Case study: integration of new sanitation technologies into current wastewater infrastructures exemplified by the Treatment Plant for Education and Research at the University of Stuttgart

C. G. Morandi*,**, S. Wasielewski*, R. Minke* and H. Steinmetz**

* Chair of Sanitary Engineering and Water Recycling, Institute for Sanitary Engineering, Water Quality and Solid Waste Management (ISWA), University of Stuttgart, Am Bandtäle 2, 70569 Stuttgart, Germany (E-mail: *carlo.morandi@iswa.uni-stuttgart.de*)
** Chair of Resource-Efficient Wastewater Technology, Faculty of Civil Engineering, Technical University of Kaiserslautern, Paul-Ehrlich-Str. Geb. 14, 67663 Kaiserslautern, Germany (E-mail: carlo.morandi@bauing.uni-kl.de)

Abstract

For the sustainable management of wastewater infrastructures, new pathways must be charted to better exploit the resources in wastewater. Source-separated sanitation systems may improve overall energy and nutrient utilization of conventional wastewater treatment plants without any major structural alterations being necessary. Thus, transition states arise during which the residual system must remain functional. The objective of this study is to assess the impacts of blackwater co-digestion upon operation of the Treatment Plant for Education and Research (LFKW) at the University of Stuttgart. It was reported that blackwater co-digestion and nutrient recovery processes can be successfully implemented within the LFKW and lead to a better energy balance (35% reduction in power consumption for aeration and 10% improvement in biogas generation) and a high nutrient recovery from sludge liquor and blackwater (up to 40% N and 60% P loading at the LFKW inlet). Nutrient recovery offsets an unfavorable C:N ratio due to C displacement to the anaerobic stage. Additionally, centralized greywater treatment proved better in terms of process stability. The integration of new sanitation systems is promising, but must be carried out in accordance with the capabilities of existing infrastructures and precise examination of the boundary conditions.

Keywords
Blackwater digestion; energy optimization; nutrient recovery; source-separated sanitation systems.

INTRODUCTION

In light of climate change, rising demographic trends, water and nutrient scarcity, a future-oriented and integrated solution to wastewater treatment is being sought; domestic wastewater must be regarded more as a source of water, energy and the fertilizing nutrients nitrogen (N) and phosphorus (P) rather than a waste stream. It is evident that conventional systems for urban drainage and wastewater treatment do not represent a satisfactory solution with regard to sustainability and local nutrient and water cycles. In spite of good cleaning efficiencies, wastewater treatment plants (WWTPs) are among the largest power consumers within a municipality. Additionally, the recovery of valuable nutrients is still not being practiced on a large scale.

The essential principle of resource-oriented wastewater treatment is both separate collection and selective treatment of wastewater split streams, so that a reduction in water pollution and the closure of water and nutrient cycles can be achieved (DWA 2008). Although planning and implementation of new sanitation systems has for the most part been carried out in the context of new developments (e.g. in the settlement Jenfelder Au in Germany, cf. Augustin *et al.* (2014)), new sanitary concepts can also contribute as a solution to pre-existing problems within current systems (DWA 2014b).

During the conventional practice of energy-intensive aerobic wastewater treatment combined with anaerobic sludge digestion, only a fraction of the energy potential of wastewater is used. If more of the energy potential in wastewater were exploited and less energy were used in the treatment of wastewater, WWTPs may become a net energy producer instead of a consumer (McCarty *et al.*

2011). Moreover, many municipal digesters in Germany are operated with a hydraulic retention time (HRT)>25 d, although 20 d would easily suffice for mesophilic digestion (Dichtl; K.-G. Schmelz 2015); in other words, WWTPs often have spare capacity for co-digestion. High organic loading in blackwater from vacuum toilets makes anaerobic digestion a feasible option for treatment. For instance, blackwater has been successfully treated in anaerobic continuously stirred tank reactors, e.g. by Wendland *et al.* (2007).

In contrast to other flushing systems, vacuum toilets achieve the lowest water consumption. Furthermore, Otterpohl (2000) reported blackwater contains 97% N and 90% P to be found in domestic wastewater. Hence, an incremental nutrient displacement to the anaerobic stage would likely increase nutrient recovery rates over the course of transitioning to new sanitation systems. With regards to phosphorus, projections for the time in which the economically exploitable reserves will be entirely depleted vary. Notwithstanding, it is important to begin to recycle it and return it to the soil. As for nitrogen, recirculated sludge liquors (typically 200–700 mg/l NH_4-N) can constitute over 25% of the total nitrogen load entering a WWTP at the inlet (Thornton *et al.* 2007). Previous studies (e.g. Fattah *et al.* 2008; Cornel; C. Schaum 2009; Batstone *et al.* 2015) proved sidestream N and P recovery processes (processes implemented on N and P-rich sidestreams within sewage sludge processing lines) emerge as an alternative to conventional N and P removal.

Although it is difficult to identify a ‘‘best overall option’’ in terms of sustainability, it is evident that resource-oriented systems are a necessity for the future of wastewater management. This study proposed an integrated approach for the transition of the LFKW from the actual state to new sanitation technologies. To the best of the authors’ knowledge no one other than the authors of this study has ever considered blackwater co-digestion in municipal digesters; it is also the first time that real operating data was used to predict the impacts of the transition to new sanitation systems upon plant operation. Therefore, critical points were assessed and discussed. As well as changes in nutrient utilization, changes in energy demand and generation were quantified, while necessary process alterations were suggested. Altogether, the main objective of this study was to assess if the transition to new sanitation systems was technically feasible and advantageous for energy and nutrient utilization.

MATERIALS AND METHODS

Simplified process flow diagrams of the LFKW in the actual state (8,483 PE, 1 PE=120 g COD/d) are depicted in Figure 1. The plant operates a nitrification and an upstream denitrification stage alongside a hydraulically underloaded digester (HRT_{actual}=66 d; $HRT_{desired}$=20 d). Furthermore, two processing lines (< 10% of influent load to LFKW) for research purposes are connected to an oxidation ditch and a rotating biological contactor. ”Return lines” (cf. Figure 1) comprise both the chargeback from sludge liquor and the lines which branched off the main plant to be used in the research hall before returning to the mechanical stage, which are not depicted in Figure 1. Decoupling wastewater streams and treating blackwater along with sewage sludge in the digester would directly affect the operation of the LFKW. Mass and volume balances per population equivalent were carried out in order to simplify application of different boundary conditions. Special emphasis was given to the critical points at which problems in denitrification process and anaerobic digestion would occur. Blackwater was assumed to be incrementally decoupled from the combined sewer by being discharged into vacuum sewers and fed directly to the LFKW digester, whereas greywater was proposed to be transported along with residual wastewater via the existing combined sewer to be further treated in the aerobic stage of the LFKW.

The inhabitant-specific balances are founded on real operating data from the LFKW for the years 2012 and 2015. As in 2013 and 2014 lower organic loading reached the WWTP and technical malfunctions occurred due to problems with high water, data referring to these years was not considered. For the calculation of different transition states, compliance with emission standards to waterbodies was the highest priority. Within this study transition was defined as the fraction of inhabitants using vacuum toilets to collect blackwater and greywater separately. For instance, for the parameter COD, 50% transition means $0.5 \cdot 120$ g/(PE·d) are contained within conventional wastewater, while the other 50% can be collected separately in the form of blackwater and greywater.

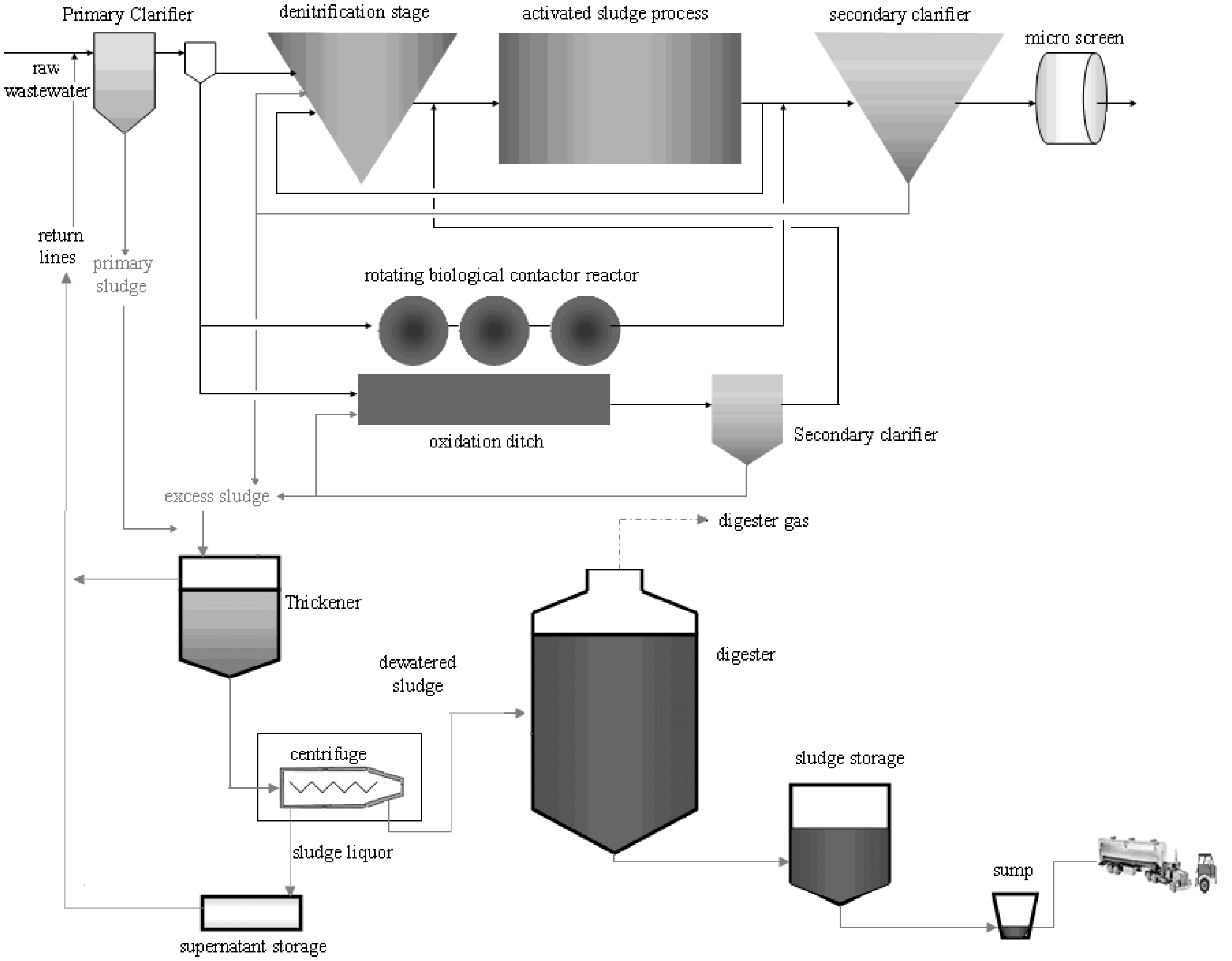

Figure 1. Process flow diagram of LFKW for the actual state.

In Figure 2 the actual state of the LFKW is represented in terms of specific COD, N_{tot} and P_{tot} loads and volume flows. Moreover, the indicated total solids contents illustrate the volume flow distribution after sludge thickening or dewatering. While any quantitative analysis can be inferred from the absolute values, the bars' height is merely qualitative, as two different scales are depicted. The data collected from the LFKW as well as corresponding calculations used to carry out mass and volume flow balances are given in Table 1. All the loads in Figure 1 which are not explicitly stated were derived therefrom.

RESULTS AND DISCUSSION

A short-term measure for process improvement is to dewater digested sludge, which is not practiced in the actual state due to possibly too high nitrogen chargeback. Nitrogen load in raw wastewater amounts in the actual state to 11.7 g/(PE·d) (cf. Figure 2); however, with a nitrogen recovery stage within sewage sludge processing lines, problems in denitrification could be minimized, while best exploiting nutrient and energy potential in blackwater and digested sludge. The centrifuge used for pre-dewatering of raw sludge could also be utilized to dewater digested sludge, as it is currently operated for approx. 3 hours a day, so no major investment costs would be incurred. A transition state of 5% proved a realistic point for implementation of dewatering of digested sludge. Through displacement of N in blackwater to the anaerobic stage and set-up of 60% nitrogen recovery from sludge liquor, a favorable C:N ratio could be maintained. Furthermore, it was reported that this ratio increased during transition due to nutrient displacement to the anaerobic stage and subsequent N recovery.

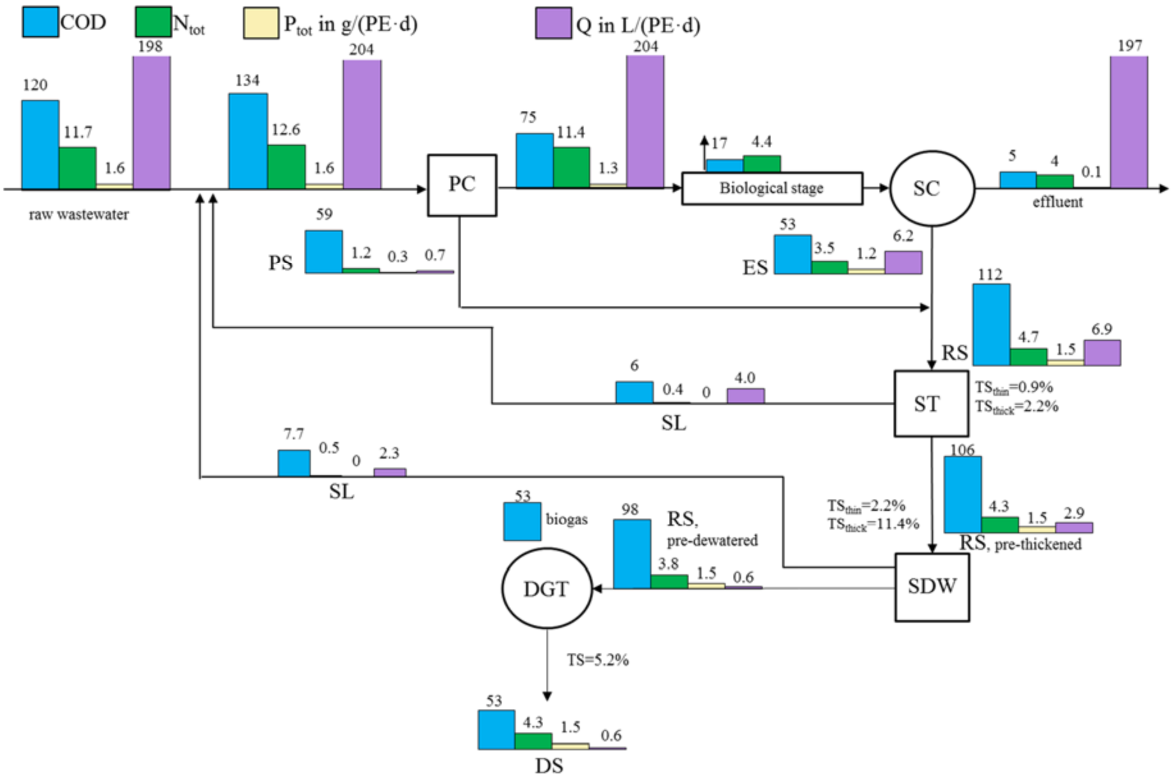

Figure 2. Mass and volume balances for the actual state (0% transition) of the LFKW, with: PC=primary clarifier; SC=secondary clarifier; ST=sludge thickener; DGT=digester; SDW=sludge dewatering, PS=primary sludge; ES=excess sludge; RS=raw sludge; DS=digested sludge; SL=sludge liquor (chargeback).

In view of the LFKW digester operating at a hydraulically underloaded state (66 d HRT in the actual state, although 20 d would suffice for mesophilic operation), co-digestion of blackwater mixed with sludge proved feasible from a hydraulic standpoint up to a transition state of 90%, provided that blackwater thickening is set up by 15–20% transition at the latest. Forgoing blackwater thickening in early transition states would, however, result in renewed dilution of pre-dewatered sludge, which is technically counterproductive. This considered, pre-thickening of blackwater was proposed for a transition state of 10 %. Previous to blackwater thickening, a HRT of approx. 30 d was reported; after set-up, a HRT of approx. 50 d could be reached. With aid of a static thickener for blackwater, a long-term transition to new sanitation systems proved realistic. Moreover, no further investments costs were incurred, because 3 tanks of 16 m^3 and a sedimentation tank of 95 m^3 are presently not in use in the LFKW and were originally designed for the pre-aeration of raw wastewater and as sedimentation/storage tanks respectively. 10% transition brings about approx. 5.9 m^3/d blackwater from vacuum toilets, while 90% transition corresponds to

53.4 m^3/d blackwater.

Table 1. Assumptions and calculations based on operating data of the LFKW for mass and volume balances in the actual state.

Wastewater stream or process step	Operating data, assumptions, calculations, references
Raw wastewater	8,483 PE; Q=198 L/(PE·d) including 33 L/(PE·d) infiltration water; COD=120, N_{tot}=11.7, P_{tot}=1.6 g/(PE·d)
Primary sludge	Q=0.69 L/(PE·d); COD=58.7, N_{tot}=1.2, P_{tot}=0.28 g/(PE·d)
Excess sludge	TS=0.82%; TS=50.6 g/(PE·d); VS=70%TS (DWA 2014a); Q=6.21 L/(PE·d); COD/VS=1.5; N_{tot}/VS=0.1 in g/g (ATV-DVWK 2000); COD=53.1, N_{tot}=3.5 g/(PE·d); P=f(P elimination extent)
Thin sludge	TS=2,2%; Q=2.86 L/(PE·d)
LFKW effluent	COD=4.50; N_{tot}=2.81; $P_{tot=}$0.09 g/(PE·d)
Pre-dewatered sludge	TSS=11.4%
Sludge liquor (after dewatering)	P_{tot} neglected; mixed sludge: COD_{mf}/COD=0.09, NH_4-N/N_{tot}=0.15 g/g.
Activated sludge process	Power demand for aeration=11.7 kWh/(PE·a); 17.3 g COD/(PE·d); $N_{Nitrification}$=(4.4+3.5) g N/(PE·d) with 4.33 g O_2/g N; $N_{Denitrification}$=4.4 g N/(PE·d) with 2.86 g O_2/g N; O_2 concentration in aeration tank=2 mg/L; O_2 saturation of 10 mg/L; oxygen mass transfer coefficient ratio α = 0.6; O_2 demand in pure water: OD_C=17.3 g O_2/(PE·d); OD_N= 4.33·(4.4+3.5)=34.1 g O_2/(PE·d); OD_{DN}=2.86·4.4= 12.6 g O_2/(PE·d) carbon savings; oxygen demand in sludge water: OD=10/(10-2)/0.6·(17.3+34.1-12.6)=81 g O_2/(PE·d); power demand for aeration; 81/2·365/1000= 29.6 kg O_2/(PE·a); $\eta_{aeration}$ of 2.5 kg O_2/kWh →11.7 kWh/(PE·a)
Digested sludge	TSS_{DS}=5.23%
Digester	Effective volume=310 m^3; HRT=66 d
Digester gas	18.6 L/(PE·a); methane concentration =66.8%; calorific value of 10 kWh/m^3 in CH_4 at STP (DWA 2014a); $\eta_{CHP,electrical}$=35%; electricity self-supply: 18.6·0.668/1000·10·0.35·365=15.9 kWh/(PE·a)

Retaining a favorable C to N ratio in the denitrification stage is important for WWTPs undergoing transition to new sanitation systems. This proved critical at 5% blackwater separation due to set-up of a dewatering stage of digested sludge, i.e. unfavorable C to N ratios were expected hereafter if no nutrient recovery were planned. Thus, a nitrogen recovery of 60% from sludge liquor and blackwater supernatant after thickening (from 10% transition onwards) was required to offset unfavorable C:N ratios in the denitrification. At 90% transition, a nitrogen recovery rate of 50% proved necessary; in**Error! Reference source not found.** a nitrogen recovery efficiency of 60% is depicted. It is evident that at higher transition states more nitrogen can be recovered, thus benefiting the biological stage with regards to aeration requirements. Also, a heightened biogas production was observed due to an increased COD load at the digester's inlet.

Table 2. Assumptions and calculations based on operating data of the LFKW for mass and volume balances undergoing transition to new sanitation systems.

Wastewater stream	Operating data, assumptions, calculations, references
Sludge liquor (after dewatering of digested sludge)	COD=2350 mg/l (Dichtl; K.-G. Schmelz 2015); N_{tot}≈1.5 g/(PE·d) P_{tot}≈5% of 1.6 g/(PE·d)=0.08 g/(PE·d) (ATV-DVWK 2000)
Blackwater	TSS=0.9%; Q=7 L/(PE·d), COD_{BW}=0.6 COD_{WW};$N_{tot,BW}$=0.8 $N_{tot,WW}$; $P_{tot,BW}$ =0.9 $P_{tot,WW}$; COD=0.6·120 g/(PE·d)=72 g/(PE·d); N_{tot}=0.8·11.7 g/(PE·d)=9.4 g/(PE·d); P_{tot}=0.9·1,6 g/(PE·d)=1.44 g/(PE·d)
Blackwater thickened	TSS=4%; Q=0.9/4·7=1.6 L/(PE·d)
Blackwater supernatant	COD_{mf}/COD=0.3; NH_4-N/N_{tot}=0.75; $P_{tot,mf}$/P_{tot}=0.35 in g/g; COD=0.3·(4-0.9)/4·72=16.7 g/(PE·d); N_{tot}=0.75·(4-0.9)/4·9.4= 5.5 g/(PE·d); P_{tot}=0.35·(4-0.9)/4·1.44=0.39 g/(PE·d)
Greywater	165 L/(PE·d) water consumption (cf. Table 1) and of 33 L/(PE·d) flush water from conventional toilets (BDEW 2011); $Q_{domestic\ WW}$=198-33= 166 L/(PE·d) water consumption: $Q_{greywater}$=166-33=132 L/(PE·d)

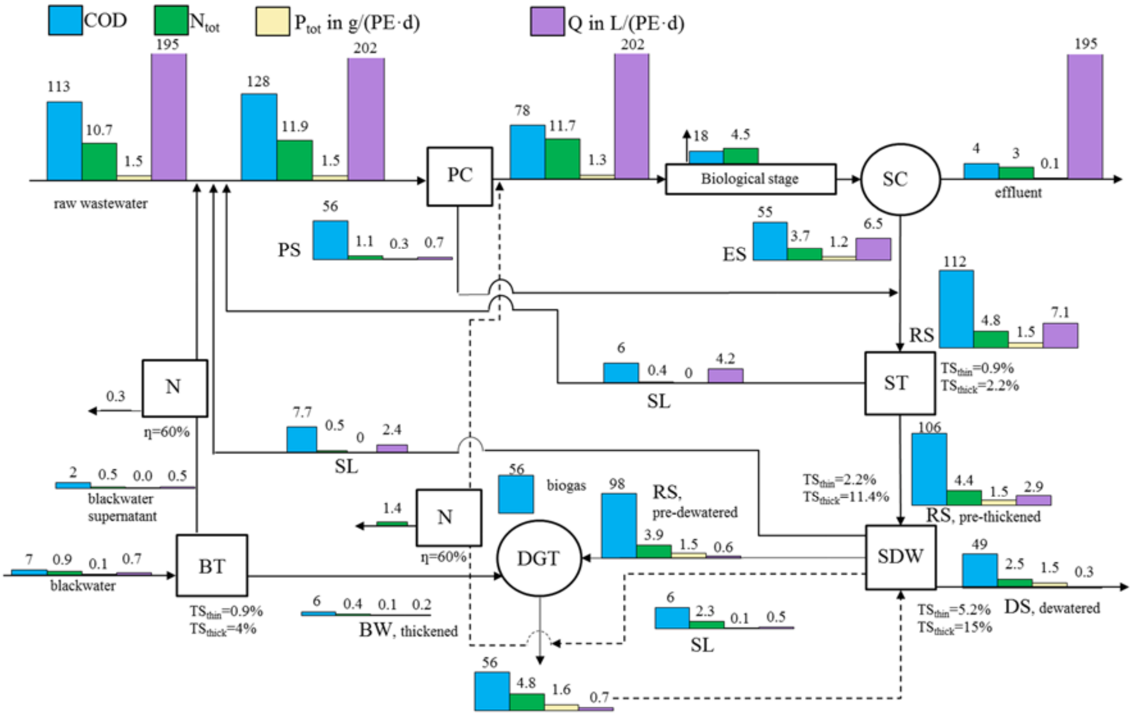

Figure 3. Mass and volume flow balances for the LFKW (10% transition state) to new sanitation technologies, with: BW=blackwater; BT=blackwater thickener, N=nitrogen recovery, cf. Figure 2 for remaining legends.

Aside from the proposals made in this case study, if greywater were decoupled from the LFKW and treated in decentralized units to promote household water recycling, less COD would reach the WWTP inlet, thus denitrification deteriorated at an earlier transition state. This also presupposed higher N recovery rates from sludge liquor and blackwater supernatant to maintain a satisfactory C:N ratio in the denitrification stage. Furthermore, the energy gain achieved by decoupling greywater from the plant due to lower aeration demand was almost fully offset by lower biogas generation through reduced sludge production and subsequent digestion. In other words, blackwater co-digestion and residual wastewater (including greywater) treatment in the conventional aerobic stage proved more suitable for both process stability as well energy and nutrient utilization. Greywater decoupling was studied in detail within a previous work (Gottardo Morandi *et al.* 2016).

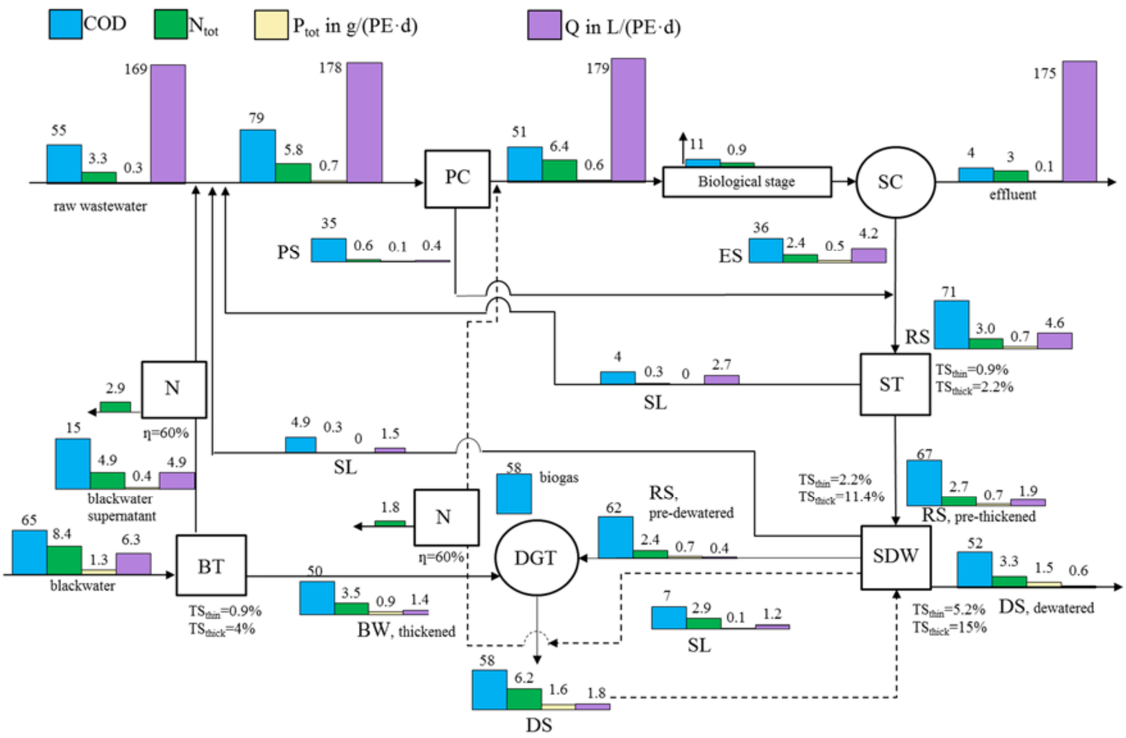

Figure 4. Mass and volume flow balances for the LFKW undergoing transition (90% transition state) to new sanitation technologies, cf. **Error! Reference source not found.** for remaining legends.

Energy demand and energy production

Aeration is the main power consumer while treating wastewater. However, through the displacement of organics and nutrients contained in blackwater to the anaerobic stage along with a nitrogen recovery, aeration requirements could be significantly reduced while at the same time more biogas was generated, as depicted in Figure 5. . Dewatering of digested sludge at 5 % transition brought about a slightly heightened power demand for aeration of approx. 1 kWh/(PE·a) due to sludge liquor recirculation into the aerobic stage – despite the set-up of a nitrogen recovery (η=60%) from both sludge liquor and blackwater supernatant. However, this was offset by an improved biogas production at 5% transition due to blackwater co-digestion. Assuming that source-separated sanitation was set up over practically the entire catchment area (90% transition), a reduction in aeration of approx. 4 kWh/(PE·a) was achieved, which corresponded to 35% reduction in power consumption (referred to the actual state). Furthermore, an approx. 1.5 kWh/(PE·a) increase in power generation was reached due to enhanced loading in the digester (10% increase on the actual state). Altogether, an energy gain of 5.5 kWh/(PE·a) was achieved at 90% transition.

Nutrient recovery

Nitrogen recovery. At 5 % transition, set-up of dewatering of digested sludge was likely to shift the C:N ratio to an unfavorable range for denitrification due to an increased load chargeback. From this transition state onwards a nitrogen recovery from the sludge liquor and blackwater supernatant was proved necessary. Alternatively, an external carbon source could be added to the denitrification; however, this would be counterproductive in terms of sustainability. Nitrogen recovery potential and recovery rates are depicted in Figure 6. It follows that recovery potential in blackwater supernatant should be fully exploited, as approx. 75% of the N load in blackwater is dissolved. At 90% transition, a nitrogen removal efficiency of η=50–60% (with regards to N in sludge liquor and blackwater supernatant) yielded a recovery rate of approx. 33–40% (in terms of N load to the WWTP) or 3.9–4.7 g NH_4-N/(PE·d). This amounted to 1–1.5 kWh/(PE·a) aeration savings. At 10% transition only 0.5–1 kWh/(PE·a) of aeration savings proved possible with η=50–60% recovery efficiency, because at identical recovery rates a yield of 1.1–1.4 g NH_4-N/(PE·d) was achieved.

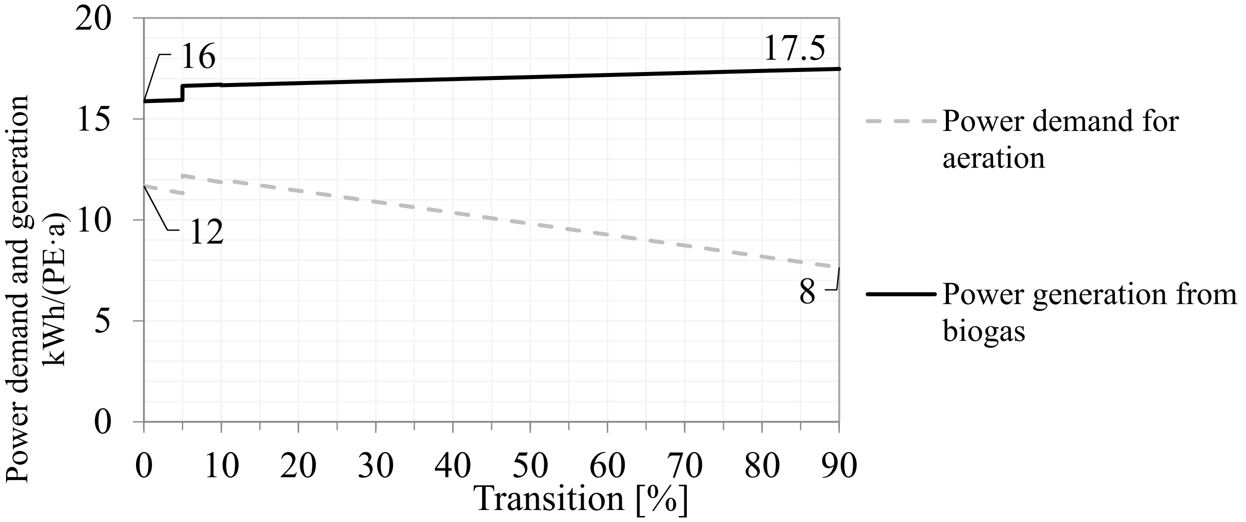

Figure 5. Expected changes in power demand for aeration and power generation from biogas in the LFKW.

Phosphorus recovery. Recovery of phosphorus is not relevant for the energy balance of the LFKW in the long-term, as phosphorus can be easily removed through precipitation. However, phosphorus is a finite resource, while more sustainable extraction processes rather than rock phosphate extraction must eventually be considered.

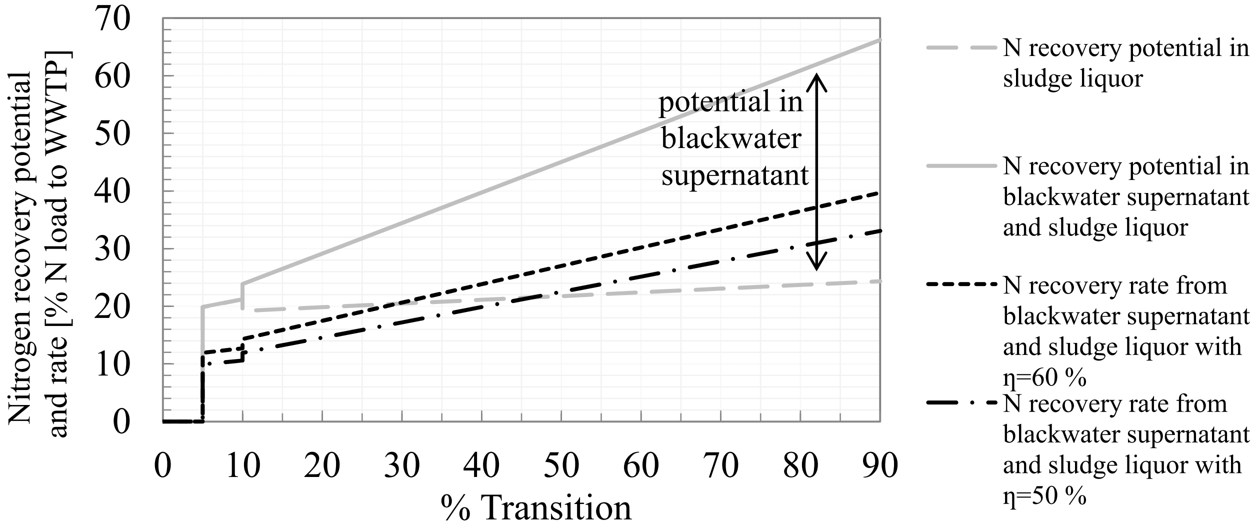

Figure 6. Total nitrogen recovery potential and recovery rates at two different recovery efficiencies.

Theoretical P recovery potentials in digested sludge are relatively high due to chemical precipitation with iron or alum salts. Yet, real P recovery rates are subordinated to the extent of P release through acidification of digested sludge. If enough P is released, while assuming high phosphate precipitation rates, a total recovery efficiency of 40–60% (with regards to P in digested sludge and blackwater supernatant) are conceivable with current technologies. This yielded 38–57% recovery of the P load upon the LFKW or in absolute values 0.6–0.9 g PO_4-P/(PE·d). At 90% transition, 15–20% of the P load at the LFKW inlet are contained in the blackwater supernatant, so additional phosphorus recovery from the blackwater supernatant is advantageous.

CONLUSIONS

This case study showed that resource-oriented concepts can be beneficially implemented within the LFKW, thus improving the energy balance and nutrient recovery potentials. Even though the LFKW represents an atypical case due to ongoing research within selected processing lines, the principles shown within this study can be carried over to other WWTPs, provided that an investigation of the boundary conditions is carried out on a case-by-case basis. Spare hydraulic capacities in the LFKW digester are available under current operating conditions, so anaerobic treatment of blackwater was considered along with raw sludge; residual wastewater was proposed to be further transported via the existing combined sewer to the LFKW. The findings of this study are a preliminary attempt to apply simple mass and volume flows to WWTPs using real operating data, while quantifying possible impacts of blackwater co-digestion upon operation.

It was shown that the centrifuge used for sludge dewatering before digestion can also be applied to dewater digested sludge. At present, chargeback originates from pre-thickening and dewatering of raw sludge only. With the additional chargeback through dewatering of digested sludge, problems in the denitrification may occur due to unfavorable C to N ratios; however, a nitrogen recovery of 60% from the sludge liquor proved to negate any problems regarding an unfavorable C to N ratio in the upstream denitrification stage. A static thickener for volume reduction of blackwater from vacuum toilets proved appropriate from a hydraulic standpoint from 15–20% transition onwards, although it is counterproductive not to operate it earlier due to dilution of dewatered raw sludge by raw blackwater. Furthermore, the tanks not in use at the LFKW (total volume of approx. 140 m^3) can be modified for blackwater thickening as needed. Therefore, set-up of blackwater thickening was appropriate at approx. 10% transition.

With regard to energy, a power gain of approx. 5.5 kWh/(PE·a) was reported at 90% transition: 4 kWh/(PE·a) due to aeration savings and 1.5 kWh/(PE·a) due to enhanced biogas production. Additionally, 50–60% nitrogen recovery efficiencies brought about 0.5–1 kWh/(PE·a) and 1–1.5 kWh/(PE·a) aeration savings at lower and higher transition states respectively due to an incremental increase in the displaced N load to the anaerobic stage at higher transition states.

Decoupling of greywater from the plant would anticipate an unfavorable C to N ratio for denitrification. Therefore, the approach “residual wastewater treatment in the LFKW” was characterized by better process stability, as enough biodegradable COD can be maintained in denitrification up to a later transition stage. Collecting blackwater with vacuum toilets displaces nutrients to the anaerobic stage. With assumed efficiencies of 50–60%, N recovery rates lay between 3.9–4.7 g N/(PE·d) at 90% transition. Practicable P recovery rates were estimated to be 0.6–0.9 g P/(PE·d).

While new sanitation system can be successfully implemented within current WWTPs, many benefits can be achieved by just a few structural alterations in the plant. This study showed that, provided that spare hydraulic reserves are available in the digester, blackwater co-digestion improves the energy balance of the treatment plant. In general, the simple mass flow method used to optimize the energy balance and nutrient utilization of the LFKW is appropriate and can be carried over to other WWTPs. Nevertheless, in each case the boundary conditions have to be considered as new sanitation technologies must comply with the capabilities of pre-existent infrastructures.

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