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Mechanisms for Reduced Excess Sludge Production in the Cannibal Process

Marc-André Labelle[1]*, Peter L. Dold[2], Yves Comeau[1]

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[1]Department of Civil, Geological and Mining Engineering, Polytechnique Montreal, P.O. Box 6079, Station Centre-ville, Montreal, Quebec, Canada H3C 3A7.

[2]EnviroSim Associates Ltd., McMaster Innovation Park, 175 Longwood Road South, Suite 114A, Hamilton, Ontario, Canada L8P 0A1.

[*]Corresponding author: marc-andre.labelle@polymtl.ca.

ABSTRACT: Reducing excess sludge production is increasingly attractive as a result of rising costs and constraints with respect to sludge treatment and disposal. A technology in which the mechanisms remain not well understood is the Cannibal process, for which very low sludge yields have been reported. The objective of this work was to use modeling as a means to characterize excess sludge production at a full-scale Cannibal facility by providing a long sludge retention time and removing trash and grit by physical processes. The facility was characterized by using its historical data, from discussion with the staff and by conducting a sampling campaign to prepare a solids inventory and an overall mass balance. At the evaluated sludge retention time of 400 days, the sum of the daily loss of suspended solids to the effluent and of the waste activated sludge solids contributed approximately equally to the sum of solids that are wasted daily as trash and grit from the solids separation module. The overall sludge production was estimated to be 0.14 g total suspended solids produced/g chemical oxygen demand removed. The essential functions of the Cannibal process for the reduction of sludge production appear to be to remove trash and grit from the sludge by physical processes of microscreening and hydrocycloning, respectively, and to provide a long sludge retention time, which allows the slow degradation of the “unbiodegradable” influent particulate organics ($X_{\mathrm{U,Inf}}$) and the endogenous residue (X_{E}). The high energy demand of 1.6 kWh/m^3 of treated wastewater at the studied facility limits the niche of the Cannibal process to small- to medium-sized facilities in which sludge disposal costs are high but electricity costs are low.

KEYWORDS: sludge minimization, sludge age, physical separation, hydrocyclone, microscreening, side-stream interchange bioreactor, fermentation, energy.

Introduction

Reducing excess sludge production at water resource recovery facilities (WRRFs) is increasingly attractive resulting from rising costs and constraints with respect to sludge treatment and disposal. A number of technologies have been developed to reduce excess sludge production from secondary treatment that use some combination of physical, chemical, biological, and thermal processes (Sandino et al., 2008). With these processes, sludge reduction takes place on the basis of one or more of three mechanisms: (1) increasing the rate and extent of particulate matter degradation by solubilizing sludge solids, (2) increasing the extent of degradation by transforming a portion of the unbiodegradable components into biodegradable matter, and (3) modifying the treatment process, such as by removing unbiodegradable components (Sandino and Whitlock, 2010).

Cannibal. A sludge reduction technology for which the mechanisms remain not well understood is the Cannibal process that was commercialized by USFilter about 15 years ago (Figure 1). Very low sludge yields have been reported in this adaptation of the conventional activated sludge (CAS) process but the fundamental mechanisms responsible for reduced excess sludge production still needs to be established (Whitlock et al., 2010). It consists of an activated sludge process treating raw wastewater (coarse screened and degritted, but not primary settled) where a portion of the return activated sludge (RAS) is directed to a quiescent side-stream “interchange” bioreactor (SSIB). Another portion of the RAS passes through a solids separation module (SSM).

Side-Stream Interchange Bioreactor. The SSIB typically is designed for a sludge retention time (SRT) of approximately 10 days and is operated under intermittent aeration based on the control of the oxidation reduction potential or on timer settings (e.g., 2 hours of aeration in a 24-hour cycle; Johnson et al., 2008). Usually, the SSIB is operated as a sequencing batch reactor (SBR) from which the supernatant is returned to the main bioreactor and the settled sludge is only wasted occasionally when the solids concentration reaches a certain level; this serves to increase SRT of the whole system. The overall SRT, based on the solids mass in both the main bioreactor and the SSIB, has been reported to reach 200 days (Johnson et al., 2008). Intermittent aeration in the SSIB is favorable for fermentation by facultative heterotrophic organisms but methanogens should be inhibited because of the toxicity of oxygen to these organisms.

Solids Separation Module. A portion of the RAS from the main bioreactor is recirculated via an SSM consisting of microscreening devices for trash removal (typically 250-µm openings) and hydrocyclones for grit removal (Figure 1). These two sludge components are normally considered unbiodegradable and would accumulate in the bioreactors if not removed in the SSM.

Previous characterization and modeling efforts were made to better describe the Cannibal process with regards to sludge reduction, with most consideration given to the effect of the process environmental conditions (Chon et al., 2011; Ramdani et al., 2010; 2012) and to model modifications concerning the production of decay products and to decay rates of particulate organics (Giraldo et al., 2007, Johnson et al., 2008; Whitlock et al., 2009, 2010). The feed pattern was also shown to influence the sludge production, with a lower observed yield in a fast-feed system before conversion to a slow-feed system (0.14 and 0.31 mg total suspended solids [TSS]/mg chemical oxygen demand [COD], respectively; Novak et al., 2011). Knowledge gaps still remain to better understand the contribution of each individual mechanisms of the Cannibal process to the reduction of excess sludge production.

Objectives. The goal of this work was to better understand the contribution of each mechanism for reduced excess sludge production in the Cannibal process. The objectives were (1) to use modeling to assess the effect on excess sludge production of (1.1) providing a long sludge retention time and (1.2) removing unbiodegradable components (trash and grit) by physical processes; and (2) to characterize a full-scale Cannibal facility to (2.1) evaluate the observed activated sludge yield and the trash and grit yield, (2.2) the SRT, and (2.3) the energy consumption of the facility.

Methods

This section first describes the model used to determine the effect on excess sludge production of the various sludge reduction mechanisms attributed to the Cannibal process. The methods used to characterize a full-scale facility are then presented with details on the design of the WRRF.

Modeling. The four main particulate components of mixed liquor are unbiodegradable particulates organics from the influent ($X_{U,Inf}$), active heterotrophic biomass (X_H), the endogenous residue from biomass decay (X_E), and inorganic suspended solids (ISS) from the influent. The sum of the first three mixed liquor components make up the volatile suspended solids (MLVSS), while the sum of these four components and the intracellular salts (considered to be of 0.08 g ISS/g TSS), make up the mixed liquor suspended solids (MLSS). Other components such as residual biodegradable particulates and autotrophic biomass were considered negligible. The $X_{U,Inf}$ and ISS are considered to be the trash and grit, respectively, and are removed to some extent by the SSM of the Cannibal process.

The effect of SRT on the sludge production and the division of the VSS into X_H, X_E, and $X_{U,Inf}$ was determined in a steady state activated sludge model by considering a typical raw wastewater composition and typical models parameters (Table 1) using eqs 1 to 3. Model parameter symbols and values are presented in Table 1. Each equation expresses the mass (*M*) of the component in the system operated at a specified SRT per unit COD removed ($1 - f_{SU}$). These model parameters were validated by Dold (2007) using more than 30 data points from nine "closely controlled systems operated at steady state conditions over a range of SRTs, treating either raw or primary settled wastewater". These systems included biological nutrient removal processes with combinations of aerobic, anoxic, and anaerobic zones. The assumptions are that effluent COD consists only of unbiodegradable soluble COD from the influent (S_U), that all the biodegradable influent COD is used and that the model kinetic parameters remain constant under various environmental conditions (aerobic, anoxic, and anaerobic). With these assumptions and the system boundaries used, the intermediate reactions occurring in the SSIB, such as fermentation and hydrolysis, are implicitly considered by the model. More details on eqs 1 to 7 and the validation of the model parameters with numerous WRRF data can be found in Dold (2007).

$$\frac{M_{\mathrm{XH\_VSS}}}{1-\mathrm{f_{SU}}} = \frac{1}{1-\mathrm{f_{SU}}} \cdot \frac{(1-\mathrm{f_{SU}}-\mathrm{f_{XU}}) \cdot Y_{\mathrm{H}} \cdot \mathrm{SRT}}{(1+b_{\mathrm{H}} \cdot \mathrm{SRT})} \qquad (1)$$

$$\frac{M_{\mathrm{XE\_VSS}}}{1-\mathrm{f_{SU}}} = \frac{M_{\mathrm{XH\_VSS}}}{1-\mathrm{f_{SU}}} \cdot (f \cdot b_{\mathrm{H}} \cdot \mathrm{SRT}) \tag{2}$$

$$\frac{M_{\mathrm{XE\_VSS}}}{1-\mathrm{f_{SU}}} = \frac{1}{1-\mathrm{f_{SU}}} \cdot \frac{(1-\mathrm{f_{SU}}-\mathrm{f_{XU}}) \cdot Y_{\mathrm{H}} \cdot \mathrm{SRT} \cdot (f \cdot b_{\mathrm{H}} \cdot \mathrm{SRT})}{(1+b_{\mathrm{H}} \cdot \mathrm{SRT})} \tag{2.1}$$

$$\frac{M_{\mathrm{XU\_VSS}}}{1-\mathrm{f_{SU}}} = \frac{1}{1-\mathrm{f_{SU}}} \cdot \frac{\mathrm{f_{XU}} \cdot \mathrm{SRT}}{\mathrm{f_{CV}}} \tag{3}$$

The effect of the studied mechanisms for the reduction of sludge production was quantified by modeling 5 cases (Table 2). The specific production of each component is given by dividing the mass in the system by the SRT. The conventional VSS production per unit COD removed is expressed in eq 4, which sums eqs 1 to 3, and divides by SRT. The effect of SRT on the activated sludge production expressed as g VSS/g COD and g ISS/g COD, using the raw wastewater and model parameters listed in Table 1, is estimated using eqs 4 and 5, respectively (Case A). Accounting for the salts associated with active biomass and endogenous residue is based on a fraction of 0.92 g VSS/g TSS ($\mathrm{f_{VT,BM}}$) for X_{H} and X_{E} in eq 5. The effect on sludge production through removing all the influent unbiodegradable particulate organics ($X_{\mathrm{U,Inf}}$) from the mixed liquor by an "ideal" microscreen is then illustrated (Case B). This was modeled by considering a revised $\mathrm{f_{XU}}$ of 0.00 only for the last term of eq 4, which corresponds to an ideal trash removal of 100% by the microscreen. The effect on sludge production through removing all the influent ISS (grit) by an "ideal" hydrocyclone is quantified by setting an influent ISS concentration of 0.00 mg ISS/L in eq 5 (Case C). The effect on sludge production of the possible slow degradation of the endogenous residue is quantified by modifying eq 4 to include a first order X_E degradation rate (b_E) of 0.007 d^{-1} as reported by Ramdani et al. (2012) (eq 6; Case D). The effect of slow degradation of both X_E and $X_{U,Inf}$ (instead of its removal via the microscreen) is quantified by extending eq 6 to include a first order $X_{U,Inf}$ degradation rate (b_U) of 0.007 d^{-1} (eq 7; Case E).

$$Y_{VSS/COD\_A} = \frac{1}{1-f_{SU}} \cdot \left(\frac{(1-f_{SU}-f_{XU}) \cdot Y_H \cdot (1+f \cdot b_H \cdot SRT)}{(1+b_H \cdot SRT)} + \frac{f_{XU}}{f_{CV}} \right) \tag{4}$$

$$Y_{ISS/COD} = \frac{1}{1-f_{SU}} \cdot \left(\left(\frac{ISS}{COD} \right) + \frac{(1-f_{SU}-f_{XU}) \cdot Y_H \cdot (1+f \cdot b_H \cdot SRT)}{(1+b_H \cdot SRT)} \cdot \frac{(1-f_{VT,BM})}{f_{VT,BM}} \right) \tag{5}$$

$$Y_{VSS/COD\_D} = \frac{1}{1-f_{SU}} \cdot \left(\frac{(1-f_{SU}-f_{XU}) \cdot Y_H}{(1+b_H \cdot SRT)} \cdot \left(1 + \frac{(f \cdot b_H \cdot SRT)}{(1+b_E \cdot SRT)} \right) + \frac{f_{XU}}{f_{CV}} \right) \tag{6}$$

$$Y_{VSS/COD\_E} = \frac{1}{1-f_{SU}} \cdot \left(\frac{(1-f_{SU}-f_{XU}) \cdot Y_H}{(1+b_H \cdot SRT)} \cdot \left(1 + \frac{(f \cdot b_H \cdot SRT)}{(1+b_E \cdot SRT)} \right) + \frac{f_{XU}}{f_{CV} \cdot (1+b_U \cdot SRT)} \right) \tag{7}$$

Full-Scale Facility. The Morongo Indian Reservation, California, full-scale Cannibal WRRF was characterized by using the facility historical data, from discussions with the facility staff, and by conducting a sampling campaign during which additional parameters required to prepare a solids inventory and an overall mass balance were measured.

The facility historical data consisted of values of flowrates (total influent, from water bottling plant and internal usage); influent and effluent COD, TSS, temperature, and pH; biological tanks MLSS; MLVSS; sludge volume index (SVI); cycle time; period duration (fill, aerate, settle, decant) levels; and sludge blanket levels. Flowrates, volumes, and masses of wasted sludge, trash, grit, and screenings to the drying beds and to the various bins were also available, as well as run hours and electrical usage for the equipment. The data were taken on a daily to weekly basis at the facility influent and effluent, in the biological tanks, and at every wastage point. The sampling campaign aimed at measuring other parameters that were not measured routinely. Additional samples were sent to an external laboratory to complete the dataset from the facility and for quality control (Babcock Laboratories, Inc., California). Influent and effluent biochemical oxygen demand (BOD) and TSS (approximately 8 times per month) and effluent ammonia, nitrates, nitrites, and total Kjeldahl nitrogen (approximately once per month) were measured in the external laboratory. The difference between the facility and the external laboratory measurements were, on average, below 4 and 6% for influent and effluent TSS, respectively.

This facility has been in operation since August 1, 2004, and data for the 3-year period from January 1, 2006, to December 31, 2008, were used for the characterization as this provided a representative description of the routine mode of operation. Data quality control over that period was made by engineering checks, by typical ratios relating COD, BOD, VSS such as BOD/COD, VSS/TSS (Melcer et al., 2003), and by plotting data to evaluate consistency between data trends such as bioreactor sludge concentrations with relation to wastage.

The facility consisted of headworks with a grinder, a 6-mm coarse screen, a vortex grit chamber, and a grit classifier; two parallel main bioreactors and an SSIB all designed as SBRs; effluent infiltration basins for groundwater recharge; and drying beds for the waste activated sludge (WAS).

A portion of mixed liquor from the main bioreactor is recirculated to the SSM, first to an internally fed inclined drum microscreen for trash removal (Wedge Wire 250 μm, Rotoshear, Parkson Corp., Florida). The screenings (trash) are washed with tap water and dewatered in a compactor. The screened sludge is then sent to four parallel-mounted 50-mm hydrocyclones for grit removal (apex size = 0.65 cm, vortex finder size = 1.27 cm, FLSmidth Krebs, Denmark). The hydrocyclone overflow is returned to the main bioreactor and the underflow, containing the denser suspended solids (grit), is sent to a grit classifier from which the overflow is further thickened in a geotextile bag that is emptied when full. The trash from the microscreen and the grit from the classifier are disposed of in a bin that is emptied on average every month and even if it is not full to prevent nuisances.

The SRT of the facility was calculated by considering the TSS mass (kg) in the main bioreactor and the SSIB, divided by the sum of the daily mass of TSS (kg TSS/d) wasted from the SSIB and the SSM and the mass leaving via the effluent. The daily TSS accumulation in the SSIB was considered to be negligible and the system to be at steady state in the SRT calculation. The trash and grit bin was assumed to be 75% full when emptied, as estimated by the facility staff, with an average dryness of 35% that was determined during the sampling campaign. The headworks trash and grit were excluded from the overall mass balance calculations and were not accounted for in the raw wastewater characterization. These were removed from the facility in a separate bin.

The overall sludge production was calculated as the sum of the activated sludge yield, the *trash and grit* yield and solids loss via the effluent, divided by the difference between the influent total COD and the filtered effluent COD. The effluent filtered COD was estimated by the difference between the effluent total COD and particulate COD, considering the effluent VSS and a particulate COD to VSS ratio (f_{CV}) of 1.48.

Results and Discussion

This section first presents the activated sludge composition and production based on the model equations by considering (or excluding) trash and grit removal and the slow degradation of the unbiodegradable organic sludge components, X_E and $X_{U,Inf}$. The characterization of the full-scale Cannibal WRRF is then presented followed by estimation of the facility's SRT and sludge production. Finally, the energy demand and expected process niche of the Cannibal process is discussed.

Modeling. The simulated activated sludge composition in terms of X_H, X_E, and $X_{U,Inf}$ for SRTs ranging from 0 to 200 days is expressed as a fraction of the total VSS in Figure 2. At the very long SRTs reported as typical for the Cannibal process (e.g., 200 days), there is a minimal fraction of X_H remaining and the activated sludge VSS is composed mainly of $X_{U,Inf}$ and X_E. Thus, with an activated sludge facility operating at a long SRT, sludge reduction processes targeting the X_H component would have little effect. Other processes acting on the X_E and $X_{U,Inf}$ components offer the potential for additional sludge reduction.

The simulated activated sludge production using the default model parameters is shown in terms of g TSS/g COD removed for SRTs ranging from 0 to 200 days (Figure 3, Case A). At a very long SRT such as 200 days, the yield would be 0.24 g TSS/g COD. For that same SRT, the activated sludge yield could be reduced to 0.14 g TSS/g COD by removing all $X_{U,Inf}$ through using an "ideal" microscreen (Case B). Adding an "ideal" hydrocyclone to remove all ISS derived from the influent would result in an activated sludge yield of 0.09 g TSS/g COD (Case C). Additional degradation of X_E at a rate of 0.007 d^{-1} would result in activated sludge yield (Case D) of 0.04 g TSS/g COD, the ultimate (but unlikely) "near zero sludge production", and a trash and grit yield (Case A minus Case C) of 0.15 g TSS/g COD. The overall sludge production would then correspond to the sum of the activated sludge yield plus the trash and grit yield of 0.19 g TSS/g COD. The same result could also have been reached with multiple combinations of b_U and trash removal efficiencies of less than 100%. As an example, in the worst case of a screening efficiency of 0%, a b_U of 0.007 d^{-1} would predict a sludge production similar to case C at an SRT of 200 days (Case E).

Increasing the SRT from 20 days, which corresponds to a relatively long SRT for the CAS process, to a very long SRT (e.g., 200 days), leads to a relatively small reduction of the sludge production, from 0.29 to a plateau of about 0.24 g TSS/g COD (Case A). The active biomass fraction is reduced from about 30% to less than 5% over the same range of SRT. Efficiently removing strictly trash and grit by physical units has a greater potential to reduce the yield, with an additional 0.15 g TSS/g COD (this value becoming the "trash and grit" yield) over the same range of SRT (Comparing Case A to Case C).

The trash and grit yield obtained from simulations corresponds closely to reported values, whereas the activated sludge production of 0.04 g TSS/g COD obtained for simulations with "ideal" microscreens and hydrocyclones and the slow degradation of X_E (Case D) corresponds to value approximately 2 to 3 times lower than reported values for the Cannibal process. Activated sludge yields ranging from 0.10 to 0.20 g TSS/g BOD_5 (0.05 to 0.10 g TSS/g COD, assuming a typical COD to BOD_5 ratio of 2.0 g/g) have been reported, provided that unbiodegradable solids and ISS are also removed at a "trash and grit yield" of 0.10 to 0.30 kg TSS/kg BOD_5 (0.05 to 0.15 g TSS/g COD) (Johnson et al, 2008; Roxburg et al., 2006; Sandino and Whitlock, 2010). A slightly higher observed sludge production of 0.17 g VSS/g COD at an SRT of 81 days was observed in a laboratory-scale Cannibal system, corresponding to a reduction of 56% of the yield when compared to a control system operated at an SRT of 10 days (Giraldo et al., 2007). A similar reduction of 60% in solids was obtained when comparing a Cannibal process with a control system with an aerobic digester (Novak et al., 2007). In comparison, typical waste activated sludge yield in CAS processes are in the range of 0.6 to 0.8 kg TSS/kg BOD_5 when treating raw wastewaters and operated at conventional SRTs. The trash and the grit removal units are of course not "ideal" in a real-life application and reducing their efficiency would result in similar predictions. The amount of trash removal was reported to range from 90 to 100% in some Cannibal facilities (Sandino and Whitlock, 2010). Based on these observations, some trash and grit removal and the slow degradation of the unbiodegradable particulate organics appear to be necessary to reach the low sludge yields reported for the Cannibal process.

Slow degradation of the so-called *unbiodegradable* sludge components $X_{U,Inf}$ and X_E have been reported in several studies on systems operated at a long SRT (Table 3). First-order degradation rates for $X_{U,Inf}$ and X_E (b_U and b_E, respectively) of 0.007 d^{-1} were estimated based on the simulation of data from more than 30 references for systems with SRTs up to 400 days or under complete sludge retention by Spérandio et al. (2013). Values of b_E from 0.0065 to 0.0075 d^{-1} at 20 °C were reported by Ramdani et al. (2012), with slightly higher values obtained under intermittent aeration conditions when compared to fully aerobic systems. Degradation rates of the endogenous residue (b_E) of 0.005 and 0.012 d^{-1} were obtained at 35 °C in batch tests of more than 90 days under anaerobic and intermittently aerated conditions, respectively (Ramdani et al., 2010). Slightly higher b_E values of 0.012 to 0.014 d^{-1} were obtained for textile and tannery wastewaters (Lubello et al., 2009). A b_E value of 0.007 d^{-1} thus appears to be a conservative estimate for the intermittent aeration conditions and temperature prevailing in an SSIB treating a raw municipal wastewater.

Cannibal Process Characterization. *Operating Conditions and Performance.* The full-scale Cannibal facility studied treats municipal wastewater from the Morongo Indian Reservation and the discharge from a water bottling plant, which contributes approximately 30% of its average influent flow. The facility is largely underloaded as it treats an average influent flow and a COD load of only 32 and 14% of the design capacity, respectively. The average influent composition and operating conditions based on 3 years of operation, from January 1, 2006, to December 31, 2008, are presented in Table 4. The influent fractionation was assumed to be that of a typical raw municipal wastewater. Only one SBR (main bioreactor) was in operation at a time, due to the excess treatment capacity, resulting in an average hydraulic retention time (HRT) of 4.1 days.

The main bioreactors are operated under intermittent aeration to provide aerobic and anoxic conditions for nitrogen removal. An SSIB, also operated as a sequencing batch reactor, receives the mixed liquor from the main bioreactors at an average daily flow of about 50 m^3/d

(not every day), resulting in average HRT and interchange rate (IR) of approximately 35 days and 1.3% (daily TSS mass sent to SSIB/TSS mass in bioreactor), respectively. SRT in the SSIB could not be determined, but it is longer than HRT considering that it was operated as an SBR returning only the supernatant to the main bioreactors. The SSIB is typically operated under a 24-hour cycle consisting of 21-, 2-, and 1-hour periods of mixing without aeration, aeration, and settling, respectively, after which the supernatant is returned to the main bioreactors, resulting in the slow accumulation of solids in the SSIB. Occasional wastage of the mixed liquor is done by sending settled sludge from the SSIB to the drying beds. A significant decrease in the sludge production in the Cannibal process was reported when increasing the IR from 4 to 7% at an SRT of 10 days (Novak et al., 2007).

The WRRF produces a high-quality effluent with greater than 95% COD and BOD_5 removal, and average effluent TSS and total nitrogen concentrations of 7 ± 3 mg TSS/L (n = 297) and 4 ± 3 mg N/L (n = 30). The activated sludge has reasonable settling properties with an SVI averaging approximately 150 mL/g in the main bioreactors (Table 4). The settleability of the sludge appeared remarkably good considering the very long SRT of the facility. Reaching such a high SRT would not be possible without good settleability in the SSIB as well. The fact that the SSIB provides long settling periods may contribute to performance by increasing floc size and density. The likely presence of dense polyphosphates accumulating organisms may also improve settleability (Johnson et al., 2008). The settling properties were found to be much better when using an anaerobic side stream reactor operated with periods without agitation, when compared to other control processes (Chon et al., 2011).

The screenings at the Morongo WRRF were continuously washed with tap water and under pressure (7.5 bar) during screening operations and appeared similar to whitish paper pulp. The screenings VSS to TSS ratio (f_{VT}) ranged from 90 to 93%, which is significantly higher than that of the mixed liquor itself prior to screening that has an average f_{VT} of 0.84 ± 0.03 g VSS/g TSS (*n* = 119). An f_{VT} value of 90% was also reported by Johnson et al. (2008) for screenings from Cannibal facilities. Microscreening tests on activated sludge and WAS from facilities without primary clarification indicated that all screenings had a similar f_{VT} of 0.90 ± 0.04 g VSS/g TSS, independently of the incoming sludge f_{VT}, ranging from 0.50 to 0.85 g VSS/g TSS (Mansour-Geoffrion, 2013). In that study, there was little capture by microscreening at facilities with primary clarification, with an average 0.005 g VSS of screening per g TSS screened (*n* = 13), compared to a facility without primary clarifiers, with an average of 0.024 g VSS of screening per g TSS screened (*n* = 10). The f_{VT} of the grit after the classifier and in the geotextile bag was of 0.32 and 0.23 g VSS/g TSS. These observations indicate that the microscreen and the hydrocyclone in the SSM selectively removed trash and grit, respectively, and a minimal proportion of other sludge fractions. Efficient fine screening and degritting at the headworks and primary clarification could possibly replace the SSM in the Cannibal process but would require much larger equipment since the total flowrate would have to be treated instead of a portion of concentrated mixed liquor. The amount of tap water used in the drum microscreen, of about 10% of influent wastewater flowrate, could be excessive for larger WRRF. Without such cleaning, a greater proportion of other sludge components would be expected to be wasted together with the trash and nuisance odors may be a concern.

The fate of the phosphorus (P) entering the Morongo facility remains unclear as no data were provided for effluent P. Chemical precipitation and enhanced biological phosphorus removal have been reported as possible mechanisms for P removal in the Cannibal process. In the simulation of a Cannibal process with an enhanced biological phosphorus removal (EBPR) process configuration, the simulated soluble phosphorus concentrations reached over 900 mg P/L in the SSIB (Johnson et al., 2008). These authors stated that lower concentrations between 100 and 200 mg P/L should be expected in real-life applications based on knowledge with full-scale systems, possibly because of the formation of precipitates (e.g., struvite) at these high P concentrations. This concentration would still be too high to return the supernatant from the SSIB to the main bioreactor without a prior side-stream P removal process in which P limits are enforced (Johnson et al., 2007). A sustained 98% P removal was achieved in a bench-scale Cannibal–EBPR process, but the authors could not conclude on the fate of the phosphorus as the P mass balance only accounted for 67% of the phosphorus load (Goel and Noguera, 2006). Unlike the Kjeldahl digestion method, the one using persulfate may not have oxidized all the solids containing P, thus leading to a poor mass balance. The robustness of the P removal processes involved in the Cannibal process still needs further investigation.

Solids Inventory and Mass Balance. The operating mode of the SSIB with return of supernatant to the main bioreactor (SBR) resulted in a 4.5 times greater MLSS concentration in the SSIB (14.1 g TSS/L) than in the SBR bioreactor (3.1 g TSS/L) and in 67% of the TSS sludge inventory being in the SSIB bioreactor (Table 4 and Figure 4). The sum of the daily loss of suspended solids to the effluent (7 kg TSS/d) and of the activated sludge solids (expressed as dry matter; DM) that are occasionally wasted from the SSIR to the drying beds (38 kg DM/d on average but not every day) contributed about equally to the sum of solids that are wasted daily as trash and grit from the SSM (43 kg DM/d; Figure 4). This daily trash and grit wastage corresponded to 15% of the daily influent BOD_5 mass (296 kg BOD_5/d), which is lower than the 20 to 30% expected (Johnson et al., 2008). The average solids accumulation in the SSIB was 9.3 kg TSS/d and 7.0 kg VSS/d over the 3-year period. This solids inventory gives better insight into the mode of operation of the facility and allows the calculation of the SRT, overall mass balance and overall sludge production.

The resulting SRT of the whole facility, based on the TSS inventory, is estimated to be approximately 400 days. The overall mass balance (Figure 4) shows that 3.2, 6.4, 5.9, and 1.5% of the COD entering the system exits as loss via the effluent, as excess mixed liquor sent to the drying beds and as trash and grit, and accumulates in the system, respectively, resulting in 83% (by difference) of the COD being oxidized. The overall sludge production, considering all exiting and accumulating solids, is estimated to be 0.14 g TSS/g COD (0.09 g VSS/g COD), including a trash and grit yield of 0.06 g TSS/g COD. This is much lower than the expected sludge production of 0.23 g TSS/g COD typical for CAS municipal wastewater treatment and default model parameters (Table 1) for that same SRT (Case A for an SRT of 400 days). Should all the trash and grit be removed by the SSM (Case C), an activated sludge yield of 0.09 g TSS/g COD would be expected at the same SRT of 400 days.

Because the removal of all the trash and grit in the SSM is unrealistic, it appears that the degradation of the “unbiodegradable” organic solids coming from the influent ($X_{U,Inf}$) and produced as endogenous residue (X_E) must be accounted for to reach the low yields reported for the Cannibal process. This degradation is most likely to be observable, as suggested by other researchers, when the SRT is long enough, which is the case at the Morongo WRRF. However, it should be recognized that the additional reduction could also be a consequence of fermentation in the SSIB (Table 3).

The sensitivity of the assumptions made to evaluate the trash and grit yield on the overall yield was assessed by changing those values to high and low values. The yield values presented above for the studied facility are based on the assumptions that the trash and grit bin was filled to an average of 75% full when disposed of, as estimated by the facility staff, and that trash and grit dryness was 35%. The trash and grit bin is the only output of the system in which assumptions were needed because of an absence of weight measurements to complete the overall mass balance. By considering the bin to be disposed of being 50 and 100% full (35% dryness), the overall sludge production varied from 0.12 to 0.16 g TSS/g COD, instead of 0.14 g TSS/g COD. By considering dryness of 20 and 50% (bin filled to 75%), the overall sludge production would be 0.11 and 0.17 g TSS/g COD, respectively. These values are in the same range as those presented above when considering the initial assumptions. Therefore, these assumptions are not sensitive enough to affect the observations and conclusions presented.

Energy Consumption and Cannibal Niche. The average electrical usage of the whole facility over the period studied was 1480 ± 354 kWh/d (n = 1095), corresponding to 1.6 kWh/m^3 of treated wastewater. This value is 2.6 times higher than the 0.6 kWh/m^3 of treated wastewater expected for a 3780 m^3/d (1 mgd) capacity CAS facility (Water Environment Federation, 2009). The fact that nearly 85% of the influent COD was oxidized compared to the more typical value of approximately 60% in a CAS process (based on an observed yield of 0.4 g COD/g COD at an SRT of 10 days from Case A) contributes to the high energy demand of the Cannibal process.

The electricity consumption associated with the Cannibal part of the process was of 116 kWh/d (data available from July 2006 to December 2008). The equipment considered in that consumption, in decreasing order of electricity consumption, are the SSIB blowers, grit pump feeding the hydrocyclones, SSIB tank mixer, microscreen, trash compactor, and grit classifier. This corresponds to approximately 8% of the total consumption in the whole facility, leaving more than 92% of the power consumption to the headworks, the SBRs, the WAS, pumps and the main building electricity.

The high electricity demand required to oxidize most of the COD and the resulting reduction of the sludge production identifies the niche of the Cannibal process. The advantage of using the Cannibal process over other secondary treatment processes is very site-specific and is most likely to be favorable for small- to medium-sized facilities, particularly those below the threshold for anaerobic digestion systems, as pointed out by Roxburgh et al. (2006), and where sludge disposal costs are high and electricity costs are low. The capacity of the 28 Cannibal facilities treating municipal wastewaters reported by Sandino and Whitlock (2010) ranged from 4000 to 230 000 m^3/d (1 to 17 mgd), with a median of 45 000 m^3/d (12 mgd), which appear just below the threshold for anaerobic digestion.

Conclusions

Based on modeling and full-scale data, the mechanisms for reduced excess sludge production in the Cannibal process are

(1) Providing a very long sludge retention time (SRT) by
   a. Using an interchange reactor to accumulate a greater mass of sludge in the system, and
   b. Extracting most of the influent trash and grit from the activated sludge through

physical processes of microscreening and hydrocycloning;

(2) Providing a very long SRT that favors X_H degradation by endogenous respiration and "unbiodegradable" influent particulate organics ($X_{U,Inf}$) and endogenous residue (X_E) slow degradation; and

(3) Increasing resulting from alternating anaerobic and aerated conditions in the interchange reactor $X_{U,Inf}$ and X_E degradation rates.

The sludge retention time of the studied facility was evaluated to be approximately 400 days. The overall sludge production was estimated to be 0.14 g TSS produced/g COD removed, including a trash and grit yield of 0.06 g TSS/g COD. With an expected sludge production of 0.23 g TSS/g COD typical for CAS municipal wastewater treatment for the same SRT, this leads to an estimated sludge reduction of 0.09 g TSS produced/g COD removed attributable to the slow degradation of "unbiodegradable" influent particulate organics ($X_{U,Inf}$).

The Cannibal facility studied consumes more than 2.5 times more electricity than a CAS process of comparable capacity. Savings on the sludge disposal costs may compensate for energy demand in some cases. The fate of the phosphorus in the Cannibal process remains unclear and needs further investigation.

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Table 1—Influent composition and model parameters (referenced to 20 °C).

	Symbol	Unit	Value
Influent			
Chemical oxygen demand	COD	mg/L	500
Inorganic suspended solids	ISS	mg/L	25
Unbiodegradable soluble COD fraction	f_{SU}	g S_U*/g COD	0.05
Unbiodegradable particulate COD fraction	f_{XU}	g X_U*/g COD	0.13
Model parameters**			
Heterotrophic biomass true yield	Y_H	g VSS/g COD	0.45
Endogenous respiration rate	b_H	d^{-1}	0.24
Endogenous residue fraction	f	g COD/g COD	0.20
Particulate COD to VSS ratio	f_{CV}	g X_{COD}/g VSS	1.48
X_H and X_E VSS to TSS ratio	$f_{VT,BM}$	g VSS/ g TSS	0.92

* Expressed in COD units.

** Adapted from Dold, 2007.

Table 2—Model cases.

Case	Description	f_{XU} g/g	ISS mg/L	b_E d^{-1}	b_U d^{-1}
A	Base case	0.13	25	0.000	0.000
B	Ideal microscreen (MS)	0.00[a]	25	0.000	0.000
C	Case B + ideal hydrocyclone (HC)	0.00[a]	0	0.000	0.000
D	Case C + X_E degradation	0.00[a]	0	0.007	0.000
E	Ideal HC + X_E and $X_{U,Inf}$ degradation	0.13	0	0.007	0.007

[a] f_{XU} value of 0.00 only for the last term in eqs 4 and 6 ($X_{U,Inf}$ accumulation term).

Table 3—Degradation kinetics for systems operated at a long SRT.

Condition*	Temperature °C	b_E d^{-1}	b_U d^{-1}	Reference
AX/OX	n.a.	0.012–0.014	0.012–0.014	Lubello et al., 2009
AN/AE	35	0.012	n.a.	Ramdani et al., 2010
AN	35	0.0075	n.a.	Jones et al., 2007
AN	35	0.005	n.a.	Ramdani et al., 2010
AN/AE	30	0.0104	n.a.	Ramdani et al., 2012
AN/AE	20	0.0072	n.a.	Ramdani et al, 2012
AN/AE	20	0.0075	n.a.	Ramdani et al., 2012
OX	20	0.0065	n.a.	Ramdani et al., 2012
OX	20	0.007	0.007	Spérandio et al., 2013

* Notes: AN = anaerobic: AN/AE = anaerobic intermittently aerated; AX = anoxic; OX = aerobic; n.a. = not applicable. (Adapted from Spérandio et al., 2013).

Table 4—Average influent parameters and bioreactor operating conditions with standard deviation (SD) and number of values (*n*).

	Unit	Value	SD	*n*
Influent				
Flowrate	m^3/d	920	250	1096
COD	mg O_2/L	774	460	50
BOD_5	mg O_2/L	321	175	161
TSS	mg TSS/L	382	253	198
pH	—	7.4	0.3	187
Temperature	°C	23.5	0.2	186
Drinking water usage	m^3/d	91	41	1096
SBR1				
Volume	m^3	3770	136	334
MLSS	mg TSS/L	3000	549	460
f_{VT}	g VSS/g TSS	0.84	0.04	74
SVI	mL/g	146	57	440
SBR2				
Volume	m^3	3880	79	80
MLSS	mg TSS/L	3120	555	261
f_{VT}	g VSS/g TSS	0.85	0.01	45
SVI	mL/g	150	39	255
SSIB				
Volume	m^3	1722	n.a.	n.a.
MLSS	mg TSS/L	14 060	3059	115
f_{VT}	g VSS/g TSS	0.75	0.02	21
Sludge accumulation rate	kg TSS/d	9.3	n.a.	n.a.

n.a. = not applicable.

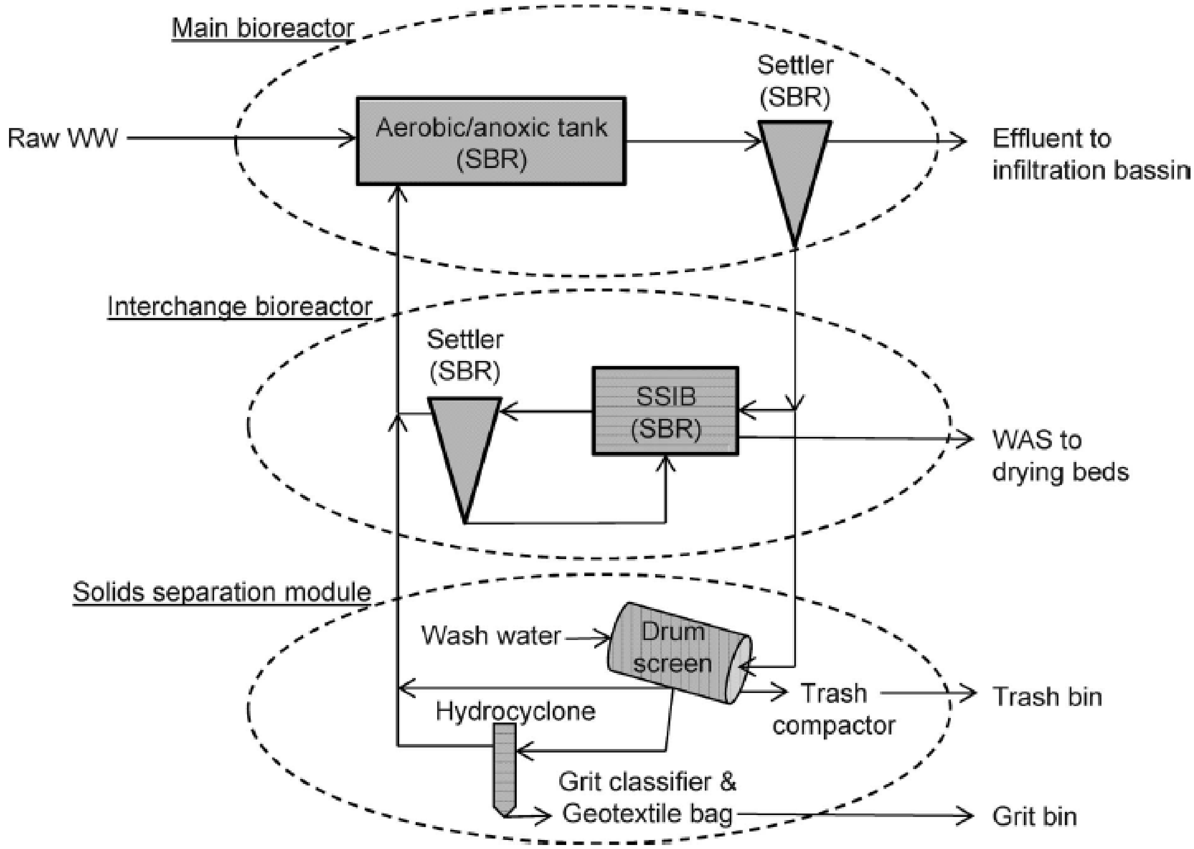

Figure 1—Schematic of the Cannibal process.

Notes: WW = wastewater; SBR = sequencing batch reactor combining main bioreactor and settler; SSIB = side-stream interchange bioreactor; WAS = waste activated sludge.

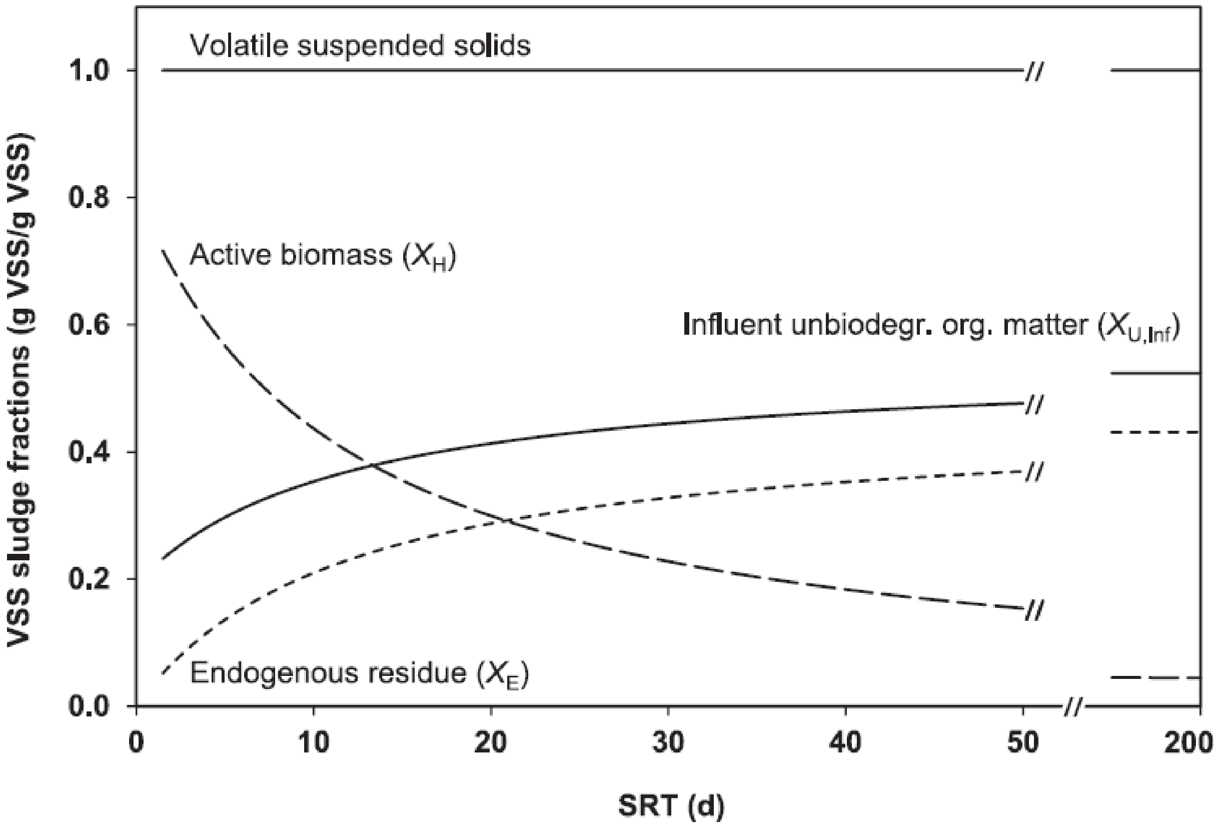

Figure 2—Effect of SRT on volatile solids sludge fractionation for a typical raw wastewater and model parameters (Table 1).

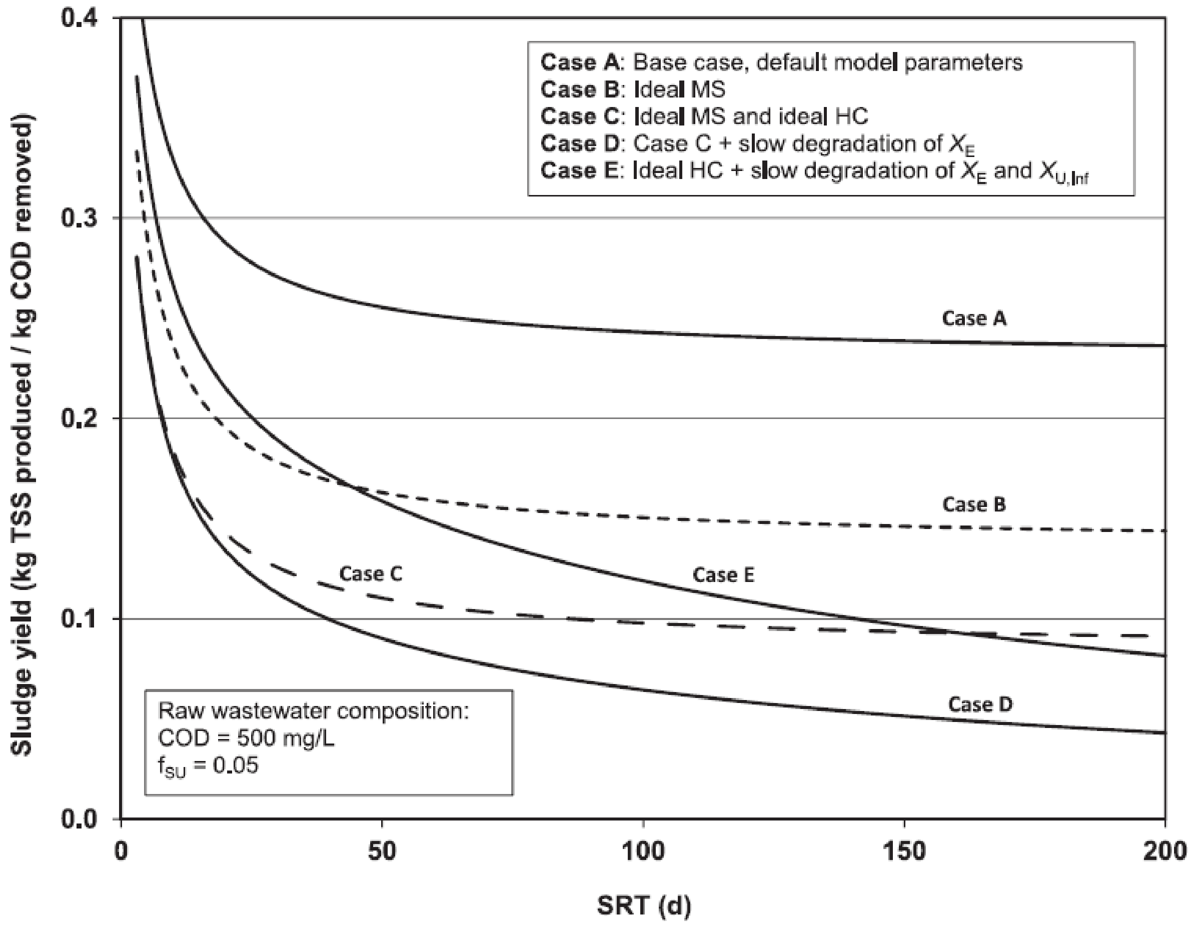

Figure 3—Effect of the sludge retention time on the activated sludge production.

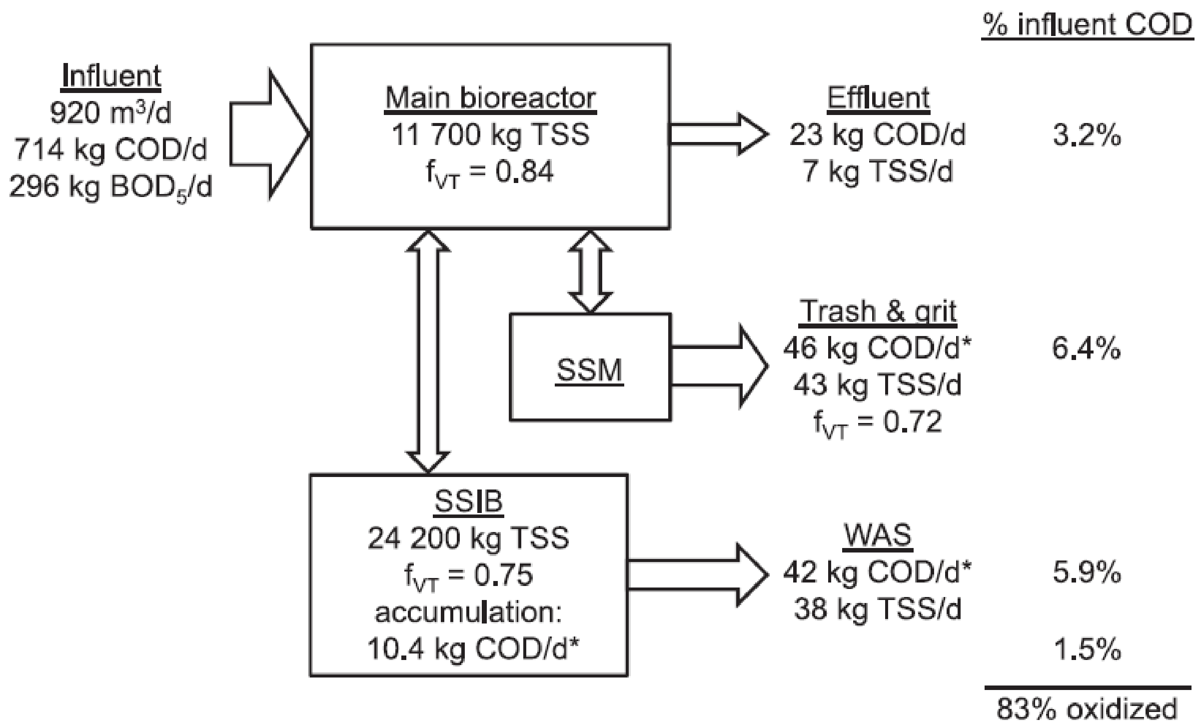

Figure 4—Solids inventory and overall mass balance for the Morongo Cannibal WRRF.

Notes: SSIB = side-stream interchange bioreactor; SSM = solids separation module.

* Assuming an f_{CV} of 1.48 g COD/g VSS.