

Optimization of a full-scale site to achieve total nitrogen removal through implementation of a denitrification submerged anoxic filter

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Abstract

A full-scale wastewater treatment plant with a 5500 population equivalent was retrofitted with a pre-denitrification submerged anoxic filter (SA_{no}F) in order to achieve new total nitrogen (TN) consent of 35 mg/L. A 36 m³ SA_{no}F was installed downstream the primary settling tanks. The optimal operation of the anoxic SA_{no}F was investigated by varying the recirculation ratio, the carbon to nitrate ratio and the hydraulic retention time. After stable operation was achieved, nitrate was removed by 80% at a loading of 0.5 kg NO₃/m³.d and retention time of 60 minutes. The SA_{no}F presented a number of advantages, including use of internal carbon for denitrification, decrease of carbon load to the trickling filter by 30% and production of alkalinity required for nitrification in the trickling filter (11 mg CaCO₃/mg NH₄ removed). Overall the SA_{no}F was satisfactory and the effluent TN concentration reached 20-25 mg TN/L.

Keywords: anoxic, carbon to nitrogen ratio, denitrification, hydraulic retention time, nitrate load, recirculation rate.

Introduction

Wastewater treatment plants (WWTPs) are key facilities to protect natural water resources and the environment from undesirable pollutant discharges. Amongst those pollutants are the nutrients that include nitrogen compounds (ammonia, nitrite and oxidised forms of nitrogen) and phosphorus that can lead to algae development, and oxygen depletion in sensitive receiving waters and ultimately resulting in eutrophication (Almstrand et al., 2011; Khan et al., 2005). To avoid these pollution events, wastewater regulations have been amended to include total nitrogen (TN) along with established ammonia consents. Consents from 15 to 35 mg TN/L have now been established for medium and small WWTPs (10,000-100,000 population equivalent) for total nitrogen by Water Framework Directive (European Commission, 1991) or by country level regulations such as the UK Environment Agency (Environment Agency, 1991).

Secondary treatment processes in WWTPs can achieve significant nitrogen removal rates up to 50% (Pearce, 2004) but higher removal rates required to meet tighter consents can only be achieved through site optimization or through specially designed and process units. The pressure to achieve higher effluent quality in WWTPs, places a particular emphasis on trickling filters based sites, which remain the dominant secondary treatment process in wastewater treatment throughout the UK at approximately 70% of the WWTPs (Huo and Hickey, 2007). Trickling filters are mainly designed for carbonaceous pollutant removal, but nitrification can also take place. In the case of the later, nitrogen removing bacteria will outcompete organic matter removing bacteria when trickling filters are operated at low hydraulic and organic loading rates, around $1-3.5 \text{ m}^3/\text{m}^2.\text{d}$ and $0.08-0.24 \text{ kg}/\text{m}^3.\text{d}$, respectively (Harnett, 2007; Satoh et al., 2000). However, to achieved TN removal both anoxic-

aerobic conditions must be present for denitrification and nitrification processes to occur. Partially denitrified effluents (50-67% N removal) can be achieved in trickling filters under certain conditions (recycle ratio 1-2, COD:N ratio around 4-10), where thick enough biofilms (> 0.3 mm, van Rijn et al., 2006) can be developed (Biesterfeld et al., 2003; Bratby et al., 2006; Vanhooren et al., 2003). However this combined system is difficult to control (Hughes et al., 2006; Pearce, 2004) and as a consequence is not widely used in full-scale sites.

Special interest has been placed into the potential of submerged aerated filters (SAF) to complete total nitrogen removal because they very compact processes, easy to build and install as package plants and therefore ideal to retrofit exist trickling filter WWTPs (Ferraz et al., 2014; Jácome et al., 2014; Osorio and Hontoria, 2002). SAFs combine a fixed biofilm (attached to a supporting media) with suspended biomass for bio-treatment (Yin et al., 2015; Lin et al., 2015). The support media is made of plastic (either random or structured) with a high void structure and large contact area that reduces the head loss and hydraulic resistance, influent wastewater and air distribution problems, and potential clogging. Submerged aerated filters have only recently operated in an anoxic mode to perform denitrification. Therefore, the optimum operating conditions are still not thoroughly described, and there is no information available on full-scale operation for denitrification SAF. Hence, this study aims to fill in this gap in knowledge and assess the main operating parameters, such as recirculation ratio, the carbon to nitrate ratio, hydraulic retention time and influence of temperature with a view to optimising the pre-denitrification submerged anoxic filter (SA_{no}F) and hence offer the option to retrofit trickling filter sites to achieve total nitrogen removal.

Materials and methods

Full-scale wastewater treatment plant (WWTP)

This study was based on the investigation of a full-scale WWTP in southern England treating wastewater from a combined catchment with a capacity of around 5500 population equivalent. The incoming wastewater was characterized by a 7-day hourly composite sampling, resulting in the average influent characteristics presented in Table 1.

Table 1 - Characteristics of the influent wastewater collected from the full scale WWTP. The results show the data collected over a 7-day hourly composite sampling campaign.

The WWTP plant consisted of hand raked (38 mm) inlet screens (duty/standby), 4 pyramidal primary settlement tanks, with copa-sacs on the outlet, followed by 4 circular mineral media trickling filters (2 filters have blast furnace slag media and 2 filters have clinker media; total volume of 1526 m³ and specific surface area about 100 m²/m³), 2 parallel nitrifying/denitrifying submerged aerated filter (SAF) units (2 units of 48 m³ volume each, and plastic media with specific surface area of 210 m²/m³; 5 cells, first 3 anoxic and last 2 aerobic) downstream of an intermediate pumping station and 2 circular humus tanks. The humus tanks effluent discharged to two separate effluent chambers prior to discharge via 4 lagoons to a soak away (Figure 1).

Figure 1 - Process diagram of the WWTP: DC: distribution chamber; PST: primary settling tank; CS: copa sacs; SC: siphon chamber, SAF: surface aerated filter; TF: trickling filter, HT: humus tank; ST: sludge tank, Si: Sampling point number *i*, Fi: Flow measurement point number *i*.

Design, installation and operation of the SA_{no}F

The SA_{no}F was installed downstream of the primary settling tanks in order to provide additional denitrification. The SA_{no}F was 36 m³ and it was divided in 4 identical cells of 9 m³ each, containing coarse plastic media with a surface area of 150 m²/m³ (PVC structured corrugated plastic media Munters BIOdek® media, GEA 2H Water Technologies Ltd, Northampton, UK). The volume occupied by the media was 31.5 m³, providing a total area for biofilm growth of 4725 m². The main operational process variables on the full-scale SAF were the recycle stream, which was controlled in terms of flow, nitrate concentration and carbon to nitrogen ratio (C/N) in the inlet. The recycle flow was estimated based on an hourly flow patten, generated from telemetry data and composite survey respectively.

A variable portion of the settled wastewater was diverted to SA_{no}F (fixed flow 10 L/s and 18L/s) in order to perform pre-denitrification with no addition of external carbon source. The recirculation ratio (settled wastewater vs. effluent from trickling filters) varied between 0.18-0.82 by changing the flows of settled wastewater and effluent from trickling filters. The SA_{no}F was operated in an intermittent aeration to scour the biofilm from the carrier plastic media. Fifteen fine bubble membrane diffusers were fitted on a stainless steel ring located beneath the media. The aeration cycle was 5 minutes per cell 3 times a week.

The SA_{no}F had a start-up period of 3 weeks required for the denitrification biofilm growth and reach stable operation. Stable operation was assumed when the nitrate removal reached a stable 75%. Ammonia and nitrate concentrations in the influent and effluent of the SAF were based on spot and composite sample data collected during the study period.

Sampling and analytical procedures

Spot samples were taken three times a week from the following sampling points: influent primary settling tank, effluent of primary settling tank to SA_{no}F, effluent of SA_{no}F, effluent of trickling filter/recycle/influent of tertiary SAF, effluent of SAFs and final effluent. A wall was built in the siphon chamber in order to isolate the denitrified stream from the settled primary settling tank effluent. Inner cells of the SA_{no}F were sampled once a week in order to evaluate the evolution of nitrate concentration within the filter.

The main parameters driving the nitrification/denitrification process were analysed, i.e. chemical oxygen demand (COD), biochemical oxygen demand (BOD) nitrate (NO₃), ammonia (NH₄), alkalinity and dissolved oxygen (DO). The spot samples (COD, ammonia, nitrate and alkalinity) were analysed onsite by a Palintest® 7500 Photometer, following the provider's specified instructions. BOD was analysed according to Standard Methods (APHA, 2005). DO was analysed by an instant measurement device: HQ30D.99.305000 (Hach Lange LTD) portable "flexi" meter. Telemetry data was collected for total flow, recycle flow (RF) and flow from works (FFW) as well as temperature and nitrate (NITRATAX plus sc Sensor, 2 mm path length, Hach Lange, Düsseldorf, Germany) and ammonia (Envitech NH₃-Sys, PBS1, Cardiff, UK) concentrations in the effluent.

Results and discussion

3.1 Full-scale WWTP performance previous to the denitrifying SA_{no}F installation

Historical data analysis demonstrated that the WWTP influent was highly loaded with both organic matter and ammonia with concentrations of 326 mg BOD/L (183 kg/day) and 59 mg NH₄/L (33 kg/day), respectively (Figure 2)

Nitrification was observed to be mainly completed in the trickling filters and in the tertiary SAF, with the average effluent ammonia reaching 2 mg/L. The trickling filters were operated with a BOD loading of 0.09 kg/m³.d which was appropriate for nitrification to take place, according to existing literature (<0.12 kg BOD/m³.d to fully nitrify (Pearce, 2004). Ammonia loading to the trickling filters was 0.15 g/m².d (average), also within the limits mentioned in the literature (0.2-1.0 g NH₄/m².d, Daigger and Boltz, 2011). However, the ratio of organic matter to ammonia (C:NH₄) was 9.6, which was above the recommended value of 4 (Harnett, 2007). This fact would give preference to heterotroph growth over the nitrifying bacteria and is possibly the reason why the trickling filter effluent ammonia concentration was in average 6 mg NH₄/L, which is above average values < 3 mg NH₄/L typically achieved in standard fully nitrifying sites (Pearce, 2004). Moreover, the hydraulic loading was less than 1 m³/m².d, which is the lowest limit mentioned by (Harnett, 2007). This could limit the oxygen transfer to the biofilm. The tertiary SAF was also nitrifying reducing the ammonia concentration to 2 mg NH₄/L. SAFs are often used as a tertiary nitrification process, nitrification can be reached at low surface organic loadings, smaller than 4 g BOD/m².d, with corresponding removal rates of around 0.4-1.45 g N-NH₄⁺/m².day achieving 70-90% ammonia removal (Hodkinson, 1997; Schulz and Menningmann, 2008).

Figure 2 - Overall wastewater treatment plant mass balance before denitrification SA_{no}F installation, with key design and operational parameters for the primary settling tanks (PST), trickling filters (TF) submerged aerated filter (SAF) and humus tank (HT) (RF - recycle flow; C:NH₄ - carbon to ammonia ratio; C:NO₃ - carbon to nitrate ratio; SA - surface area; V - volume; HRT -hydraulic retention time; HL - hydraulic loading).

Poor denitrification was observed in the WWTP with the trickling filters removing 20% of the nitrate and 5% in the tertiary SAF, as consequence the average concentration of nitrate in the effluent was 34 mg NO₃/L. Although the tertiary SAF was operated with 3 cells in an anoxic mode to compliment the lack of denitrification in the trickling filters, the carbon availability was only 20 mg BOD/L and the carbon to nitrate ratio (BOD:NO₃⁻) was 0.5, which was far below the recommended ratio of 6.45 (Bratby et al., 2003). Therefore, the denitrifiers did not have optimum conditions to develop in this unit either. Overall the mass balance demonstrated that 43 kg TN/d were being removed in the trickling filters and additional 4 kg TN/d in the tertiary SAF but this TN removal was not enough to ensure site compliance and therefore a denitrifying anoxic SAF (SA_{no}F) was installed after the primary settling tanks.

Optimization of the pre-denitrifying SA_{no}F

An SA_{no}F was installed down-stream the primary settling tank and number of operational variables were investigated in order to optimize its performance with the main goal of achieving total nitrogen removal on site. The variables investigated included loading rates, recycling rates, retention time and influence of temperature.

SA_{no}F loading and recycling ratio

The percentage of influent flow recycled to the SA_{no}F varied from 0.18 to 0.82 allowing the investigation of the optimum loading rate and recycle ratios. The flow to

the SA_{no}F was 10 L/s to start and increased to 18 L/s to find out the maximum loading to which the unit could be fed. Although only two fixed flows were utilized, some clogging issues on the flow control valve made the flow differ from the set values allowing the evaluation of the SA_{no}F at intermediate flows.

Figure 3 demonstrates the variability of the concentrations of nitrate and COD according the recycle ratio into the pre-denitrification SA_{no}F. The nitrate concentration in the feed was observed to vary between 2-18 mg NO₃/L (with an average of 7.7 mg NO₃/L; loading of 0.07 to 0.63 kg NO₃/m³.d) and the concentration of COD between 140-440 mg COD/L (average of 315 mg COD/L) with loads between 2.4-5.9 kg COD/m³.d. These values are in agreement with literature that recommends nitrate-loading rates of 0.6-1.2 kg NO₃/m³.d (Pujol and Tarallo, 2000) and 1.9 kg NO₃/m³.d (Dee et al., 1994).

Figure 3 - Correlation between the recycle ratio and the influent concentrations of COD (white squares and dashed line) and nitrate (black dots and black line) on the SA_{no}F.

As expected, a proportional correlation was found between the recycle ratio and the nitrate concentration in the inlet of the SA_{no}F and the inverse for the COD concentration (Figure 3). The correlation was limited due to the natural variability of the concentration pollutants in the wastewater but also because the recycle was pumped to the head of the works rather than directly to the SA_{no}F making the COD and the nitrated concentrations variables not completely independent from each other. Nevertheless it was possible to show a relationship between the recycle ratio and the COD:NO₃⁻ ratios, i.e., a recycle ratio between 0.18-0.4 resulted in a COD:NO₃⁻ ratio of 68 ± 21 ; a recycle ratio between 0.4-0.7 resulted in a COD:NO₃⁻ ratio of 39 ± 11 and finally a recycle ratio between 0.7-0.82 resulted in a COD:NO₃⁻ ratio of 26 ± 8 .

These COD:NO₃ ratios were significantly above the other values found in literature, others have recommended COD:NO₃⁻ ratio of domestic wastewater between 9-12 (Soares et al., 2010) and 6-11, (Henze et al., 1994). This emphasizes the benefits of pre-denitrification since the wastewater (even after primary sedimentation) contains enough carbon to sustain the process.

A correlation was also found between the nitrate inlet loading and the load of nitrate removed in the SA_{no}F (Figure 4). The nitrate load removed in the SA_{no}F was proportional to the inlet loading until a loading of 0.5 kg NO₃/m³.d reaching an average removal of 80%. When the nitrate load increased above 0.5 kg NO₃/m³.d the removal efficiency decreased to 70% and the effluent concentration was 2.5-4 mg NO₃/L.

Figure 4 - Correlation between nitrate load removed the inlet nitrate load in the SA_{no}F. The nitrate load removed was calculated by subtracting the inlet nitrate load (kg/m³.day) and the effluent nitrate (kg/m³.day).

Exhaustive sampling of the nitrate concentrations within each cell of the anoxic SA_{no}F was also completed to observe the impact of loading rates and each individual cell (Figure 5).

Figure 5 - Overall trend of the nitrate concentration across the SA_{no}F 4 cells for different nitrate loading rates.

At low loadings between 0.16-0.24 kg NO₃/m³.d it was clearly observed that the concentrations of nitrate reaching cells 3 and 4 were below 2 mg/L indicating that extra capacity for treatment was available and hence the SA_{no}F was under loaded. Good performance was obtained at loading rates between 0.45-0.49 kg NO₃/m³.d, but under loading of cell 4 could still be observed with only 2-3 mg NO₃/L reaching the 4th cell. Loadings above 0.5 kg NO₃/m³.d there was a complete utilization of the

media, showing considerable removal in every cell of the anoxic SAF. The maximum loading rate could not be determined in this study but others investigating pre-denitrification submerged filters recommend nitrate loading rates between 0.6-1.2 kg NO₃/m³.d (Pujol and Tarallo, 2000) 1.9 kg NO₃/m³.d (Dee et al., 1994) for feed wastewater with COD < 450 mg/L, similar to the study here presented. Others studies present significantly higher nitrate loading rates for higher strength wastewaters, between 4.3-5.7 kg NO₃/m³.d for high C:N ratio of 10, i.e., with an average influent BOD of 414 mg/L (Nikolavcic et al., 2000) and critical nitrate loading rates of 9 kg NO₃/m³.d for C:N ratios between 3-3.9 using methanol dosing (Oh et al., 2001).

Influence of hydraulic retention time

In order to examine the influence of hydraulic retention time (HRT) on the SA_{no}F operation, the unit was operated between 30 and 120 minutes, given by a fixed volume of 36 m³ and variable inlet flows (Figure 6).

Figure 6 - Correlation between the nitrate removal in the anoxic SAF and the hydraulic retention time.

An analysis of the filter performance data over that range showed that the nitrate removal decreased to 70% removal when retention times were below 60 minutes. Since the lowest retention time data (around 30 minutes) corresponded to the highest nitrate loadings into the anoxic SA_{no}F, it was difficult to establish a minimum admissible retention time. There is limited information available in literature on the influence of HRT on denitrification efficiency on submerged filters, but HRT below 60 min have been demonstrated for nitrate loading rates between 0.6-1.2 kg NO₃/m³.d

(HRT of 40-60 min) (Pujol and Tarallo, 2000), 1.9 kg NO₃/m³.d (HRT of 15-60) (Dee et al., 1994), comparable to the study here presented.

Alkalinity production on the anoxic SAF

Alkalinity was also measured in the influent and effluent of the anoxic SAF. In average, the alkalinity on the anoxic SAF influent was 531 mg CaCO₃/L and 573 mg CaCO₃/L on the effluent, resulting on an average production of 42 mg CaCO₃/L. It is well document the production of alkalinity during the denitrification process with theoretical values reaching 4.36 mg HCO₃/mg of NO₃ reduced (Tchobanoglous et al., 2003). In the case of the anoxic SA_{no}F here described the production of alkalinity was 4.2 mg HCO₃/mg of NO₃ reduced (or 7.1 mg CaCO₃/mg of NO₃ reduced), and therefore in the same range of theoretical values.

On the other hand, a substantial decrease alkalinity, from 576 to 240 mg CaCO₃/L, occurred in the trickling filters; approximately 11 mg CaCO₃ were consumed per mg of NH₄ removed (or 6.7 mg HCO₃/NH₄ removed). Nitrification is known to consume alkalinity, about 7.1 mg HCO₃/mg NH₄ removed (Tchobanoglous et al., 2003) and in sites low alkalinity levels, nitrification can be stopped and dosing of chemicals is required (Tchobanoglous et al., 2003). Hence alkalinity production is a major benefit of pre-denitrification in the anoxic SA_{no}F to support subsequent nitrification.

Media scouring through aeration and impact of temperature

The anoxic SA_{no}F was operated in an intermittent scour regime, with 5 minutes of scouring per cell every 2 days and no clogging problems were observed during the operation. The DO was in average 0.2 mg/L in the SA_{no}F during normal operation but this value increased to 1.8 mg/L during aeration for intermittent scouring. A slight

decrease in denitrification rate was observed during this period (from 80% to 60%) but due to the limited aeration period, no significant impact was on the SAAnoF is expected.

Wastewater temperature was approximately constant during the trial at 18-22°C. However, a SAF with three pre-denitrification anoxic cells (total volume 36 m³) that has been in operation in a nearby site showed a correlation between denitrification in SAF and temperature (Figure 7). Although the nitrate removal was significantly lower (effluent nitrate concentrations between 10-18 mg NO₃/L) than in the studied SAAnoF, temperature seemed to affect denitrification. It was estimated that nitrate concentration increased 1 mg/L per 5°C decrease of temperature (calculated in the range of 5-20°C for the mentioned site). Other have already reported the impact of temperature on denitrification having found that maximum growth rate (μ_{\max}) of denitrifying organisms decreased $\mu_{\max}=1$ 1/day at 19°C to $\mu_{\max}=0.5$ 1/day at 13°C using methanol as external carbon and from $\mu_{\max}=3.7$ 1/day at 19°C to $\mu_{\max}=1.2$ 1/day using acetate as carbon source (Mokhayeri et al., 2006).

Figure 7 - Influence of temperature on the nitrate concentration on the effluent of a nearby SAF. The SAF contained randomly packed media, with a total number of 12 cells (3 anoxic and 9 aerobic - total anoxic volume of 36 m³ and aerobic volume of 128 m³) and treated domestic wastewater from a 844 population equivalent similar in composition to the SAAnoF.

Overall site performance with the SAAnoF

The overall mass balance for the entire WWTP after SAAnoF installation demonstrated that the TN in effluent was 20-25 mg TN/L, and hence the 35 mg TN/L compliance limit could be achieved (Environment Agency, 1991). While effluent ammonia concentration was lower than 1 mg/L, the effluent nitrate concentration stabilised at

17 mg/L. Figure 8 shows that the most effective unit for nitrate removal was the anoxic SAF (82%), followed by the primary settling tanks (55%). In fact, the DO measurements carried out during the implementation period indicated that the primary settling tanks were septic with DO readings measuring between 0.6-1.4 mg O₂/L. Low DO together with the considerable algae growth that was observed, could be the reasons why nitrate was consumed within the primary settling tanks. However, the physical, chemical and biological mechanisms relating to this unit are not fully understood and further research would require to be undertaken in order to evaluate denitrification within this environment.

Figure 1 - Comparison of total nitrogen, nitrate and ammonia removal percentages in each unit in the full-scale WWTP, including primary settling tanks (PST), pre-denitrification submerged anoxic filter (anoxic SAF) trickling filters (TF) tertiary submerged aerated filter (SAF) and humus tank (HT).

In terms of ammonia, the nitrification efficiency in the trickling filters was demonstrated with an 83% ammonia removal (Figure 8) and although the tertiary SAF had a lower efficiency, 59% (Figure 8) effluent ammonia concentration was maintained below the consent of 5 mg/L. Furthermore the BOD and COD at the inlet of the TF decreased to 111 mg BOD/L and 277 mg COD/L, which represented a reduction of 30% on the carbon load reaching the TF after the wastewater was treated in the SAAnF, showing another benefit of the pre-denitrification process.

Conclusions

1. A full-scale WWTP was failing the total nitrogen consent of 35 mg/L, with a rolling annual average of 38.5 mg TN/L due to low denitrification capacity in the trickling filters (TF) and tertiary submerged aerated filter.
2. To promote denitrification an anoxic SA_{no}F was installed upstream of the trickling filters and the operation optimised. Up to 80% nitrate could be removed with an optimum loading of 0.5 kg NO₃/m³.d and a retention time of 1 hour.
3. The SA_{no}F produced 7.1 mg CaCO₃/mg of NO₃ reduced in the denitrification process, while 11 mg CaCO₃ were consumed per mg of NH₄ for nitrification in the trickling filters.
4. The combination of a pre-denitrification SA_{no}F and nitrification in the trickling filters was satisfactory to achieve effluent compliance of 35 mg TN/L, as the effluent presented a 20-25 mg TN/L.
5. Although it is estimated around a 4 mg/L increase in effluent nitrate due to a decrease in temperature over the winter months, the site would still comply with the annual average consent.

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Table 1 - Characteristics of the influent wastewater collected from the full scale WWTP. The results show the data collected over a 7-day hourly composite sampling campaign.

| Parameter | Average of 7-day hourly composite sampling |
|--------------------------------------|--|
| BOD (mg/L) | 370 |
| COD (mg/L) | 870 |
| SS (mg/L) | 400 |
| Alkalinity (mg/L) | 520 |
| Ammonia (mg/L) | 57 |
| Total Kjeldahl nitrogen (TKN) (mg/L) | 66 |
| pH | 8 |
| Flow to treatment (FTT) (L/s) | 17.7 |

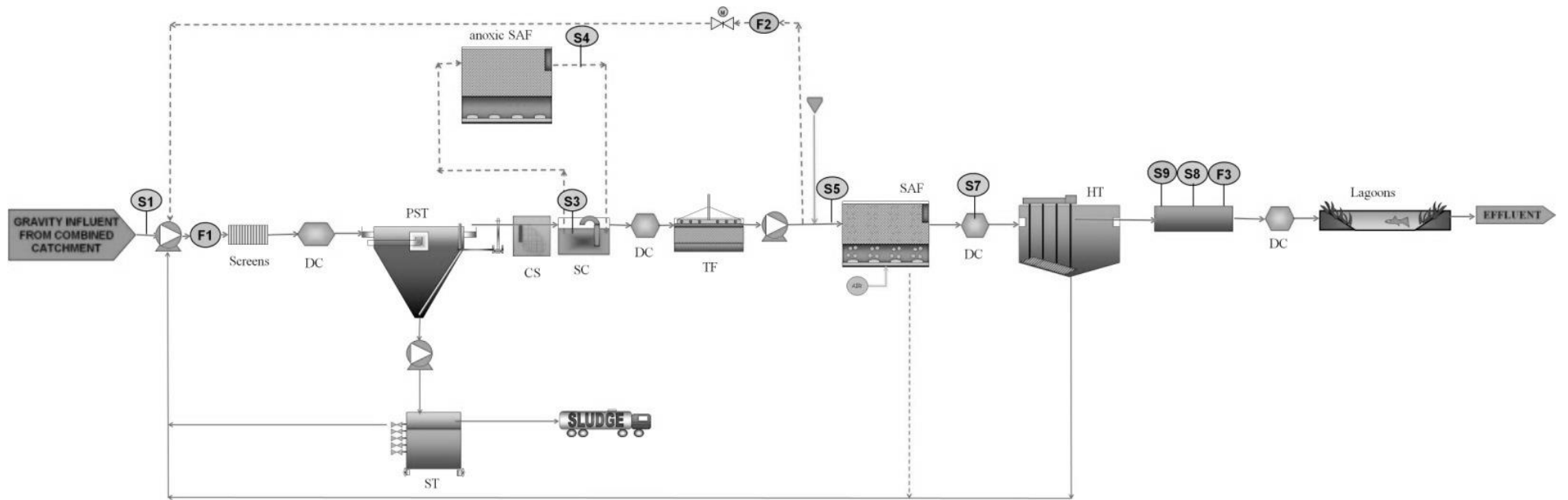


Figure 1 - Process diagram of the WWTP: DC: distribution chamber; PST: primary settling tank; CS: copa sacs; SC: siphon chamber, SAF: surface aerated filter; TF: trickling filter, HT: humus tank; ST: sludge tank, S_i : Sampling point number i , F_i : Flow measurement point number i .

| | | RF/TF (%) 37% | | | | | | | | | | | | | |
|------------|------|---------------|---|---------|------|---|-------------------|-------------------|---------|---|-------|---|------|------|----------|
| Influent | | Recycle | | 4 PST | | 4 TF | | | Recycle | | 2 SAF | | 2 HT | | Effluent |
| | mg/L | kg/d | kg/d | Removal | mg/L | kg/m ³ .d | C:NH ₄ | C:NO ₃ | mg/L | kg/m ³ .d | mg/L | | | mg/L | |
| COD | 797 | 448 | 19.8 | 25% | 393 | 0.23 | 9.6 | 98.3 | 60 | 0.35 | 46 | | | 46 | |
| BOD | 326 | 183 | 6.6 | 25% | 160 | 0.09 | 3.9 | 39.9 | 20 | 0.12 | 5 | | | 5 | |
| Ammonia | 59 | 33 | 2.0 | | 41 | 0.024 | - | - | 6 | 0.035 | 2 | | | 2 | |
| Nitrate | 0 | 0 | 13.5 | | 4 | 0.002 | - | - | 41 | 0.24 | 38 | | | 34 | |
| Flow (L/s) | 6.50 | | | 10.32 | | 10.32 | | | 3.82 | | 6.50 | | 6.50 | | |
| | | | SA (m ²) | 66.06 | | SA media (m ²) | 152600 | | | SA media (m ²) | 20160 | SA (m ²) | 62.8 | | |
| | | | V (m ³) | 184.17 | | V (m ³) | 1526 | | | V (m ³) | 96 | V (m ³) | 136 | | |
| | | | HRT (h) | 4.96 | | HL (m ³ /m ² .d) | 0.98 | | | HRT (h) | 4.1 | HRT (h) | 5.8 | | |
| | | | Upflow rate (m ³ /m ² .h) | 0.56 | | Specific SA (m ² /m ³) | 100 | | | Specific SA (m ² /m ³) | 210 | Upflow rate (m ³ /m ² .h) | 0.37 | | |

Figure 2 - Overall wastewater treatment plant mass balance before denitrification SAnoF installation, with key design and operational parameters for the primary settling tanks (PST), trickling filters (TF) submerged aerated filter (SAF) and humus tank (HT) (RF - recycle flow; C:NH₄ - carbon to ammonia ratio; C:NO₃ - carbon to nitrate ratio; SA - surface area; V - volume; HRT -hydraulic retention time; HL - hydraulic loading).

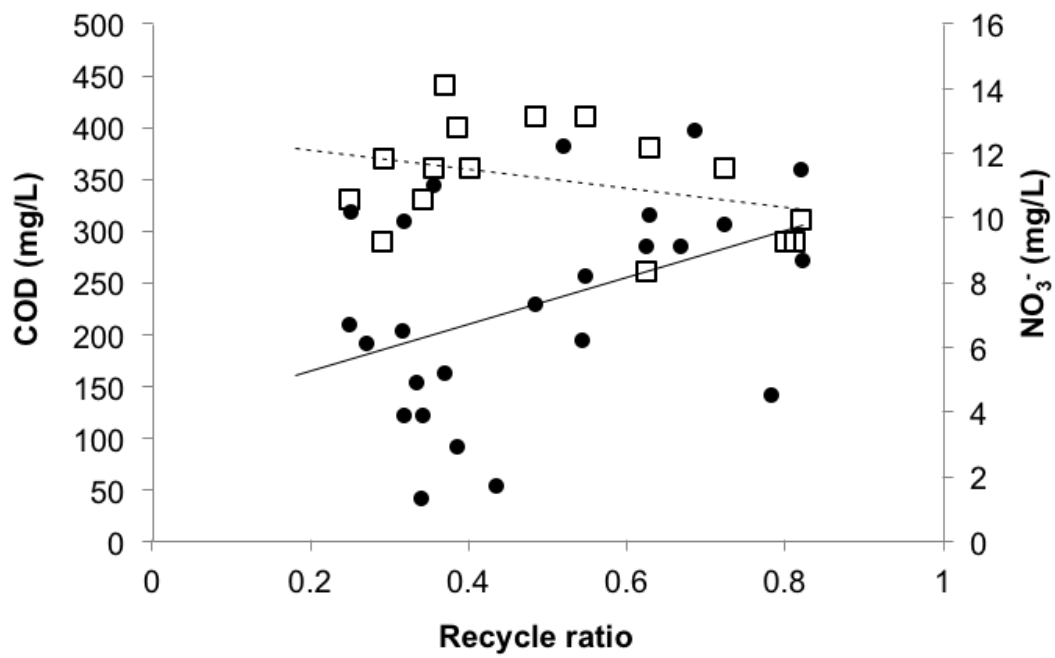


Figure 3 - Correlation between the recycle ratio and the influent concentrations of COD (white squares and dashed line) and nitrate (black dots and black line) on the SAnoF.

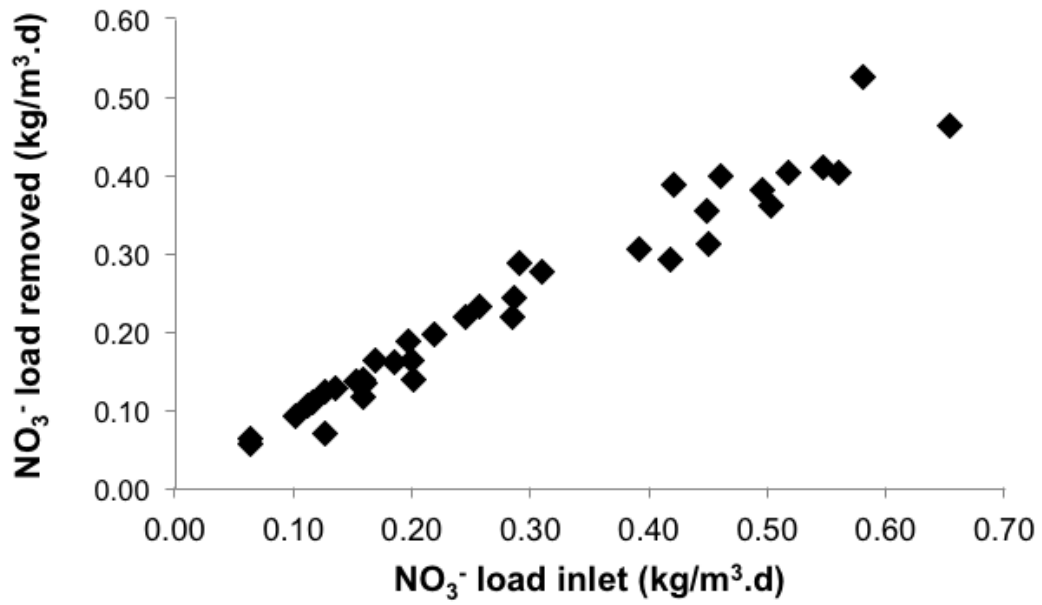


Figure 4 - Correlation between nitrate load removed the inlet nitrate load in the SAoF. The nitrate load removed was calculated by subtracting the inlet nitrate load (kg/m³.day) and the effluent nitrate (kg/m³.day).

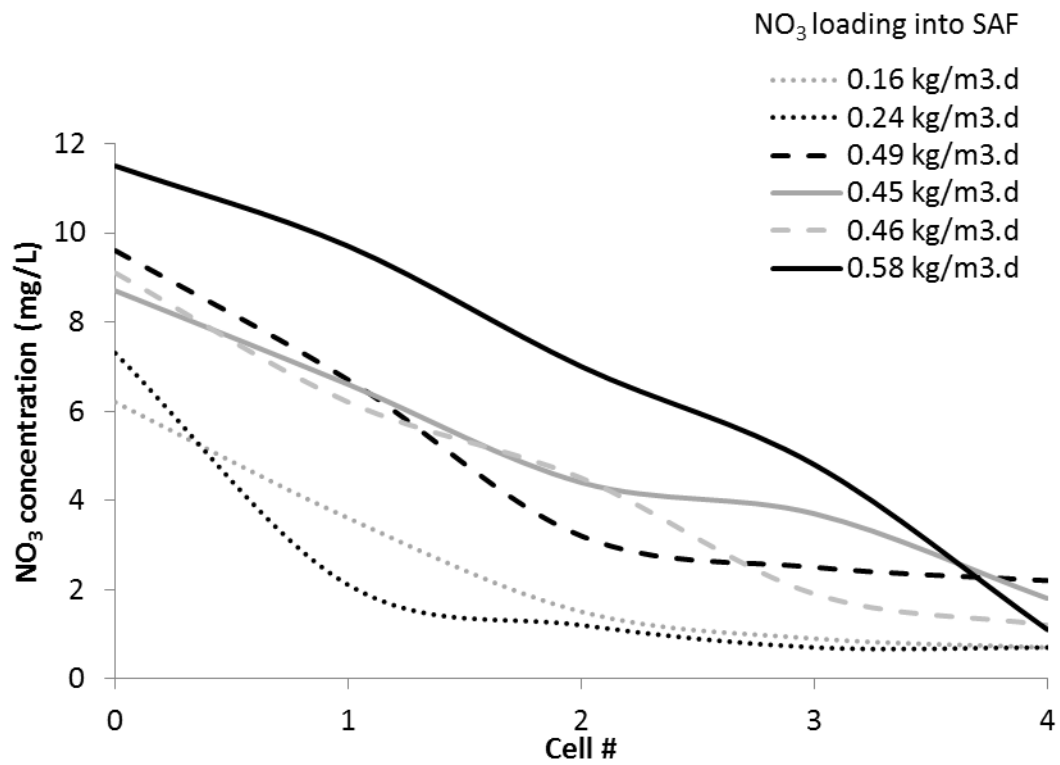


Figure 5 - Overall trend of the nitrate concentration across the SA_{no}F 4 cells for different nitrate loading rates.

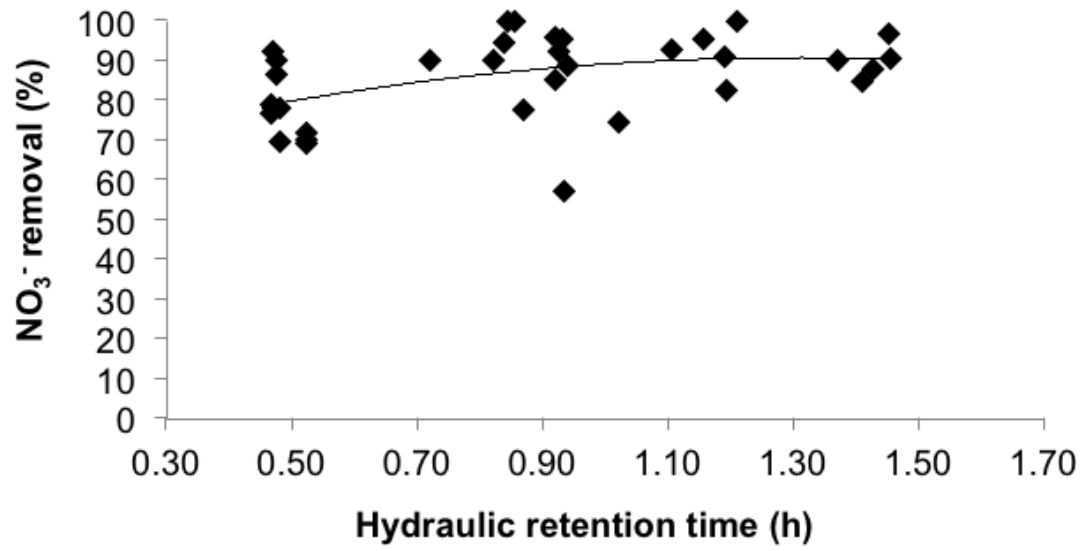


Figure 6 - Correlation between the nitrate removal in the anoxic SAF and the hydraulic retention time.

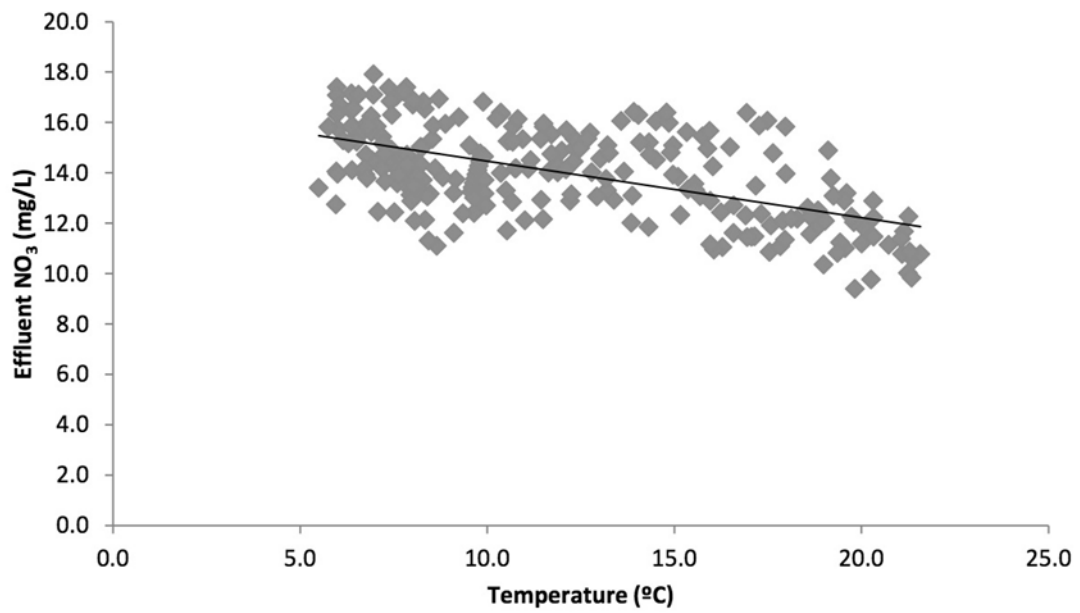


Figure 7 - Influence of temperature on the nitrate concentration on the effluent of a nearby SAF. The SAF contained randomly packed media, with a total number of 12 cells (3 anoxic and 9 aerobic - total anoxic volume of 36 m³ and aerobic volume of 128 m³) and treated domestic wastewater from a 844 population equivalent similar in composition to the SA_{no}F.

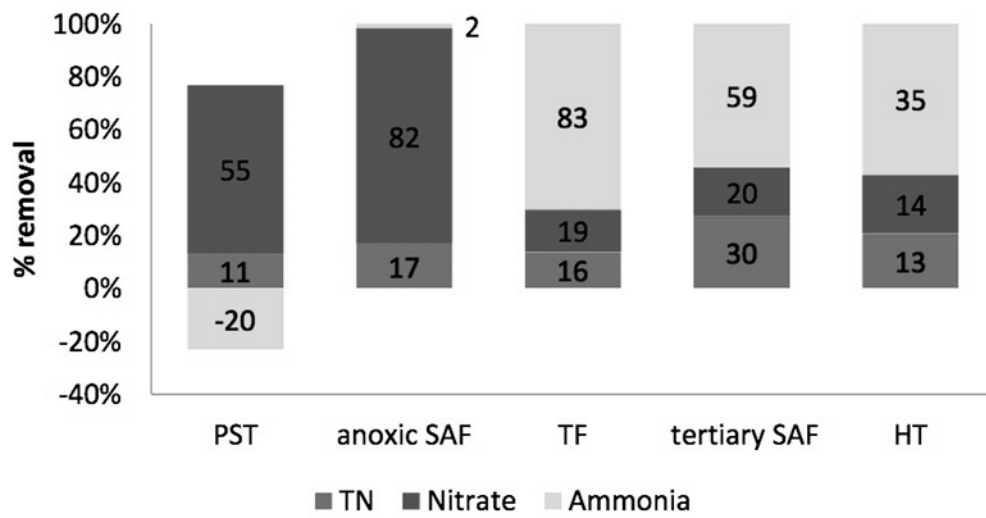


Figure 8 - Comparison of total nitrogen, nitrate and ammonia removal percentages in each unit in the full-scale WWTP, including primary settling tanks (PST), pre-denitrification submerged anoxic filter (anoxic SAF) trickling filters (TF) tertiary submerged aerated filter (SAF) and humus tank (HT).

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Optimization of a full-scale site to achieve total nitrogen removal through implementation of a denitrification-submerged anoxic filter

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Wiley

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