The role of food/microorganism ratio in denitrification reactors: how it affects the sizing and operation of the denitrification process

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ABSTRACT

Two calculation models of the Specific Denitrification Rate (SDNR) are analyzed to highlight the sensitivity of this parameter to the Food:Microorganisms ratio in the denitrification reactor (F:M_A Den). One of these models is empirical while the second was elaborated on a deterministic basis. Both models reveal a linear dependence of SDNR_20°C on F:M_A Den and in a first approximation they are comparable only in a narrow range of concentration of dissolved oxygen (DO) in denitrification, specifically DO=0.25-0.35 mg L^{-1}. These values frequently occur in well designed and well operated sewage treatment plants. Outside this range, the role of F:M_A Den must necessarily be examined in combination with DO because of the relevant influence of the latter on the efficiency of the denitrification process.

Keywords: activated sludge, biological process, denitrification, nitrogen removal, sewage treatment.

O papel da fração alimento/microrganismos nos reatores de desnitrificação: como afeta o dimensionamento e a operação do processo de desnitrificação

RESUMO

Dois modelos de cálculo do SDNR-Specific Denitrification Rate são analisados para destacar a sensibilidade deste parâmetro em relação à fração Alimento/Microrganismos no reator de desnitrificação (A: M_A Den). Um desses modelos é empírico, enquanto o segundo foi elaborado em uma base determinística. Ambos os modelos revelam uma dependência linear de SDNR_20°C em A:M_A Den e, em primeira aproximação, eles são comparáveis apenas dentro de uma faixa estreita de concentração de oxigênio dissolvido (OD) na desnitrificação, especificamente OD=0,25-0,35 mg L^{-1}. Esses valores ocorrem frequentemente em estações de tratamento de esgoto bem projetadas e operadas. Fora dessa faixa, o papel do A:M_A Den precisa ser examinado em combinação com o OD devido à influência relevante deste último na eficiência do processo de desnitrificação.

Palavras-chave: desnitrificação, lodo ativado, processo biológico, remoção de nitrogênio, tratamento de esgoto.
1. INTRODUCTION

Physico-Chemical and biological processes are used for the removal of nitrogen from wastewater. The former mainly consists of chlorination or stripping processes and is widely used for the treatment of industrial wastewaters with high concentrations of ammonia (Capodaglio et al., 2015; Raboni et al., 2013a; Raboni and Viotti, 2017). Alternatively, the biological processes are essentially used in the treatment of sewage, as they are significantly cheaper than physico-chemical processes (Copelli et al., 2015; Subtil et al., 2013; Torretta et al., 2014; Collivignarelli et al. 2019, Butzen et al. 2020). At present, the most widely used biological denitrification technology is biological pre-denitrification in activated sludge treatment processes. Figure 1 shows a typical scheme consisting of an anoxic denitrification reactor (DEN) placed upstream of the oxidizing-nitrifying aerobic reactor (OX-NIT), which provides for the removal of BOD₅ and the nitrification of total Kjeldhal nitrogen (TKN) (Ekama et al., 1999; Gerardi, 2002; Ucker et al., 2012; Major Barbosa et al., 2016; Capodaglio et al., 2016; Wuhrmann, 2017; Pereira Ribeiro et al., 2018; Abeysiriwardana-Arachchige et al., 2020; Pires da Silva et al., 2020).

The removal of nitrogen in the pre-denitrification stage is carried out by denitrifying heterotrophic bacteria capable of reducing nitrates to nitrogen gas through a biochemical reaction that uses the BOD₅ of the raw sewage as an electron donor. The process has been widely used in full-scale plants for many years. Nevertheless, the scientific research is very active in this field, above all to gain a better understanding of the influence exerted by various parameters on the efficiency of the process, among which is sludge loading in denitrification (F:MDEN). This parameter proved to be important in the sizing of the pre-denitrification reactor.

Currently, the sizing of the denitrification reactor is based on the parameter Specific Denitrification Rate (SDNR) defined as follows (Equation 1):

$$\text{SDNR}_T = \frac{Q \cdot N}{V \cdot MLVSS}$$ (1)

The value at the real temperature $T$ of the mixed-liquor can be calculated by the modified Arrhenius Equation 2 (Ekama et al., 2011):

$$\text{SDNR}_T = \text{SDNR}_{20^\circ C} \cdot g(T-20)$$ (2)

Where:
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SDNR$_T$ Specific Denitrification Rate at the temperature $T$ (kgNO$_3^-$-N kgMLVSS$^{-1}$ d$^{-1}$)

SDNR$_{20^\circ C}$ Specific Denitrification Rate at the temperature of 20$^\circ$C (kgNO$_3^-$-N kgMLVSS$^{-1}$ d$^{-1}$)

$Q$ $\Delta N$ Load of nitrogen removed in denitrification (kg d$^{-1}$)

MLVSS Mixed-Liquor Volatile Suspended Solids in denitrification (kg VSS m$^{-3}$)

V Volume of the denitrification reactor (m$^3$)

$T$ temperature ($^\circ$C)

(temperature coefficient: $\theta = 1.026$ (USEPA, 2009); $\theta = 1.07$ (Tchobanoglous et al., 2003).

As defined, the SDNR$_T$ is given by two contributions: the biochemical reduction of NO$_3^-$ to N$_2$ and the synthesis of new cells.

Knowing SDNR$_{20^\circ C}$, it is easy to calculate the volume using Equations (1) and (2). For the calculation of SDNR$_{20^\circ C}$ different models are proposed, which take into account the main variables capable of influencing the denitrification kinetics, which specifically are F:M$_{DEN}$ and residual oxygen concentration DO.

The present research aims to highlight the influence of F:M$_{DEN}$ in the calculation of SDNR$_{20^\circ C}$ (and consequently in the calculation of the reactor volume). The scientific literature reports various data on this influence (Raboni et al., 2013b; 2014a; 2015)

In full scale plants F:MDEN is often found in the range 0.15-0.40 kg BOD$_5$ d$^{-1}$ kgMLVSS$^{-1}$ (Raboni et al., 2017).

2. MATERIALS AND METHODS

The influence of F:M$_{DEN}$ on the sizing of the denitrification reactor can be evaluated through the analysis of the calculation models of SDNR$_{20^\circ C}$. In particular, in this research two models are considered. The first model (Model I) is very empirical and it correlates SDNR$_{20^\circ C}$ with only the variable $F:M_{DEN}$. This model was first described by Tchobanoglous et al. (2003). It was later implemented (USEPA, 2010) by introducing a correction factor $F_b$ to the $F:M_{DEN}$ (Equation 3).

$$SDNR_{20^\circ C} = 0.029 + 0.03 \cdot (F_b / 0.30) \cdot (F:M_{DEN})$$

$F_b$ takes into account the greater or lesser concentration of active biomass in the mixed-liquor, which in turn depends on the SRT-Sludge Retention Time. For more details on Fb see USEPA (2010). In biological plants with high efficiency for both oxidation-nitrification and denitrification the SRT is normally found in the range 18-20 d. With SRT=20 the factor results $F_b=0.35$.

The second model (Model II) is more advanced than the first, as it expresses the dependence of SDNR$_{20^\circ C}$ not only on F:MDEN but also on DO another variable capable of significantly influencing the efficiency of the denitrification process (Oh and Silverstein, 1999; Plosz et al., 2003; Torti et al., 2013; Urbini et al., 2015; Viotti et al., 2016). This model was elaborated through a deterministic calculation (Raboni et al., 2014b) and then it was validated by a pilot plant study (Raboni et al., 2014a) and by checking many real-scale plants (Raboni and Torretta, 2017) (Equation 4).

$$SDNR_{20^\circ C} = 0.0864 \left( \frac{K'_0}{K'_{0,D}+DO} \right) + 0.05 \cdot F:M_{DEN} \cdot \eta_{BOD} \cdot \left( \frac{DO}{0.2+DO} \right)$$

Where:

$K'_0 = 0.18$ mgO$_2$ L$^{-1}$;
3. RESULTS AND DISCUSSION

Figure 2 shows the trend of SDNR\(_{20\,^\circ\text{C}}\) as a function of the F:M\(_{\text{DEN}}\), according to the two models under study. Model II is represented at 5 different DO values. Due to the mathematical structure of the equations, all curves represented are straight lines.

\[ \eta_{\text{BOD}}: \text{removal efficiency of BOD}_5 \ (\eta_{\text{BOD}}=0.85-0.95 \text{ depending on the value assumed by F:M}_{\text{DEN}}) \]

The observation of the Figure leads to three important considerations:

a) the variable F:M\(_{\text{DEN}}\) affects the SDNR\(_{20\,^\circ\text{C}}\) in a directly proportional way, i.e., each increase determines a proportional increase in the SDNR\(_{20\,^\circ\text{C}}\). In this regard, however, it must be considered that there is a limit to this progressive growth beyond which a strong wash-out of the denitrifying bacteria can occur. As the denitrifying bacteria are heterotrophic in nature (like BOD oxidizing bacteria), the typical limit not to be exceeded is close to F:M\(_{\text{DEN}}\)=0.40 kg BOD\(_5\) d\(^{-1}\) kgMLVSS\(^{-1}\) (in plant design a slightly lower values is suggested, close to 0.3 kg BOD\(_5\) d\(^{-1}\) kgMLVSS\(^{-1}\)).

b) DO proves to be a variable of considerable importance, especially if the sizing and operation of the plant are such as to maintain dissolved oxygen concentrations appreciably lower than DO=0.3-0.4 mg L\(^{-1}\). For DO below this range, there is a progressive and more than proportional increase in SDNR\(_{20\,^\circ\text{C}}\). Several solutions are feasible to achieve this result (Viotti \textit{et al.}, 2016; Urbini \textit{et al.}, 2015)

c) the line of Model I as a first approximation is comparable only with two lines of Model II, those characterized by DO=0.3 mg L\(^{-1}\) and DO=0.4 mg L\(^{-1}\). In fact, the range DO=0.3-0.4 mg L\(^{-1}\) is frequently found on full scale plants (Raboni and Torretta, 2017).

Figure 3 shows the deviation of the SDNR\(_{20\,^\circ\text{C}}\) values of Model I from Model II. Deviation is defined as the % difference between the SDNR\(_{20\,^\circ\text{C}}\) of the models at the same value of F:M\(_{\text{DEN}}\). It can be observed that the deviation is quite limited, as it is mostly in the ±5% range.
Instead, in Figure 3, which shows the deviation of Model I from Model II (the latter at various DO values), the deviation falls within the range of 5% only in a very narrow range of DO (approximately DO=0.30-0.35 mg L⁻¹). These findings are a further confirmation of the limited field of validity of the empirical model and also how important is the influence of DO in the denitrification process, especially when the same DO values are outside the above-mentioned range.

![Figure 3](image-url)

**Figure 3.** Deviation of SDNR₂₀°C of Models I from Model II (at different DO), as a function F:M\textsubscript{DEN}.

Figure 4 shows the % fraction of SDNR₂₀°C, as a function of F:M\textsubscript{DEN}, assuming that the value relative to F:M\textsubscript{DEN}=0.3 kg BOD₅/kg MLVSS⁻¹ d⁻¹ is equal to 100%.

![Figure 4](image-url)

**Figure 4.** Fraction (%) of SDNR₂₀°C, as a function of F:M\textsubscript{DEN}, at different DO (curves are referred to Model II; SDNR₂₀°C relative to F:M\textsubscript{DEN}=0.3 is assumed equal to 100%).
It is noted the linear trend of all models. As regards to Model II, in correspondence of DO=0.3 mg L\(^{-1}\), a 6% reduction of SDNR\(_{20^\circ C}\) is observed for any reduction of F:M\(_{DEN}\)=0.1 kgBOD\(_5\)/d\(^{-1}\) kg MLVSS\(^{-1}\). A reduction less and less marked occurs at lower DO values and vice versa at higher values.

Figure 5 shows the mathematical derivative \(\frac{\partial SDNR_{20^\circ C}}{\partial F:M_{DEN}}\) relative to models I and II. In this sensitivity analysis, this derivative has a significant importance because it expresses the direct response of SDNR\(_{20^\circ C}\) to the stresses of F:M\(_{DEN}\).

As it can be seen, all derivatives are constant, due to the linear dependence of F:M\(_{DEN}\) from SDNR\(_{20^\circ C}\). However, these constants differ significantly from case to case. In particular, with reference to Model II, they tend to get close to each other as DO concentrations increase.

Figure 6 shows very well the trend of the same derivative as a function of the DO. It is an increasing logarithmic curve with an asymptotic tendency to the value \(\frac{\partial SDNR_{20^\circ C}}{\partial F:M_{DEN}} = 0.45\) kg NO\(_3^-\)N kg BOD\(_5\)^{-1}. The strong initial gradient of the curve proves the lower sensitivity of SDNR\(_{20^\circ C}\) to F:M\(_{DEN}\) at small DO concentrations, and vice versa. This graph is a further confirmation of how much also the DO variable can affect the denitrification kinetics and the consequent performance of the process.

Overall, the results of the present analysis highlight the need to keep the F:M\(_{DEN}\) as high as possible to favor the SDNR\(_{20^\circ C}\) and consequently acquire advantages in terms of reactor sizing and denitrification efficiency. However, F:M\(_{DEN}\) cannot exceed the limit beyond which the sludge retention time-SRT is too small to determine the wash-out of the denitrifying heterotrophic bacteria, with consequent losses in efficiency. This limit is approximately in the range F:M\(_{DEN}\) = 0.3-0.4 kgNO\(_3^-\)N kgMLVSS\(^{-1}\) d\(^{-1}\) where the lower value is suggested. There is full evidence that the incidence of the variable F: M\(_{DEN}\) on SDNR\(_{20^\circ C}\) should be examined in combination with the residual DO values in denitrification, which also significantly affects the efficiency of the process.
4. CONCLUSIONS

The sizing of the biological pre-denitrification reactors as well as the denitrification efficiency are closely related to SDNR-specific denitrification rate. Two mathematical models used for the calculation of SDNR$_{20^\circ C}$ indicate a growing linear dependence of this parameter on the sludge loading in denitrification (F:M$_{DEN}$). Therefore high values of F:M$_{DEN}$ favor the SDNR$_{20^\circ C}$ and consequently the sizing of the denitrification volume as well as the denitrification efficiency. However, F:M$_{DEN}$ cannot exceed the limit beyond which the sludge retention time-SRT becomes too small to determine the wash-out of the denitrifying heterotrophic bacteria, with consequent losses in efficiency. This limit is approximately in the range F:M$_{DEN}$=0.3-0.4 kgNO$_3$-N kgMLVSS$^{-1}$ d$^{-1}$ where the lower value is suggested.

Of the two models examined, one is purely empirical and the other more advanced, of a deterministic type. The empirical model expresses the SDNR$_{20^\circ C}$ as depending on the single variable F:M$_{DEN}$. Instead, the deterministic model expresses the SDNR$_{20^\circ C}$ as depending also on the dissolved oxygen in denitrification (DO).

The two models prove to be comparable only in a narrow range of DO (about DO=0.25-0.35 mg L$^{-1}$). However, values within this range are frequently found in well-designed and well-operated sewage treatment plants. Outside this range, the incidence of DO is relevant and cannot be neglected. All observations demonstrate a sensitivity of SDNR$_{20^\circ C}$ to F:M$_{DEN}$ just as smaller the DO concentrations are (DO<0.3 mg L$^{-1}$). At DO>0.3-0.4 mg L$^{-1}$ this sensitivity tends progressively to grow towards an asymptotic value. There is extensive evidence that the impact on the process of the variable F:M$_{DEN}$ should be examined in combination with the residual DO in denitrification.

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