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Simultaneous removal of BOD, N and P in a single continuous flow real scale activated sludge reactor with cyclic aeration

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Abstract

The present study evaluates the performance of a real scale domestic wastewater treatment plant (WWTP), operating under continuous flow conditions with ‘extremely high sludge age’, designed to remove organic matter and perform nitrification-denitrification within a single reactor under cyclic aeration. Composite samples were withdrawn from the reactor for one week and their analysis results compared satisfactorily with the calculations of the design models. The WWTP is operating under stable conditions with a BOD5 removal of 86%, COD removal of 87%, TKN removal of 73% and, unexpectedly, a stable removal of 55% of total phosphorus. The design of the WWTP is simple and consists of a single aeration tank with a kinetic selector and a secondary sedimentation tank, operating under cyclic conditions in the aeration tank, with 45-minute aeration **on** (oxic environment) and 15 minutes aeration **off** (anoxic environment). The system can be applied to upgrade WWTP from secondary to tertiary treatment with only small modifications. A phosphorus removal mechanism is also proposed.

Key words: complete-mixed single-reactor, continuous flow, cyclic aeration, extremely high sludge age, nitrification-denitrification, phosphorus removal

INTRODUCTION

This article presents the evaluation of: (i) a real-scale continuous flow activated sludge plant under Extremely High Sludge Age (EHSA) conditions, which maximizes treatment efficiency and decreases net sludge production; (ii) nitrification-denitrification in a continuous flow in the same reactor with the application of cyclic aeration, producing successive oxic and anoxic environments over time, without the need to have separate zones or tanks for denitrification, and (iii) phosphorous removal in the same reactor under cyclic aeration. Although it was not anticipated, there is also a stable phosphorus removal in the reactor, probably due to denitrifying phosphorus accumulating organisms (DNPAO).

The evaluation was made on a full-scale wastewater treatment plant (WWTP). The plant is operating with the wastewater from the hotel *Movich-Las Lomas* in Rionegro, Colombia, with an average operating flow $Q = 2.5\ m^3/h$ and an inflow wastewater quality of: $BOD_5 = 430$ mg/L, COD = 925 mg/L, N-Total = 93.0 mg/L and P-Total = 7.3 mg/L. The operating conditions are such that the sludge age (θ_c) or cell retention time, TRC = $\theta c \geq 30$ d. The cycle of operation of the aerator is 45 minutes **on** (oxic) and 15 minutes **off** without mixing (anoxic).

The plant is currently operating successfully. A complete presentation of the theory of activated sludge under EHSA conditions and the nitrification-denitrification process with cyclic aeration in a single tank is presented in Orozco-Jaramillo (2014). See also Libhaber & Orozco-Jaramillo (2012), Cheng & Liu (2001) and González & Saldarriaga (2008).

The plant produces a significant P-Total removal (55%) that was not foreseen in the design. Probably, this is due to the action of Accumulating Phosphorus Denitrifying Organisms (APDNO), which can cause the absorption of phosphorus in anoxic conditions (anoxic phosphorus uptake), see Yuan & Oleszkiewicz (2009).

The WWTP was designed by the authors Orozco-Jaramillo (Process Engineering), and Vélez-Velásquez (Detail Engineering). The present evaluation was carried out with data taken during the normal operation of the plant that is carried out by the staff of the Hotel.

METHODS

Theoretical summary

In this research, the removal of organic matter measured as COD and BOD_5 in activated sludge plants with extremely high sludge ages (EHSA) is evaluated. This system improves the efficiency of organic matter removal and achieves a minimum generation of sludge.

Here, the nitrification-denitrification of wastewater is also evaluated, with cyclic aeration. The cyclic aeration allows the necessary nitrification-denitrification processes to be carried out at continuous flow in the same aeration tank in which the removal of carbonaceous organic matter occurs (Orozco-Jaramillo 2014).

This system also opens the possibility of converting secondary plants of conventional activated sludge to tertiary treatment plants, without the need to expand the reactor. This means obtaining advanced treatment in terms of increased removal in BOD and nitrogen elimination. In addition, phosphorus removal is achieved.

Extremely high sludge age (EHSA)

For a high biomass concentration applied at low substrate concentration ($X \gg S$), the Contois equation is applied. Contois (1959) and Shuler & Kargi (1992). This equation is equivalent to the following substrate removal equation proposed by Orozco (1976, 1977):

$$-\frac{dS}{Xdt} = \frac{kS/X}{k_c + S/X} \tag{1}$$

where:

X: Reactor biomass (mg VSS/L)
S: Reactor substrate (mg BOD/L)
k: Kinetic constant, maximum unit removal rate (d^{-1})
k_c: *Contoiś* Saturation constant (mgDBO/mgSSV)

This condition is the most common in aerobic treatment with high sludge ages and in anaerobic treatment. For a complete study of this equation see Orozco-Jaramillo (2014).

The production of biomass or bacterial growth is widely interpreted as follows:

$$\frac{dX}{Xdt} = Y\frac{dS}{Xdt} - k_e \tag{2}$$

where:

dX/Xdt: Net biomass growth rate (d^{-1})
Y: Stoichiometric yield coefficient (mgSSV/mgDBO)

k_e: Endogenous coefficient (d^{-1}).

The cell retention time or sludge age (θ_c) of the bacteria in the reactor is defined as:

$$\theta_c = \frac{X}{dX/dt} \tag{3}$$

From Equations (2) and (3) it is received that for a completely mixed reactor,

$$\frac{1}{\theta_c} = Y\frac{dS}{Xdt} - k_e \tag{4}$$

Common values for domestic wastewater of the constants k, k_c, Y and k_e are presented in Table 1.

Table 1 | Kinetics and stoichiometric constants

Constant	Units	Aerobic	Anaerobic
k	mgDBO/mgSSV.d	5.0	2.5
k_c	mgDBO/mgSSV	0.02	0.04
Y	mgSSV/mg/DBO	0.5	0.08
k_e	d^{-1}	0.05	0.03
T	°C	20	25
θ		1.04	1.04

Source: Orozco-Jaramillo (2014), Metcalf & Eddy (2003), Pavlostathis & Giraldo-Gómez (1991).

The kinetic constants k and k_e must be corrected for temperature according to the equation:

$$k(T) = k(T_0)\theta^{(T_0 - T)} \tag{5}$$

$T_0 = 20$ °C for aerobic treatment. Now, if t_d is the detention time, for a completely mixed reactor the following equivalence can be made:

$$-\frac{dS}{dt} = \frac{S_0 - S}{t_d} \tag{6}$$

Combining Equation (6) into Equation (4) gives X (biomass concentration) as follows:

$$X = \frac{\theta_c Y(S_0 - S)}{t_d(1 + k_e\theta_c)} = \frac{Y(S_0 - S)}{t_d\left(k_e + \frac{1}{\theta_c}\right)} \tag{7}$$

The non-biodegradable fraction of the MLSS, (XT-X), or fixed suspended solids (XF), is calculated using the following equation:

$$X_F = 0.05k_c\theta_c X + X_{ii}\theta_c/t_d \tag{8}$$

where X_{ii}: Influent FSS, and supposing 0.05 g FSS/g VSS. Then $X_T = X_F + X$.

Likewise, if in Equation (4) we replace Equation (1), we received that:

$$\frac{S}{X}=\frac{K_c(1+k_e\theta_c)}{\theta_c(Yk-k_e)-1}=\frac{K_c\left(k_e+\dfrac{1}{\theta_c}\right)}{Yk-\left(k_e+\dfrac{1}{\theta_c}\right)} \tag{9}$$

Now, placing Equation (7) into Equation (9), the equation for the effluent substrate is obtained:

$$S=\frac{S_0}{1+\left[\dfrac{kY-\left(\dfrac{1}{\theta_c}+k_e\right)}{K_cY}\right]t_d} \tag{10}$$

If θ_c tends to infinity, or $(1/\theta_c)\to 0$, it is said that there is extremely high sludge age (EHSA) and implies that, for a given S_0, S depends solely on t_d, according to Equation (10). In these conditions X also depends on t_d, according to Equation (7), which has as a direct consequence that the smaller t_d the greater X.

Another conclusion of great importance under EHSA conditions is that, theoretically, biomass production is zero. In effect, as $(1/\theta_c)\to 0$, then we obtain,

$$\frac{dX}{Xdt}=\frac{1}{\theta_c}=0 \tag{11}$$

This is because the biomass produced, $\boldsymbol{Y}(dS/dt)$, is equal to that consumed in the endogenous phase, k_eX.

In summary, under theoretic EHSA conditions, for a given t_d:

- Efficiency of substrate is the maximum possible.
- Sludge production is virtually non-existent.
- The concentration of biomass in the reactor is at maximum. This fact means that special care must be taken in the design of the secondary settler or the solids separation process.

Cyclic aeration for nitrification-denitrification

Nitrification occurs when the aeration demand considers the amount of DBON present in the wastewater, there is a sufficiently high sludge age, and environmental conditions are favorable for development of nitrifying bacteria – Nitrosomonas and Nitrobacter – in the MLSS, see Orozco-Jaramillo (2014).

Nitrification is a process that consumes oxygen and therefore energy, so from the point of view of energy it is convenient to do denitrification, in order to recover much of the oxygen used in nitrification, and at the same time eliminate from the effluent a nutrient (nitrogen) which may cause eutrophication of effluent receiving water bodies. Nitrification requires 4.57 $gO_2/gNTK$ (Total Kjeldhal nitrogen).

For denitrification, the design uses raw or nitrified wastewater as a source of organic matter and the reactor is subjected to anoxic conditions.

If the equivalent O_2 to the nitrites and nitrates used as electron acceptors is calculated, it is found that 2.86 gO_2/gNO_3-N and 1.71 gO_2/NO_2-N are saved, which makes it very convenient to carry out the reduction of BOD and nitrification-denitrification in the same reactor tank, because this brings considerable saving in the required amount of O_2. This is achieved very well in carousel channel reactors when leaving an anoxic zone for denitrification, or with alternate periods of nitrification-denitrification in the same tank (a very common design is sequential batch reactors, SBRs). However, the common practice is to build a denitrification reactor in addition to the aeration tank.

The method of cyclic aeration, already mentioned in the book 'Biological Nutrient Removal Operation in Wastewater Treatment Plants' (2006), has been used only sporadically at real scale; see Saunders (2018). This system allows the simultaneous occurrence of the processes of BOD removal, nitrification and denitrification in a continuous flow single tank reactor. When the aerators are turned **off** in the biological reactor, the denitrification phase begins and the inflow to the reactor continues to introduce the organic matter of the WW necessary for the process, so it behaves as pre-denitrification (and is more efficient). Now, under the EHSA conditions, we have a very good solution from the point of view of economy and efficiency.

Denitrification is usually designed with an engineering method that allows the calculation of the Denitrification Potential (NO_r) based on the Specific Denitrification Rate (SDNR, in g $N\text{-}NO_3$/g SSVLM). For cyclic aeration, the following equation is applied (see Metcalf & Eddy 2003):

$$SNDR = \frac{K_D A_n}{(Y_{obs}\theta_c)} = 0.175\left(\frac{dO_2}{dt}\right) \tag{12}$$

with $K_D = 0.175 = 0.5$ (1/(2.86 gO_2/g $N\text{-}NO_3$), it means that only 50% of X can use nitrates as an electron acceptor, if this percentage changes, the value of K_D changes. See Equation (14) to observe how the NO_r depends on the heterotrophic mass, X.

A_n: net oxygen utilization coefficient, g O_2/g DBO_u.
$Y_{obs} = \mathbf{Y}/(1 + k_e\ \theta_c)$: observed yield coefficient.

The net oxygen utilization coefficient, A_n, can be calculated if $BOD_u = 1.5\ BOD_5$, with:

$$A_n = \frac{(dO_2/dt)}{(dS/dt)} = 1.5\left[1 - 1.42Y + \frac{(1.42k_e Y\theta_c)}{(1 + k_e\theta_c)}\right] \tag{13}$$

Finally, the Denitrification Potential NO_r (g $N\text{-}NO_3$ removed/d) is calculated as:

$$NO_r = \eta V(SDNR)X \tag{14}$$

where:

η: fraction of anoxic time
V: volume of the aeration tank or reactor, m^3
X: MLVSS, mg/L

The determinant variable in Equation (14) is the *SDNR*, which varies with K_D, *OD*, sludge age, *MLVSS*, etc., so it is necessary to use it carefully.

Phosphorus removal

A study by Yuan & Oleszkiewicz (2009) demonstrates the action of denitrifying phosphorus accumulating organisms (DNPAO). In their experiment it is demonstrated that the enhanced biological phosphorus removal (EBPR) is rapidly established by the application of the anaerobic/aerobic (A/O) process, and the accumulation of DNPAO is achieved by the introduction of an anoxic phase. With an extension of the anoxic period and increase in the nitrate dose, a change was observed between aerobic phosphorus accumulating organisms (PAO) and DNPAO, where an approximate fraction of 60% of the later was obtained.

On the other hand, Yuan *et al.* (2007) states that DNPAO are observed as soon as nitrate is applied instead of oxygen after the anaerobic stage, which is a vital premise for DNPAO. In the design of the secondary clarifier for high concentrations of SSLM, the calculated surface area with the solids load predominates; that is, the clarifier operates mainly as a thickener. This is how the plant was designed, as will be seen below. This creates a high concentration of sludge at the bottom of the settling basin that favor an anaerobic environment that would give the conditions for the DNPAO formation. The removal of excess sludge with DNPAO causes the removal of phosphorus.

This mechanism is proposed as a possible cause of the unexpected removal of phosphorus.

Another possibility is that the cyclic operation together with the continuous flow introducing fresh wastewater cause simultaneous anaerobic, aerobic and anoxic conditions to exist throughout the biological flocs, hence producing biological organisms within the activated sludge including phosphate accumulating organisms (PAO), nitrifiers, denitrifiers and glycogen accumulating organisms (GAOs). This eliminates the need for multiple tanks.

The Nereda® Technology utilizes this principle with production of aerobic granules in an SBR process. See Naicker *et al.* (2015).

Secondary clarification

According to Equation (7), in order to have a low t_d in EHSA conditions it is necessary to have a high concentration of X (which can reach 5,000 mg MLSS/L). This value allows for effective sedimentation if it is designed with the following parameters: (i) Surface Overflow Rate $= SOR = Q/A_s = 0.5\ \mathrm{m^3/m^2{\cdot}h}$, and (ii) Solids Load $= Q_x = (1 + R)$. $XQ/A_s' = 3.0\ \mathrm{kgMLSS/m^2{\cdot}h}$. For high concentrations of X, the A_s' calculated with Q_x dominates; that is, the settler operates mainly as a thickener. Under these conditions the effluent SS, X_e, should not exceed 30 mg/L.

RESULTS AND DISCUSSION

WWTP evaluation

The treatment plant was designed to comply with Colombian regulations for the disposing of domestic wastwater, as follows: BOD $\leq$ 90 mg/L, COD $\leq$ 180 mg/L, TSS $\leq$ 90 mg/L, G&O $\leq$ 20 mg/L and pH range from 6 to 9. The design introduced cyclic aeration to: (i) effect denitrification, (ii) save oxygen and energy, and (iii) perform metabolic selection to improve sedimentation, in addition to the designed kinetic selection. The cyclic aeration creates successive oxic-anoxic periods, which allow the mentioned objectives to be achieved. In addition, an unexpected phosphorus removal was found to occur.

The design conditions were selected for a flow greater than the current one, in anticipation of future expansions of the hotel. The plant was completed in June 2017, at which date its operation was started up and it was then delivered to the hotel staff for regular continuous operation, which has been satisfactory and stable since then. Table 2 shows the design parameters of the plant.

The research sampling was carried out during a week, to measure the removal levels of BOD, COD and nitrification-denitrification in the same tank, maintaining a continuous flow, and also P removal, with cyclic aeration.

The analyses of the composite samples during four (4) days were carried out in the Environmental Laboratory of CORANTIOQUIA, the environmental authority of the department of Antioquia-Colombia, accredited under the Norm NTC ISO/IEC 17025.

Figure 1 shows the final design of the WWTP with plan, section and elevation views of the plant.

Table 2 | Design parameters

Parameter	Value
Flow:	$5.63\ m^3/h$
Peak flow:	$8.50\ m^3/h$
Sludge age	40 d
Hydraulic detention time:	14 h
Inflow BOD_5	325 mg/L
Kinetics constants:	$Y = 0.5$, $k_e = 0.05\ d^{-1}$, $k = 5.0\ d^{-1}$, $k_c = 0.025$ mg/L
X (MLVSS)	3,703 mg/L
X_T (MLSS)	4,628 mg/L
Ratio MLVSS/MLSS:	0.8
SVI (Sludge Value Index):	100
Recycling ratio	1.0
Altitude, metres above sea level:	2,000 masl
OR (overflow rate)	$0.5\ m^3/h$
Q_s (solids load):	$3\ kg/m^2\ h$
BOD_5 effluent (SS)	30 mg/L

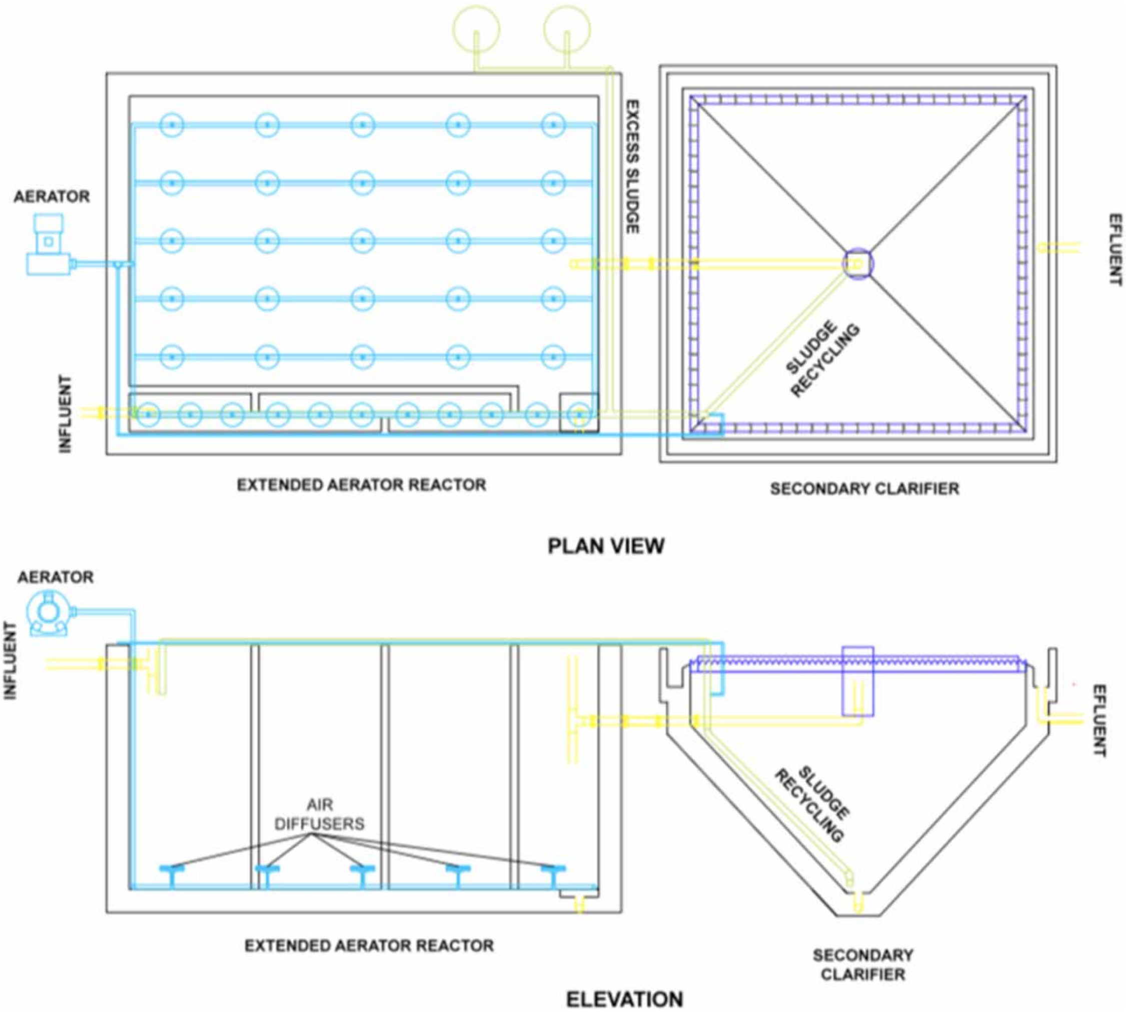

Figure 1 | Plan and elevation view of the WWTP.

Tables 3 and 4 present a summary of the daily results obtained and the average, values that will be used for the comparisons, as well as the removal efficiencies of each parameter.

Table 3 | Summary of characteristic test results

		Outflow WWTP						
Parameter	**Inflow WWTP**	**12/03/18**	**14/03/18**	**15/03/18**	**16/03/18**	**Average**	**Standard deviation**	**% Removal**
BOD_5 (mg/L)	430	64.1	48.4	74.3	45.8	**58.15**	13.46	**86%**
COD (mg/L)	925	109	98.1	144	124	**118.78**	19.89	**87%**
TSS (mg/L)	166	29	29	30	27	**28.75**	1.26	**83%**
VSS (mg/L)	164	27	27	29	26	**27.25**	1.26	**83%**
P total (mg/L)	7.3	2.76	2.96	4.94	2.39	**3.26**	1.14	**55%**
NH_3 (mg/L-N)	21.1	5	5.84	21.2	20.7	**13.19**	8.98	**38%**
NTK (mg/L-N)	87.6	29	13.8	24.2	28.2	**23.80**	6.99	**73%**
NO_2 (mg/L-N)	0.02	1.28	2.58	0.027	0.049	**0.98**	1.21	
NO_3 (mg/L-N)	<5.0	<5.0	<5.0	<5.0	<5.0	<**5.0**	0.0	

Table 4 | MLSS during characterization

	Mixed liquor				
Parameter	**12/03/18**	**14/03/18**	**15/03/18**	**16/03/18**	**Average**
MLSS, X_T	2,114	2,446	3,134	2,853	2,636.75
MLVSS, X	1,940	2,181	2,871	2,600	2,398
X/X_T					0.91
Flow Lps	0.86	0.68	0.58	0.58	0.68

Figures 2–5 show the stability of the effluent concentrations of BOD_5, COD, NTK and Total P, indicating that the WWTP is consolidated and does not present strong variations in the effluent quality.

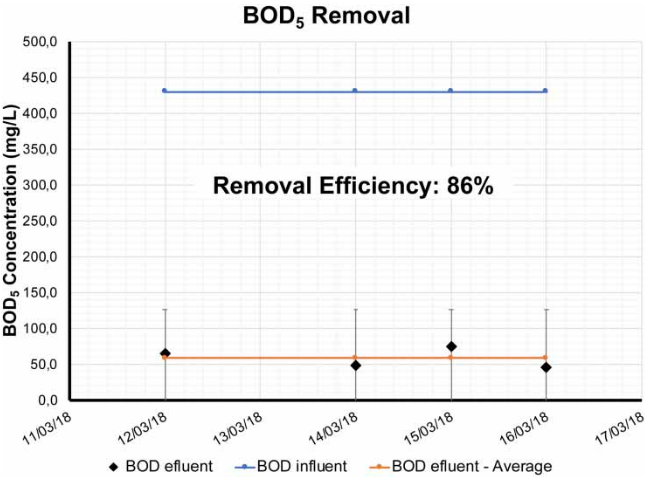

Figure 2 | Total BOD_5 removal.

Models testing

We applied the equations of the Theoretical Summary to check the proposed models.

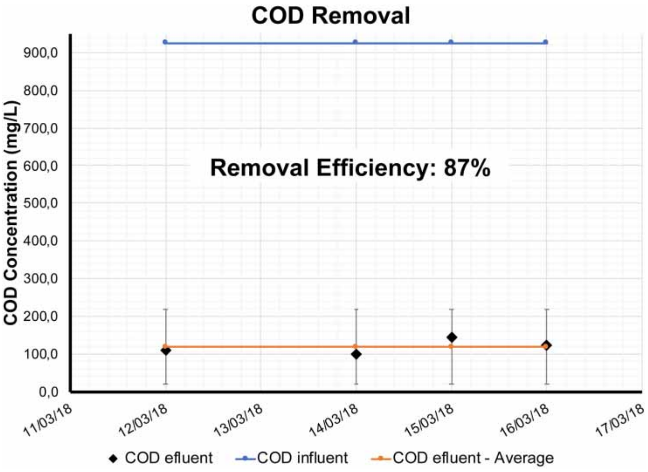

Figure 3 | Total COD removal.

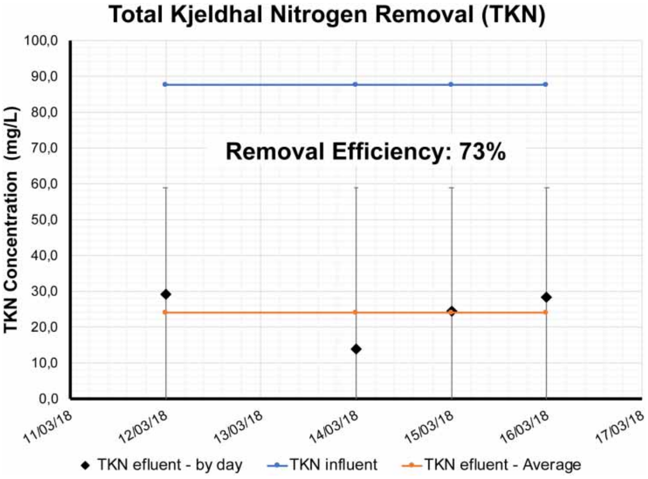

Figure 4 | Total TKN removal.

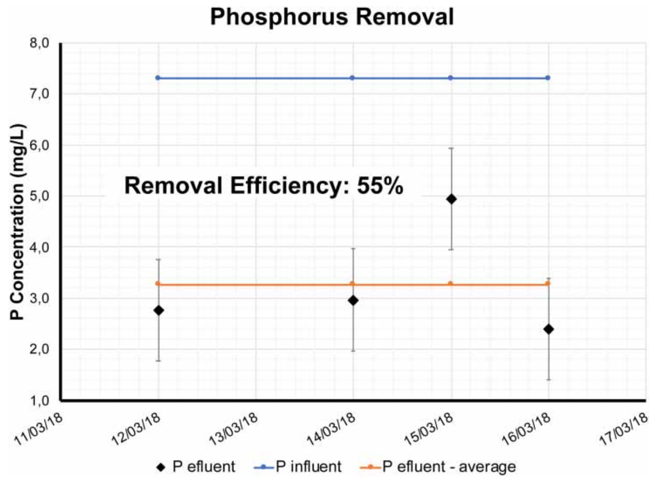

Figure 5 | Total P removal.

Organic matter removal at EHSA conditions

With Equation (10) we can calculate the effluent soluble substrate, S. Now, adding the BOD of the effluent SSV, X_e, the total effluent substrate, S_e, is:

$$S_e = S + 1.42X_e \tag{15}$$

1.42 converts solids not removed by the settler, X_e, into O_2 units. The calculation of the MLVSS was made with Equation (7), for an S (soluble) defined by Equation (10), the working θ_c and the $t_d = V/Q$ of the actual operation conditions. Recall that $X_T = X + X_F$ as calculated with Equations (7) and (8). The calculations above are presented in Table 5. It is clear from the table that for a sludge age of 32 days, $X = 2{,}385$ and $X_T = 2{,}640$ mg MLSS/L. Compared with the four-day measured averages of 2,398 mg/L and 2,637 mg/L, it is concluded that the model can predict very well the operation of the system.

Now, the BOD effluent can be calculated with Equation (15), where S_e (calculated) = 42.0 mg/L DBO_5. Compared to the actual measured average of 58.15 mg/L, a good approximation is found.

Table 5 | Comparison between measured and theoretically calculated parameter

Parameter	Theoretical model calculation	Measured average of four samples
X, mg MLVSS/L	2,385	2,398
X_T, mg MLSS/L	2,640	2,637
S_e, mg BOD_5-Total/L	42.00	58,15
Removal of N, %	83	73

Table 5 summarizes the comparison between what was predicted by the model and the measured averages of four composite samples of the characterization during the actual operation.

Nitrification-denitrification

For the final calculation of the denitrification potential, NO_r (gN-NO_3/d), nitrification-denitrification was analyzed with Equations (12) (calculation of the *SNRD*), 13 (calculation of A_n) and 14 (NO_r).

Tables 6 and 7 shows a theoretical nitrogen removal of 83%, while the real removal was 73%. The lower than calculated efficiency is a result of the fact that there is no mixing during the anoxic stage, when the aerators are turned off. Introduction of mixing should improve the efficiency of denitrification.

Table 6 | SNDR for cyclic aeration[a]

SDNR for cyclic aeration, Metcalf & Eddy, pp. 776–779, Ed 4	
Yield coefficient, Y	0.4
Observed yield coefficient, $Yobs$	0.08
Endogenous coefficient, k_e	0.12
Sludge age, θ_c	32.00
Net oxygen uptake, gO_2/gBODu: $As = 1.5{*}(1 - 1.42Y + (1.42Yke\theta_c)/(1 + ke\theta_c))$	1.32
$SNRDcic = KD{*}As/(Yobs{*}\theta c)$	0.09
SDNR constant, 0.175 = (1/2.86) *(50% denitrifiers)	0.175
Denitrifiers in MLVSS, %	0.5

[a] $Y = 0.4$ and $k_e = 0.12$, for $SNRD_{cic}$ computations.

Table 7 | Denitrification potential: actual and calculated

Potential of Denitrification (actual)		
N-KTN influent (mg/L)	KTN_{in}	87.00
N-KTN biomass (mg/L)	$NH_{4X} = 0{,}1^{*}Y_{obs}.Q(S_I\text{-}S)/Q$	0.00
N-KTN treated water(mg/L)	NH_{4e}	23.80
Nitrification potential (mg/L N-KTN)	$KTN_{rem} = KTN_{in} -$ $(NH4_X - NH_{4e})$	63.20
Efficiency (%):	$KTN_{rem}/KTN_{in} \times 100$	72.64
Daily production of nitrates, (kg/d)	Q. KTN_{rem}	3.70
Potential of denitrification (calculated with the model)		
$SDNR_{cic}$, (gN-NO_3/gSSVLM.d)	Calculated Equation (12)	0.09
NO_r, calculated potential of denitrification (kg/d)	ηV_D (SDNR*X)	4.23
N-NO_3 eliminated (mg/L)	ΔN-$NO_3 = \eta V_D$ (SDNR*X)/Q	72.34
N-NO_3 remaining (mg/L)	KTN_{rem} – ΔN-NO_3	14.66
Calculated denitrification efficiency	N-NO_{3rem}/KTN_{in}%	83.15

Phosphorus removal

As previously indicated, the removal of phosphorus was unexpected and should be taken as an additional bonus of the process. The authors endeavored to incorporate a calculation method for this process to optimize it. The typical method for calculating phosphorus removal is to estimate the absorption of P in the anaerobic and oxic environments, and then calculate the removal that takes place with excess sludge.

Since the WWTP was designed for EHSA, the excess sludge quantity is very low, but even so a removal of 55% is not to be neglected, especially if it is a process that arises spontaneously from the basic design of BOD removal and nitrification-denitrification. The discovery by Yuan & Oleszkiewicz (2009) of the DNPAO in the oxic environment explained in the Theoretical Summary presented above suggests a mechanism that explains the removal of P with this design.

CONCLUSIONS

The first finding that must be emphasized is that it is a real-scale plant, operated by personnel without experience in wastewater treatment, with very simple methods of control, mainly the sedimentation of the MLSS in an Imhoff cone, and without other interest in meeting the standards required by the environmental authority. This demonstrates the robust design of the system, which in addition to meeting contractual objectives (meeting the standard) also satisfactorily fulfilled the non-contractual goal of nitrification-denitrification (removal of nitrogen of 73%), with the additional bonus of a removal of 55% of phosphorus. It is anticipated that the same design of a WWTP operated with high technical standards would further improve the results.

From the material presented above, the following conclusions emerge:

- The WWTP with a single continuous flow reactor, operated cyclically and under EHSA conditions, fulfills significant objectives of removal of BOD, nitrogen and phosphorus, with simple operation and without sophisticated control requirements.
- The previous conclusion opens the possibility of easily converting secondary treatment plants with a single aeration tank (BOD removal), into plants of tertiary treatment (nitrification-denitrification) and advanced treatment (phosphorus removal).

- The models used for the original design of the WWTP predict with enough accuracy the results obtained in the operation at real scale.
- The efficiencies obtained for denitrification can be improved by increasing the sludge age and adding mixers to be operated in the anoxic phase.
- The obtained P removal of 55% is excellent for an operation of the plant with a $\theta c = 32$ days, since the excess sludge amount is very small. It is therefore presumed that the phosphorus removal efficiency cannot be improved much more, especially considering that the improvement of the processes of BOD removal and nitrification-denitrification require a higher sludge age.
- The variation of the oxic/anoxic cycles can fine-tune the design efficiencies, and if automatic control was added to the system, the oxidation-reduction potential (POR) could be used as a control parameter.

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