

## Course « Water and wastewater treatment », Fall 2025

### Part II « Wastewater treatment »

#### Homework 2

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##### Homework 2-1 : « BOD due to nitrification »

Nitrification consumes oxygen and has to be taken into consideration in WWTPs where a low ammonium effluent concentration has to be achieved.

- a) Calculate the nitrogenous oxygen demand NOD for normal wastewaters (see lecture slides) by neglecting biomass production by nitrifiers and compare it to  $BOD_5$  of these wastewaters.
- b) How would this oxygen demand change if one takes into consideration biomass production by nitrifiers with ammonium as nitrogen source ?

##### Solution

- a) For wastewater,  $37.5 \text{ g}_{\text{N-NH}_4} \text{ m}^{-3}$  have to be nitrified .

According to equations, 1 mole of  $\text{NH}_4^+$  consumes 2 moles of  $\text{O}_2$ . This is equivalent to  $4.57 \text{ g}_{\text{O}_2} \text{ g}_{\text{N-NH}_4}^{-1}$ .

Hence, the  $BOD_{\text{NH}_4}$  is  $171.4 \text{ g}_{\text{O}_2} \text{ m}^{-3}$  for normal, concentrated and diluted wastewater. This is 69% of the  $BOD_5$  present in these wastewater.

- b) According to the equation that includes biomass production, 1 mole of  $\text{NH}_4^+$  consumes only 1.86 moles of  $\text{O}_2$ . This is equivalent to  $4.25 \text{ g}_{\text{O}_2} \text{ g}_{\text{N-NH}_4}^{-1}$ .

Hence, the  $BOD_{\text{NH}_4}$  would then be  $159.4 \text{ g}_{\text{O}_2} \text{ m}^{-3}$  for normal wastewater.

The oxygen demand would thus decrease, and this by 7%.

## **Homework 2-2 : « Nitrification in a specific WWTP »**

For the design of nitrifying activated sludge plants, a security factor can be taken into account that is defined as:

$$SF = \mu \times \theta_x$$

with SF = security factor  
 $\mu$  = growth rate of nitrifiers  
 $\theta_x$  = solids retention time / sludge age

If SF is  $< 1.0$ , it is very probable that the plant does not nitrify.

A WWTP was designed to nitrify at  $15^\circ\text{C}$  with an oxygen concentration of  $2 \text{ g m}^{-3}$  and a sludge age of 5 days. The pH of the wastewater is between 7.0 – 7.5.

Does that WWTP nitrify according the security factor concept at  $15^\circ\text{C}$  ?

*Hints: 1. Use the information on growth rates presented on the lecture slides. The half-saturation constant  $K_{O_2}$  for nitrifiers is  $0.5 - 1.0 \text{ g}_{O_2} \text{ m}^{-3}$ .  
2. The norm for  $\text{N-NH}_4$  is  $2 \text{ g m}^{-3}$  and the aeration tank is designed as a completely stirred tank reactor.*

### **Solution**

We have to take the following parameters into account from slide:

- equations for  $\mu_{\max}(T)$  and  $\mu$  dependence on  $\text{NH}_4$ , DO, and pH .
- $K_{O_2} = 0.5 - 1.0 \text{ g}_{O_2} \text{ m}^{-3}$

$$\mu_{\max}(T_{15}) = 0.50 \text{ d}^{-1}. \text{ We need to take care of the slower one } \textit{Nitrobacter}$$

The growth rate is also influenced by the  $\text{NH}_4^+$  concentration, the oxygen concentration and pH.

For the  $\text{NH}_4^+$  concentration, we can take  $2 \text{ g}_{\text{N-NH}_4} \text{ m}^{-3}$  by supposing that it is a completely stirred tank reactor and therefore nitrification takes place at effluent concentration.

For the oxygen concentration, we can choose a typical value controlled by the aeration system, e.g.  $2 \text{ g}_{O_2} \text{ m}^{-3}$ .

For the pH, we can consider a value between 7.0 – 7.5 and as optimal value 7.2.

With  $K_{O_2}$  of  $0.5 \text{ g}_{O_2} \text{ m}^{-3}$ , pH of 7.0 and the equation for the calculation of growth rates, we get a growth rate  $\mu = 0.277 \text{ d}^{-1}$ , with  $K_{O_2}$  of  $1.0 \text{ g}_{O_2} \text{ m}^{-3}$  and pH of 7.5 the growth rate is  $\mu = 0.208 \text{ d}^{-1}$ .

Independent of the affinity of the biomass for oxygen and the sensitivity to pH, the WWTP will nitrify because the SFs for both  $K_{O_2}$  values and pHs are  $> 1.0$  (1.39 and 1.04, respectively; calculated by multiplying the growth rates with the given sludge age (5 days)).

### **Homework 2-3 : « Biomass production due to aerobic and denitrifying heterotrophs and nitrifiers »**

An average wastewater has a COD concentration of  $340 \text{ g}_{\text{O}_2} \text{ m}^{-3}$ , a  $\text{BOD}_5$  concentration of  $170 \text{ g}_{\text{O}_2} \text{ m}^{-3}$ , and a TKN concentration of  $30 \text{ g}_{\text{N}} \text{ m}^{-3}$ . The aerobic heterotrophs have a growth yield of  $0.5 \text{ g}_X \text{ g}^{-1}$  organic matter, the nitrifiers produce biomass according to the equation given on a lecture slide, and denitrifiers according to the equation on another slide with the assumption that enough nitrate is available to oxidize all organic matter. Compare the biomasses produced by either aerobic and denitrifying heterotrophs and by the nitrifiers ?

#### **Solution**

##### ***Aerobic heterotrophs***

In Homework 1, we have calculated the COD of organic matter (OM) to be  $1.42 \text{ g}_{\text{O}_2} \text{ g}_{\text{OM}}^{-1}$ . Hence, the COD of  $340 \text{ g}_{\text{O}_2} \text{ m}^{-3}$  corresponds to  $239.4 \text{ g}_{\text{OM}} \text{ m}^{-3}$ . With a yield of  $0.5 \text{ g}_X \text{ g}_{\text{OM}}^{-1}$ , the aerobic heterotrophs produce  **$119.7 \text{ g m}^{-3}$** .

##### ***Denitrifiers***

The organic matter available is  $239.4 \text{ g}_{\text{OM}} \text{ m}^{-3}$  which corresponds to 0.61 mol. This is exactly the amount needed to produce one mole of biomass (see equation for denitrification including biomass production), hence, denitrifiers produce  **$113 \text{ g m}^{-3}$**  if they oxidize all organic matter available.

##### ***Nitrifiers***

The wastewater has a  $\text{BOD}_5$  of  $170 \text{ g}_{\text{O}_2} \text{ m}^{-3}$ , and therefore about  $7.65 \text{ g}_{\text{N}} \text{ m}^{-3}$  will be eliminated by the waste sludge. The remaining  $22.35 \text{ g}_{\text{N}} \text{ m}^{-3}$  have to be nitrified.

The growth yield of nitrifiers according to the specific equation is  $0.161 \text{ g}_X \text{ g}_{\text{N-NH}_4}$ . Hence, the nitrifiers produce  **$3.60 \text{ g}_X \text{ m}^{-3}$** .

Hence, nitrifiers produce 31- to 33-times less biomass than denitrifying and aerobic heterotrophs, respectively.

### **Homework 2-4 : « Alkalinity change due to denitrification »**

Alkalinity is measured by conventional titration with acid to an end pH of 4.5. The higher the value is, the greater the buffering capacity. Normally municipal wastewaters with an alkalinity over  $5 \text{ eqv m}^{-3}$  (more than 5 mol of protons/acid is needed per  $\text{m}^3$  to reach pH 4.5) will not cause problems in connection with nitrification and simultaneous precipitation of phosphate.

Denitrification also influences alkalinity. If in a wastewater that has an alkalinity of  $4.1 \text{ eqv m}^{-3}$  before denitrification,  $25 \text{ g}_{\text{N-NO}_3} \text{ m}^{-3}$  are denitrified, what will be the alkalinity TAL after the denitrification process ?

*Hints: Assume that denitrification is done in a pre-denitrification process and that therefore ammonium is available as nitrogen source.*

### **Solution**

- From the denitrification equation including biomass production, it is found that  $0.91 \text{ eqv alkalinity per mol N-NO}_3$  converted ( $4.15/4.54$ ) are produced.
- $25 \text{ g}_{\text{N-NO}_3} \text{ m}^{-3} = 1.79 \text{ mol N-NO}_3 \text{ m}^{-3}$  ( $25/14$ ).
- The change in alkalinity  $\Delta\text{TAL}$  is therefore
$$\Delta\text{TAL} = 0.91 \times 1.79 = 1.63 \text{ eqv m}^{-3}$$
- The alkalinity of the wastewater is thus  $4.1 + 1.6 = 5.7 \text{ eqv m}^{-3}$ , a level that can be considered non-problematic if nitrification and phosphorous precipitation follow.

### Homework 2-5 : « Oxygen savings due to denitrification »

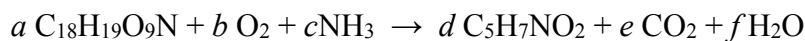
Denitrification consumes organic matter (OM) as carbon and energy source in order to reduce nitrate to dinitrogen gas. If one would use the influent BOD<sub>5</sub> for denitrification, how much less oxygen has to be provided for BOD<sub>5</sub> removal if one has to denitrify 20 g<sub>N-NO<sub>3</sub></sub> m<sup>-3</sup>.

*Hints: - Use the empirical formula C<sub>18</sub>H<sub>19</sub>O<sub>9</sub>N for OM and assume a growth yield for aerobic heterotrophs of 0.5 g<sub>X</sub> g<sub>OM</sub><sup>-1</sup>.*

*- Establish an equation for aerobic degradation of OM like the equation for denitrifying degradation of OM to be able to determine BOD for OM degradation.*

### Solution

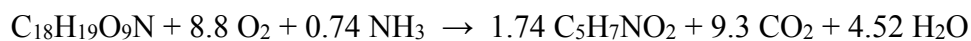
- The molecular mass of organic matter is 393 g/mole.
- According to the equation with biomass production with ammonium, 3.77 g<sub>OM</sub> are degraded per g<sub>N-NO<sub>3</sub></sub> denitrified ((0.61x393) / (4.54x14)).
- We have to denitrify 20 g<sub>N-NO<sub>3</sub></sub> m<sup>-3</sup> and need for that 75.43 g<sub>OM</sub> m<sup>-3</sup> (20x3.77).
- Organic matter is aerobically degraded as follows:



$$\text{where } \frac{d \times \text{MW}_X}{a \times \text{MW}_{\text{OM}}} = Y_{\text{obs}}$$

$$\text{We can set } a = 1 \text{ and calculate } d: d = \frac{Y_{\text{obs}} \times a \times \text{MW}_{\text{OM}}}{\text{MW}_X} = \frac{0.5 \times 1 \times 393}{113} = 1.74$$

- We can now write the equation for aerobic degradation of organic matter taking biomass production into account:



Note that  $c$  is the inorganic nitrogen needed in addition to the nitrogen present in organic matter to form the biomass. It has been obtained by subtracting  $a$  from  $d$ .

- The BOD of organic matter can now be calculated and is 0.72 g<sub>O<sub>2</sub></sub> g<sub>OM</sub> (8.8x32/393).
- Since denitrification consumes 75.43 g<sub>OM</sub> m<sup>-3</sup> that would otherwise have to be degraded aerobically, we have to provide **54.31 g m<sup>-3</sup> less O<sub>2</sub>** by aeration for the BOD removal in the aerobic part of the WWTP.