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Poultry slaughterhouse wastewater treatment using a static granular bed reactor coupled with single stage nitrification-denitrification and ultrafiltration systems

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ABSTRACT

This study evaluated the performance of a lab-scale poultry slaughterhouse wastewater (PSW) treatment system consisting of a static granular bed reactor (SGBR) coupled with single stage nitrification-denitrification (SND) bioreactor and ultrafiltration membrane module (ufMM) systems. The feasibility of treating PSW to a water quality standard compliant with industrial wastewater discharge standards was investigated. The SGBR was operated at hydraulic retention times (HRTs) ranging from 24 to 96 h and organic loading rates (OLRs) ranging from 0.73 to 12.49 g COD/L.day, for 138 days. The chemical oxygen demand (COD), total suspended solids (TSS), biological oxygen demand (BOD_5) and fats, oils and grease (FOG) removal efficiencies achieved by the SGBR averaged 80%, 95%, 89% and 80%, respectively. The SND bioreactor achieved total nitrogen (TN) removal efficiencies of 33% and 79% for the SGBR effluent, when operated in down-flow mode without aeration and up-flow mode with aeration, respectively. The ufMMs, operated in dead-end filtration mode, were able to further reduce the COD and TSS by an average of 65% and 54%, respectively. The results for the PSW treatment system demonstrated the combined benefits of biological and physical treatment processes, with averaged COD, ortho-phosphate (PO_4^{3-}-P), TSS and total dissolved solids (TDS) removal efficiencies of 91%, 51%, 97% and 52%, respectively, being achieved over 52 days. The final effluent was deemed suitable for discharge; although, the PO_4^{3-} and NH_4^+-N requires further monitoring and the PSW treatment system design requires refinement.

1. Introduction

The poultry industry is the largest industry within the agricultural sector in South Africa (SA) and is the largest poultry product producer in the Southern African Development Community (SADC) region. The growth in poultry product consumption in SA has steadily increased due to the products being inexpensive and therefore the preferred source of protein for the majority of the population [1]. The South African poultry industry utilises a large quantity of potable water for slaughtering and production processes [2]. An average of 15–20 L of water is utilized per processed bird, of which approximately 80–90% of this process water is discharged as PSW [3]. The PSW generated is typically classified as medium-strength wastewater due to the high concentration of organic matter (i.e. COD and BOD_5), inorganic matter, suspended solids, fats, pathogens, and nutrients (i.e. nitrogen and phosphorous) [3–5]. These contaminants result in heightened organic loads for municipal sewer treatment systems and the environment if discharged untreated, which can culminate in eutrophication and deoxygenation of fresh water bodies [6,7]. In SA, poultry slaughterhouses which have been granted permission to discharge wastewater directly into municipal sewer treatment systems are required to abide by the municipal by-laws within each municipality as prescribed by the Water Services Act of 1997; although, monitoring is limited [8,9].

On-site wastewater treatment systems employed by poultry slaughterhouses generally consist of screening followed by an equalisation tank and a dissolved air flotation (DAF) system [3,10]. In addition to these treatment processes, several other processes have been reported for PSW treatment, with high-rate anaerobic processes being the most commonly used due to their high overall treatment efficiency (up to 90%) and suitability for treating wastewater with a high organic load [4,11]. These high-rate anaerobic reactors which include the up-flow anaerobic sludge blanket (UASB) bioreactor, expanded granular sludge bed (EGSB) bioreactor, and SGBR, operate at long HRTs and short solids retention times (SRTs) which facilitates the treatment of a

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large quantity of wastewater using highly-active biomass in the form of anaerobic sludge or granules [12–14]. The SGBR was developed with the purpose of simplifying the design, operation, and maintenance of high-rate anaerobic reactors whilst still maintaining high-quality influent treatment [15,16]. The design of the SGBR is based on the UASB reactor design; however, the distinguishing feature of the SGBR is its down-flow configuration which eases the separation of the wastewater, solids, and biogas [17]. The SGBR has proven to be successful in the treatment of various low- to medium-strength wastewaters including PSW; however, further treatment of SGBR effluents is usually required [4,7,9,14,18].

Due to increasingly stringent environmental regulations with regard to high nutrient levels as well as growing interest in water re-use and reclamation, simultaneous nitrification and denitrification (SND), which combines heterotrophic nitrification and aerobic denitrification processes, can be considered as an attractive post-treatment for anaerobic effluents. The oxidation of organic matter and the SND process can occur under aerobic conditions within a single bioreactor; i.e. single stage nitrification-denitrification (SND) (Seifi & Fazaelipoor, 2012). Furthermore, UF membranes have proven to be efficient in the removal of particulate matter, pathogens and environmentally hazardous nutrients from PSW [3,19,20]; and has demonstrated its suitability as a post-treatment system for anaerobically treated PSW [10].

The use of the SGBR, SND bioreactor and ufMM systems have proven to be successful in the treatment of various industrial wastewaters. However, no study has reported on the performance and efficiency of the combined use of these processes for the treatment of PSW. The aim of this study was to investigate the feasibility of treating PSW from a poultry slaughterhouse to a water quality standard compliant with industrial wastewater discharge standards and to evaluate the performance of SGBR, SND bioreactor and ufMM systems and the overall PSW treatment system.

2. Material and methods

2.1. Poultry slaughterhouse wastewater (PSW) characterisation

The PSW used in this study was obtained from a poultry slaughterhouse located in the Western Cape Province (SA). PSW samples were collected as grab samples from the sump of the poultry slaughterhouse's existing wastewater treatment facility, stored in 25 L polyvinyl chloride (PVC) containers, and refrigerated at 4 °C. The characteristics of the untreated (unfiltered) PSW used in this study are listed in Table 1.

Table 1
Characteristics of the untreated PSW used in this study in comparison to the industrial wastewater discharge and potable water limits.

Parameter	Unit	Value	[a]CCT by-law limit	[b]SANS 241: 2011
COD	mg/L	4317	5000	–
BOD_5	mg/L	2875	–	–
pH at 25 °C	–	5.6	5.5-12	5-9.7
Conductivity at 25 °C	mS/m	159	500	≤170
Ammonia (as N)	mg/L	25.2	–	< 1.5
PO_4^{3-}	mg/L	24.3	10	–
Alkalinity (as $CaCO_3$)	mg/L	170	–	–
O&G	mg/L	1110	400	–
NO_3^-	mg/L	1.0	–	≤11
TDS	mg/L	1208	–	≤1200
TSS	mg/L	1580	1000	–
VSS	mg/L	1533	–	–
VFA	mg/L	421	–	–

[a] CCT: City of Cape Town wastewater and industrial effluent by-law (2013).
[b] SANS 241: South African National Standards 241 drinking water standards (2011).

2.2. Lab-scale PSW treatment system

In this study, the lab-scale PSW treatment system consisted of: 1) an anaerobic SGBR for organic matter and suspended solids removal; 2) a SND aerobic bioreactor for total nitrogen (TN) removal; and 3) an ufMM system as a final treatment stage for residual organic matter and suspended solids removal (Fig. 1).

2.3. SGBR set-up and inoculation

The down-flow SGBR was made from a cylindrical glass column with a working volume of 2 L (height and inner diameter of 0.62 m and 0.065 m, respectively). Pumice stones (average diameter of 5–20 mm) were used as the underdrain bed to prevent the washout of anaerobic granules. A stainless steel sieve (2 mm pore size) was fixed to the bottom of the SGBR to retain the pumice stones and granules. A MINIPULS® Evolution peristaltic pump (Gilson, USA) was used for feeding the PSW into the SGBR and a circulating water bath was used to supply the water jacket. The SGBR was inoculated with 0.4 L of anaerobic granules obtained from a full-scale mesophilic UASB reactor operated at a local brewery plant (Newlands, South Africa) and fed with 1.6 L of untreated (unfiltered) PSW.

2.4. SGBR start-up and operating conditions

The SGBR was operated continuously at mesophilic temperature (i.e. 35–37 °C) for 138 days. The PSW was filtered through a mesh screen (2 mm pore size) to remove large floating solids and particulate matter prior to feeding the SGBR. The filtered PSW was diluted with potable water to prevent overloading the SGBR. The SGBR was fed with 50% (v/v) and 25% (v/v) PSW for a period of 43 and 8 days, respectively. After the 48-hour acclimatization period, the HRT was set to 55 h and the SGBR was fed with 50% (v/v) PSW to initiate the start-up period (OLR of 1.18 g COD/L.day). A second start-up was implemented due to the washout of fine granules via the effluent stream during the first start-up period. In order to restore the granular bed to its original volume, granule re-supplementation into the SGBR was implemented, allowing for a further 24 h for acclimatization. The HRT was increased step-wise from 55 h (1st start-up) to 96 h (2nd start-up) to enable the biomass to restabilize whilst preventing further washout of granules. The HRTs at which the SGBR operated was based on conditions reported in Debik and Coskun [4] and Basitere, Rinquest [9].The SGBR operating conditions are summarised in Table 2.

2.5. SND bioreactor set-up and inoculation

The SND aerobic bioreactor used in this study had a total volume of 19 L (height and inner diameter of 2 m and 0.11 m, respectively) and a working volume of 10 L (Fig. 1). The bioreactor was made from a cylindrical PVC column. Packing material in the form of gravel (average diameter of 20–30 mm) and gravel-integrated-with-sponge (average diameter of 25–35 mm) were used as filter and supporting media for the nitrifiers and dentrifiers which are known to perform better when immobilised than in free-floating form [21]. The total packed bed height was 1 m. A perforated PVC cylinder (height and inner diameter of 0.52 m and 0.09 m, respectively), holding 20 mm sponge cubes for microbial attachment, was positioned at the top of the bioreactor. The HRT was controlled by a MINIPULS® Evolution peristaltic pump (Gilson, USA). During the aeration stage, a Resun® AC-9906 air pump (Resun®, China) was used to supply air via an air stone positioned at a height of 0.85 m from the top of the bioreactor.

The SND bioreactor was inoculated with 10 L of untreated (unfiltered) PSW and fed with 100 ml of basal medium periodically at 24 intervals for 7 days. A quantity of 100 ml of PSW was removed prior to adding the basal medium. The basal medium comprised (per 1 L): 1.5 g/L KH_2PO_4, 7.9 g/L Na_2HPO_4, 0.5 g/L $MgSO_4.7H_2O$ and 1 ml trace

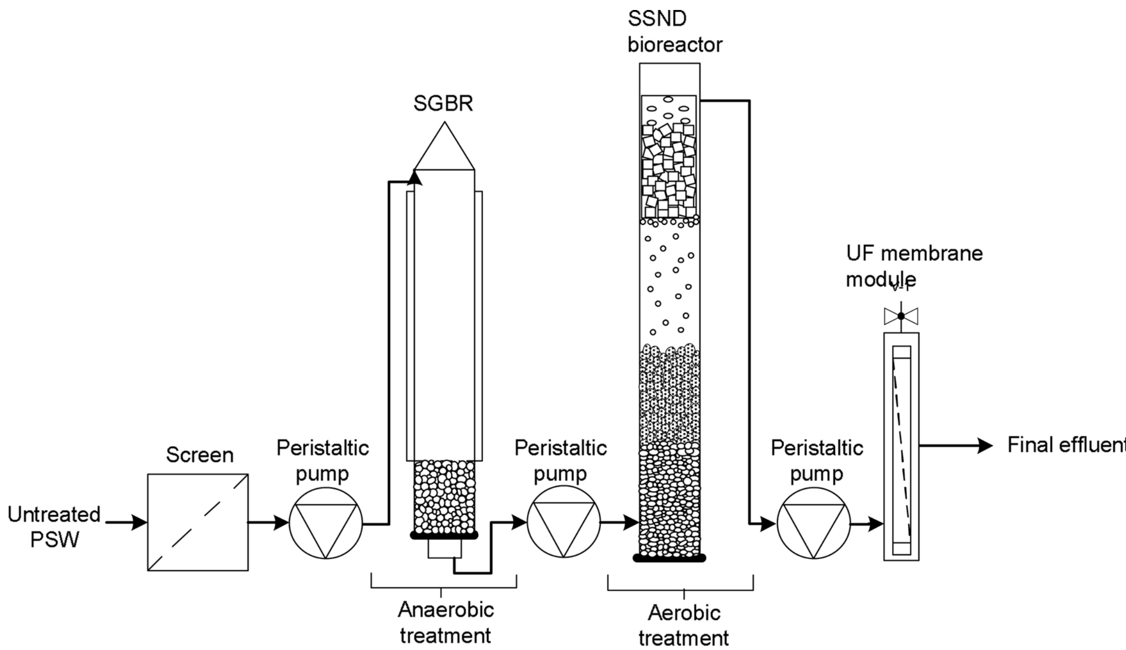

Fig. 1. Lab-scale PSW treatment system.

Table 2
Summary of the SGBR operating conditions for 138 days of operation.

Operating stage	Operating time (days)	HRT (h)	Flow rate (L/h)	Average OLR (g COD/L.day)	Dilution (v/v)(%)
1st start-up	28	55	0.0364	1.18	50
2nd start-up	15	96	0.0208	0.78	50
	8	96	0.0208	0.78	25
	6	96	0.0208	0.78	None
	27	48	0.0364	1.96	None
	28	36	0.0486	4.10	None
	26	24	0.0729	5.74	None

element (50 g/L EDTA, 2.2 g/L $ZnSO_4.7H_2O$, 5.5 g/L $CaCl_2$, 5.06 g/L $MnCl_2.4H_2O$, 5.0 g/L $FeSO_4.7H_2O$, 1.1 g/L $(NH_4)_6Mo_7O_2.4H_2O$, 1.57 g/L $CuSO_4.5H_2O$, 1.61 g/L $CoCl_2.6H_2O$). Yeast extract (7.8 g/L) was supplemented in the basal medium which was filter-sterilised (0.22 µm pore size) and adjusted to a pH of 7 using sodium hydroxide. The SGBR effluent was fed into the bioreactor after the acclimatization period of 7 days.

2.6. SND operation and operating conditions

The SND bioreactor was continuously operated at ambient temperature (i.e. 23–25 °C) for 87 days. Two operating strategies were tested. During stage 1, the bioreactor was operated in a down-flow configuration without aeration. During stage 2, the configuration was changed to up-flow mode and air was continuously supplied into the bioreactor. The dissolved oxygen (DO) concentration in the aerobic zone was maintained between 1.8–3.2 mg/L. The HRT was varied stepwise as shown in Table 3.

2.7. ufMM system set-up and operation

Hollow-fibre (HF), ceramic UF membranes were used in this study. The membranes were enclosed in glass, cylindrical modules, each with a volume of 45 ml (Fig. 1). The UF membrane specifications are presented in Table 4.

The ufMMs were operated under dead-end filtration mode. The feed (i.e. a weekly composite sample of the SND bioreactor effluent) was pumped into the bottom of the module into the lumen side of the membrane at constant feed flow rate using a MINIPULS® Evolution peristaltic pump (Gilson, USA). The permeate was collected from the shell side of the ufMM. The ufMMs were operated at ambient temperature (i.e. 23–25 °C). The operating conditions of the UF membrane are summarised in Table 5.

2.8. Sampling and analytical methods

The performance of the SGBR, SND bioreactor and ufMMs were monitored and evaluated using the analyses of the feed and effluent samples. The temperature; pH; conductivity; TDS; and salinity were measured using a PCSTestr 35 multiparameter, and the turbidity using a TN-100 Turbidimeter. The COD; NH_4-N; NO_3-N; NO_2-N and PO_4-P were determined using Merck COD solutions (solution A Cat. No. 1.14538.0065 and 1.14679.049; solution B Cat. No. 1.14539.0495 and 1.14680.1495) and Merck Spectroquant test kits (NH_4-N: test kit Cat. No. 1.00683.0001; NO_3-N: test kit Cat. No. 1.14773.0001; and PO_4-P: cell test Cat. No. 1.14729.0001). The TSS and VSS were measured using ESS Method 340.2. The DO was measured using an 820 portable DO meter. The in-house analyses were completed in triplicate and an

Table 3
Summary of the SND bioreactor operating conditions for 87 days of operation.

Operating stage	Operating time (days)	HRT (days)	Flow rate (L/h)	Average OLR (g COD/L.day)	Average NLR (g TN[a]/L.day)
Start-up	12	6	0.066	0.13	0.03
1	33	6	0.066	0.12	0.04
2	33	11	0.039	0.08	0.03

[a] TN: In this study, total nitrogen (TN) is equivalent to the sum of the ammonium-nitrogen (NH_4-N), nitrate-nitrogen (NO_3-N) and nitrite-nitrogen (NO_2-N).

Table 4
UF membrane specifications.

Specification	Description
Type of membrane	Hollow fibre (HF)
Material	Alpha aluminium oxide (Al_2O_3)
Surface properties/Hydrophobicity	Neutral, hydrophilic
Surface area	0.005498 m^2
Pore size	100 nm
Membrane diameter	6 mm (inner), 8 mm (outer)

Table 5
Summary of the ufMM operating conditions.

SND- ufMM operating stage	Operating time (days)	Feed flow rate (L/h)
1	19	0.0282
2	33	0.0282

average for each parameter was calculated from the measurements recorded. A weekly composite sample of the SGBR feed and effluent was sent to a South African National Accreditation System (SANAS) accredited lab (Scientific Services, SA), for alkalinity; BOD_5; O&G; and VFA analyses.

3. Results and discussion

The findings of this study represent the operation of the SGBR, SND bioreactor, ufMMs, and overall PSW treatment system under varying conditions. The SGBR effluent was used as feed for the SND bioreactor and a composite sample of the SND bioreactor effluent was used as feed for the ufMMs.The HRTs of the SGBR operated for 138 days in this study, were specifically maintained (kept constant) for 26 (min) to 30 (max) days, based on bioreactor performances as indicated in previous studies, i.e. Basitere et al. and Debik & Coskun, which was within a range suitable to attain an appropriate anaerobic biomass response. The change of HRTs and OLRs was motivated by the necessity to assess the performance of the SGBR, as the wastewater quality characteristics of the PSW varied depending on the slaughterhouse operations at a specific time. Furthermore, the active anaerobic biomass used in the SGBR was procured from an operational UASB treating wastewater with characteristics similar to those observed for the PSW, which rendered an ability to withstand OLR fluctuations at HRTs of 24 to 96 h; HRTs maintained for 26 (min) to 30 (max) – an operational strategy deemed sufficient for the biomass to acclimatize to the PSW being treated.

3.1. SGBR efficiency at varying HRTs and OLRs

The COD, TSS, FOG, and BOD_5 removal efficiencies in relation to the varying HRTs and average OLRs are represented in Fig. 2. Fluctuations in the OLR were due to the organic matter concentrations in the feed varying according to the operation in the poultry slaughterhouse at the time of sampling. The feed COD concentrations ranged between 2195 and 12,490 mg/L and averaged at 4344 ± 2312 mg/L, with corresponding average OLRs of 0.96, 12.5 and 2.75 ± 2.11 g COD/Lday, respectively. The effluent COD was consistently low throughout this study, which was attributed to the high activity the granular bed and the downflow configuration which enabled pneumatic mixing within the SGBR. Furthermore, the gravel underdrain system helps to retain the granules within the reactor which ensures that there is sufficient microbial activity for the degradation of the organic matter present in the feed wastewater. The COD, TSS, and BOD_5 removal efficiencies were consistently above 70%, 80% and 90%, respectively, throughout this study; with the intermittent performance reduction on several days, attributed to backwashing operations. The FOG removal efficiencies, however, were relatively low during the start-up period due to the insoluble nature of FOG and the inept biodegradable proficiency of the granular bed during the initialization of the SGBR operation. The FOG removal efficiency increased to above 80% on average after the start-up period (Fig. 2).

Removal efficiencies reached a maximum of 86% for COD, 95% for TSS, 94% for FOG, and 99% for BOD_5, respectively, at an OLR of 4.10 g COD/Lday and HRT of 36 h. Similarly, Basitere, Rinquest [9] reported COD, TSS and FOG removal efficiencies of 93%, 95% and 90%, respectively, when operating a SGBR for PSW treatment at HRTs of 55 and 40 h with average OLRs of 1.01 and 3.14 g COD/Lday. The lowest removal efficiencies were observed during the start-up period during which the washout of granules occurred from the SGBR which created the need for granules re-supplementation and subsequently an additional 24 h for acclimatization.

The COD, TSS, and BOD_5 removal efficiencies increased as the OLR increased; whereas, the FOG removal efficiencies were not a function of the OLR (Fig. 2). A similar trend was reported by Lim and Fox [12] in the treatment of swine wastewater using a lab-scale SGBR operated at 24 °C. The increase in the removal efficiencies at higher OLRs was as a result of the SGBRs' ability to effectively tolerate increasing OLRs as the biomass matured as well as due the biological degradation and the physical filtration and retention of the organic matter and suspended solids, fats and proteins within the SGBR [22]. However, the combination of a 48 h HRT and an average OLR of 1.96 g COD/L.day significantly contributed to the quantity of accumulated suspended solids in the SGBR. This ultimately led to clogging of the granular bed which impacted on the operability of the SGBR.

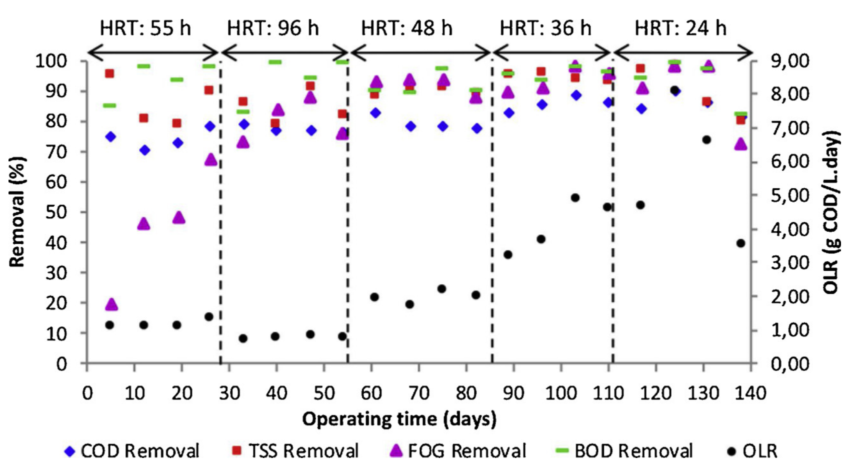

Fig. 2. Treatment efficiency of the SGBR at varying HRTs and average OLRs.

Table 6
SGBR feed and effluent characteristics.

		SGBR Feed			SGBR Effluent		
Parameter	Unit	Minimum	Maximum	Average	Minimum	Maximum	Average
pH	–	6.13	7.24	–	6.29	8.59	–
Cond.	μS/cm	973	2405	1604 ± 414	1021	2323	1608 ± 328
TDS	mg/L	691	1693	1138 ± 294	725	1653	1142 ± 232
Salinity	mg/L	529	1413	916 ± 179	529	1187	882 ± 134
Turbidity	NTU	237	997	719 ± 201	3.57	234	14.7 ± 24.6
TSS	mg/L	313	8200	1654 ± 1695	13	160	63 ± 38
VSS	mg/L	239	8920	1906 ± 1498	20	1465	744 ± 343
COD	mg/L	2517	12,490	5216 ± 2534	482	974	729 ± 98
NH_4-N	mg/L	135	447	216 ± 56	103	283	177 ± 36
NO_3-N	mg/L	0.63	22.7	3.33 ± 4.45	1.07	24	12.1 ± 6.98
PO_4-P	mg/L	29	54	38 ± 6	65	141	94 ± 18
VFA	mg/L	105	898	375 ± 213	21	402	124 ± 118
Alkalinity	mg/L	322	923	499 ± 158	347	933	588 ± 163
BOD_5	mg/L	925	5000	2477 ± 1347	10	175	95 ± 62
FOG	mg/L	156	1710	715 ± 506	24	100	51 ± 22

3.2. SGBR performance in relation to discharge standards

The characteristics of the SGBR feed and effluent are summarized in Table 6. The variation in the feed characteristics can be attributed to the wastewater samples being collected from the poultry slaughterhouse at irregular intervals. The effluent pH ranged between 6.29 to 8.59 which was within the acceptable range for discharge (i.e. > 5–9.7). The SGBR successfully reduced the COD of the PSW to a maximum of 974 mg/L which is less than the permitted discharge limit of 5000 mg/L. Despite the COD averaging at 4344 mg/L, further reduction to a value below 1000 mg/L eliminates the penalties imposed on industries, including poultry slaughterhouses. Similarly, the effluent TSS and FOG of 160 and 100 mg/L were well below their respective limits of 1000 and 400 mg/L, respectively. However, further treatment of the SGBR effluent was required for the PO_4^{3-}, NH_4^+-N, NO_3–N, and TDS which exceeded the maximum limits for permitted discharge as expected with anaerobic effluents.

3.3. Performance of the SND bioreactor

Fig. 3 shows the TN removal efficiencies achieved by the SND bioreactor for 87 days. Under DO limiting conditions and the down-flow configuration (stage 1), the SND bioreactor achieved average NH_4-N, NO_3-N, NO_2-N and TN removal efficiencies of 25%, 96%, 93% and 33%, respectively. The relatively low TN removal efficiencies observed during the first week was due to the system lacking a readily available biodegradable carbon source and the slow growth of ammonium-oxidising bacteria (AOB) [23]. The bioreactor was therefore inoculated with untreated PSW on day 17 which resulted in an increase in both the TN and NH_4^+-N removal efficiencies. The NH_4^+-N remained significantly low indicating that nitrification was inhibited due to the AOB and nitrite-oxidising bacteria (NOB) competing for DO (Seifi & Fazaelipoor). The high NH_4^+-N and relatively low effluent NO_3^--N and NO_2^--N effluent concentrations (< 1 mg/L) suggested that the initial oxidation of NH_4^+-N was the rate-limiting step in the nitrogen removal.

The nitrogen removal increased significantly to satisfactory levels after the reconfiguration of the bioreactor from down-flow to up-flow operation and the addition of a sparging system (Stage 2). As a result of the up-flow configuration, the nitrification was followed by denitrification and the HRT was therefore increased to 11 days to minimise the washout of the nitrifying microorganisms, via the effluent stream exiting the top of the bioreactor, and to provide sufficient conversion time for the adjustment of the biofilm to the new operating configuration. The SND bioreactor achieved NH_4-N, NO_3-N, NO_2-N and TN removal efficiencies of 90%, 87%, 78% and 79%, respectively. The high NH_4-N and TN removal efficiencies indicated that nitrification was the dominant process occurring within the SND bioreactor and verified that the oxygen supply was an important factor for efficient NH_4^+-N oxidation and a successful SND process. Furthermore, the low NH_4^+-N, NO_3^--N, and NO_2^--N concentrations in the effluent and high TN

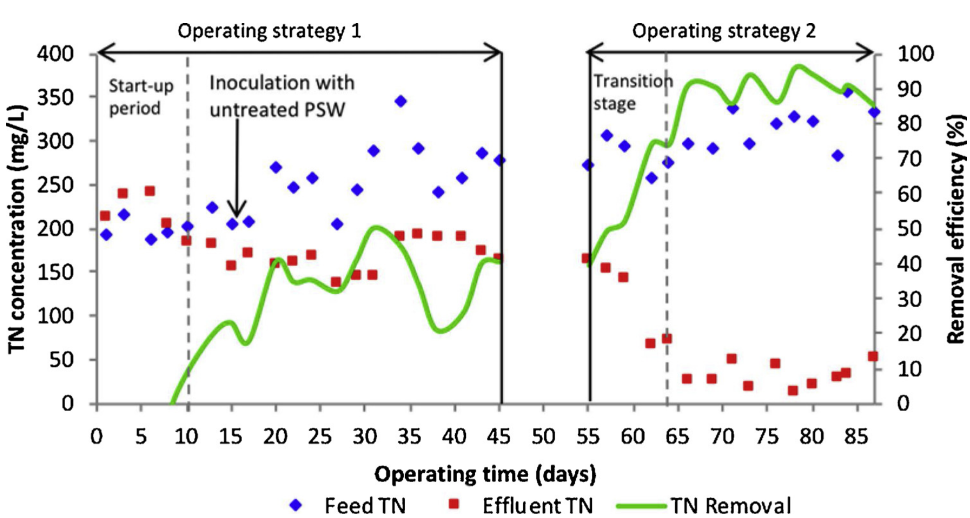

Fig. 3. SND bioreactor feed and effluent TN concentrations and removal efficiencies.

Table 7
Average performance of the combined SGBR, SND bioreactor and ufMMs system for 87 days of operation.

Parameter	Unit	SGBR Feed	SGBR Effluent	% SGBR	SND-ufMM Effluent	% SND-ufMM	% Overall System	[a]CCT by-law limit	[b]SANS 241: 2011
pH	–	6.94	7.46	–	8.08	–	–	5.5-12	5-9.7
Conductivity	mS/cm	2761	2244	19	1325	11	52	5000	≤1700
TDS	mg/L	1956	1588	19	940	11	52	4000	≤1200
Turbidity	NTU	710	19	97	2	90	99.7	–	≤1
TSS	mg/L	1084	64	94	32	54	97	1000	–
COD	mg/L	4245	832	80	341	53	91	5000	–
PO_4^{3-}	mg/L	45	36	19	22	18	51	10	–

[a] CCT: City of Cape Town wastewater and industrial effluent by-law (2013).
[b] SANS 241: South African National Standards (SANS 241) drinking water standards (2011).

removal efficiency, suggested that a significant nitrification-denitrification process occurred during this stage; however, the SND bioreactor setup was not yet optimized with respect to the DO transfer.

Although complete nitrogen removal was not achieved, the aim was to assess the possibility of a SND process occurring within a single-stage bioreactor without the addition of external carbon sources and activated sludge, a strategy required to mitigate operational costs at an industrial scale. In a study performed by Mpongwana, Ntwampe [24], it was proven that bacterial isolates (i.e. *Enterobacter* sp., *Yersinia* sp. and *Serratia* sp.) from PSW, obtained from the same source as the PSW used in this study, are capable of carrying out simultaneous nitrification and aerobic denitrification (SND). Therefore, the biological potential exists for SND without supplemental organic carbon sources. The nitrogen removal due to SND was 97.8% and 97.9% during Stage 1 and 2, respectively. Furthermore, the bioreactor was not designed as an activated sludge process for simultaneous COD and PO_4-P removal; hence there was no significant COD and PO_4-P removal observed.

3.4. Performance of the ufMM system

The ufMM system was initiated on day 27 of the SND bioreactor operation. During stage 1 of the combined SND-ufMM system operation, the ufMMs achieved rejection efficiencies of 59% for COD, 61% for TSS, 88% for turbidity with an average effluent TDS concentration of 1198 mg/L. The permeate produced during stage 2 was characterized by an average TDS of 785 mg/L and rejection efficiencies of 78% for COD, 50% for TSS, and 92% for turbidity. The marginal reduction in the TSS rejection efficiency from stage 1 to 2 was attributed to fouling of the UF membranes, since the permeate flux observed during stage 2 (4.77 L/m^2h) was lower than stage 1 (5 L/m^2h) in spite of the constant feed flow rate applied during both stages. Although the complete removal of the residual COD and TSS was not achieved, the ufMMs performed more efficiently during stage 2 due to the superior quality of the SND bioreactor effluent as a result of the upflow configuration and air supply implemented during stage 2. Similarly, Basitere, Rinquest [9] reported an average rejection efficiency of 64% for COD and 88% for TSS for UF membranes used as a post-primary treatment for PSW which was pre-treated by a SGBR.

3.5. Performance of the PSW treatment system

Table 7 shows the performance of the SGBR, SND-ufMM and overall PSW systems for a period of 87 days. The PSW system was evaluated at HRTs of 6 and 11 days, OLRs of 0.08 to 0.12 g COD/Lday, and an average nitrogen loading rate (NLR) of 0.04 g TN/Lday. The PSW system achieved higher COD and TSS removal efficiencies in comparison to the individual SGBR and SND-ufMM systems, thus demonstrating the efficacy of coupling biological and physical treatment processes for PSW treatment. The final effluent produced was compliant with the industrial wastewater discharge standards with the exception of the PO_4^{3-} and NH_4^+-N.

4. Conclusions

The SGBR was able to consistently reduce the organic matter, suspended solids and fats content of the pre-filtered PSW throughout its 138 days of operation, with removal efficiencies exceeding 80% on average. However, periodic backwashing was required to mitigate clogging and further treatment of the SGBR effluent was required with regard to the nutrient and TDS levels. The SND bioreactor performed satisfactorily with regard to the TN removal in the SGBR effluent. Even without the addition of carbon sources and the use of activated sludge, the SND bioreactor achieved optimum results when operated in up-flow mode with a continuous air supply, achieving a TN removal of 79%. The ufMMs were able to further reduce the residual COD and TSS by 65% and 54%, respectively. The final effluent produced by the PSW treatment system was compliant with the industrial wastewater discharge standards, with the exclusion of the PO_4^{3-} and NH_4^+-N, thus indicating refinement of the designed system is required in order to optimize the treatment of the PSW.

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