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KEY DESIGN PARAMETERS FOR OPTIMIZING TERTIARY WASTEWATER TREATMENT

BY

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Abstract. The main goal of the work consists in the optimization from the point of view of energy efficiency and the reduction of the implementation and operation costs of the advanced (tertiary) treatment stage of urban and industrial treatment plants, through the correct choice of the staged sequence of calculation of the still used primary parameters from the design phase of the tertiary stage component equipment. In the evaluation of the biological treatment stage within a wastewater treatment plant, several critical operational and design parameters must be rigorously analyzed. Primarily, the focus is on quantifying the concentration of organic pollutants (CBO₅) in the influent to the biological reactor, alongside the total pollutant load, which includes both organic and inorganic constituents. These concentrations are essential for dimensioning the reactor and determining the oxygen demand. Furthermore, a detailed mass balance is performed for nutrients, particularly nitrogen and phosphorus.

Keywords: energy efficiency, improvement and dimensioning of the parameters.

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1. Introduction

The advanced treatment stage represents a crucial step in the wastewater treatment process, aiming to remove residual pollutants from the water that could not be completely eliminated in earlier treatment stages. This additional stage is applied primarily in municipal and industrial wastewater treatment plants and utilizes advanced technologies to ensure a high level of water purification.

The main objective of the advanced treatment stage is to significantly reduce concentrations of organic and inorganic substances, nutrients, heavy metals, chemicals, and other pollutants in wastewater, so that the water can be discharged into the environment in as clean and bacteriologically safe a state as possible.

Among the advanced technologies used in this treatment stage are:

- membrane filtration, this technology involves using porous membranes that retain particles and pollutants larger than the membrane pores. This allows for the separation of clean water from contaminants, ensuring superior treated water quality;

- ozonation, ozone is a powerful oxidant that can be used to destroy bacteria, viruses, and other microorganisms present in wastewater. This process has a disinfecting effect and helps eliminate unpleasant odors from the water (Tang *et al.*, 2020);

- activated carbon adsorption, this method involves using a porous material, such as activated carbon, which has strong adsorption properties. Through this technology, dissolved organic and inorganic substances in the water can be retained, ensuring more efficient purification;

- advanced oxidation processes, these processes involve using strong oxidizing chemicals, such as hydrogen peroxide or potassium permanganate, to break down pollutants into less harmful or more easily removable compounds.

The advanced treatment stage is a complex and costly phase of the wastewater treatment process, but it is essential for protecting the environment and ensuring the quality of water discharged into natural water bodies (Tyagi *et al.*, 2024). By employing these advanced technologies, this stage contributes to reducing the impact of pollution on aquatic ecosystems and human health.

The optimization of advanced wastewater treatment plants requires an integrated approach that simultaneously addresses biological stability, effluent quality, energy consumption, and operational costs. This study proposes an energy-oriented design methodology for biological nutrient removal systems and tertiary treatment processes, applied to a municipal wastewater treatment plant with a capacity of 10,000 population equivalent (PE).

Mass balance equations for carbon, nitrogen, and phosphorus removal are combined with sludge production modeling, volumetric loading criteria, and aeration energy estimation. A complete case study demonstrates that conventional design criteria lead to a specific energy consumption of 1.69 kWh/m³. By

optimizing sludge age, internal recirculation, dissolved oxygen control, and integrating biogas recovery, total energy demand can be reduced by approximately 40%, reaching 1.0 kWh/m³.

Comparative analysis between conventional activated sludge (CAS), membrane bioreactor (MBR), sequencing batch reactor (SBR), moving bed biofilm reactor (MBBR), and constructed wetlands highlights the trade-off between energy efficiency, footprint, and effluent quality. The proposed methodology supports the transition from purely hydraulic-biological dimensioning to sustainable, energy-driven wastewater treatment design.

2. Methodology

Increasingly stringent discharge standards and climate-neutrality objectives require wastewater treatment plants to operate with high removal efficiency and reduced carbon footprint. Biological nutrient removal systems remain the most widely applied solution for medium-sized municipal plants. However, aeration for carbon oxidation and nitrification represents the dominant energy consumer, typically accounting for 50-70% of total plant energy use.

For plants of approximately 10,000 PE, optimization during the design stage is critical because oversizing increases capital costs and aeration demand, while undersizing compromises nitrification stability during low-temperature periods.

This study develops a design and optimization framework integrating:

- pollutant mass balance;
- sludge age control;
- reactor volume dimensioning;
- internal recirculation design;
- sludge production estimation;
- aeration energy calculation;
- energy recovery assessment.

Designing the advanced treatment stage requires consideration of several key parameters to ensure the system's efficiency and proper operation.

The dimensioning of parameters necessary for designing the advanced treatment stage is based on specific criteria and methods, such as:

– Wastewater volume and characteristics: Evaluate the volume of wastewater to be treated and its characteristics, including specific pollutant concentrations. This determines the required capacity of the advanced treatment stage and the appropriate technologies (Pratap *et al.*, 2023);

– Pollutant removal efficiency: Establish the pollutant removal levels according to local regulations or standards, including limits for organic substances, nutrients, heavy metals, and other chemicals in treated water. This dictates the necessary technologies and processes;

– Flow rate and contact time: Determine the water flow rate to be treated (e.g., m³/day or L/s) and the contact time required between wastewater and treatment processes for efficient removal;

– Equipment sizing: Properly size filters, storage tanks, ozonation reactors, or other equipment based on treatment requirements;

– Energy consumption: Consider the energy requirements of chosen technologies and processes to optimize overall energy efficiency (Cui *et al.*, 2024).

The sequence of calculation steps for dimensioning is as follows:

1) *Organic pollutant concentration in biological stage influent (kg/day):*

$$C_x^B = C_x(1 - E_M) \quad (1)$$

where:

C_x^B - concentration of pollutant x entering the biological stage, [kg/day];

C_x - concentration of pollutant x in the plant influent [kg/day];

E_M - purification efficiency of the mechanical stage highlighted in Table 1 according to settling time (T).

Table 1
Primary Settling Mechanical Treatment Efficiency
(NP 133, 2022)

Parameter	Water loading (g/PE·day)	E_M efficiency in primary settling	
		T = 0.5 ... 1.0 h	T = 1.5 ... 2.0 h
MTS	70	35 %	25 %
CBO5	60	45 %	40 %
CCO	120	90 %	80 %
NT	11	10 %	10 %
PT	1.8	1.6 %	1.6 %

2) *Total pollutant concentration in the influent of the biological stage:*

$$X^B = \frac{C_x^B}{Q_c} \quad (2)$$

where:

X^B - the amount of pollutant X in the influent of the biological stage, [mg/L];

Q_c - calculation flow, maximum daily flow [m³/day];

3) *Nitrogen balance* expressed in mg/L, the total amount of nitrogen that must be biologically removed through nitrification - denitrification processes, namely:

$$N_D = N_T^B - N_{org E} - (NH_4^+ - N)_E - NO_{3E}^- - N_{BM} \quad (3)$$

where:

N_D - the total amount of nitrogen nitrate that needs to be denitrified;

N_T^B - total nitrogen entering the biological stage;

$N_{org E}$ - the amount of organic nitrogen admitted into the effluent [$N_{org E} = 2$ mg/L];

$(NH_4^+ - N)_E$ - the amount of ammonium (ammonia nitrogen) admitted into the effluent [usually varies within the limits 0 - 1 mg/L];

NO_{3E}^- - the amount of nitrate allowed in the effluent which can be within the limits of 6-8 mg/L;

N_{BM} - the amount of organic nitrogen contained in biomass [$N_{BM} = \max 5\% \cdot CBO_5^B$].

4) *The phosphorus balance* represents the amount of phosphorus in kg/day that must be removed from wastewater by chemical precipitation, using the following relationship:

$$P_P = P_T - P_E - P_{BM} - P_{bio} \quad (4)$$

where:

P_P - the amount of phosphorus that needs to be precipitated;

P_T - the total amount of phosphorus entering the biological stage;

P_E - the amount of phosphorus admitted into the effluent;

P_{BM} - synthesized phosphorus necessary for biomass development, estimated at 1% of CBO_5 or 5% of CCO^B [$P_{BM} = 0.01 \cdot CBO_5^B$];

P_{bio} - the amount of phosphorus removed biologically in the anaerobic zone upstream of the reactor where the contact time is 0.5 - 0.75 hours. Values of 0.01 - 0.015 of CBO_5^B or 0.005 - 0.007 of CCO^B , if there is no anaerobic zone but only anoxic zone for denitrification, the value $P_{bio} = 0.005 \cdot CBO_5^B$ or $0.002 \cdot CCO^B$.

The amount of reagent, in kg/day, required for chemical precipitation will be:

$$C_{RP} = P_P \cdot C_R \quad (5)$$

where:

P_P - the amount of phosphorus that needs to be precipitated;

C_R - the dose of reagent required for precipitation (2.7 kg Fe / kg P_p or 1.3 kg Al / kg P_p).

5) *Denitrification capacity (C_D)* expresses the ratio between the total amount of nitrogen that must be denitrified and the amount of CBO_5 entering the biological stage, that is:

$$C_D = \frac{N_D}{C_{CBO_5}^B} \quad (6)$$

where:

$N_D = N_s \cdot Q_C$ - the daily amount of nitrogen that needs to be denitrified [kg/zi];
 $C_{CBO_5}^B$ - the amount of CBO₅ in the primary effluent entering the biological stage, [kg/day].

The nitrate load to be denitrified (ND) requires an organic matter concentration (CBO) equivalent to this process. Typically, this organic load is found in the composition of the wastewater, applying the technological scheme with pre-denitrification for the development of this process (Quintero-Castañeda *et al.*, 2023).

To calculate the mass balance, it must be taken into account that a percentage of approximately 75% of the organic substances contained in the influent will be used by the denitrification process bacteria in an anoxic environment (Mažeikienė and Šarko, 2022).

The ratio between nitrate loading and equivalent organic matter concentration derived from an oxygen mass balance in the anoxic zone of a biological reactor leads to the following relationship:

$$N_D \cdot 2.9 = 0.75 \cdot O_c \cdot \frac{V_D}{V_{BA}} \cdot C_{CBO_5}^B \quad (7)$$

where:

2.9 - (in more rigorous calculations the value is 2.86) represents the amount of oxygen required for denitrification, [kg O₂/kg];
 N_D - multiplied by the inflow value $\frac{N_D \cdot Q_C}{1000}$, [kg/day];
 O_c - the oxygen needed for the oxidation of carbon compounds, [kg O₂/day];
 $\frac{V_D}{V_{BA}}$ - ratio of the volume of the anoxic zone to the total volume of the reactor;
 $C_{CBO_5}^B$ - concentration of organic substances, expressed in kg CBO₅/day from the influence of the biological stage.

From equation (7) the volume of the anoxic zone (V_D) can be calculated from the total volume of the reactor, using the relation:

$$V_D = V_{BA} \cdot \frac{V_D}{V_{BA}} \quad (8)$$

Depending on the denitrification capacity (C_D) and the denitrification process chosen, the values $\frac{V_D}{V_{BA}}$ ratio can be obtained from Table 2, which are valid for wastewater with a temperature between 10 and 20°C. For water temperatures above 12°C, the denitrification capacity can be increased by approx. 1% per °C. For intermediate values of denitrification capacity, the calculation of the volume ratio can be established by interpolation.

Table 2
Denitrification capacity
(NP 107, 2004)

V_D / V_{BA}	C_D	
	Pre-denitrification or similar processes	Simultaneous or intermittent denitrification
0.1	0.08	0.03
0.2	0.11	0.06
0.3	0.13	0.09
0.4	0.14	0.12
0.5	0.15	0.15

Denitrification volumes exceeding the ratio $\frac{V_D}{V_{BA}} = 0.2$ and $\frac{V_D}{V_{BA}} = 0.5$ are not recommended for sizing (Dima *et al.*, 2014).

As a guide, the carbon requirement in the denitrification process is approximately 5 kg CBO_5 /kg NO_3^- . If this requirement is not met, denitrification is limited due to the slow rate of metabolic reactions. In this context, commercial carbon compounds (methanol, ethanol, acetic acid) must be introduced into the water, and the technological scheme applied is post-denitrification (Nkosi *et al.*, 2022).

6) *Sludge age* represents the ratio between the dry mass of activated sludge existing in the reactor (product $V_{BA} \cdot C_N$) and the dry mass of excess sludge discharged as a daily average.

For biological schemes without nitrification, values of 4 - 5 days for the sludge age will be assumed when dimensioning.

The sludge age required for sizing, in accordance with the treatment objective, temperature and size of the treatment plant can be determined from Table 3 (intermediate values will be established by interpolation).

Table 3
Installation size
 (NP 107, 2004)

Purification objective		<i>Plant size according to CBO₅</i>			
		up to 1200 kg/day		over 6000 kg/day	
Design temperature		10°C	12°C	10°C	12°C
No nitrification		5		4	
With nitrification		10	8.2	8	6.6
VD / VBA	0.2	12.5	10.3	10.0	8.3
	0.3	14.3	11.7	11.4	9.4
	0.4	16.7	13.7	13.3	11.0
	0.5	20.0	16.4	16.0	13.2
Sludge stabilization including nitrogen removal		25		inadvisable	

In the aerobic environment (nitrification zone), the sludge age required for the process, in days, is calculated with the relationship:

$$T_N = SF \cdot 3.4 \cdot 1.103^{(15-T)} \quad (9)$$

where:

SF - is a safety factor that takes into account variations in wastewater loads, thus:

- for small towns, up to 20000 PE, $SF = 1.8$;
- for large localities, over 100 000 PE, $SF = 1.45$.

3.4 - value consisting of the maximum growth rate of nitrifying bacteria (Nitrosomonas type) at a temperature of 15°C, which corresponds to a sludge age of 2-13 days and a coefficient of 1.6 which ensures sufficient oxygen transfer for nitrification to survive in the sludge;

T - the temperature at which nitrogen removal occurs (according to European legislation, $T = 12^\circ\text{C}$).

The sludge age required for sizing the biological stage provided with nitrification - denitrification processes is calculated with the relationship:

$$T_N = SF \cdot 3.4 \cdot 1.103^{(15-T)} \cdot \frac{1}{1 - (V_D/V_{BA})} \quad (10)$$

In winter, when the water temperature is lower than 12°C (allowed in German standards), the process is slow, the ratio V_D/V_{BA} is calculated, with the relationship:

$$V_D/V_{BA} = \frac{SF \cdot 3.4 \cdot 1.103^{(15-T)}}{T_N} \quad (11)$$

7) The calculation of the total amount of sludge is made up of the sludge resulting from the elimination of organic carbon compounds, to which is added that resulting from the reduction of phosphorus.

The amount of sludge, in kg SU / kg CBO₅, resulting from carbon removal can be determined with the following empirical relationship corrected with Hartwig coefficients:

$$\frac{N_c}{CBO_5^B} = \left(0.75 + 0.6 \frac{MTS^B}{CBO_5^B} - \frac{(1 - 0.2) \cdot 0.17 \cdot 0.75 \cdot T_N \cdot F_T}{1 + 0.17 \cdot T_N \cdot F_T} \right) \quad (12)$$

where:

F_T - is the temperature factor for endogenous respiration ($F_T = 1.072^{(T-15)}$).

Table 4 presents the specific quantities of sludge, in kg SU / kg CBO₅, at temperatures between 10 and 12°C and depending on the age of the sludge.

Table 4
Specific quantities of sludge (Dima et al., 2014)

$\frac{MTS^B}{CBO_5^B}$	Sludge age, in days					
	4	8	10	15	20	25
0.1	0.79	0.69	0.65	0.59	0.56	0.53
0.2	0.91	0.81	0.77	0.71	0.68	0.65
0.3	1.03	0.93	0.89	0.83	0.80	0.77
0.4	1.15	1.05	1.01	0.95	0.92	0.89
0.5	1.27	1.17	1.13	1.07	1.04	1.01

Intermediate values will be established by interpolation.

The amount of sludge resulting from phosphorus removal, in kg SU / kg CBO₅, is calculated with the relationship:

$$N_p = \left(\frac{3 \cdot P_{bio} + 2.7 \cdot 2.5 \cdot P_{Fe} + 1.3 \cdot 4 \cdot P_{Al}}{C_{CBO_5}^B} \right) \quad (13)$$

where:

N_p - the amount of sludge resulting from phosphorus removal;

P_{bio} - the amount of phosphorus reduced biologically - anaerobic;

P_{Fe} - the amount of phosphorus to be precipitated using iron oxide as a reagent. To remove one kg of $(PO_4)^{3-}$, a dose of 2.7 kg Fe^{3+} is required, and the resulting sludge amount is 2.5 kg SU / kg Fe^{3+} ;

P_{Al} - the amount of phosphorus to be precipitated using an aluminum-based reagent. To remove one kg of phosphorus by precipitation, a dose of 1.3 kg Al^{3+} is required, and the resulting sludge amount is 4 kg SU / kg Al^{3+} .

If lime is used as a precipitation reagent, then the sludge production will be 1.35 kg SU / kg $Ca(OH)_2$.

The specific sludge production, in kg SU / kg CBO_5 , represents the sum of the quantities in equations (12) and (13), that is:

$$N_s = N_C + N_P \quad (14)$$

The total sludge production, in kg SU/day, from the biological stage will be:

$$N_T = N_s + C_{CBO_5}^B \quad (15)$$

The volumetric loading of the reactor, in $kg/m^3 \cdot day$, represents the amount of biodegradable organic matter in one cubic meter of the basin. It is calculated with the relationship:

$$I_{OB} = \frac{C_N}{T_N \cdot N_s} \quad (16)$$

where:

C_N - sludge (biomass) concentration in the reactor, using, as a guideline, the values in Table 5;

T_N - sludge age, in days;

N_s - specific sludge production, in kg SU / kg CBO_5 .

Table 5
Biomass concentration in the reactor
(Dima, 2002)

Type of purification	C_N (kg/m ³)	
	with primary settling	without primary settling
No nitrification	2.5 - 3.5	3.5 - 4.5
With nitrification (and denitrification)	2.5 - 3.5	3.5 - 4.5
With sludge stabilization	-	4.0 - 5.0
With phosphorus removal (simultaneous precipitation)	3.5 - 4.5	4.0 - 5.0

Another dimensioning parameter is the organic load of the sludge, in kg CBO₅ / kg SU·day, which represents the amount of biodegradable organic matter per kg of dry matter present in the aeration tank (biomass, expressed in volatile matter - SV).

$$I_{ON} = \frac{I_{OB}}{C_N} \quad (17)$$

The total volume of the reactor (pool) in which nitrification - denitrification processes take place will be:

$$V_{BA} = \frac{C_{CBO_5}^B}{I_{OB}} \quad (18)$$

The denitrification volume is calculated with the relationship:

$$V_D = \left(\frac{V_D}{V_{BA}} \right) \cdot V_{BA} \quad (19)$$

The nitrification volume represents the difference, respectively:

$$V_N = V_{BA} - V_D \quad (20)$$

8) *Calculation of the recirculation flow rate using the technological scheme with pre-denitrification and the combined scheme.*

Given the existence of the three zones (anaerobic, anoxic and aerobic) in this treatment scheme, it is necessary to calculate the sludge flow rate recirculated from the secondary decanter (external recirculation) and the nitrate flow rate recirculated from the nitrification zone to the anoxic zone (internal recirculation).

The volume required for biological - anaerobic reduction of sludge can be calculated with the relationship:

$$V_{P_{bio}} = Q_t (1 + R_N) \cdot t_{P_{bio}} \quad (21)$$

where:

Q_t - the maximum daily flow (influent), calculated for a period of 16 hours, respectively $Q_t/16$;

R_N - sludge recirculation coefficient (external), indicated with values of 0.78 - 1.0;

$t_{P_{bio}}$ - the time required for biological dephosphorization (recommended values of 0.75 - 0.80 h).

In the denitrification process, where internal recirculation (R_i) occurs, the following equality resulting from the mass balance can be written:

$$N_{NO_3^- recirc} = N_D - N_{NO_3^- sludge recirc} \quad (22)$$

where:

- $N_{NO_3^- recirc}$ - NO_3^- concentration from the internal recirculation (R_i) of nitrate;
- N_D - the amount of nitrogen to be denitrified;
- $N_{NO_3^- sludge recirc}$ - NO_3^- concentration in recirculated sludge (R).

The internal recirculation ratio in the denitrification process will be:

$$R_i = \frac{N_D}{NO_3^- effluent} - 1 \quad (23)$$

The internal nitrate recycling rate will be:

$$Q_{NO_3^- recirc} = N_{NO_3^- sludge recirc} / NO_3^- effluent \quad (24)$$

If the organic load in the wastewater does not meet the reactor's anoxic volume requirements (denitrification is partial), then a complete technological scheme with an additional anoxic volume will be adopted, resulting in a solution with after denitrification (Bărbieru *et al.*, 2016).

In the additional tank (postdenitrification) intermittent aeration takes place for short periods of time during the day to satisfy the anoxic requirements. Here the bacteria consume nitrate instead of oxygen for endogenous respiration (respiration to ensure basic metabolism, without the degradation of organic substances). This process is slower than denitrification in before denitrification where the substrate CBO_5 from the influent is used (Dima *et al.*, 2014).

The amount of nitrate removed in the after-denitrification basin can be calculated with the following relationship:

$$N_{NO_3^- afterDN} = N_D - NO_3^- beforeDN \quad (25)$$

The volume of the additional anoxic zone ($V_{afterDN}$) is calculated depending on the kinetic reaction rate of the process, namely:

$$V_{afterDN} = \frac{N_{NO_3^- afterDN}}{K_{NO_3^- endogen} \cdot X} \quad (26)$$

where:

$N_{NO_3^- \text{ after DN}}$ - the amount of nitrate eliminated after denitrification;

$K_{NO_3^- \text{ endogen}}$ - the kinetic constant of the endogenous denitrification process, which for a temperature of 12°C is recommended as the value 2.18 g NO₃⁻ - N / kg SU·day;

X - the biomass concentration in the basin expressed in dry matter, with values of 3 - 4.5 kg SU/m³.

Regarding the internal recirculation (R_i), a clarification is required, namely, the NO₃⁻ recirculation does not start at the end of the advanced biological treatment scheme (with after denitrification), but at the end of the nitrification zone, because in this zone the nitrate concentration related to the effluent is higher than that in the after-denitrification zone. Therefore, the internal recirculation rate is lower for the same nitrate concentration (Robescu *et al.*, 2011).

The maximum denitrification efficiency in % will be:

$$E_D = \left(1 - \frac{1}{1 + R_i}\right) \cdot 100 \quad (27)$$

When the cascade (combined) denitrification technological scheme is applied, the efficiency is determined for the load X assigned to each stage.

$$E_D = 1 - \frac{X}{1 + R_N} \quad (\text{without internal recirculation}) \quad (28)$$

$$E_D = 1 - \frac{1}{X(1 + R_i)} \quad (\text{with internal recirculation}) \quad (29)$$

where:

R_N - sludge recirculation coefficient, $R_N = Q_R / Q_c$.

The cycle time, in hours, for intermittent denitrification will be:

$$t_{ci} = \frac{V_{BA}}{Q_c} \cdot \frac{NO_{3E}^-}{N_D} \quad (30)$$

$$t_{ci} = T_{RH} \cdot \frac{NO_{3E}^-}{N_D} \quad (31)$$

where:

- the ratio $\frac{V_{BA}}{Q_c}$ expresses the hydraulic retention time.

3. Materials and Methods

Design Basis – 10.000 PE

Specific domestic loads adopted:

- Water consumption: 110 L/PE·day;
- CBO₅: 60 g/ PE·day;
- Total Nitrogen: 11 g/ PE·day;
- Total Phosphorus: 1.8 g/ PE·day.

Hydraulic load

$$Q_{avg} = 10000 \cdot 0.11 = 1100 \text{ m}^3/\text{day} \quad (32)$$

$$Q_{max} = 1.3 \cdot Q_{avg} = 1430 \text{ m}^3/\text{day} \quad (33)$$

Organic load

$$L_{CBO} = 10000 \cdot 0.06 = 600 \text{ kg/day} \quad (34)$$

$$L_N = 600 \text{ kg/day} \quad (35)$$

$$L_P = 18 \text{ kg/day} \quad (36)$$

Sludge age for nitrification

The required sludge age for nitrification at 12°C is:

$$T_N = SF \cdot 3.4 \cdot 1.103^{(15-T)} \quad (37)$$

For small plants (SF = 1.8):

$$T_N \approx 10.6 \text{ days} \quad (38)$$

For nitrification-denitrification systems:

$$T_N = 13 \text{ days (selected)} \quad (39)$$

Volumetric loading and reactor volume

Assuming optimized volumetric loading:

$$I_{OB} = 0.12 = \text{kgCBO}/\text{m}^3 \cdot \text{day} \quad (40)$$

$$V_{BA} = \frac{600}{0.12} = 5000 \text{ m}^3 \quad (41)$$

Denitrification volume

For denitrification capacity:

$$\frac{V_D}{V_{BA}} = 0.3 \quad (42)$$

$$V_D = 1500 \text{ m}^3 \quad (43)$$

$$V_N = 3500 \text{ m}^3 \quad (44)$$

Sludge Production

Specific sludge yield:

$$V_s = 0.75 \text{ kgSU/kgCBO} \quad (45)$$

$$N_{sludge} = 0.75 \cdot 600 = 450 \text{ kgSU/day} \quad (46)$$

Energy Analysis

Oxygen requirement for carbon removal:

$$O_C = 1.42 \cdot 600 = 852 \text{ kg O}_2/\text{day} \quad (47)$$

Energy for aeration:

$$E_C = 852 \cdot 1.1 = 937 \text{ kWh/day} \quad (48)$$

Oxygen requirement for nitrification

$$O_N = 4.57 \cdot 110 = 503 \text{ kgO}_2/\text{day} \quad (49)$$

$$E_N = 503 \cdot 1.1 = 553 \text{ kWh/day} \quad (50)$$

Total energy demand:

- Aeration (carbon) = 937 kWh/day;
- Aeration (nitrogen) = 553 kWh/day;
- Pumping = 150 kWh/day;

- Recirculation = 120 kWh/day;
- Sludge dewatering = 100 kWh/day;
- Total = 1860 kWh/day.

Specific energy consumption:

$$E_S = \frac{1860}{1100} = 1.69 \text{ kWh/m}^3 \quad (51)$$

Optimization strategy

Sludge age reduction

Reducing sludge age from 13 to 11 days:

- reactor volume: - 8%;
- aeration: - 6-8%.

Dynamic control

Maintaining DO between 0,8-1,5 mg/L:

- aeration energy: - 15%.

Variable frequency drives:

- blower energy: - 10-12%.

Biogas recovery

Sludge digestion yield (Biogas = 360 m³/day):

$$360 \cdot 2.1 = 750 \text{ kWh/day} \quad (52)$$

Optimized net energy

$$E_S = 1860 - 750 = 1110 \text{ kWh/day} \quad (53)$$

$$E_S = 1.01 \text{ kWh/m}^3 \quad (54)$$

Energy reduction \approx 40%

Comparative technology assessment

Table 6

Comparativ evaluation of the technology used in wastewater treatment

Technology	Energy (kWh/m ³)	Investment	Footprint	Effluent quality	Suitability (10000 PE)
CAS (optimized)	1.0	medium	medium	good	Highly suitable
MBR	1.4-1.8	high	low	excellent	Technically feasible
SBR	0.9-1.2	medium	medium	good-very good	Suitable
MBBR	0.8-1.1	medium	low-med	good	Very suitable
Constructed Wetlands	0.2-0.4	low	high	moderate	Land-dependent

Nitrogen removal represents approximately 30% of total plant energy consumption. The selected sludge age strongly influences both reactor volume and aeration demand.

Energy recovery from sludge digestion significantly improves sustainability and reduces net specific energy below 1.1 kWh/m³, aligning with modern EU efficiency benchmarks for medium-sized plants.

MBR systems provide superior effluent quality but at 40–70% higher energy demand. MBBR systems reduce footprint while maintaining moderate energy consumption. For a 10,000 PE installation, optimized CAS with pre-denitrification offers the best balance between capital cost and operational efficiency.

4. Conclusions

The case study demonstrates that conventional biological dimensioning without energy optimization leads to excessive specific energy consumption (1.69 kWh/m³).

By integrating energy indicators during design and applying sludge age optimization, internal recirculation adjustment, DO control, and biogas recovery, energy demand can be reduced by approximately 40%, reaching 1.0 kWh/m³.

The dimensioning of the parameters required for the design of the advanced treatment stage is the foundation for ensuring the optimal performance of modern wastewater treatment plants. First of all, it is essential to characterize the wastewater in detail, by determining the physico-chemical and biological parameters (CBO₅, SST, nitrates, phosphates, etc.), as well as the analysis of the variability of flows and concentrations to guarantee the resilience of the system under peak conditions. Based on these data, the daily volume and the maximum

hourly flow are calculated, which allows the definition of specific organic and hydraulic loads, critical elements in the design of basins and recirculation circuits.

The selection of dedicated technologies, from activated carbon adsorption and advanced oxidation with UV/H₂O₂, to ion exchange processes and membranes, must correspond to the objectives of eliminating residual pollutants, micropollutants and pathogens. In parallel, optimizing energy efficiency involves sizing pumps, aerators and automation systems so that specific energy consumption (kWh/m³ treated) is minimized, with the integration of energy recovery solutions where feasible. Finally, the rigorous economic evaluation, which includes the estimation of the initial investment, operating costs (energy, consumables, maintenance, personnel) and the calculation of financial indicators such as IRR and the amortization period, complemented by an analysis of the environmental impact and carbon footprint, ensures the substantiation of decisions and the long-term sustainability of the advanced tertiary treatment project.

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PARAMETRII CHEIE DE PROIECTARE PENTRU OPTIMIZAREA TRATĂRII TERȚIARE A APELOR UZATE

(Rezumat)

Scopul principal al lucrării constă în optimizarea din punct de vedere al eficienței energetice și reducerea costurilor de implementare și operare a etapei de epurare avansată (terțiară) a stațiilor de epurare urbane și industriale, prin alegerea corectă a secvenței etapizate de calcul al parametrilor primari încă utilizați din faza de proiectare a echipamentelor componente ale etapei terțiare. În evaluarea etapei de epurare biologică din cadrul unei stații de epurare a apelor uzate, trebuie analizați riguros mai mulți parametri critici de operare și proiectare. În primul rând, accentul se pune pe cuantificarea concentrației de poluanți organici (CBO₅) în influentul reactorului biologic, alături de încărcătura totală de poluanți, care include atât constituenți organici, cât și anorganici. Aceste concentrații sunt esențiale pentru dimensionarea reactorului și determinarea necesarului de oxigen. În plus, se efectuează un bilanț masic detaliat pentru nutrienți, în special azot și fosfor.