Procesing '24
37. Međunarodni kongres o procesnoj industriji
29–31. maj 2024, Beograd

Originalni naučni rad

ODRŽIVI TRETMAN KOMUNALNIH OTPADNIH VODA I MULJA: SIMULACIJA TEHNOLOŠKIH PROCESA

TOWARDS SUSTAINABLE MUNICIPAL WASTEWATER AND SLUDGE TREATMENT: SIMULATION OF TECHNOLOGICAL PROCESSES

Jovana Đokić*[1], Zoran Anđić[1], Dragana Radovanović[2], Marija Štulović[2], Nataša Gajić[2], Željko Kamberović[3],

[1]Univerzitet u Beogradu, Inovacioni centar Hemijskog fakulteta, Beograd
[2]Univerzitet u Beogradu, Inovacioni Centar Tehnološko-metalurškog fakulteta u Beogradu
[3]Univerzitet u Beogradu, Tehnološko-metalurški fakultet, Beograd

Komunalni otpadni mulj (MWS) je nezaobilazni nusproizvod u postrojenjima za prečišćavanje komunalnih otpadnih voda (MWTPs) i predstavlja ekološke i regulatorne izazove zbog visokog sadržaja biorazgradivih materija. U ovom radu urađena je simulacija biotretmana komunalnih otpadnih voda (MWB) primenom aktivnog mulja, praćena procesom stabilizacije i solidifikacije (S/S) komunalnog otpadnog mulja primenom CaO kao aditiva. Tretman ima za cilj proizvodnju neopasnog solidifikata u skladu sa propisima. Simulacija je urađena kombinacijom softverskih programa HSC Chemistry and SuperPro Designer, integrišući rezultate karakterizacije realnog uzorka komunalnih otpadnih voda i MWS, MWB ulazne i izlazne parametre i termodinamičke parametre reakcija procesa. Rezultati pokazuju da je za tretman MWS neophodno 38% CaO, čime se dobija solidifikat sa 14,5% vode, i koji čini 69,9% mase tretiranog mulja. Dobijeni proizvod pokazuje povoljna svojstva, sa visokim sadržajem $Ca(OH)_2$ (27,3%), $CaCO_3$ (36,8%) i neorganskih oksida (2,9%), što ga čini pogodnim za bezbedno odlaganje ili upotrebu - proizvodnja građevinskih materijala, betona, kao aditiv za asfalt, ili punjenje puteva i deponija. Tehno-ekonomska procena, skalirana za kapacitete MWTP od 2000 - 10000 t/god, pokazuje održivost najvećeg razmatranog kapaciteta, za period od 12 godina. Procena uticaja na životnu sredinu potvrđuje održivost S/S procesa, minimizirajući emisije uz efikasno iskorišćenje resursa. Ova studija naglašava izvodljivost implementacije naprednog sistema upravljanja otpadom, osiguravajući usklađenost sa propisima uz ekonomsku dobit.

Ključne reči: *komunalne otpadne vode; komunalni otpadni mulj; stabilizacija/solidifikacija; simulacija procesa; upravljanje otpadom*

Municipal wastewater sludge (MWS) is an unavoidable byproduct of wastewater treatment plants (MWTPs) and poses environmental and regulatory challenges due to its high biodegradable content. This study presents a simulation of municipal wastewater biotreatment (MWB) with activated sludge followed by a stabilization and solidification process (S/S) of MWS with CaO. The treatment aims to produce non-hazardous solidificate in accordance with regulations. Using HSC Chemistry

* Corresponding author: djokic@chem.bg.ac.rs
https://orcid.org/0000-0001-6949-668X

Zoran Anđić: https://orcid.org/0000-0003-2015-0607
Dragana Radovanović: https://orcid.org/0000-0002-2935-7711
Marija Štulović: https://orcid.org/0000-0002-7647-999X
Nataša Gajić: https://orcid.org/0000-0001-7546-9186
Željko Kamberović: https://orcid.org/0000-0003-0507-5346

and SuperPro Designer programs, simulations integrate municipal wastewater and MWS characterization results, MWB process and output parameters, and thermodynamic data. The results indicate that treatment requires 38% CaO, yielding solidificate with 14.5% water, comprising 69.9% of the treated sludge mass. The resulting product displays favorable properties for safe disposal or use, with high content of $Ca(OH)_2$ (27.3%), $CaCO_3$ (36.8%) and inorganic oxides (2.9%), making it suitable for various applications like producing building materials, concrete, asphalt additives, or filling road surfaces and landfills. The techno-economic assessment, scaled for 2000 - 10000 t/year MWTPs shows the viability of the largest capacity considered, for a period of 12 years. Environmental impact assessment confirms S/S sustainability, minimizing emissions and maximizing resource utilization. This study emphasizes the feasibility of an advanced waste management system, ensuring regulatory compliance and economic benefits.

Key words: *municipal wastewater; municipal waste sludge; stabilization/solidification; process simulation; waste management*

1. Introduction

Development and implementation of wastewater treatment plants (MWTPs) poses challenges for most countries, driven by factors such as economic resources, institutional strength, and technological aspects, all of which also influence pollution control. Concurrently, sewage production continues to rise, necessitating more efficient treatment solutions [1]. Traditional processes can be implemented individually or in combination to meet conditions regarding land availability, costs, mechanization, and compliance with regulatory standards regarding effluent quality. Factors influencing process selection, among others, include reliability, climate conditions, influent characteristics, flow variability, process kinetics, sludge processing, chemical and energy requirements, and environmental constraints (such as air, soil, and surface contamination, odors, noise, and devaluation of nearby areas, as well as sludge transportation) [2, 3]. In addition, a sustainable management strategy requires the efficient utilization of resources through policies and technologies that promote material and energy valorization while reducing pollutant emissions, especially sludge, often through a stabilization process [4]. This applies not only to municipal but also to industrial and other secondary materials [5, 6]. Common management for sludge was disposal in landfills. However, European regulations now prioritize waste stabilization and safe recycling over storage methods. This approach aims to recover valuable raw materials from potentially hazardous materials, enabling their use in agriculture, various industries, or energy recovery. To mitigate environmental degradation, the European Union has established directives concerning wastewater treatment, to regulate discharge into water or soil more strictly. All products derived from treatment must meet legal requirements for environmental safety to prevent risks to water, soil, air, plants, and animals, and avoid generating odors or other pollutants [7, 8].

Municipal wastewater comprises approximately 99.9% water, with the remaining portion consisting of organic and inorganic solids in various forms (suspended, dissolved, or settleable) and microorganisms, including pathogens and the coliform group. These constituents are considered pollutants, necessitating treatment to prevent adverse impacts on the environment and public health [9].

Besides physical and chemical methods, biological processes are the most significant and widely applied for municipal wastewater treatment. Various biological treatment methods are employed, including stabilization ponds, anaerobic or aerobic reactors, or activated sludge systems. The primary objectives include the removal of soluble organic matter, stabilization of insoluble organic matter, and transformation or removal of nutrients (N, P, S, K, Mg, Na, Ca, Cl, Mn), and method of choice depends largely on influent characteristics, climatic conditions and available space at the treatment plant [2]. Typically, the process begins with preliminary treatment to remove suspended particles and floating solids. Subsequently, organic substances are removed using appropriate biological treatment, and activated sludge systems conducted in sequencing batch reactors (SBR) is the most commonly used [10]. The activated sludge process in SBR consists of two phases: aeration and sludge settlement. Generally, for every kilogram of BOD_5 removed, 0.5-0.8 kg of dry-weight sludge containing 0.5-2.0% dry solids is produced. Parameters such as the food-to-microorganism ratio (0.2-0.5) and cell residence time (7-15 days) are crucial for controlling the activated sludge process. This process offers advantages such as low capital costs, minimal area requirements, low-temperature sensitivity, and high technical control [11]. However, it is susceptible to toxic shocks and changes in wastewater loads [12]. Regardless of the treatment method applied, the final step involves separating water from biomass, which represents MWS, along with additional nitrogen and phosphorus removal [13].

Essentially, traditional wastewater treatment methods are effective, but sustainable solutions for generated MWS remain elusive, necessitating the enhancement of existing approaches. The composition of MWS depends on the wastewater treatment step and process it originates from. Typically, it represents a mixture of all treatment levels, comprising over 95% water, which further complicates and limits its processing and handling. The MWS generated in MWB treatment using the activated sludge process contains organic matter primarily derived from biomass used in wastewater purification, along with inorganic compounds. Its processing involves volume and mass reduction, removal of pathogenic organisms through disinfection, and disposal. The selection of each processing step and method is determined by previous wastewater treatment and the ultimate MWS disposal objective [2, 14]. During disinfection, the sludge microflora changes; methane fermentation reduces the overall carbon content, while thermal processing, depending on temperature, may densify the sludge or transform organic matter into inorganic compounds. Disinfection is crucial for further sludge use. Common methods include composting, aerobic digestion, pasteurization, lime stabilization, and/or thermal drying. Each method has its advantages and drawbacks, with the choice influenced by cost, climate conditions, land availability, pollution control, and legislation [15]. Stabilizing dewatered MWS with calcium-rich alkaline agents and utilizing the resulting product as a cement manufacturing raw material is an attractive alternative [16, 17]. This process ensures a pH above 12, leading to microbial inactivation and low moisture levels (below 15%) due to the exothermic reaction, along with heavy metal immobilization [4, 18].

Before the actual experimental research, the step that enables better planning and the design of the experiments itself is the simulation of the selected process, which gives an insight into the process flow. Based on the review of available technologies, this study conducted simulations of municipal wastewater treatment using the activated sludge method in an SBR reactor. Additionally, simulations of stabilization and solidification of generated MWS using CaO were performed to obtain products suitable for disposal and further use, with minimal negative environmental impact while complying with regulations. Furthermore, a techno-economic analysis of the process was conducted, along with an assessment of environmental aspects, ensuring sustainability throughout the treatment process.

2. Experimental

2.1. Materials

The characterization of a real sample of municipal wastewater from a regional MWTP was conducted to determine the input parameters necessary for simulating the purification process. The values of Biochemical Oxygen Demand (BOD), Total Solids (TS), Total Nitrogen (TN), and Total Phosphate (TP) were determined, and their values are presented in Table 1. Additionally, the composition of oxides present as particles, contained in TS, in the wastewater was identified (Table 2).

Table 1. Municipal wastewater quality parameters

Parameter	*kg/day*	*Method*
BOD	4113.9	EN 1899.2:2009
TS	4799.6	EPA 351.3:1978
TN*	753.0	ISO 10304-1:2007
TP	123.9	SM 2540 F

*As NH_3 content

Table 2. Oxide particles contained in water

Oxide	*Content**
SiO_2	27.82
CaO	17.71
Fe_2O_3	16.85
P_2O_5	11.21
Al_2O_3	10.71
SO_3	10.59
MgO	2.56
K_2O	1.56
TiO_2	1.00

*Analytical method applied: EN 1899.2:2009

2.2. Simulations

For simulation of the biological treatment of municipal wastewater with activated sludge the SuperPro Designer program was used. Due to the multi-step processes in the SBR reactor, the simulation was considered through subsequent steps (Fig. 1).

Input data were values shown in Tables 1 and 2. The reactions from aerobic processes - carbonization and nitrification (eq. 1 and 2), anaerobic processes - denitrification (eq. 3 and 4), phosphorus removal (eq. 5 and 6) were also incorporated in the simulation:

$$C_2H_5O_2N + 1.5O_2 \rightarrow 2CO_2 + NH_3 + H_2O \quad (1)$$

$$NH_3 + 2O_2 \rightarrow HNO_3 + H_2O \quad (2)$$

$$5C_2H_5O_2N + 9HNO_3 \rightarrow 7N_2 + 10CO_2 + 17H_2O \quad (3)$$

$$2HNO_3 \rightarrow N_2 + H_2O + 2.5O_2 \quad (4)$$

$$FeCl_3 + H_3PO_4 \rightarrow FePO_4 + 3HCl \quad (5)$$

$$FePO_4 \rightarrow Fe_2O_3 + P_2O_5 \quad (6)$$

Considering the biological treatment of wastewater is carried out by metabolic processes of microorganisms – biomass which represents activated sludge, treatment results in the biomass growth and this is also included in the simulation (eq. 7):

$$\text{Organic matter} + \text{Biomass} \rightarrow \text{Biomass Growth} \quad (7)$$

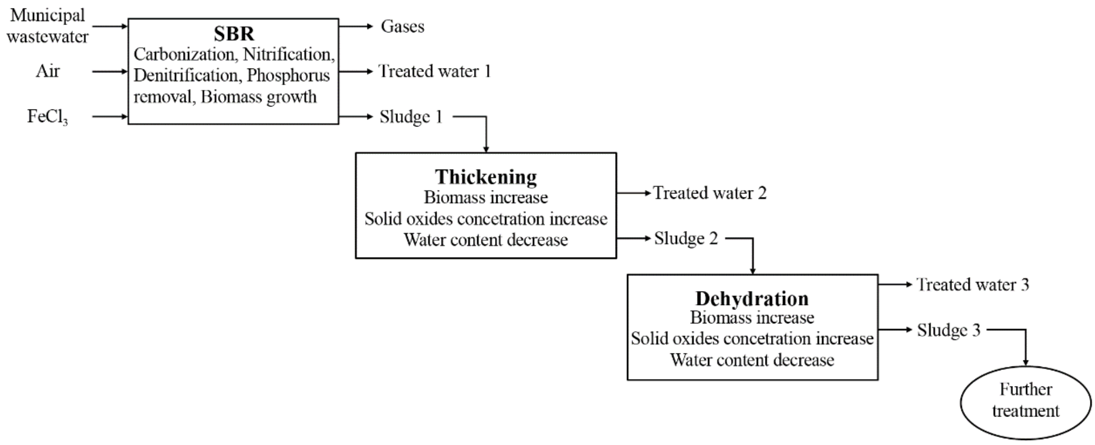

Figure 1. Simulation scheme of municipal wastewater biotreatment

Additionally, data for plant capacity and wastewater volume provided by the regional MWTP were used. The wastewater treatment simulation aimed to evaluate the feasibility of the process and determine the quantity and composition of generated MWS and treated wastewater.

The output data from the MWB simulation were further utilized to simulate the treatment of MWS generated within the previous process. The reactions involved in the sludge stabilization and solidification through the addition of CaO as an additive encompass lime hydration (eq. 8), biomass mineralization (eq. 9), carbonization (eq. 10), and water evaporation (eq. 11):

$$CaO + H_2O \rightarrow Ca(OH)_2 \quad (8)$$

$$Biomass + 5.25xO_2 + 5xCaO \rightarrow 5xCaCO_3 + 3xH_2O + xNH_3 \quad (9)$$

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (10)$$

$$H_2O(l) \rightarrow H_2O(g) \quad (11)$$

Alongside, the S/S process simulation included thermodynamic parameters, specifically the process enthalpies (ΔH, kJ/mol) and Gibbs energies (ΔG, kJ/mol), at various temperatures, depicted by reactions (8 - 11), determined using the HSC Chemistry software [19]. The thermodynamic data are presented in Table 3. The SuperPro Designer program consolidates all the obtained data, and the process scheme is presented in Figure 2.

Table 3. Thermodynamic data of possible reactions in the MWS treatment process

Process	*Equation*	*Parameter, kJ/mol*	*Temperature, °C*				
			20	*40*	*60*	*80*	*100*
Hydration	(8)	ΔH	-65.594	-66.178	-66.751	-67.315	-65.001
		ΔG	-57.420	-56.879	-56.304	-55.697	-57.923
Mineralization	(9)	ΔH*	-1778.454	/	/	/	/
Carbonization	(10)	ΔH	-113.201	-112.511	-111.811	-111.112	-110.413
		ΔG	-73.302	-70.603	-67.948	-65.335	-62.763
Evaporation	(11)	ΔH	44.212	43.379	42.545	41.713	40.873
		ΔG	9.155	6.792	4.481	2.221	0.007

*Due to the complexity of the process ΔH of the mineralization reaction was not calculated in the HSC Chemistry program [4]

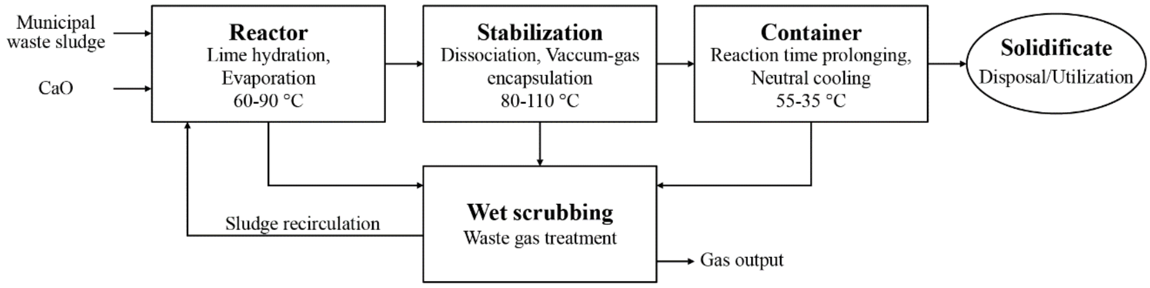

Figure 2. Simulation scheme of municipal waste sludge treatment

Based on the simulation data, the capacity of the MWS treatment plant was dimensioned for MWS production of 2.200, 5.500 and 10.000 t/y, along with the corresponding material balance calculations, following the standard methodological approach of united nations industrial development organization (UNIDO) and the World Bank. The basic elements for planning financial flows, upon which the profitability of the project has been analyzed, were: *(i)* the amount of capital investment in the project, *(ii)* sources of financing for capital investments in the project, *(iii)* the economic lifespan of the project, *(iv)* net cash flow expected from the project, namely the annual financial benefits expected from the project (the difference between inflows and outflows per year), and *(v)* the amount of cash that will be released at the end of the economic lifespan of the project. Additionally, an assessment of the environmental impact of the stabilized MWS (solidificate) was conducted as part of the S/S process evaluation.

3. Results and discussion

3.1. Simulation of municipal wastewater biotreatment

The results of the simulation of biological treatment with activated sludge in the SBR reactor are shown in Tables 4 to 6, as the composition of the input and output streams of the process. Table 4 represents the results of the simulation for the first step of the treatment – SBR process.

Table 4. Biological treatment of the municipal wastewater – simulation of SBR proces

Process	*Component*	*Flow, kg/h*	*Content, %*	*Concentration, g/l*
		Input		
Municipal wastewater	Al_2O_3	0.7872	0.0003	0.0035
	NH_3	102.5350	0.0451	0.4506
	CaO	1.3018	0.0006	0.0057
	$C_2H_5O_2N$	109.4110	0.0481	0.4808
	K_2O	0.1146	0.0001	0.0005
	MgO	0.1881	0.0001	0.0008
	TiO_2	0.0735	0.0000	0.0003
	H_3PO_4	0.2448	0.0001	0.0011
	SiO_2	2.0457	0.0009	0.0090
	SO_3	0.7786	0.0003	0.0034
	H_2O	227354.43658	99.9044	999.0443

Process	*Component*	*Flow, kg/h*	*Content, %*	*Concentration, g/l*
	Total	227571.9170	/	/
Air	N_2	6961.8252	76.8200	0.9603
	O_2	2100.6914	23.1800	0.2898
	Total	9062.5166	/	/
$FeCl_3$	$FeCl_3$	0.6148	40.0000	397.8817
	H_2O	0.9222	60.0000	596.8226
	Total	1.5370	/	/
		Output		
Gases	CO_2	10.4889	0.1162	0.0014
	HCl	0.2733	0.0030	0.00003
	N_2	7055.9856	78.1783	0.9204
	O_2	1958.7537	21.7024	0.2555
	Total	9025.5020	/	/
Treated water 1	H_2O	217414.8068	100.0000	994.7043
Sludge 1	Al_2O_3	0.7872	0.0077	0.0767
	Biomass	65.9160	0.6464	6.4311
	CaO	1.30182	0.0128	0.1270
	Fe_2O_3	0.19943	0.0020	0.0195
	$FeCl_3$	0.2096	0.0021	0.0205
	K_2O	0.1146	0.0011	0.0112
	MgO	0.1881	0.0018	0.0183
	TiO_2	0.0735	0.0007	0.0071
	P_2O_5	0.1773	0.0017	0.0173
	SiO_2	2.0457	0.0201	0.1996
	SO_3	0.7786	0.0076	0.0759
	H_2O	10125.5457	99.2960	987.9027
	Total solid	/	/	7.0000
	Total	10197.3380	/	/

As shown in Table 4, for the total municipal wastewater flow (value provided by the sample supplier), the treated water (denoted as Treated water 1) from the SBR process is free from impurities and safe for discharge [20]. The emitted gas primarily consists of a mixture of N_2 and O_2, corresponding to the composition of environmental air. The generated waste sludge (denoted as Sludge 1) contains over 99% water, with the remainder consisting of biomass - active sludge, used for wastewater treatment, and inorganic substances inherited from the input material. Further, the simulation of the second step of the treatment – thickening - was performed, and the results are shown in Table 5.

Table 5. Biological treatment of the municipal wastewater – simulation of the thickening process

Process	*Component*	*Flow, kg/h*	*Content, %*	*Concentration, g/l*
Input				
Sludge 1	As shown in Table 4			
Output				
Treated water 2	Al_2O_3	0.0393	0.0005	0.0049
	Biomass	3.2958	0.0407	0.4067
	CaO	0.0651	0.0008	0.0080
	Fe_2O_3	0.0099	0.0001	0.0012
	$FeCl_3$	0.0105	0.0001	0.0013
	K_2O	0.0057	0.0001	0.0007
	MgO	0.0094	0.0001	0.0012
	TiO_2	0.0037	0.0000	0.0005
	P_2O_5	0.0089	0.0001	0.0011
	SiO_2	0.1023	0.0013	0.0126
	SO_3	0.0389	0.0005	0.0048
	H_2O	8100.4366	99.9557	999.5571
	Total	8104.0260	/	/
Sludge 2	Al_2O_3	0.7478	0.0357	0.3557
	Biomass	62.6202	2.9914	29.7841
	CaO	1.2367	0.0591	0.5882
	Fe_2O_3	0.1895	0.0091	0.0901
	$FeCl_3$	0.1992	0.0095	0.0947
	K_2O	0.1089	0.0052	0.0518
	MgO	0.1787	0.0085	0.0850
	TiO_2	0.0699	0.0033	0.0332
	P_2O_5	0.1684	0.0080	0.0801
	SiO_2	1.9434	0.0928	0.9244
	SO_3	0.7397	0.0353	0.3518
	H_2O	2025.1091	96.7419	963.2044
	Total	2093.3110	/	/

In a simulation of the thickening process conducted on the waste sludge generated in an SBR (Sludge 1), it is observed that the treated water exiting the process contains metal oxide impurities in the form of solid particles. However, the individual concentrations of these particles are found to be below the prescribed limit concentrations, rendering the discharge safe for release into the designated receiving environment, as per regulatory standards [20]. Notably, no gas emissions are recorded during the duration of this process. The waste sludge produced in this second step (denoted as Sludge 2), due to removal of the water not associated with the sludge particles or flocs, exhibits a *(i)* notably higher biomass concentration, ranging from 4 to 5 times greater than that of Sludge 1 and *(ii)* an increase in the concentration of inorganic components.

In the last step, a simulation of the dehydration process was performed, to further reduce the water content in the waste sludge, and the results are shown in Table 6.

Based on the presented simulation results, it has been determined that the water exiting the system contains a 4 to 5 times higher proportion of oxide solid particles compared to the effluent from the previous cycle. However, the flow rate per hour is up to 5 times lower. Additionally, the expected concentrations of individual compounds are below the recommended limits, as in the previous case [20]. Once again, no waste gas generation is observed. The waste sludge generated (denoted as Sludge 3) represents the total sludge of the MWB. The simulation revealed that Sludge 3 contains nearly 8 times higher biomass content and an equal amount of oxide solid particles, while the water content after the dehydration process, initially at 96.74% (Table 5), is reduced to 75% (Table 6). The generated waste sludge (Sludge 3) is biologically stabilized and dehydrated, and according to its characteristics, it belongs to the group of non-hazardous/inert wastes, characterized by the increased concentration of components present in the influent wastewater. Moreover, it contains compounds resulting from the MWB process (phosphates, organic residues). However, despite being biologically stabilized, the generated waste sludge fails to meet two essential criteria for disposal or further use due to the high content of organic matter [20]. Additionally, the high water content significantly complicates the transport of this waste. Therefore, due to all the aforementioned reasons, it is necessary to treat the generated MWS before further disposal or use.

3.2. Simulation of municipal waste sludge treatment

Based on the results of the MWB simulation and using thermodynamic data (Table 3) of the reactions involved in the process itself (eq. 8-11), simulation of the MWS stabilization and solidification process was done. Also, calculation of the CaO amount required as an additive for S/S was conducted. The results are presented in Table 7.

The simulation results indicate that 38% of CaO relative to the mass of waste sludge is required for the treatment, resulting in a solidified product with 14.5% water content and a mass of 69.9% relative to the treated sludge. Sludge stabilization is achieved through the processes of lime hydration, mineralization of organic components (biomass), carbonization of hydrated lime and water evaporation. Specifically, the MWS formed by the biological treatment of municipal wastewater, with a high water content (75%), is mixed with CaO in the reactor, resulting in an extremely exothermic reaction. An increase in temperature, caused by the exothermic reaction, leads to the evaporation of water from the system, the decomposition of organic matter and its mineralization [4], while the released CO_2 reacts with hydrated lime in the carbonation reaction. Those processes are described by the equations (8-11). As a result of the sludge treatment, an inert material is obtained. The ultimate effect of production of the solidificate is the reduction of the initial waste quantity and the attainment of a product with utility value.

Table 6. Biological treatment of the municipal wastewater – simulation of the dehydration process

Process	*Component*	*Flow, kg/h*	*Content, %*	*Concentration, g/l*
Input				
Sludge 2	As shown in Table 5			
Output				
Treated water 3	Al_2O_3	0.0374	0.0020	0.0203
	Biomass	3.1310	0.1707	1.6982
	CaO	0.0618	0.0034	0.0335
	Fe_2O_3	0.0095	0.0005	0.0051
	$FeCl_3$	0.0099	0.0005	0.0054
	K_2O	0.0054	0.0003	0.0029
	MgO	0.0089	0.0005	0.0049
	TiO_2	0.0035	0.0002	0.0019
	P_2O_5	0.0084	0.0005	0.0046
	SiO_2	0.0972	0.0053	0.0527
	SO_3	0.0369	0.0020	0.0200
	H_2O	1830.6987	99.8141	992.9083
	Total	1834.1090	/	/
Sludge 3	Al_2O_3	0.7104	0.2741	2.7461
	Biomass	59.4892	22.9508	229.9573
	CaO	1.1749	0.4533	4.5416
	Fe_2O_3	0.1799	0.0694	0.6958
	$FeCl_3$	0.1892	0.0730	0.7313
	K_2O	0.1034	0.0399	0.3998
	MgO	0.1698	0.0655	0.6563
	TiO_2	0.0664	0.0256	0.2564
	P_2O_5	0.1599	0.0617	0.6185
	SiO_2	1.8463	0.7123	7.1368
	SO_3	0.7027	0.2711	2.7164
	H_2O	194.4105	75.0033	751.4998
	Total	259.2030	/	/

Table 7. Simulation results of the municipal waste sludge S/S process

Process	*Component*	*Flow, kg/h*	*Content, %*
		Input	
Sludge 3	H_2O	194.4105	75.0033
	Biomass	59.4892	22.9508
	Inorganic oxides	5.3030	2.0459
	Total	259.2030	/
Additive	CaO	98.4970	100.0000
		Output	
Solidificate	$Ca(OH)_2$	49.4243	27.2749
	$CaCO_3$	66.7620	36.8425
	H_2O	26.2303	14.4751
	Biomass	33.4892	18.4810
	Inorganic oxides	5.3030	2.9265
	Total	181.2088	/

3.3. Possibilities of solidificate disposal and its utility value

MWS solidificate obtained from waste treatment processes, due to the high content of minerals: $Ca(OH)_2$ 27.3%, $CaCO_3$ 36.8% and inorganic oxides 2.9% (Table 7), possesses properties and characteristics that make it suitable for disposal as well as for further use [4]. The utility value of solidificate is reflected in its potential use as a raw material for producing various building materials. By adding cement, sand, and other additives, concrete or other construction elements can be manufactured, which can have wide applications in construction, considering they are non-ecotoxic and non-biodegradable. Solidificate can be applied as a covering layer in municipal waste landfills, employed for neutralizing acidic waste streams in waste gas or water treatment, utilized as a raw material for producing cement clinker, added to asphalt mixes, mixed with gravel for road base and landfill liner construction [4, 21].

3.4. MWS treatment plant capacity sizing

Based on the simulation of wastewater and MWS treatment, with input data for a plant capacity of nearly 2M tons/year of wastewater, sizing was performed for 5.500 and 10K tons/year of generated sludge. The calculation results, including hourly, daily, and annual flow rates, are presented in Table 8.

Acording to the simulation results of the treatment and the considered capacities of the treatment plants, the consumption of CaO, as the sole reagent/additive used in the stabilisation and solidification process, was calculated. These data, based on the required quantity of 38% CaO relative to the mass of generated waste sludge, were further utilized for the techno-economic analysis of the process.

Table 8. Capacity sizing for municipal waste sludge treatment

Capacity	*Component*	*Flow*		
		kg/h	*kg/d*	*kg/y*
Simulation base	Municipal wastewater	227571.9	5461726.0	1993530.0
	MWS	259.2	6220.9	2270.6
	Additive	98.5	2363.9	862.8
	Solidificate	181.2	4349.0	1587.4
Scale 1	Municipal wastewater	557083.3	13370000.0	4880050.0
	MWS	634.5	15229.1	5558.6
	Additive	241.1	5787.1	2112.3
	Solidificate	443.5	10645.2	3885.5
Scale 2	Municipal wastewater	1002310.9	24055462.0	8780244.0
	MWS	1141.6	27397.3	10000.0
	Additive	433.8	10411.0	3800.0
	Solidificate	797.9	19150.7	6990.0

3.5. Analysis of the process economic viability

Incorporating the sized capacities of the treatment plants and the initial assumptions: a one-year investment cycle, a project economic life of 15 years, and defined project costs, an evaluation of the process was conducted. Based on the analytical examination of the profit and loss account and economic trajectory of the project, it is determined that the payback period for the annual production capacity of the plant, set at 5.500 t/y of MWS, extends to 17 years and 170 days. This duration surpasses the established economic lifespan of the project. Consequently, investments allocated towards this capacity are deemed unjustifiable. Conversely, the evaluation of investments reveals that for the annual production capacity of 10.000 t/y of MWS, the repayment period does not exceed the economic duration of the project, set at 15 years. Specifically, the investment return period for this capacity is calculated at 12 years and 145 days, thus validating investments directed towards this capacity as justified. This indicates that the considered MWB and MWS treatment process using CaO as the sole additive is economically viable.

3.6. Environmental impact analysis

Considering the stabilization and solidification process of waste sludge, including the reactions (eq. 8-11) and process products (Table 7), it has been determined that the gases and vapors generated are a result of water evaporation and degradation of organic matter. Waste gases and vapors, aside from dust particles, predominantly contain water vapor, which arises from the solidification reaction, i.e. from the reaction of the CaO additive with water/moisture contained in the waste sludge. Additionally, traces of organic vapors may be found in the waste stream as a consequence the temperature increase. Therefore, it is necessary to purify the generated waste gas using filters. The filtered dust, possessing characteristics of the final product, is collected and deposited in the tank for solidificate. On the other hand, gas with vapors and water vapor, liberated from the dust of the solidification, is further subjected to scrubbing (gas washing), after which it is safely released into the atmosphere. The sludge generated in the wet scrubber is recirculated back to the S/S reactor. Another potential waste stream analyzed is the wastewater from the S/S process. However, considering the pronounced exothermic nature of the process reactions, wastewater as a liquid phase is not generated. Based on the consideration and analysis of possible waste streams of the sole S/S process, it is concluded that through the application of simple apparatus-technical solutions, it does not pose a source of environmental pollution and that the considered process for MWS treatment offers a sustainable solution.

4. Conclusion

Insight into the current legal regulations in waste management, as well as a review of available technologies, allowed defining the optimal processes for municipal wastewater treatment, altogether with further MWS treatment. Accordingly, this study conducted a simulation of MWB using activated sludge in an SBR reactor, followed by a simulation of stabilization and solidification of the generated MWS using CaO as the sole additive. It was determined that wastewater treatment offers environmental-frendly output when it comes to water as an effluent, but the generated sludge requires additional treatment. Further, it is concluded that S/S with calcium oxide allows extensive chemical changes in the sludge, providing the chemical and thermal energy required to evaporate the moisture contained in waste sludge, leading to the degradation and mineralization of organic matter, and thus carbonization of hydrated lime. All of the aforementioned results in a reduction of the initial waste quantity and the attainment of a product with utility value following legal recommendations. By sizing the simulation results for different MWTPs capacities, it was determined that for a production capacity of 10,000.0 tons/year, the investment return period is 12 years and 145 days, which makes investments in the project for the said capacity justified. Furthermore, through an analysis of the environmental impact, it was determined that the sole S/S process exhibits sustainability, with no negative environmental impact, allowing the recirculation of by-products.

5. Acknowledgements

Presented research was supported by the Ministry of Science, Technological Development and Innovation of Republic of Serbia, Contract numbers: 451-03-66/2024-03/200288, 451-03-65/2024-03/200135 and 451-03-66/2024-03/200287.

6. Nomenclature

BOD - biochemical oxygen demand
MWB - municipal wastewater biotreatment
MWS - municipal wastewater sludge
MWTPs - wastewater treatment plants
SBR - sequencing batch reactors
S/S - stabilization and solidification process
TN - total nitrogen
TP - total phosphate
TS - total solids
UNIDO - united nations industrial development organization

7. References

[1] **Akyol, Ç., A. Foglia, E. G. Ozbayram, N. Frison, E. Katsou, A.L. Eusebi, F. Fatone,** Validated innovative approaches for energy-efficient resource recovery and re-use from municipal wastewater: From anaerobic treatment systems to a biorefinery concept, *Critical Reviews in Environmental Science and Technology, 50*(2020), 9, pp. 869–902. https://doi.org/10.1080/10643389.2019.1634456

[2] **Von Sperling, M.**, *Wastewater characteristics, treatment and disposal,* IWA publishig, London, UK, 2007. https://doi.org/10.2166/9781780402086

[3] **Karolinczak, B., J. Walczak, M. Bogacka, M. Zubrowska-Sudol**, Life Cycle Assessment of sewage sludge mono-digestion and co-digestion with the organic fraction of municipal solid waste at a wastewater treatment plant, *Science of the total environment*, *907*(2024), pp. 16780, https://doi.org/10.1016/j.scitotenv.2023.167801

[4] **Valderrama, C., R. Granados, J.L. Cortina,** Stabilisation of dewatered domestic sewage sludge by lime addition as raw material for the cement industry: Understanding process and reactor performance, *Chemical Engineering Journal, 232*(2013), pp. 458–467, http://dx.doi.org/10.1016/j.cej.2013.07.104

[5] **Radovanović, D., M. Ranitović, Ž. Kamberović, M. Korać, M. Gavrilovski,** Treatment of wastewater from new copper smelter RTB Bor, Process Engineering, *29*(2017), 1, pp. 20-26, https://doi.org/10.24094/ptc.017.29.1.20

[6] **Štulović, M., D. Radovanović, Ž. Kamberović, M. Korać, Z. Anđić, M. Ranitović,** Leaching of toxic elements from secondary alkaline lead slag and stabilized/solidified products. *Journal of Material Cycles and Waste Management, 21*(2019), pp. 1402–1413, https://doi.org/10.1007/s10163-019-00892-8

[7] *** European Parliament, Council Directive 91/271/EEC, http://data.europa.eu/eli/dir/1991/271/2014-01-01

[8] *** European Parliament**,** Council Directive 2008/98/EC, http://data.europa.eu/eli/dir/2008/98/2024-02-18

[9] **Demirbas, A., G. Edris, W.M. Alalayah,** Sludge production from municipal wastewater treatment in sewage treatment plant, *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *39*(2017), 10, pp. 999–1006, https://doi.org/10.1080/15567036.2017.1283551

[10] **Meng, X., Z. Huang, G. Ge,** Upgrade and reconstruction of biological processes in municipal wastewater treatment plants, *Desalination and Water Treatment*, *317*(2024), pp. 100299, https://doi.org/10.1016/j.dwt.2024.100299

[11] **Scholz, M.**, *Chapter 15 - Activated Sludge Processes. Wetlands for Water Pollution Control*, Elsevier, 2016, pp. 91-105, https://doi.org/10.1016/B978-0-444-63607-2.00015-0

[12] **Hang, Z., P. Tong, P. Zhao, Z. He, L. Shao, Y. Jia, X.C. Wang, Z. Li,** Hierarchical stringent response behaviors of activated sludge system to stressed conditions, *Science of The Total Environment, 870*(2023), pp. 161832, https://doi.org/10.1016/j.scitotenv.2023.161832

[13] **Gao, X., Q. Zhang, S. Zhang, J. Li, C. Gu, G. Chen, Y. Peng,** Novel three-sludge municipal wastewater treatment process coupling denitrifying phosphorus removal with anaerobic ammonium oxidation, *Bioresource Technology, 399*(2024), pp. 130562, https://doi.org/10.1016/j.biortech.2024.130562

[14] **Fang, Y., H. Xie, B. Chen, Z. Han, D. An, W. Cai, W. Zhang, Y. Wang,** Achieving carbon neutrality in Shanghai's municipal wastewater treatment sector requires coordinated water

conservation and technical improvement, *Journal of Cleaner Production*, *443*(2024), pp. 141134, https://doi.org/10.1016/j.jclepro.2024.141134

[15] **Cieślik, B.M., J. Namieśnik, P. Konieczka,** Review of sewage sludge management: standards, regulations and analytical methods, *Journal of Cleaner Production, 90*(2015), pp. 1-15, https://doi.org/10.1016/j.jclepro.2014.11.031

[16] **North, J.M., J.G. Becker, E.A. Seagren, A.M. Asce, M. Ramirez,** Methods for quantifying lime incorporation into dewatered sludge. II: field-scale application, *Journal of Environmental Engineering*, *134*(2008), 9, pp. 762–770, https://doi.org/10.1061/(ASCE)0733-9372(2008)134:9(762)

[17] **Marcinkowski ,T.A.,** Effect of alkalization process on changes in the chemical composition of secondary sludge, *Environment Protection Engineering, 36*(2010), 2, pp. 153–160.

[18] **Srivastava, A.N., S. Chakma**, Lime sludge assisted anaerobic bioreactor landfilling of municipal solid waste for enhanced leachate stabilization and bioenergy yield, *Process Safety and Environmental Protection, 178*(2023), pp. 278-286. https://doi.org/10.1016/j.psep.2023.08.039

[19] **Roine, A.,** (2016) HSC Chemistry® v 9.0 [Software]. Outotec Research Oy Center, Pori

[20] Rulebook on categories, testing and classification of waste, 67/2011, 48/2012, and 1/2016. Official Gazette of the Republic of Serbia, Belgrade, Serbia, 2017.

[21] Rodríguez, N.H., R.J. Granados, M.T. Blanco-Varela, J.L. Cortina, S. Martínez-Ramírez, M. Marsal, M. Guillem, J. Puig, C. Fos, E. Larrotcha, J. Flores, Evaluation of a lime-mediated sewage sludge stabilisation process. Product characterisation and technological validation for its use in the cement industry, *Waste Manage*ment, *32*(2012), 3, pp. 550-560, https://doi.org/10.1016/j.wasman.2011.10.021