, respectively, using BioWin® and AQUIFAS® were in close agreement with the experimental values of 120 and 600 μm in anoxic and aerobic, the total biomass in both models was underpredicted by 20% and 33% in phases I and II, respectively. In phase I, the total biomass using BioWin® in the anoxic and aerobic reactors was 1371 g VSS and 1886 g VSS, compared to measured of 2037 g VSS and 2505 g VSS, respectively, while in phase II model biomass was 1471 g VSS and 2057 g VSS, versus experimental anoxic and aerobic biomass of 2337 g VSS and 3081 g VSS, respectively, with an APE of 30%. The total anoxic and aerobic biomass in phase I using AQUIFAS® was 1801 g VSS and 1882 g VSS, compared to anoxic and aerobic biomass of 2057 g VSS and 2505 g VSS, respectively, while in phase II biomass was 1984 g VSS and 2004 g VSS as compared to anoxic and aerobic biomass of 2337 g VSS and 3081 g VSS, respectively, with an APE of 20%.

Both models ignore the accumulation of the influent nonbiodegradable VSS (nbVSS) in the system, which is usually about 10% [36] translating to 16 g nbVSS/d in phases I and II or a total of 1472 g nbVSS over the 92 d study duration.

4.5. Nutrient uptake rates

Anoxic COD removal by AQUIFAS® in phases I and II (Table 8) were close to the experimental data with an APE of 1.4% and 7%, respectively, whereas BioWin® overpredicted COD removal values by an APE of 17% and 35%, respectively. However, aerobic COD consumption predicted by BioWin® with APE of 0% and 33% in phases I and II were much more precise than aerobic COD removal simulated by AQUIFAS®.

Nitrification and denitrification rates of 0.24–0.27 kg N/d and 0.2–0.23 kg N/d, respectively, predicted by BioWin® were comparable with the observed nitrification and denitrification rates, estimated from the amount of nitrogen nitrified and denitrified. AQUIFAS® nitrification and denitrification rates in phases I and II were in close agreement with the experimental data within APE of 0–10%.

As mentioned previously, the biomass yield predicted by BioWin® was 50% higher than measured due to shorter simulated SRTs of 15.7 d and 14 d in phases I and II, respectively. In AQUIFAS®, the biomass yield predicted in the model was in close agreement with the observed experimental yield with an APE of 6%. AQUIFAS® predicted SRTs of 22 d and 20 d compared to measured (based on VSS) of 38 d and 31 d in phases I and II, respectively. The SRT predicted by BioWin® and AQUIFAS® is based on the biomass only, i.e. ignores accumulation of nonbiodegradable influent VSS. Considering the specific nitrification rate (SNR) and specific denitrification rate (SDNR) of the attached and detached biomass of 0.14 g NH_4-N/g VSS d, 0.19 g NO_3-N/g VSS d, 1.57 g NH_4-N/g VSS d, and 1.57 g NO_3-N/g VSS d demonstrates that the established active SRT was 18 d in both phases compared to overall SRT of 38 d and 31 d in phases I and II, respectively.

As shown in Fig. 5, the predicted orthophosphate and TP by BioWin® matched those measured with an APE of 10% in both phases. AQUIFAS® also predicted orthophosphate and TP well with an APE of 10%. Phosphorous removal by both models was predominantly governed by biomass assimilation accounting for 70% of phosphorus removal based on the 2% phosphorous content of sludge produced.

5. Summary and conclusions

Comparison between the calibrated BioWin® and AQUIFAS® models and the experimental data from the pilot-scale CFBBR shows that the modeling of landfill leachate along with attached growth systems was challenging due to the complex hydrodynamics involving changing biofilm thicknesses, varying detachment and attrition rates, and the complexity of leachate characteristics with C/N ratio of 3:1, TCOD/VSS ratio of 8:1 and TBOD/TCOD of 0.44.

BioWin® and AQUIFAS® predicted the soluble parameters with an APE of 10%. However, effluent SBOD and BOD were predominately underpredicted due to soluble microbial products (SMPs) in the effluent as a result of long SRTs in the CFBBR.

AQUIFAS® predicted the total biomass and biomass yield as well as the anoxic COD, anoxic N, and aerobic N removal rates in the CFBBR systems more accurately than BioWin®. BioWin® which predicted more accurately aerobic COD uptake. The challenges faced during the modeling by BioWin® and AQUIFAS® were:

- The influent specifier associated with BioWin® was only limited for municipal wastewater simulation only whereas the AQUIFAS® has no influent specifier and the influent characteristics were adjusted in the model.
- The biomass detachment rates in a fixed-film system cannot be controlled by setting a desired SRT in the entire system.
- Although the media fill and SSA in the reactor can be adjusted, the models do not provide the users with the weight of media which is essential for system design.
- Each column can be only aerobic, anoxic or anaerobic whereas in real fixed-film systems biofilms perform differently throughout the inner layers. As a result simultaneous nitrification and denitrification which may occur in the same reactor cannot be simulated by any of the two models.

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References

[1] S. Park, K.S. Choi, K.S. Joe, W.H. Kim, H.S. Kim, Variations of landfill leachate properties in conjunction with the treatment process, Environ. Technol. 22 (2001) 639–645.
[2] S. Renou, J.G. Givaudan, S. Poulain, F. Dirassouyan, P. Moulin, Landfill leachate treatment: review and opportunity, J. Hazard. Mater. 150 (2008) 468–493.
[3] A.L. Gálvez, L. Giusti, M. Zamorano, A.F. Ramos-Ridao, Stability and efficiency of biofilms for landfill leachate treatment, Bioresour. Technol. 100 (2009) 4895–4898.
[4] K.Y. Foo, B.H. Hameed, An overview of landfill leachate treatment via activated carbon adsorption process, J. Hazard. Mater. 171 (2009) 54–60.
[5] G. Nakhla, J. Zhu, Y. Cui, Liquid–solid circulating fluidized bed wastewater treatment system for simultaneous removal of carbon, nitrogen, and phosphorus, US Patent No. 7,261,811 (2004), Int'l PCT patent awarded (2005).
[6] A. Eldyasti, N. Chowdhury, G. Nakhla, J. Zhu, Biological nutrient removal from leachate using a pilot liquid–solid circulating fluidized bed bioreactor (LSCFB), J. Hazard. Mater. 181 (2010) 289–297.
[7] R.H. Kettunen, T.H. Hoilijoki, J.A. Rintala, Anaerobic sequential anaerobic–aerobic treatments of municipal landfill leachate at low temperatures, Bioresour. Technol. 58 (1996) 31–40.
[8] R.H. Kettunen, J.A. Rintala, Performance of an on-site UASB reactor treating leachate at low temperature, Water Res. 32 (1998) 537–546.
[9] K.J. Kennedy, E.M. Lentz, Treatment of landfill leachate using sequencing batch and continuous flow upflow anaerobic sludge blanket (UASB) reactors, Water Res. 34 (2000) 3640–3656.
[10] R.H. Kettunen, J.A. Rintala, Sequential anaerobic–aerobic treatment of sulphur rich phenolic leachates, J. Chem. Technol. Biotechnol. 62 (1995) 177–184.
[11] N.J. Horan, H. Gohar, B. Hill, Application of a granular active carbon-biological fluidized bed for the treatment of landfill leachates containing high concentrations of ammonia, Water Sci. Technol. 36 (1997) 369–375.

[12] U. Welander, T. Henrysson, T. Welander, Nitrification of landfill leachate using suspended-carrier biofilm technology, Water Res. 31 (1997) 2351–2355.
[13] O. Wanner, P. Reichart, Mathematical modeling of mixed-culture biofilm, Biotechnol. Bioeng. 49 (1996) 172–184.
[14] H. Wanner, G. Hainan, S. Dorn, Nutritional value of floral nectar sources for flight in the parasitoid wasp Cotesia glomerata, Physiol. Entomol. 31 (2006) 127–133.
[15] O. Wanner, W. Gujer, Competition in biofilms, Water Sci. Technol. 17 (1984) 27–44.
[16] O. Wanner, A multispecies biofilm model, Biotechnol. Bioeng. 28 (1986) 314–328.
[17] P. Reichert, AQUASIM—a tool for simulation and data analysis of aquatic systems, Water Sci. Technol. 30 (1994) 21–30.
[18] J.B. Xavier, C. Picioreanu, M.C. Van Loosdrecht, A framework for multidimensional modeling of activity and structure of multispecies biofilms, Environ. Microbiol. 7 (2005) 1085–1103.
[19] M. Henze, W. Gujer, T. Mino, T. Matsuo, M.C. Wentzel, G.V.R. Marais, Activated Sludge Model No. 2. IAWQ Scientific and Technical Report No. 3, IAWQ, London, England, 1995.
[20] D. Sen, C.W. Randall, Improved computational model (AQUIFAS) for activated sludge, integrated fixed-film activated sludge, and moving-bed biofilm reactor systems. Part I: semi-empirical Model Development, Water Environ. Res. 80 (2008 a) 439–453.
[21] D. Sen, C.W. Randall, Improved computational model (AQUIFAS) for activated sludge, integrated fixed-film activated sludge, and moving-bed biofilm reactor systems. Part II: multilayer biofilm diffusion model, Water Environ. Res. 80 (2008 b) 624–632.
[22] D. Sen, C.W. Randall, Improved computational model (AQUIFAS) for activated sludge, integrated fixed-film activated sludge and moving bed biofilm reactor systems, part III: analysis and verification, Water Environ. Res. 80 (2008 c) 633–645.
[23] H.M. Phillips, M. Maxwell, T. Johnson, J. Barnard, K. Rutt, J. Seda, B. Corning, J.M. Grebenc, N. Love, S. Ellis, Optimizing IFAS and MBBR designs using full-scale data, in: Proceedings of the Water Environment Federation 81ST Annual Technical Exhibition & Conference, Chicago, IL, USA, 2008.
[24] M. McGehee, J. Gellner, J. Beck, C. White, T. Bruton, D. Howard, BioWin modeling of a three reactor IFAS system, in: Proceedings of the Water Environment Federation 82nd Annual Technical Exhibition & Conference, Orlando, FL, USA, 2009.
[25] H. Rupp, G. Roy, B. Tautic, J. Bushey, Pilot study confirms design of IFAS system for nitrogen reduction in Connecticut, in: Water Environment Federation Specialized Conference on Nutrient Removal, Washington, DC, 2009.
[26] Y. Cui, G. Nakhla, J. Zhu, A. Patel, Simultaneous carbon and nitrogen removal in anoxic-aerobic circulating fluidized bed biological reactor (LSCFB), Environ. Technol. 25 (2004) 699–712.
[27] A. Patel, J. Zhu, G. Nakhla, Simultaneous carbon, nitrogen and phosphorus removal from municipal wastewater in a circulating fluidized bed bioreactor, Chemosphere 65 (2006) 1103–1112.
[28] N. Chowdhury, G. Nakhla, J. Zhu, Load maximization of a liquid–solid circulating fluidized bed bioreactor for nitrogen removal from synthetic municipal wastewater, Chemosphere 71 (2008) 807–815.
[29] N. Chowdhury, G. Nakhla, J. Zhu, M. Islam, Pilot-scale experience with biological nutrient and biomass yield reduction in a liquid–solid circulating fluidized bed bioreactor, Water Environ. Res. (2009), doi:10.2175/WER 09-11-1541.
[30] APHA, AWWA, WEF, Standard Methods for the Examination of Water and Wastewater, 20th ed., American Public Health Association, Washington, DC, US, 1998.
[31] P.S. Barker, P.L. Dold, General model for biological nutrient removal activated-sludge systems: model presentation, Water Environ. Res. 69 (5) (1997) 969–984.
[32] Y. Comeau, I. Taka, Schematic representation of activated sludge models, in: Proceedings of the Water Environment Federation Technical Exhibition and Conference, vol. 3, Chicago, IL, USA, 2008, pp. 266–328.
[33] J.P. Boltz, E. Morgenroth, D. Sen, Mathematical modelling of biofilms and bio-film reactors for engineering design, Water Sci. Technol. 62 (8) (2010) 1821–1836.
[34] Waste Discharge By-law-16, City of London, Ontario, Canada (2007).
[35] D.J. Barker, D.C. Stuckey, A review of soluble microbial products (SMP) in wastewater treatment systems, Water Res. 33 (1999) 3063–3308.
[36] Metcalf, Eddy, Wastewater Engineering: Treatment and Reuse, 4th ed., McGraw-Hill, New York, 2003, pp. 622–623.