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INCREASING THE EFFICIENCY OF BIOLOGICAL SLUDGE STABILIZATION PROCESSES WITHIN WASTEWATER TREATMENT PLANTS

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Abstract

Wastewater treatment plants are complex systems designed to deal both with wastewater and with resulting sludge. Physical, chemical and especially biological processes depend significantly on technological factors, the conditions for the development of biochemical reactions having complex dynamics. Due to hourly and seasonal variations in inputs (flows and pollutant concentrations), and to the conditions of the treatment process, continuous technological adjustments are necessary. The economic sizing of wastewater treatment plants can lead to operating situations at the organic pollutant load limit in terms of efficiency, making it necessary to adopt additional technological measures. The paper presents a one-year long case study on adjusting the stabilization processes and reducing the quantity of sludge produced (50% in warm seasons, 10% in cold season) in a wastewater treatment plant based on specialized microbial products. The monitorized parametres are dissolved organic carbon (COD), N_{total}, P_{total} The results highlight the need to ensure all technological factors for wastewater treatment and for sludge mineralization, simultaneously with the maintaining of desired efficiency and the corrective measures implementation.

Key words: *biological processes, biopreparations, sludge stabilization, wastewater treatment plant.*

INTRODUCTION

Wastewater treatment plants become increasingly important for the environment and human activities in the context of climate change and the major imbalance between water demand and available water quantities.

The technological challenge of management of the sludge quantities was addressed using microbial products by Chinese scientist (Li et al., 2022) isolating strains of *Firmicutes* and *Proteobacteria* confirming the possible use.

The study main objective is the decrease of the sludge quantities by 50% all over the year, independently of temperature, on average flux of 100 m^3/h and average COD of 2000 mg/L, by adding microbial products.

Sewage sludge management has historically been achieved (EU, 2024) through methods that did not take into account all environmental factors, with major implications generated over time; Table 1 presents the main methods used and their advantages/disadvantages.

Table 1. Treatment methods for sludge resulting from wastewater treatment processes

Method	Disadvantages	Advantages
Spreading on agricultural land	- technological difficulties in transporting and applying for sludges with high moisture - pedological changes in the pH indicator, and the need to monitor soil characteristics over time - high consumption of lime for sludge stabilization and dehydration, respectively for soil amendment - accumulation of heavy metals in soil, cumulative evolution - need for large land areas	- unloading of significant quantities of materials considered waste – circular economy - nutrient supply for agricultural lands - improving soil structure
Reduction of sludge quantities through aerobic stabilization	- increase in technological wastewater treatment volumes - additional energy consumption for aeration,	- reducing the sludge volumes generated by wastewater treatment plants

Method	Disadvantages	Advantages
at the technological wastewater flux or in specific compartments	homogenization and recirculation - consumption of coagulants for phosphorus correction - all the aspects mentioned for the previous method	- reducing the amount of stabilization lime - improving sludge management/dewatering processes, including reducing the quantities of dehydrated reagents required - reducing the amount of carbon discharged into the environment with the possibility of generating secondary pollution
Anaerobic stabilization	- difficult process to manage due to the range required for feeding the fermenter with raw material, the restricted pH and temperature range necessary to be ensured in the process - significant consumption of electrical and thermal energy even in the case of complete solutions for valorization of the biogas produced - incompatibility between the need to reduce nitrogen in wastewater and biogas production for low C:N ratios - oversizing biological tanks for treating nitrogen and phosphorus generated in fermentation processes -the need for additional stabilization of the fermented sludge compared to an aerobic process	- reduction of the final sludge amount - obtaining energy by utilizing biogas and gaining wastewater treatment plant energy independence - obtaining expensive energy by optimizing cogeneration processes
Incineration	- CO_2 generation and removal into the atmosphere in contradiction with the concept of carbon storage - need to dehydrate sludge to low moisture levels (35%) - generation of gases and water vapor in the dehydration and incineration process - dust generation - additional fuel requirement	- reducing the quantities of waste that must subsequently be managed - obtaining thermal energy - simplifying the wastewater technological flux and sludge technological flux, by reducing the technological volumes necessary for sludge stabilization

From the analysis of the advantages and disadvantages listed, the optimal solution seems to be the centralized management of sludge in regional depots (Neamt et al., 2013; Rosiek, 2020), ensuring: centralized collection of sewage sludge from economic operators; quantitative and qualitative control of sludge and application of efficient technologies for each category of sludge and for by-products; storage in plots depending on chemical characteristics; development of specific processing technologies for each type of sludge.

A regional sludge depot can be structured as follows:

- plots for stabilizing good quality organic sludge, with minimal content of toxic substances and heavy metals for agricultural use or composting (mixed with organic waste as organic fertilizers);
- anaerobic fermentation with energy recovery or storage in plots that naturally ensure the process;
- washing and reconditioning of sludge with recovery of some components;
- concentration of leached solutions/solutions resulting from various processes and their valorization;
- treatment and cremation of petroleum products, stable products, etc.

In such a sludge management structure, the technological challenge for economic agents is to reduce the amount of sludge and raw (wet) sludge. Reducing sludge amount can be approached in two technological directions: aerobic or anaerobic biological mineralization and improving dehydration processes. It thus becomes of interest to address aspects related to efficiency and technology in the case of the use of biopreparations intended to reduce the amount of sludge generated in biological wastewater treatment plants.

CONSIDERATIONS REGARDING BIOLOGICAL PROCESSES IN WASTEWATER TREATMENT PLANTS

Initially, the treatment plants were sized and constructed to ensure the reduction of BOD_5

and suspended matter indicators. It is considered that reducing oxygen consumption in biological processes to a minimum accepted level can eliminate oxygen deficiency situations in the receiving watercourse and maintain environmental factors away from any quality degradation risk. Every study, design and operation recommendation, and treatment efficiency concept took into account BOD_5 as indicator. Within biological nitrogen reduction wastewater treatment plants, C:N ratio is the principal efficiency indicator, also governing the sizing of biological nitrification/denitrification compartments.

Within wastewater treatment plants using biological sludge stabilization and/or bioaugmentation, where part of the sludge is biologically mineralized, C:N Kjeldahl indicator became the main parameter for determining the oxygen requirement for the process and also for sizing of additional volumes in the nitrification/denitrification compartments.

Applications designed based on BOD5 indicator recorded increased specific technological consumption indicators due to the processing of larger quantities of COC-Cr or TOC (especially in applications that ensure sludge mineralization/stabilization).

Table 2 presents the degree of carbon reduction for standard design situations corresponding to the standards NTPA 002 (MAPM-b, 2002) treatment influent and NTPA001 (MAPM-a, 2002) effluent. It could be noticed that in the case of plant sizing with the COC-Cr indicator, it is necessary to process additional quantities of organic substances (about 100 mgO_2/L). The design process becomes difficult when the BOD5/COD-Cr ratio is low and, also, there are high COC-Cr concentrations. For these specific reasons, the design of wastewater treatment plants with the COC-Cr parameter was adopted.

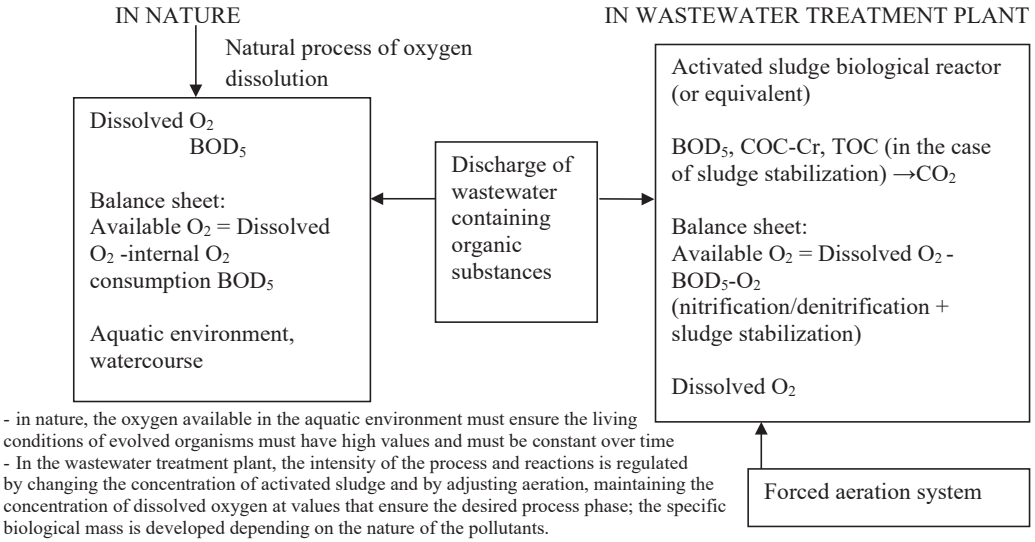
From a technical point of view, the design model adopted does not reflect the effective situation in the wastewater treatment plant. Figure 1 shows the difference between a wastewater self-treatment process in a watercourse and the wastewater treatment plant process.

Table 2. Minimum treatment efficiencies for domestic wastewater treatment plants (MAPM-b, 2002)

Indicator	NTPA 002/2002	Effective reduction	
	(mg/L)	(mg/L)	(%)
BOD_5	300	275	91.67
COC-Cr	500	375	75.00
BOD_5/COC-Cr = 0.6, as a result of values in NTPA 002/2002			

From the point of view of the accuracy of determining the design quality indicators, the BOD_5 indicator implies a reduced accuracy due to the dilution required for determination, compared to the COC-Cr determination where the accuracy is high due to the simplicity of the method.

The design standard NP 133/2022 (MDLPA, 2022) provides for the determination of the oxygen requirement depending on the COC-Cr value in the situation where the COC-Cr/BOD_5 ratio > 2.2 or BOD_5/COC-Cr = 0.45, without specifying the how to do it when the ratio varies in the range (0.6 - 0.45); in this situation the bioaugmentation is a solution, combined with the increase of oxygen added in the process NP 133/2022 requires the calculation of sludge production and oxygen demand with influent COC-Cr values (MDLPA, 2022). Consequently, wastewater treatment plants sized based on the influent BOD_5 indicator, without taking into account the critical nitrogen indicator (ammonia nitrogen) or plants with sludge stabilization calculated without the COC-Cr or TOC indicator, encounter operational difficulties in ensuring the oxygen requirement, sludge production and management and, in many situations, do not ensure mandatory discharge conditions. In the design of wastewater plants without sludge stabilization, an activated sludge concentration of 3000 mg/L and a sludge age of (10-20) days is recommended (MDLPA, 2013; DWA, 2000). In the design of wastewater plants with sludge stabilization, an activated sludge concentration of 4500 mg/L and a sludge age of (20-30) days is recommended (MDLPA, 2013; DWA, 2000), resulting in a technological volume 18% higher than in the first situation, which proves in operation that are not enough in cold seasons.



- in nature, the oxygen available in the aquatic environment must ensure the living conditions of evolved organisms must have high values and must be constant over time
- In the wastewater treatment plant, the intensity of the process and reactions is regulated by changing the concentration of activated sludge and by adjusting aeration, maintaining the concentration of dissolved oxygen at values that ensure the desired process phase; the specific biological mass is developed depending on the nature of the pollutants.

Figure 1. Scheme of O_2 provision for biological processes in nature and in wastewater treatment systems

For these specific plants or for those with aerobic sludge stabilization in separate compartments, the technological variant with microbial products based on bacterial strains support in sludge digestion can be adopted. For plants having nitrification-denitrification and sludge stabilization at the technological wastewater flux, complex solutions can be adopted by dosing two types of biopreparations, one to improve the mineralization, one to maintain the efficiency of the main treatment process; in both processes, must be ensured the technological factors related the necessary oxygen and re-circulations.

The wastewater treatment technological scheme will be developed so that the process takes place in individual nitrification and denitrification tanks, respectively sludge stabilization tanks, and allows the optimization of each phase of the process (Figure 2).

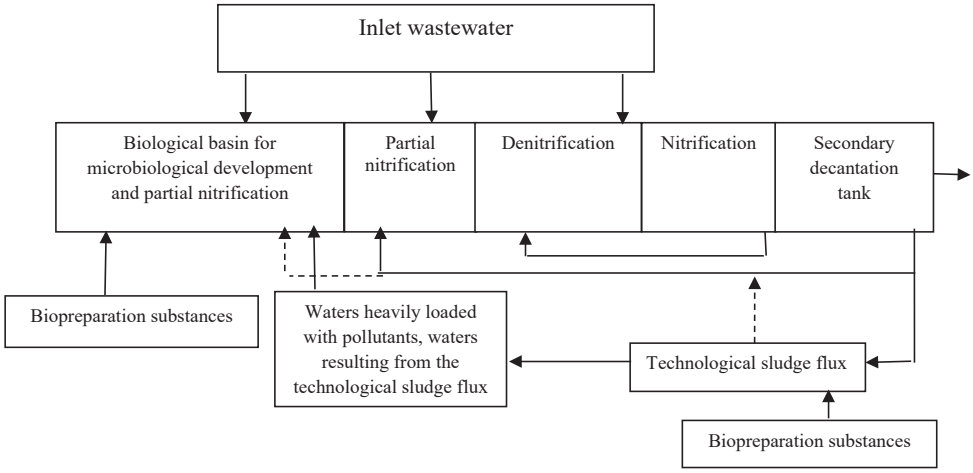


Figure 2. General scheme of an optimized biological stage with specialized biopreparation substances

Efficiency is achieved by maintaining a high biological capacity by dosing microbiological preparation substances, by successive nitrification and denitrification phases, by

appropriate fractional feeding and, in particular, to maintain denitrification capacity, microbiological dosing for sludge stabilization both on the technological wastewater flux and on the technological sludge flux.

DYNAMICS OF BACTERIAL DEVELOPMENT WITHIN WASTEWATER TREATMENT PLANTS

The calculation models used in the design standard for wastewater treatment plants provide relationships that depend on the temperature and sludge age, which modify the rate of sludge mineralization/stabilization.
In the evolution of biological sludge, four development stages were highlighted, corresponding to process starting (primary bacteria), development and appearance of protozoa, sludge maturation and aging, corresponding to the nematode appearance (Figure 3).
For bacterial development, it is necessary to permanently ensure the needed nutrients and avoid toxic elements. Within wastewater treatment plants operation, both discharges of highly toxic substances and variations in nutrient concentrations are recorded, the dynamics of bacterial development being thus variable. Achieving optimal conditions in specialized compartments lead to obtaining the bacterial base stock that ensures the treatment of consumption peaks.

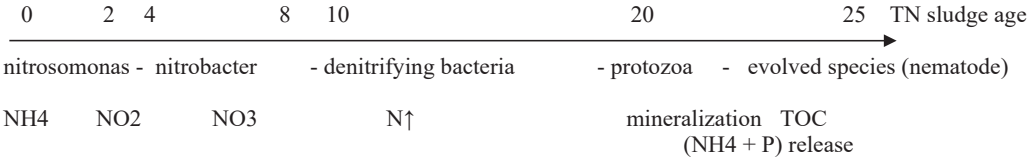


Figure 3. Phases of activated sludge development

When the nutritional conditions are met, depending on the temperature, pure bacterial population can double in a time interval of (20-50) min - bacterial doubling time t.D – under ideal lab conditions (Simionescu, 2009). In Figure 4 the bacterial growth is presented assuming the necessary nutritional conditions are provided; for this model, the treatment plant capacity doubles in a short time, with sufficient adaptability to wastewater load changes: this is the valid model for the priming phase, as there are no nutritional deficiencies. In practice, the need to adapt the biological mass to the quality conditions of the influent wastewater has been highlighted, the period defined as the "lag phase" (Simionescu, 2009).

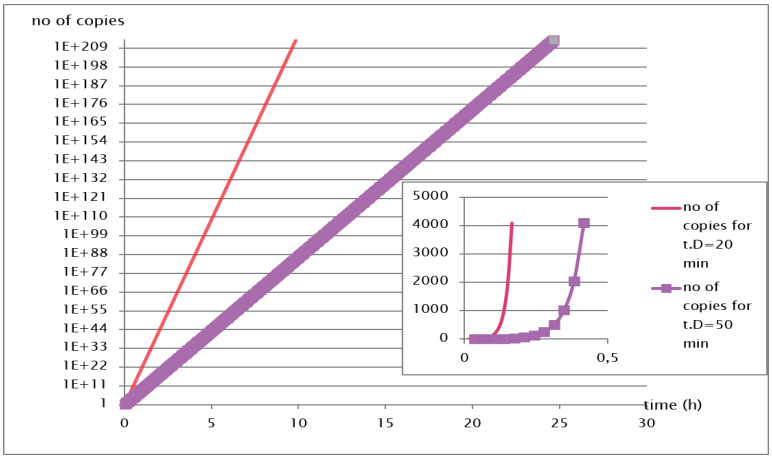


Figure 4. Bacterial development assuming optimal development conditions (t.D - bacterial doubling time)

In the following phases of activated sludge development (development of protozoa and nematodes) the dynamics change significantly, organic matter being hydrolyzed, metabolized and eliminated with secondary products, CO_2, NH_4 and P. The increase in suspended mass of activated sludge is thus diminished.

The mathematical models adopted in the wastewater treatment standard are based on the "sludge age" indicator, which can be interpreted as the period of development of the activated sludge that ensures the processing of a certain amount of pollutant (carbon, ammonia nitrogen, nitrates, phosphorus, and sludge stabilization), the maturation and stabilization of the activated sludge.

For the development of the bacterial mass capable of processing the corresponding loads of wastewater at the entrance to the treatment plants (MAPM-b, 2002), the proposed relationships depend on the temperature (equation 1):

$$T_{N,aerob} = FS \cdot 3{,}4 \cdot 1{,}103^{(15-T)}(days) \quad (1)$$

where:

$$T_{N,dim} = \frac{T_{N,aerob}}{1 - \frac{V_D}{V}}(days)$$

FS - security factor; 1.45-1.8 - depends on load variations at the inlet of the wastewater treatment plant
V - biological reactor total volume
V_D - denitrification compartment volume

In the case of nitrogen reduction in denitrification processes and biological stabilization of sludge at the technologic wastewater flux, the proposed relationships for sludge age defined as stock compared to daily production, the dynamics depend on sludge production determined with equation 2 (MDLPA, 2013):

$$N_{eC} = C_b(0{,}75 + 0{,}6\frac{c^b_{uz}}{x^b_{5,uz}} - \frac{0{,}102.T_N.F_T}{1+0{,}17.T_N.F_T}\left(kg\ d\frac{s}{day}\right) \quad (2)$$

where:
-N_{eC} - sludge production in kg d.s./day (dry substance/day)
-C_b - the amount of organic matter entering the wastewater treatment plant
-C^b_{uz} - suspension concentration in the influent of the biological reactor
-$x^b_{5,uz}$ - BOD_5 concentration in the influent of the biological reactor
T_N - sludge age
F_T - temperature factor for endogenous respiration

Determining the sludge age requires an iterative calculus.

Considering the equations presented and applied for standard situations, a biological reactor of 1 m^3 biological, operated with a load Iob (organic load index of the biological tank) in various temperature scenarios, results in the values for the graphs presented in Figure 5.

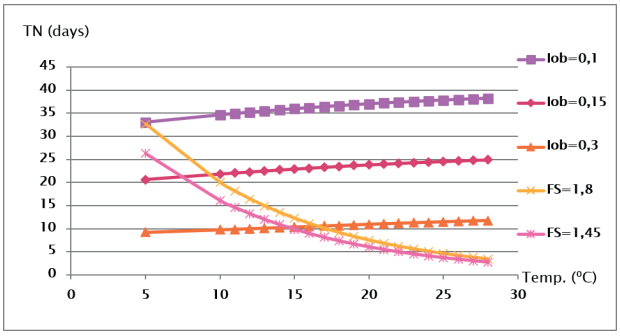


Figure 5. Sludge age determined for different temperature and organic load scenarios in the case of a standard wastewater treatment plant with an activated sludge concentration of 3000 mg/L

The analysis of the determined values results in reduced sludge ages in the case of low loads, Iob = 0.1 kg BOD_5/m^3 and day, respectively over 15 days in the case of loads of Iob = 0.3 kg BOD_5/m^3 and day.

In the exploitation variant with sludge stabilization, the third term in equation 2, which expresses the mineralization fraction, depends on the temperature and age of the sludge, respectively the bacterial development of the activated sludge.

The values of mineralization factor in Figure 6 are greater than 0.4 (inferior limit doable for operation) in the case of exploitation for

temperature greater than 10^0C and sludge age over 18 days. At a temperature of 25^0C, the mineralization factor greater than 0,4 is reached at a sludge age of 6 days.

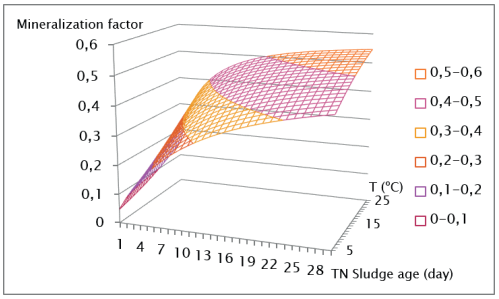


Figure 6. The mineralization factor for activated sludge determined in equation 2

When microbial products for sludge mineralization are used the result is the augmentation with 0.1 of mineralization factor in the case of exploitation for temperature greater than 10^0C and sludge age over 18 days. At a temperature of 25^0C and the sludge age of 6 days there is obtained a mineralization factor of 0.6. In operation, improving the mineralization factor becomes important, the values being a function of sludge doses and age.

CASE STUDY

Operation of wastewater treatment plants highlights the multitude of variants related to pollutant loads. In the case of industrial wastewater treatment plants, the operating range is wide and for these reasons the regulation capacity of the plants must ensure the treatment efficiencies.

Results are presented for a biological wastewater treatment plant in the food industry designed for a flow rate of 100 m^3/h and dissolved organic carbon concentrations of 2000 mg/L Technological problems are recorded, due to the sludge decantability, the high sludge volume index of over 200 ml/g the entrainment of suspensions in the treated wastewater, the high sludge production, and its low age. Table 3 presents the calculation of sludge age and sludge production according to equation 2 at maximum load.

According to the operating parameters, the critical section from the point of view of wastewater treatment is the "settlement" due to sludge load high values: the superficial load with total suspended matter of about 215 kg dry matter/m^2day (recommended range of 90-140), respectively the superficial volumetric load with sludge of 928 dm^3/m^2h (recommended range of 450-500), limits provided by the national design regulation NP 133/2013 (MDLPA 2013).

Table 3. Sludge age determined for the maximum load situation

Q (m^3/day)	2400
BOC influent (mg/L)	2000
Influent suspensions (mg/L)	100
T (^{0}C)	12
F.T. (-)	0.811738
Estimated T.N. (days)	4.28
Third term (-)	0.221475
$\frac{c^b_{uz}}{x^b_{5,uz}}$(-)	0.05
Sludge production (kg/day)	2680.92
V reactor (m^3/day)	4000
c.na (mg/L	3000
Sludge stock (kg/day)	12000
Calculated T.N. (days)–iterated result	4.245204

*third term – sludge mineralization factor

To improve the settling properties and increase the mineralization degree, microbial products (described in Table 4) were dosed, a mixture of microorganisms (over 3 x 109 microorganisms/g) and enzymes. The product is dosed directly into the aeration area of the wastewater treatment plant, with doses ranging from 3 kg/1000 m^3/day for starting de process, to 0.12 kg/1000 m^3/day for maintenance phase. The product can be applied in a wide range of temperature and pH indicator (Table 4).

Table 4. Microbial products utilized range of application

Conditions	Range	Optimum
dissolved oxygen, ppm	0-2.0	>0.5
pH	6-9	7
temperature, ^{0}C	10-40	35
toxic heavy metals, ppm	low presence	absent
nutrients		
BOD_5: NH_3-N	10:1 - 10:0.5	10:1
BOD_5: PO_4-P	100:1-100:0.5	100:1

The biological product contains microbiological strains capable of breaking down a wide

range of substances such as: lignocellulose, fats, greases, proteins, fibers, etc., without generating additional cell mass. The synergistic content of microbial strains, oligo-elements, minerals and vitamins improves the quality of wastewater treatment by reducing pollutants, optimizing sedimentation and reducing total costs. The frequency and amount of application dose are related to the influent volume, pollutant loading, biological reactors capacity, hydraulic retention time, physical and chemical parameters, etc.

Testing was carried out starting in the autumn-winter months and continued into the warm season. For the cold season, the minimum temperature in the biological reactors being 12^0C, sludge production decreased by 10% (estimated on sludge management sheets). During the warm season, at temperatures above 20^0C, sludge production decreased by 50%, the costs generated by sludge management being very low. These values are valid only for wastewater treatment plants designed for an average flux of 100 m^3/h and average COD of 2000 mg/L, by adding microbial products.

The cold period represents the critical operating interval, and in this case the additional biological activity due to the biological product addition generated a reduction in wastewater treatment efficiency. The values of effluent water quality indicators for carbon, nitrogen, phosphorus and suspensions increased as process temperatures decreased. Figure 7 shows the evolution of the biological product doses applied within every phase of the wastewater treatment process in September. A dose of 5.5 kg/day of microbial product is the maximum for the first stage and for the restoring.

Frequently, the phosphorus records increase in the discharged water when the input water loads are reduced and the biological process is unbalanced for sludge stabilization. Important variations in the quantities of pollutants at the entrance imply significant changes for the biological process. Sludge stabilization ensures good sludge decantability and filterability, therefore good mechanical dehydration, these processes are observed in the operation of the wastewater treatment plant. During the testing period, the release of phosphorus was highlighted by increases in concentrations in the discharged water and the need to increase dephosphorization doses (Figure 8).

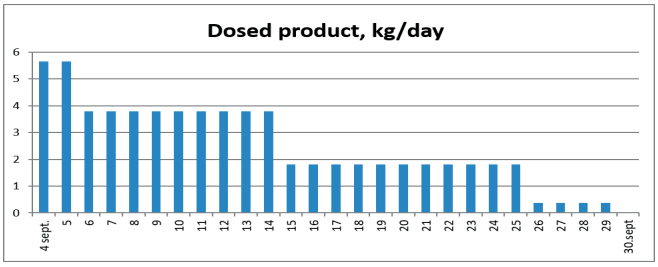


Figure 7. Product doses used in the process starting and maintenance phases

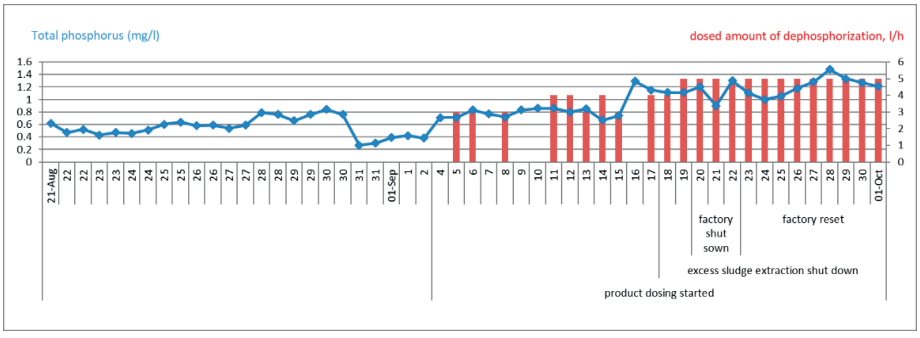


Figure 8. Evolution of the quantities of reagents for dephosphorization and the phosphorus indicator for discharged water

Concerning the biological activity, the decrease in wastewater treatment efficiency (Figures 9 and 10) was caused by: sludge mineralization processes due to the product use; decrease in temperatures decrease; treated wastewater flow rates increase; frequent use of biocidal products in the sterilization processes of the factory's production facilities.

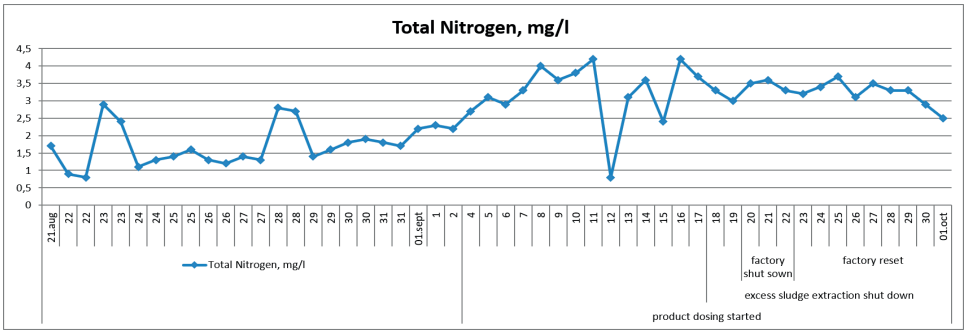


Figure 9. Evolution of the total nitrogen indicator for discharged water

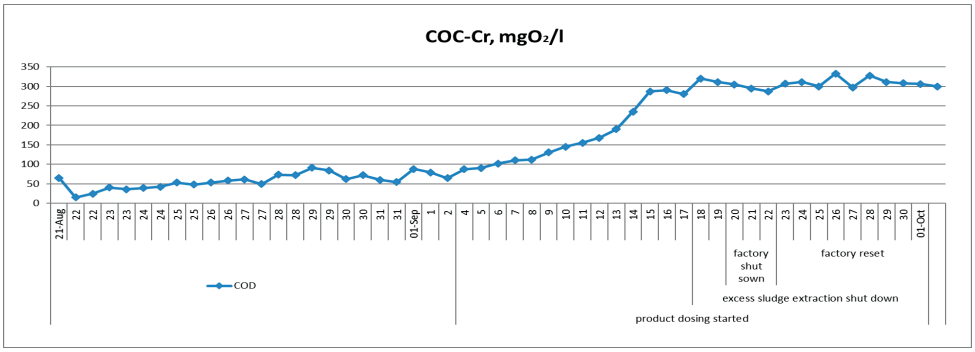


Figure 10. Evolution of the oxidizable organic substances COC-Cr indicator for discharged water

Technologically, the dissolved oxygen was maintained in the range (2-4) mg/L in automatic mode, with aeration reserves of over 100%, and for the external recirculation value, a level of approximately 1000% of the maximum input flow rate were ensured.
During the warm season, the microbial product ensured the sludge reduction by 50%; for the cold period, the use of biological product stimulates the sludge mineralization ensuring the sludge reduction of 50%

CONCLUSIONS

Industrial and domestic wastewater treatment plants do not always fulfill the tasks related to the stabilization of biological sludge.
The use of microbiological products in the case study shows a decrease of 10% to 50% of sludge quantities, depending on the season. The decreases mentioned above imply also modification of technological volumes, dissolved oxygen and additional dosing of dephosphorization reagents.
When reduced organic pollutant loads (under 50% design COD, namely 1000 mg/L) and temperatures below 10^0C within the process are present it is necessary to restore the capacity to assimilate and metabolize pollutants through additional dosing of microbial products of maximum 5.5 kg/day.
For industrial wastewater it would be benefic to revise the existing Regulation used for domestic wastewater treatment and adapting it for non-standardized loads.
Products to stimulate biological activity are beneficial, technological compartments are mandatory in order to develop specialized

biological mass and optimize wastewater treatment process.

Changing technological conditions impose modifying the wastewater treatment scheme and the type of products used. The case study and its results demonstrate the importance of the dynamic response in terms of introduction and dosing the microbial products when needed. As future works, the research will focus on using simultaneous two different microbial products, one for sludge mineralization, the second for the bacterial assimilation, in order to compare the results with the present study, for the cold season.

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REFERENCES

DWA (2000). ATV-DVWK-A131 – Standard for dimensioning of single-stage activated sludge plants

EU, 2024/3019 (2024). Directive of the European Parliament and of the Council of 27 nov 2024 concerning urban wastewater treatment (recast of Directive 91/271/CEE of 21 mai 1991 concerning urban wastewater treatment)

Li, J., Yang, X, Hu, A., Li, Y., Li, Y, Fu, L., & Yu, C.P. (2022). The performance and mechanism of sludge reduction by the biaoaugmentation approach, *Life,* 12 (10), 1649, 1-13.

MAPM-a (2002). NTPA 001/2002 - Regulation for establishing pollutant load limits for industrial and urban wastewater discharged into natural receptors

MAPM-b (2002). NTPA 002/2002 - Regulation regarding the conditions for discharging wastewater into the sewage networks of localities and directly into the wastewater treatment plants

MDLPA (2013). NP 133/2013 - Regulation for design, execution and operation of water supply and sewage systems of localities

MDLPA (2022). NP 133/2022 - Regulation for design, execution and operation of water supply and sewage systems of localities, volume I - Water supply systems; volume II – Sewage systems

Neamt, I., Ionel, I., & Vlaicu, I. (2013). Energy recovery of sludge in wastewater treatment plants in Romania, AGIR Bulletin, Supplement 1/2013, pp. 34–37, available at: https://www.agir.ro/buletine/1752.pdf

Rosiek, K. (2020). Directions and challenges in the management of municipal sewage sludge in Poland in the context of the circular economy, Sustainability, 12, 3686; doi:10.3390/su12093686, pp. 1–28

Simionescu, C. M. (2009). Biological wastewater treatment, MatrixRom Publishing House.