Short-Cut Enhanced Nutrients Abatement (SCENA) From Reject Water: Moving The System Into Practice

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Abstract

The feasibility of the Short-Cut Enhanced Nutrients Abatement (SCENA) system was for the first time validated at pilot scale in the real environment of the municipal wastewater treatment plant of Carbonera (Veneto Region, Italy). The system was integrated in the sewage sludge treatment line for the short-cut nitrogen and via-nitrite phosphorus removal from the reject water. Ammonia and phosphorus concentration in the reject water were around 500 mgN/L and 60 mgP/L. Compared to municipal wastewater, this stream overloaded the mainstream treatment train of 26% and 12% total nitrogen and phosphorus, respectively. The sewage sludge (alkaline) fermentation liquid (SFL) was used as best available carbon source to enhance the nutrients removal via-nitrite. These contained the following mixture of short-chain fatty acids: 41% acetic, 29% propionic, 16% butyric. After 20 days of start-up operation, the specific ammonium utilization rate (sAUR) increased up to 10 mgN/gVSSh at 20°C. Under steady state conditions, the SCENA system was stably fed with a volumetric nitrogen loading rate (vNLR) of 0.55 kgN/(m^3 d) and biologically removed up to 85% of nitrogen and 65% of phosphorus. The BioP dry sludge showed P content of 55 mgP/gTS which has enhanced agro-valorisation potential after composting. Relevant residues of polyelectrolyte in the anaerobic supernatant caused strong overnight decrease of mixed liquor suspended solids in the bioreactor, which soon recovered its stability without affecting the specific removal performances.

Keywords
Via-Nitrite Enhanced Biological Phosphorus Removal, Reject Water, Volatile Fatty Acids, Pilot and full scale.

INRODUCTION

Nitrogen flow from the reject water constitutes from 10 to 30% of the total N-load influent to municipal wastewater treatment plants (WWTPs) (Cervantes, 2009; Gustavsson et al., 2011), while phosphorus concentration in reject water can be as high as 130 mg L^{-1} (Oleszkiewicz JA and Barnard, 2006, Pitman, 1999, Ivanovet al., 2008). High P concentrations may be reached when anaerobic co-digestion of sewage sludge and organic waste are applied (Malamis et al., 2014; Battistoni et al., 2005). As a consequence, the enhanced nutrient removal from the digester supernatant is proposed to take place separately from the main stream and becomes a significant stage within the new-conceived WWTPs.
The adoption of the short-cut nitrogen removal (SCNR) with nitritation and denitritation, reduces the oxygen demand up to 25% and requires up to 40% less organic carbon source. Furthermore, it decreases sludge production by 20-40% and carbon dioxide emissions by 20% (Gustavsson, 2010). Over the last years the completely autotrophic nitrogen removal process has gained a lot of interest since it may reduce the energy demand and avoid the addition of an external carbon source.
Various patented systems were recently developed adopting complete autotrophic biomass to reduce the energy demand for nitrogen removal. Among them, the most applied at full scale are the SHARON-Anammox process (van Dongen et al., 2001), DEMON (Deammonification, Wett et al.,), CANON (Completely Autotrophic Nitrogen Removal Over Nitrite, Slieker et al., (2003), OLAND (Oxygen Limited Autotrophic Nitrification-Denitrification (Wyffels et al., (2004)). However, its operational and environmental sensitivity and the facts that neither enhanced biological phosphorus removal can be achieved nor nitrogen is completely removed can be drawbacks for its widespread implementation (Malamis et al., 2014).
SCNR can be conveniently coupled with bioprocesses for enhanced phosphorus removal through its accumulation in biomass also under anoxic conditions by denitrifying phosphorus accumulating organisms (PAOs), that can utilize nitrate or nitrite as electron acceptors (Kishida et al., 2006; Carvalho et al., 2007). However, the enhancement of an effectiveness biological phosphorus removal required optimal mixture of volatile fatty acids, which may be internally procured by the controlled sewage sludge fermentation. This work reports the first long-term application of the SCENA system

(Figure 1) at pilot scale for the treatment of supernatant from the real anaerobic digestion of sewage sludge.

MATERIAL AND METHODS

2.1 The SCENA system

The pilot-scale SCENA system was started-up and operated within the municipal wastewater treatment plant (WWTP) of Carbonera (Veneto, Italy). The SCENA system consists of three main units: (1) the production of volatile fatty acids (VFAs) by the controlled fermentation of the sewage sludge; (2) the solid/liquid separation of the fermentation effluent; (3) the sequencing batch reactor (SBR) for the via nitrite nutrients removal.

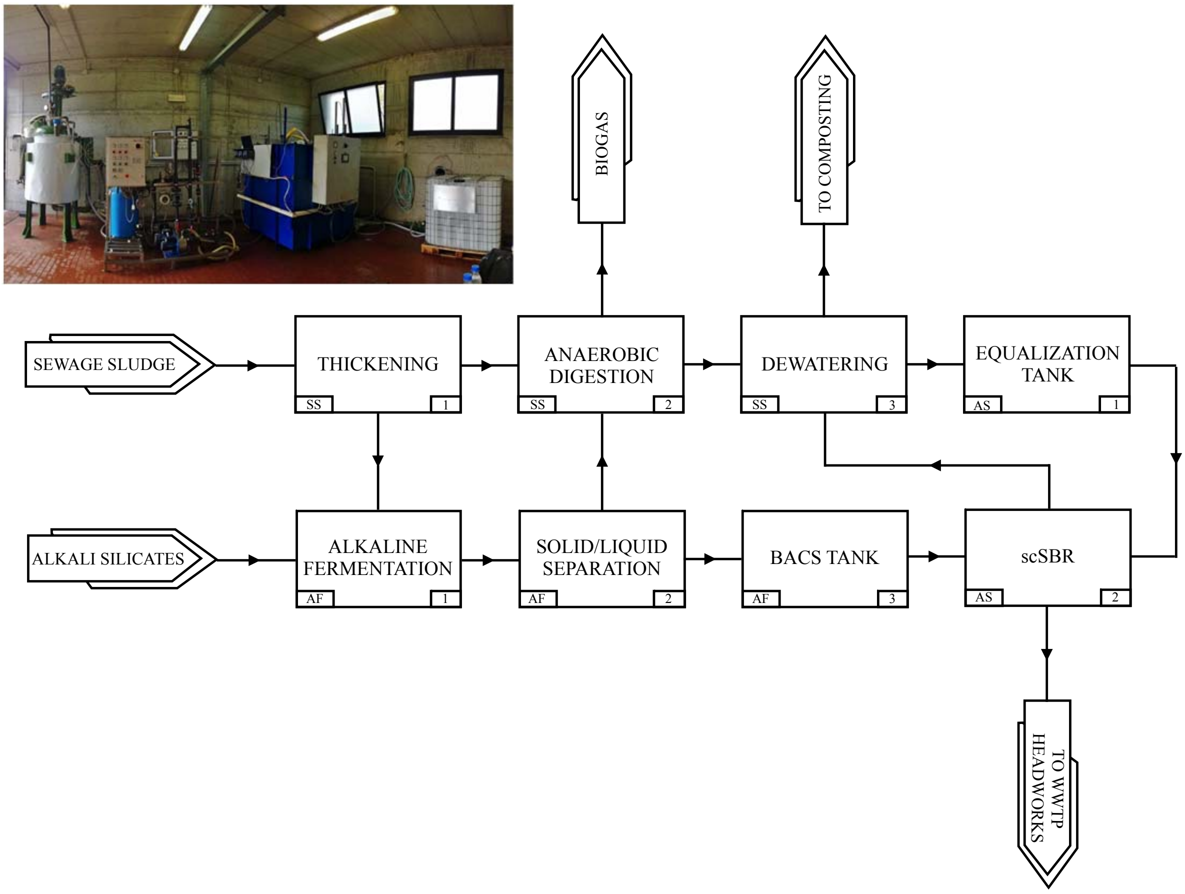

Figure 1. Scheme of SCENA system integrated in the Carbonera municipal WWTP. Legend: SS = Sewage Sludge; AF = Alkaline Fermentation; AS = Anaerobic Supernatant. Top left: picture of the pilot-scale SCENA system in the municipal WWTP of Carbonera.

2.2 In-situ Production and Separation of the best available mixture of Volatile Fatty Acids (VFAs)

The system mainly comprised of a semi-continuous anaerobic fermentation reactor (aFR) to carry out the acidogenic alkaline fermentation of the sewage sludge coupled with a tubular membrane reactor (MO P13U 1 m, Berghof, Germany) to separate the sludge fermentation liquid (SFL). The membrane reactor employed the cross-flow ultrafiltration (UF) membrane modules, operating in the inside–outside filtration mode. The membrane modules were made of polyvinylidene fluoride (PVDF) with internal diameter of 8 mm and molecular weight cutoff (MWCO) of 15 kDa. The length of the membrane was 1 m and each module had a filtration area of 0.32 m^2. The maximum pressure of the module was 600 kPa and the maximum operating temperature was 40 °C. The permeation-backwashing cycles and flows were operated by means of a centrifuge pump, two ball-type back pressure valves and two pressure gauges (Endress + Hauser type Cerabar M) installed in the inlet and outlet of the membrane unit. The flow rates in the filtration modules were recorded by an Endress

+ Hauser Promag 50 flow meter, while Riels FHKU flow meter was used to measure the permeate flow rate.

The fermentation unit (500 Liters of reaction volume) was fed with the mixed primary sludge and operated with hydraulic retention time of 4-5 days and temperature of 35 °C. Also, a mesh-screen was installed in the inlet of the fermentation unit in order to remove gross inert particles and fibres, which might clog the tubular membrane. The fermentation process was also driven mantaining a constant concentration of 40 g/L of alkali silicates mineral (wollastonite) in the reactor. The permeated sludge fermentation liquid (SFL) was first collected in a storage tank of 1 m^3 of volume and then used for the scSBR during the anaerobic and anoxic phases.

2.3 The short-cut Sequencing Batch Reactor (scSBR)

The scSBR (reaction volume of 2.8 m^3) was seeded with the conventional activated sludge coming from the main WWTP of Carbonera. The initial concentration in the reactor was 2.5 gMLVSS/L. The control strategy during the start-up, to achieve a complete nitritation was detailed in Frison et al., 2012. After the start-up (after day 20), the length of the SBR cycle during the ordinary conditions was 8 hours with the stages reported in Figure 2.

Sequence						
Filling						
Anaerobic						
Aerobic						
Anoxic						
Settling						
Discharge						
Time (min)	**15**	**60**	**300**	**60**	**30**	**15**

Figure 2. Distribution of the operating cycle of the SBR

The concentration of dissolved oxygen (DO) during the nitrifying conditions was maintained constant at 1.5 mg/L using three automatic blowers, controlled by a PLC (cRIO-9075, National Instruments). Under anaerobic and anoxic conditions a peristaltic pump provided the suitable dosage of SFL according to an initial ratio respectively of 10 kgCOD/kgPO_4-P (Metcalf and Eddy, 2014) and a ratio of 2.5 kgCOD/kgNO_2-N (Frison et al., 2013).

2.3 Calculations

The nitrogen mass balance (Eq. 1) was used to calculate the specific ammonium oxidation rate (sAOR, Eq. 2) and the specific nitrogen rate (sNUR, Eq. 3) as follows:

$$\Delta TN_{den}\ (kgN/d)=TN_{in}-TN_{out}-TN_{w}\ (1)$$

$$sAUR\ (mgN/gVSS\ h) = [\Delta N_{den}+TNOx\ (out)]/[MLVSS\ \vartheta_{ox}]\ (2)$$

$$sNUR\ (mgN/gVSS\ h) = [\Delta N_{den}]/[MLVSS\ \vartheta_{anox}]\ (3)$$

where: ΔTN_{den} is the total nitrogen denitrified by the scSBR; TN_{in} (kg/d) is the total nitrogen influent into the scSBR; TN_{out} (kg/d) is the total nitrogen in the outlet of the scSBR; $TNOx_{out}$ (kg/d) is the total NO_x-N present in the effluent; TN_w (kg/d) is the total nitrogen in the waste activated sludge; ϑ_{ox} (h/d) and ϑ_{anox} (h/d) are the durations of aerobic and anoxic phase, respectively.

The percentage of removal efficiency in terms of nitrification and denitrification were expressed with the following equations:

$$Ed(\%)=(\Delta TN_{den}/TN_{in})x100\ (4)$$

$$En(\%)=(\Delta TN_{den}+TNO_{x}\ (out)/LTN_{in})x100\ (5)$$

The phosphorus mass balance was accomplished considering the Eq. 6:

$$\Delta TP\ (kgP/d)=TP_{in}-TP_{out}\ (6)$$

where: ΔTP is the total phosphorus that is removed with the daily waste activated sludge; TP_{in} is the total phosphorus inlet in the scSBR; TP_{out} is the total phosphorus outlet from the scSBR.

2.4 Analytical Methods

All analyses were conducted in triplicate. Total and volatile solids (TS, VS) TSS, VSS, pH, COD, sCOD ammonium, total nitrogen (TN), total phosphorus (TP), pH and alkalinity were determined according to standard methods (APHA AWWA WEF, 1998). The soluble COD (sCOD) was determined in the filtrated fraction of the sample through a 0.45 µm membrane filters. Nitrite, nitrate, and phosphate were measured by ion chromatography (Dionex ICS-90 with AS14). The short-chain fatty acids were analysed by gas chromatography (Column: Nukol 15 m, 0.53 ID; temperature 85-125 °C, 30 °C min^{-1}; carrier: N_2, 5 mL•min-1).

RESULTS AND DISCUSSION

3.1 Operation of the pilot-scale SCENA system

Out of 450 days of operation, the obtained results from the anaerobic supernatant revealed that the average total nitrogen concentration along the overall period was around 501±14% mgN/L (Figure 3), while the concentration of phosphorus was 45±25% mgP/L.

The evaluation of the stability of the scSBR was evaluated by tuning with the vNLR, which was gradually increased along the experimental period from 0.2 (Start-up, 0-20 days) to 0.55 kgN/m^{3}d (days 160 to 450). Specifically, during the start-up (0-20 days) the feeding and the aerobic phase were controlled in order to maintain a sufficiently high value of free ammonia (FA), i.e. between 1.2 and 3.4 mgN/L as minimum and maximum value, respectively.

After 20 days, a stable via-nitrite route was achieved (100% NO_2-N/NO_x-N). At the end of the start-up operation, a strong increase in ammonia uptake rate (sAUR) of up to 9-10 mgN/gVSSh was observed.

The real environment brought some extra-ordinary conditions that influenced the treatment capacity of the system, in particular when the temperature in the mixed liquor dropped to 9.6°C during the cold season (day 60, Figure 4). Although a high nitrification efficiency was maintained almost constant (at 90-95%), it was necessary to decrease the vNLR to 0.13 kgN/m^{3}d. During the colder season, higher concentration of biomass in the reactor could compensate for the decrease of the activity but, after centrifugation, abundant residues of polyelectrolyte in the anaerobic supernatant were observed (day 67 and 267), causing significant losses of biomass from the reactor. The flocculant effect of the polyelectrolyte in combination with the fine bubble aeration of the scSBR formed porous and compact aggregates which floated or created a thick foam layer on the surface of the mixed liquor. The floating biomass (as MLVSS) was discharged with the treated anaerobic supernatant, resulting in a slight decrease in the biomass concentration in the reactor from 4.0 to 1.6 g/L (from day 20 to day 60) and from 2.6 to 0.3 g/L (Figure 4). In the latter case, the reactor was partially inoculated in order to easily recover the maximal treatment capacity.

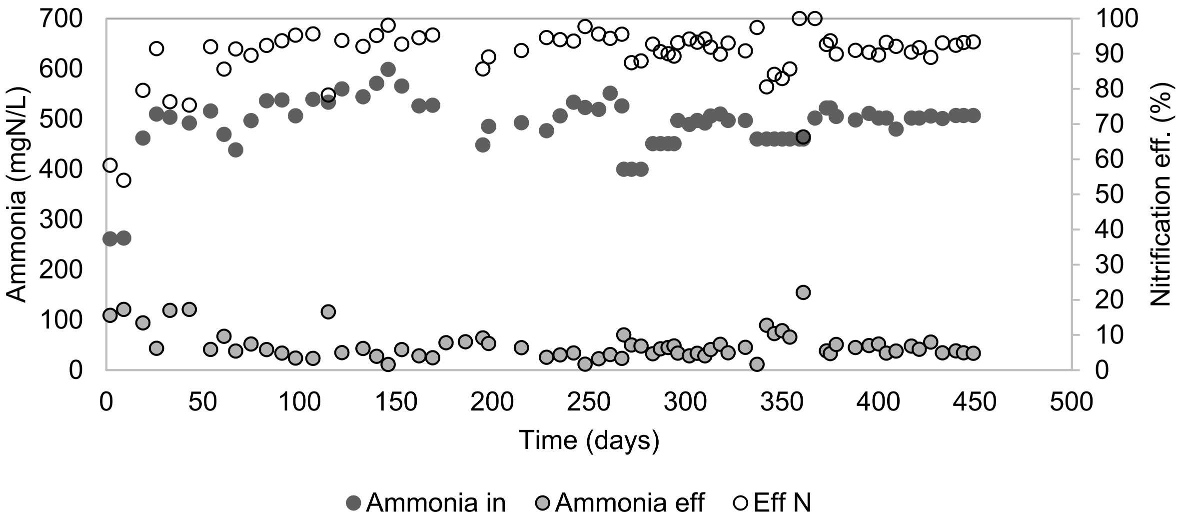

Figure 3. Concentration of ammonia influent (anaerobic supernatant), ammonia effluent (treated ammonia supernatant) in the scSBR and nitrification efficiency (Eff% nitrification).

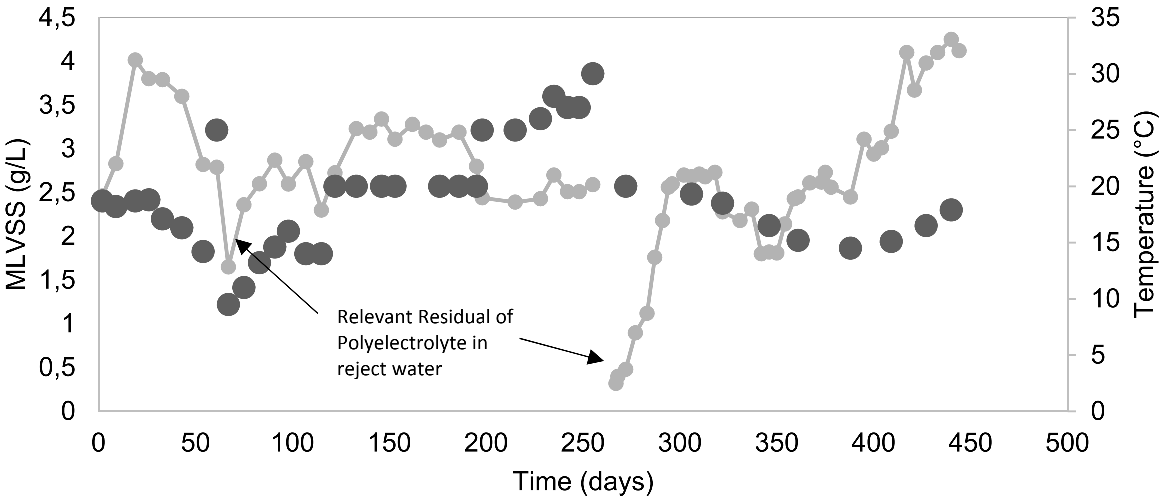

Figure 4. Profile of the environmental temperatures and the MLVSS during the experimental period.

3.2 Optimal dosage of VFAs for biological nutrients removal

The thickening of the sewage sludge and the production of volatile fatty acids during the fermentation were fundamental to provide sufficient carbon source for an efficient denitrification and biological phosphorus removal. In fact, a satisfactory VFAs yield from the sewage sludge fermentation was achieved for the majority of the experimental period (0.27-0.31 $gCOD_{VFA}/gTVS$), but a low total solids concentration in the thickened sewage sludge (less than 25 g/L) limited the VFAs production in the fermentation unit (Period 1 and Period 2).

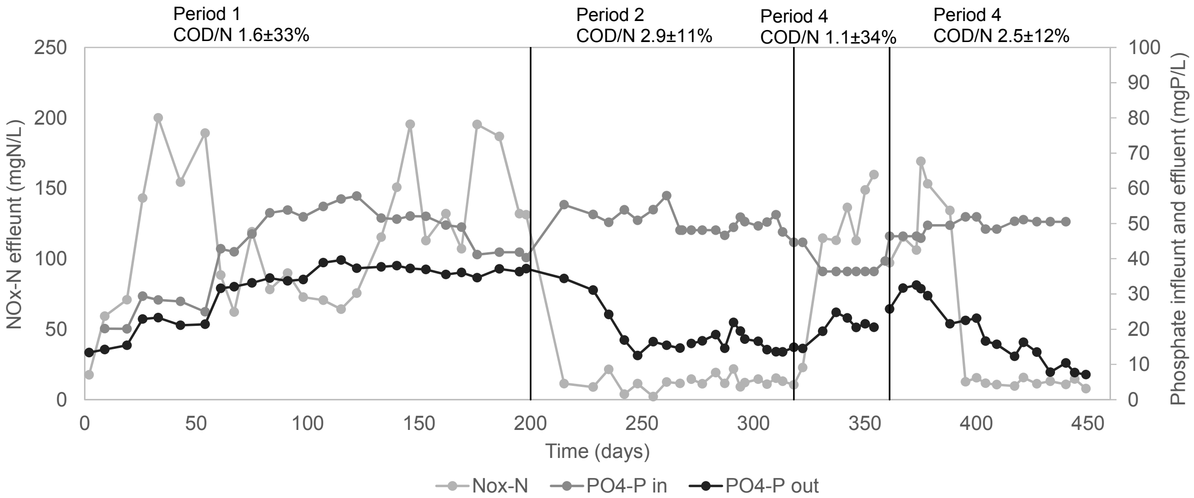

Figure 5. Concentration of the effluent NO_x-N (mainly nitrite), and the influent and effluent phosphate during the experimental periods

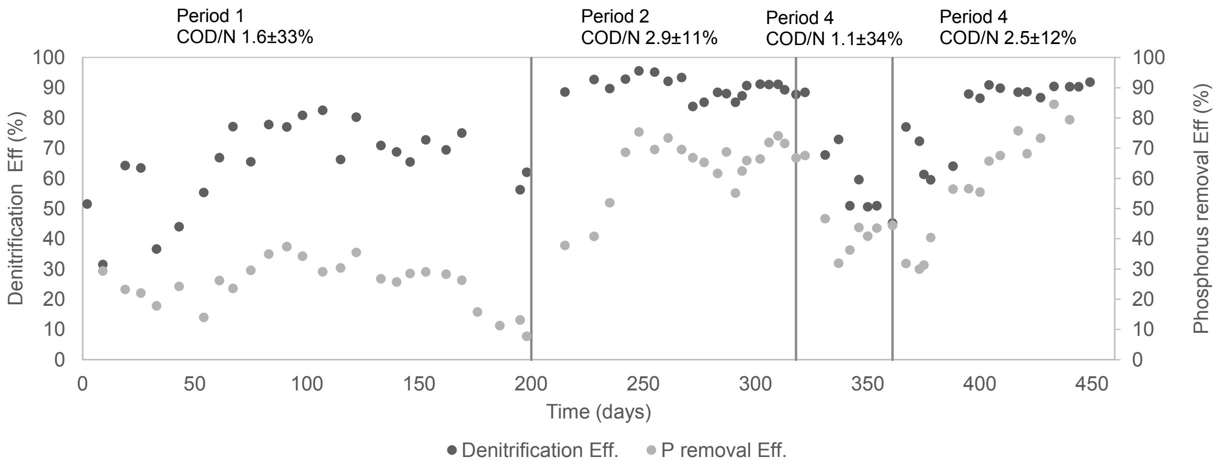

Figure 6. Efficiency of denitrification and phosphorus removal during the experimental periods.

The average denitritation and phosphorus removal efficiencies over the experimental period were 73% and 52%, respectively. In Period 1 (days 0 to 200) and Period 3 (days 331-338), the average COD/N applied was limited to 1.6±33% and 1.1±33% gCOD/gN, mainly during the anoxic phase, resulting in accumulated nitrite concentrations of 200 mgNO_2-N/L, but without any evidence of inhibition caused by free nitrous acids (FNA). In these conditions, the average denitrification efficiency did not exceed 80%. The activity of PAOs bacteria decreased significantly since most of the carbon was used by the denitrifier organisms. The phosphorus removal efficiencies in these two Periods were 28 and 38%, respectively, and the final effluent concentrations were 31.2 and 21.2 mgP/L, respectively.

Period 3 and Period 4 were characterized by higher availability of VFAs in the sewage sludge fermentation liquid, which were dosed properly under anaerobic and anoxic conditions. The permeate SFL produced in the membrane UF process was characterized by high total COD concentration (10430±569 mgCOD/L). A great part of the total COD was characterized as SCFAs, i.e. up to 76%. Acetic, propionic and butyric were the dominant acids in the SFL (i.e. 41%, 29% and 16% respectively). As result of the high VFA content, the denitritation and phosphorus removal efficiencies were enhanced to 87 % and 64 %, respectively.

3.3 Mass Balances under steady state conditions

The mass balance of the pilot plant is summarized in Figure 7. The vNLR selected to design the scSBR was 0.55 kg N/(m^3 d). Based on previous experimental results, this value represents the optimal conditions tested to remove nitrogen and phosphorus via nitrite. The amount of fermentation liquid of primary and waste activated sludge required for an effective nitrogen and phosphorus removal via-nitrite was around 3 grams of COD each gram of nitrogen removed.

The SFL was characterized by high COD/N ratio (23.8 gCOD/gN) while the phosphate concentration was very low since a significant fraction was precipitated by wollastonite. The dosage of the fermentation liquid accounted for about 11% of the vNLR and less than 1% of the volumetric phosphorus loading rate (PLR). Ammonia concentration in the treated effluent varied between 27.5 to 63.6 mgNH_4-N/L during the entire experimental periods and high nitritation efficiency was obtained (91%). The average nitrite concentration in the treated effluent was 7.5±4.3 mgNO_2-N/L and the denitritation efficiency was 87%. The SCENA process allowed significant biological phosphorus removal. The average phosphorus removal efficiency was 64.2%. Around 60% of the phosphorus removed was accumulated by PAOs and DPAOs activities, which resulted in P content in the WAS up to 55 mgP/gTS. The remaining P removed was attributed to the biomass growth (27%) and chemical precipitation within the reactor (10%). The precipitation of struvite in the accumulation tank can justify the 24.2% error in the phosphorus mass balance.

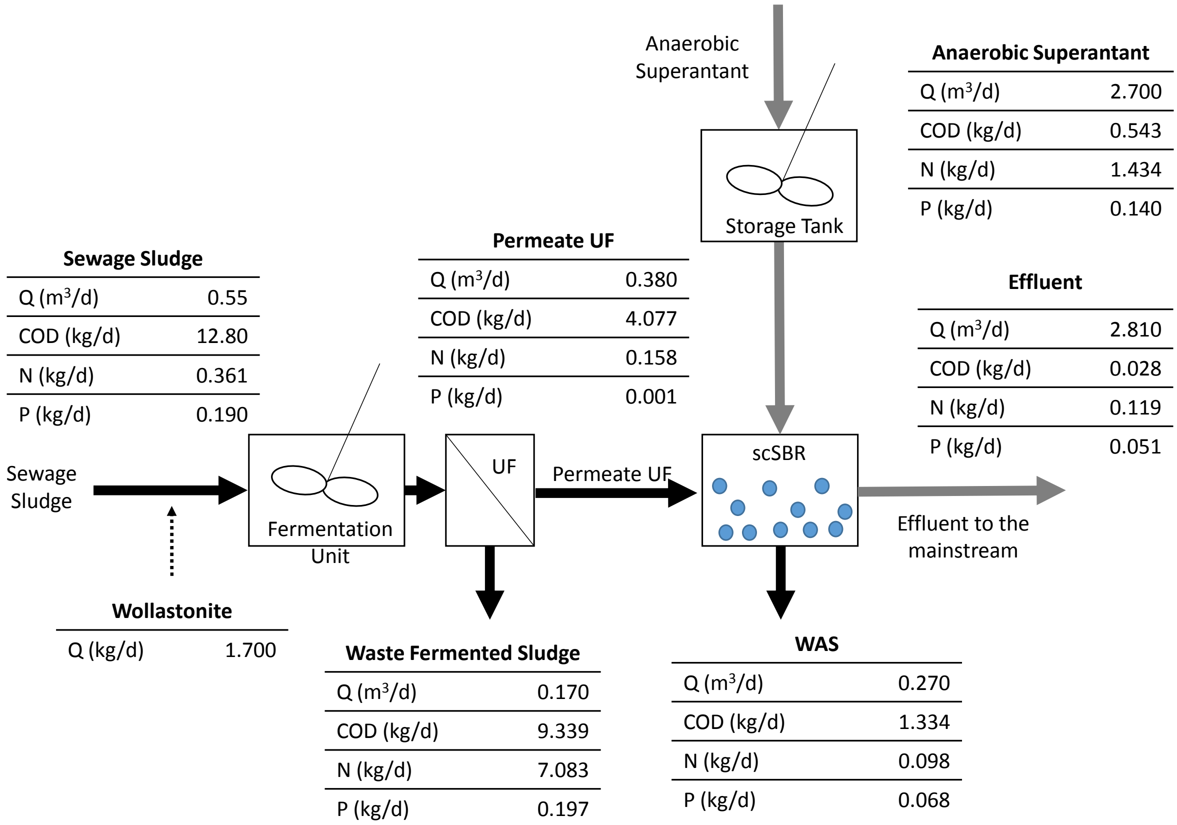

Figure 7. Mass balance of pilot SCENA

3.4 Final remarks

The long term validation of the pilot-scale SCENA was used to design the full scale system which is currently under construction. We estimated that the implementation of SCENA system will allow the removal of 50 kgN/d and 3.5 kgP/d and consequent reduction of the oxygen requirement of 240 kgO_2/d and 30 kg/d of PAC in the mainstream treatment train.

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