Impact of solids management on nutrient ratios for in-line wastewater prefermenters

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Abstract The full-scale evaluation of in-line prefermentation effects on wastewater nutrient ratios was performed under three different sludge operating conditions, with regards to sludge elutriation rates (0.7, 2.2 and 3.7 kg dry sludge/m^3 raw sewage) and the corresponding sludge ages (17.3, 2.5 and 7.5 days). At all three operating conditions the TKN/COD ratio increased (64, 46 and 20% respectively), with an average ratio of 0.057 mg N/mg COD in the raw sewage increasing to 0.082 mg N/mg COD in the settled sewage. These ratio increases can limit the use and performance of certain biological nutrient removal process configurations. This study has further highlighted the importance to counterbalance fermentation, thickening and solids removal requirements in a single tank in-line prefermenter. The minimum suspended solids removal (33%) was achieved at the lowest settled sludge solids content (4.3%), against a corresponding maximum volatile fatty acid generation rate (5.7 mg VFA/l/h). The total solids and volatile fatty acid concentration profiles down the prefermenter tank depth were determined at a high sludge blanket level condition. It was demonstrated that the accumulated constituent mass inventory increase was about constant throughout the water and sludge layers respectively under such operational conditions.

Keywords Activated primary tank; elutriation; nutrient ratio; prefermentation; sludge age; volatile fatty acids

Introduction

The presence of appropriate proportions of nutrients (nitrogen (N) and phosphorus (P)) and carbonaceous material in wastewater is important for the efficient performance of a biological nutrient removal (BNR) process. These constituents are characterised by the total Kjeldahl nitrogen (TKN) and the total phosphorus (TP) to chemical oxidation demand (COD) ratios respectively. The TKN/COD ratio principally determines which BNR process configuration is the most appropriate, with a ratio smaller than 0.07 to 0.08 mg N/mg COD required for the frequently utilised modified Phoredox (3-stage Bardenpho) process (Ekama *et al*., 1983). In typical South African wastewaters the TKN/COD ratio range of 0.07 to 0.10 in raw sewage increases towards 0.09 to 0.12 mg N/mg COD in the settled sewage (WRC, 1984). This change towards a low strength (low COD concentration) sewage feed to the BNR reactor can be counteracted by the prefermentation of the primary settled solids, to enrich the settled sewage with soluble organic matter, as represented by the volatile fatty acids (VFA) content.

The full-scale prefermentation of primary wastewater sludge was implemented successfully in the early 1980s to enhance BNR (Pitman *et al*., 1992). Primary settling tanks (PST) were retrofitted or constructed from this stage as in-line or side-stream configurations to enrich the settled sewage with soluble fermentation products, which are suitable carbon and energy sources for BNR. In a single (in-line) primary tank configuration, formulated as an activated primary tank (APT) (Barnard, 1984), the settled sludge is recycled back to the raw sewage tank inflow to maintain a sludge blanket and elutriate (wash out) the generated soluble organic matter from the "active" sludge blanket. The solids removal and thickening objectives of a PST must be counterbalanced with organic matter fermentation needs in an APT. The amount of VFA elutriated should be directly related to the elutriation rate, but the

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potential settled sewage solids carry over could limit the elutriation rate.

This paper describes the impact of elutriation rate and sludge age variations at a full-scale APT on the production of VFA and the resulting changes in constituent removal and TKN/COD ratios.

Materials and methods

Activated primary tank

The experiments were performed at a full-scale uncovered circular APT, equipped with a single-arm peripherally driven half-bridge. The total tank volume is 5039 m^3, with a sludge hopper of 967 m^3, and the tank diameter is 36 m, with a stilling chamber diameter of 5.5 m. The tank and sidewall depths are 6.69 and 4.0 m respectively, and the floor is sloped 9° to the horizontal. The raw sewage flow (mixed with recycled sludge) enters the tank in a central stilling chamber and the settled sewage exits the tank over a peripheral V-notch weir, as indicated in Figure 1. The settled sludge is pumped into a recycle channel for screening and mixing with the raw sewage. The recycled sludge flow can be redirected in the channel by manual sluice gate adjustments for wastage, or it can be diverted directly into the settled sewage flow towards the BNR reactor.

Method of operation

The APT was operated during three stages as a continuous, semi-batch and intermittent sludge elutriation system, as summarised in Table 1. Stage A started in mid-summer and stage C ended at the onset of winter.

On-site experimental data

Sample taking. Raw and settled sewage samples were obtained from automated samplers (ISCO 3700 Series), programmed for 5 minute sampling intervals to obtain 24-hour composite samples at the APT raw sewage inlet and settled sewage outlet. Grab samples were taken from the waste sludge in the sludge recycle channel.

Volumetric flow determination. The raw sewage volumetric flow quantity was recorded as diurnal flow profiles and the waste sludge volumetric flow quantity was recorded as daily totals. The settled sewage volumetric rate was calculated from the difference between the raw sewage and the waste sludge volumetric rates. The sludge recycling volumetric rate

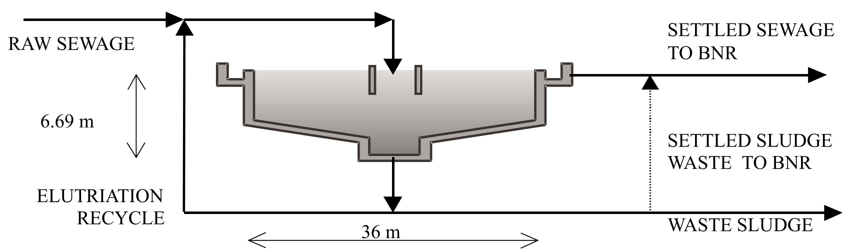

Figure 1 Schematic presentation of the full-scale APT configuration

Table 1 Sludge operational modes of full-scale APT evaluation

Operation	Sludge recycle mode	Recycle operation [hours/day]	Duration [days]
Stage A	Continuous	24 h/d (24 h on, 0 h off)	60 d
Stage B	Semi-batch	3 h/d (1 h on in every 8 h shift)	90 d
Stage C	Intermittent	12 h/d (0.5 h on, 0.5 h off)	30 d

was determined from the pump design output data and verified by open channel linear flow velocity measurements (wetted area multiplied by the linear velocity of a floating object). The sludge recycle volumetric rate was based on the pump operation running hours.

Sludge quantity determination. A handheld Suspended Solids/Interface Level monitor (Royce Instrument Corporation, Model 711) with a single gap optical sensor, attached to an 8 m cable, was used about once a week during stage A and B to indicate the water and sludge blanket interface level. A custom made sludge blanket sampler, consisting of three 2.5 m connectable stainless steel rods and a string operated detachable 500 ml sampling chamber, was manufactured during stage B and used to take water and sludge samples up to 6 m deep in the APT. During the end of stage B a dual function ultrasonic interface blanket level and surface water clarity monitor (Drexelbrook Engineering Company, Model CCS 2000) was temporarily installed 4.75 m from the centre column to the walkway handrail of the rotating bridge. The controller output was connected to a 24-hour chart recorder. The total sludge volume in the tank was obtained from a calculated tank depth to tank volume relationship.

Temperature measurements. A digital thermometer, supplied with a 4 m sensor cable, was used weekly for tank surface water temperature measurements.

Analyses

Laboratory analyses on daily composite samples of the APT raw and settled sewage were based on Standard Methods (1995), and consisted of suspended solids (SS), settleable solids (SetS), COD and TKN analyses. The VFA analyses were performed twice per week according to a two-point titration estimation method (Ripley *et al*., 1986). Total solids (TS, % dry solids) and VFA analyses on grab samples of the waste sludge were performed twice per week. Sludge samples were centrifuged for 5 minutes (5000 rpm) to separate the supernatant for VFA analysis (calculated as VFA-COD).

Calculations

Sludge quantity determination. Water and sludge grab samples were collected with the manual sampler at 0.5 m vertical tank depth intervals during the high sludge blanket condition of stage B. The water and sludge interface level depth was measured from the surface at 3.5 m (sludge blanket height from floor at 3.2 m), representing a 30% volumetric sludge content in the tank. The concentration layer between 6.0 and 6.69 m (at the tank floor) was presumed to be equal to the constituent concentration at 6.0 m, due to the inaccessibility of the sampler on the sloped floor below the stilling chamber.

Hydraulic and solid loading. The hydraulic evaluation of the APT is based on the raw sewage average dry weather flow (ADWF), the average and peak upflow velocity rate (UR and UR_p) and the nominal hydraulic retention time (HRT). The UR is calculated as the hourly ADWF divided by the wetted tank water surface (stilling chamber surface excluded), and the HRT calculated as the total tank volume divided by the hourly ADWF. The solids loading rate (SLR) is presented as the daily total inflow mass of dry solids from the raw sewage and the recycled sludge per square metre wetted tank water surface.

Recycle and elutriation rate. The sludge recycle rate (SRR) is calculated as the total volume of sludge recycled per day divided by the raw sewage ADWF. The sludge elutriation rate (SER) is calculated as the mass of dry sludge solids recycled per day divided by the raw sewage ADWF.

Sludge age. The mass based solids retention time (SRT), or sludge age, is derived from the mass of settled sludge in the blanket divided by the daily mass of solids wasted and carried over in the settled sewage. The sludge blanket solids concentration is estimated as equal to the stabilised recycle (or waste) sludge concentration.

VFA production rate. The VFA production rate (r_{VFA}) is obtained from the difference between the raw sewage hourly VFA mass and the waste sludge and settled sewage hourly VFA mass, and dividing the resultant hourly VFA mass increase in the APT by the total tank volume. The VFA concentrations are expressed as COD, based on an estimated 1.28 g-COD equivalent/g VFA (Rössle, 1999).

Results and discussion

Sludge quantity determination

The solid and organic constituents concentration profiles impact is reduced due to the conical shape of the APT, as indicated in Figure 2. The high concentration in the hopper is cancelled by the relatively low hopper volume compared to the total tank volume (19% of the total tank volume), creating a fairly constant mass inventory increase in the respective water and sludge blanket sections. The mass profiles in the water and sludge sections further indicate the presence of a distinct water and sludge blanket interface, as shown in Figure 2. Under these conditions, the constituents in the water level above the sludge blanket do not play a significant role in the total tank constituent inventory.

The continuous recycle of settled sludge does not affect the blanket stability substantially, with the on-line sludge blanket level chart recordings indicating hourly vertical level variations not larger than 1 m. There was however a tendency noted that the blanket became unstable during the morning peak inflow stages, when the blanket level rose up to about 0.5 m from the water surface, resulting in a potential carry over of solids in the settled sewage.

Hydraulic loading

From the 3-stage average (ABC) summary listed in Table 2, the UR of 1.12 m/h and the UR_p of 1.79 m/h are comparable to the reported guidelines of 1.5 to 2 m/h for settling tanks

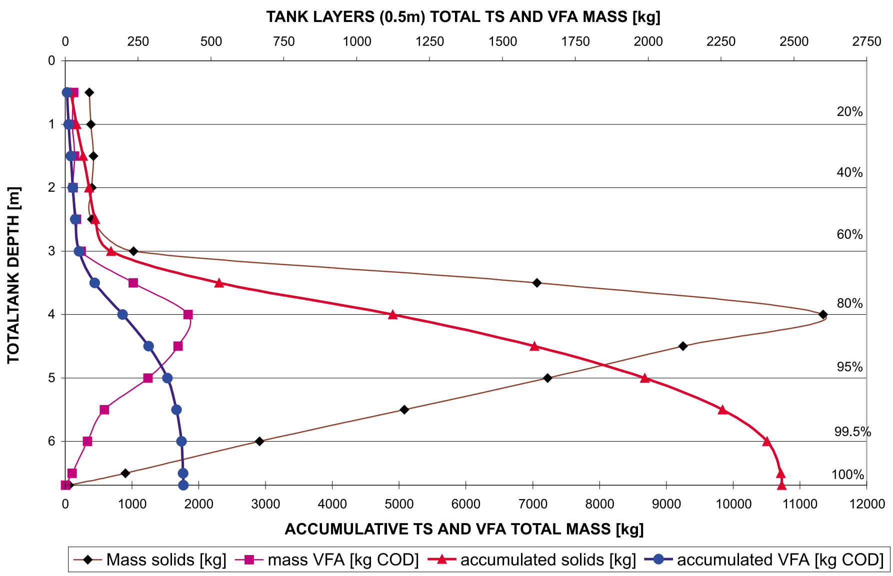

Figure 2 TS and VFA mass and cumulative mass profiles, high sludge blanket APT

Table 2 General conditions of APT evaluation

Stage	UR [m/h]	UR_p [m/h]	HRT [h]	SRR [m^3/m^3]	SER [kg/m^3]	SLR [$kg/m^2/d$]	SRT [d]	TS [%]	T [°C]
A	1.22	1.95	4.06	0.09	3.7	120	7.5	4.25	24
B	1.11	1.78	4.46	0.01	0.7	31	17.3	6.24	22
C	1.17	1.88	4.24	0.05	2.2	74	2.5	4.90	18
ABC	1.12	1.79	4.43	0.05	2.9	83	7.4	5.62	21

deeper than 3 m (WRC, 1984). The average HRT of 4.4 h can be related to the recommended minimum of 2 to 3 h. The potential impact of the average SLR of 83 $kg/m^2/d$ on APT solids management is emphasized, when compared to a SLR of about 11 $kg/m^2/d$ found in a comparable PST (sludge recycle absent), with a raw sewage average solids inflow of 425 mg SS/l.

Elutriation rate and sludge age

The SER, as listed in Table 2, indicates the potential contact between the raw sewage and fermented sludge solids, to elutriate the generated VFA. The SRT of stages A and B are higher than the prevalent guideline of 6 d (Banister and Pretorius, 1998). The management of the settled sludge blanket level and the solids carry over in the settled sewage predominantly governed the SRT. The average 5.6% TS in the APT sludge blanket is above the recommended limit of 2% TS, and can lead to inhibitory effects and limited VFA generation (Banister and Pretorius, 1998). The maximised sludge thickening and removal functions of an in-line APT are however generally essential to manage the downstream sludge treatment capacity. The sludge concentration in an in-line APT may therefore be higher when compared to conditions in a side-stream prefermenter configuration.

Constituent removal

At the prevailing hydraulic conditions between 30 to 50% of the COD, 50 to 80% of the SS and 90 to 95% of SetS should be removed (WRC, 1984). The low removal (R) of constituents (25% COD, 33% SS, 62% SetS) during stage A, as listed in Table 3, indicates that solids carry over occurred during the high sludge blanket condition experienced at the high SER. During the semi-batch and intermittent sludge recycle mode (stages B and C), at a lower SER, the average COD and solids removal efficiency increased (average 49% COD, 65% SS, 80% SetS) to expected levels. This confirms the reported failures (Pitman *et al.*, 1992) of solids removal at prefermenters, due to the continuous settled sludge recycling for elutriation purposes.

VFA production rate

The r_{VFA} for the first two stages, as listed in Table 3, were within the reported range of 1 to 10 mg VFA/l/h expected for an APT (Münch, 1998). The stage A SRT of 7.5 d resulted in the highest r_{VFA} of 5.7 mg VFA/l/h. The stage B SRT of 17.3 d was too long and the average settled sludge concentration of 6.2% TS was too high for conventional sludge collection

Table 3 General performance results of APT evaluation

Stage	R_{COD} [%]	R_{SS} [%]	R_{SetS} [%]	r_{VFA} [mg VFA/l/h]
A	25	33	62	5.7
B	48	64	80	1.4
C	50	66	79	–4.4
ABC	40	56	76	1.3

equipment. The reported trend (Hartley *et al.*, 1999) of a higher rate of VFA transfer into the settled sewage during a continuous recycle mode at a high elutriation rate (stage A) has also been confirmed in this study. During stage C a too short SRT and industrial contaminants contributed to the observed VFA generation failure.

TKN/COD ratio

The TKN/COD ratio of the raw sewage increased from 0.057 to 0.082 mg N/mg COD (44%) in the settled sewage over the total evaluation period, as listed in Table 4. Over this evaluation period the TKN/COD ratios of the raw sewage were lower than the reported typical range for South African wastewaters. The ratio increased from 20% during the continuous recycle mode (stage A) to 46% in the intermittent recycle mode (stage C) and 64% during the semi-batch recycle mode (stage B). The TKN/COD ratio is expected to increase only 20 to 30% across a PST (WRC, 1984), as was recorded during stage A. The large nutrient ratio increase recorded during stage B and C, due to the high COD removal, indicates a potential adverse impact of APT prefermentation on certain BNR processes.

For a given BNR process configuration the removals of N and P per influent COD are fixed once the BNR reactor sludge age, total volume and the subdivision of anaerobic and anoxic zones are fixed (Ekama *et al*. 1983). This implies that with unfavourable TKN/COD ratios, the failure of denitrification (nitrate (NO_3-N) removal) in the BNR reactor leads to a higher effluent nitrate concentration (as N), with a simultaneous decrease in P removal in the reactor. The modified Phoredox (3-stage Bardenpho) process, frequently utilised in South Africa, has a limited recommended maximum TKN/COD ratio of 0.07 to 0.08 mg N/mg COD. Higher TKN/COD ratios can contribute to the failure of the denitrification process, and it can lead subsequently to reduced biological P removal (Lilley *et al.*, 1997).

General trends

Constituent removal, VFA generation and TKN/COD nutrient ratio changes are displayed in Figure 3 as a function of SLR and SER. It can be deduced from Figure 3 that a compromised operational control system must be established between sufficiently thickened solids removal at an acceptable small TKN/COD increase, against an inversely related high enough VFA generation level. The different requirements should thus be prioritised at individual APT installations to find an optimised operational and process control structure.

Conclusions

It has been established during three experimental stages at a full-scale APT that the extent of solids thickening and solids removal, to be maximised, was inversely related to the sludge elutriation and solids loading rates. This relationship was also followed by the nutrient ratio increase, to be minimised at the APT. These two trends were found to be in conflict with the fermentation reactions, where the VFA generation rate was directly related to the sludge elutriation rate, provided a suitable process environment and sludge age was maintained. A distinct water and sludge interface was detected in the APT, and an adequate

Table 4 Nutrient ratio changes across APT

Stage	A	B	C	ABC
Sewage	TKN/COD [mg N/mg COD]	TKN/COD [mg N/mg COD]	TKN/COD [mg N/mg COD]	TKN/COD [mg N/mg COD]
Raw	0.061	0.059	0.050	0.057
Settled	0.073	0.097	0.073	0.082
% Change	20	64	46	44

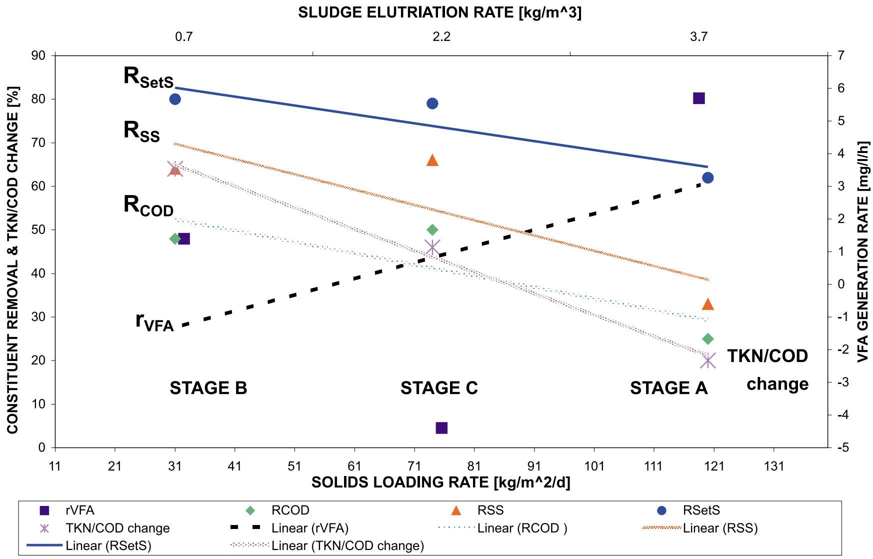

Figure 3 General performance trends at APT

sludge recycle is required to elutriate the fermentation products from the thickened settled sludge concentrated in the bottom of the APT.

The operational complexity at an in-line single APT to regulate thickening and solids removal, concurrently with the fermentation of organic matter, requires detailed evaluations to optimise the required local functions. In-line single tank prefermenter efficiency appraisals, at individual treatment plants, must be based on a combination of acceptable VFA generation levels, suitable TKN/COD ratios and sufficient solids managing capacity.

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