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STRUCTURAL ANALYSIS OF SLUDGE FROM THE ARAD WASTEWATER TREATMENT PLANT: REDUCING QUANTITY AND ENHANCING ITS POTENTIAL AS FERTILIZER

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Abstract

Sludge from sewage treatment plants is a byproduct of wastewater treatment processes, consisting of solid particles, microorganisms, and organic and inorganic substances. It is generated during sedimentation and digestion processes to remove contaminants such as organic matter, heavy metals, and chemicals from water. Before storage or disposal, sludge is typically treated to reduce its volume and eliminate pathogens. Standard treatment methods include dehydration, biological stabilization, and incineration. Depending on its composition, treated sludge can be repurposed for agricultural use as fertilizer, provided it meets strict regulatory standards to prevent soil and groundwater contamination. In Romania, sewage sludge is generally classified as waste under European and national legislation. According to the European Union Waste Directive 2008/98/EC, sludge is considered waste if it cannot be safely treated, recovered, or reused. Studies have explored its potential environmental risks, including soil contamination and its suitability as a fertilizer. This article presents a structural sludge analysis, focusing on its physicochemical properties and moisture content. Experiments were conducted to evaluate the behavior of sludge samples under varying temperatures, exposure durations, and drying conditions. Results showed that evaporation rates increased with temperature, with significant differences observed between ventilated and non-ventilated drying environments. At temperatures ranging from 50°C to 100°C, sludge mass consistently decreased, with the lowest masses recorded in ventilated drying processes at 100°C. In non-ventilated conditions, the percentage of evaporation increased progressively with prolonged heat treatment. Additionally, heavy metal concentrations in the sludge were experimentally determined and found to be below the limits imposed by national legislation. These results confirm that the analyzed sludge samples are suitable for agricultural use, aligning with regulatory requirements.

***Key words**: chemical composition, heavy metals, sludge, unventilated currying, ventilated heat currying.*

INTRODUCTION

During the pre-accession period to the European Union (EU), various strategies for sludge management were formulated, though their execution differed among countries. A primary strategy involved aligning national legislation with EU directives, specifically the Urban Wastewater Treatment Directive (91/271/EEC) and the Sewage Sludge Directive (86/278/EEC), which set forth regulations for sludge treatment, monitoring, and land application (Council of the European Communities, 1991; Council of the European Communities, 1986). Simultaneously, investments were directed towards enhancing wastewater treatment infrastructure to upgrade facilities and optimize sludge handling processes. Various disposal and valorisation strategies have been investigated in light of the rising sludge production. Land application in agriculture is advocated as a sustainable practice, contingent upon the sludge adhering to strict criteria concerning heavy metal levels and pathogen reduction (Fytili & Zabaniotou, 2008). Due to constrained treatment capacities, numerous countries have opted for landfilling or temporary storage, contrary to the EU's long-term goal of minimizing sludge disposal in landfills. Composting and co-composting are promoted as methods for transforming sludge into a beneficial soil amendment for agricultural, landscaping, and land reclamation purposes (Smith, 2009). The exploration of anaerobic digestion as a method for reducing sludge volume and generating biogas for renewable energy production was initiated. However, the adoption of this technology was limited at that time (Yaser et al., 2022). In addition to these technical strategies, public awareness campaigns and institutional capacity-building initiatives were launched to inform stakeholders, such as municipalities, farmers, and industries, about the safe and effective management of sludge (Benedetti et al., 2008; Vinayagam et al., 2024). The initial strategies established a foundation for developing more sophisticated sludge management policies after EU accession. Thus, only 0.2% of the sludge was used on agricultural land (Ministerul Mediului și Pădurilor, Direcția Generală AM POS Mediu, 2011).

Accumulated sewage sludge is essentially wet matter, which can currently be stored on special platforms equipped with drainage systems or directly on the ground (Qasim & Shareefdeen, 2022), subsequently finding a solution to remove it, to make room for another amount of sludge, or it can be used in some branches of agriculture, to improve the quality of soils, through the content of phosphorus and nitrogen (Shi et al., 2021).

Sludge recovery is not the main objective of the urban wastewater treatment process. Still, it should be considered as a means of removing sludge from the treatment plant area without having a negative impact on the environment. Therefore, it is crucial to balance the amount of sludge generated and recovered through effective sludge management (Andreoli et al., 2015).

Unfortunately, significant amounts of dewatered sewage sludge are stored in improper conditions, causing the sludge to become a source of pollution (Iacob & Deac, 2021).

The peculiarities of the circular economy (CE) in the management of municipal wastewater and sewage sludge in the specific context of local conditions, such as those in Poland, were analyzed by Kacprzak (Kacprzak & Kupich, 2021) and Lipińska (Lipińska, 2018), with a focus on clean and ecological technologies. From the perspective of the circular economy, in addition to the recovery, collection, and use of biogas as an energy source, the recovery of materials resulting from the purification process, such as gravel, or the extraction of phosphorus from sludge or ash (piles) can also be considered (Domini et al., 2022).

Russian Federation researchers conducted a preliminary assessment of the possible uses of biogas from sewage sludge in the Water - Wastewater - Sludge and Circular Economy sector. They used a computational model for biogas and biomethane, $MCBioCH_4$, comparing the results with laboratory tests on sewage sludge fermentation (Kiselev et al., 2019).

Bratina et al. (2016) carried out a study in which it presented a method of drying the sludge in a vacuum at low temperatures, as well as treating the sludge by reducing heavy metals with nanoparticles covered with chitosan.

MATERIALS AND METHODS

To analyze the influence of temperature on the drying of dewatered sludge under different ventilation conditions, 14 sludge samples were collected from the sewage treatment plant in the Municipality of Arad. They were dried in an oven and weighed at regular intervals. The purpose of the determinations was to evaluate the efficiency of the drying process according to its duration. As part of the experiment, tests were carried out using sludge samples with known moisture, exposed to drying for different periods. The drying time was divided into three intervals: 30 minutes, 60 minutes, and 100 minutes.

To study the evaporation phenomenon in more detail, the impact of temperature on the drying process of dewatered sludge was also investigated, using two distinct temperatures: 50°C and 100°C. Before and after drying, the samples were weighed using Petri dishes and a high-precision analytical balance Kern Adb 100-4. After measuring the initial mass of the dewatered sludge samples (m_1) and the final mass (m_2) after drying, the degree of evaporation (GE) was calculated, which represents the evaporated mass concentration, expressed as a percentage (Olsson & Newell, 2015), which was later used to evaluate the degree of evaporation of the sludge samples analyzed in this research using the calculation formula:

$$GE = ((m_1 - m_2) / m_1)) \cdot 100 \; [\%] \qquad (1)$$

Experiments were conducted under both ventilated and unventilated conditions to assess the impact of airflow on the drying process. Additionally, heavy metal content was determined using flame and electrothermal atomic absorption spectrometry (FAAS/ETAAS) to evaluate the potential environmental risks associated with sludge re-use (ISO 11047:1998).

The collected sludge was subjected to a physicochemical analysis to check if the samples meet the necessary parameters for use in other fields, according to the requirements established in the experimental research.

RESULTS AND DISCUSSIONS

The dehydrated sludge at 50°C under unventilated conditions

To carry out the experiments in non-ventilated conditions of the drying space, three of the 14 samples taken and prepared by weighing will be used. Sampling was performed in duplicate, and the estimated value is the average of the two measurements. Dewatered sludge with a solids (SS) content of 22% was the source from which the samples were selected for the experiments. The three samples will be introduced simultaneously into the drying space at a temperature of 50°C. Samples will be drawn at 30, 60, and 100 minute intervals. After each draw, the samples will be weighed immediately to determine the percentage of water evaporated.

It is assumed that all parameters are identical, namely the size of the drying space, the temperature, and the absence of ventilation. Table 1 shows the values obtained by calculation, according to formula (1), for the three samples subjected to drying in a non-ventilated space at 50°C for 30, 60, and 100 minutes.

Table 1. Results for 50°C - unventilated

Time [min]	Initial mass m_1 [g]	Final mass m_2 [g]	Petri dish [g]	Evaporation rate [%]
30	15.32	14.16	36.2	7.57
60	16.12	14.33	36.2	11.10
100	17.23	13.51	36.2	21.59

It can be seen from Table 1 that after 30 minutes, the percentage of humidity decrease is 7.57%. After 60 minutes, the humidity decreases by 11.10%, increasing to 21.59% at a holding time of 100 minutes.

In order to determine the optimal temperature at which sludge drying is effective, another 3 (three) samples from the remaining 11 samples were used.

The dehydrated sludge at 100°C under unventilated conditions

The research was carried out under the same conditions (unventilated closed space), increasing the working temperature from 50°C to 100°C. For this set of experiments, the conditions of the previous experiment were maintained in terms of periods.

The parameter change is only the temperature, which has increased from 50°C to 100°C. In conditions where the workspace is not ventilated, the parameter that influences the degree of evaporation is the temperature, which increases from 50°C to 100°C.

This experiment was done to show how water evaporation is influenced by increasing temperature. The first experiment showed how water evaporation is influenced by holding time to dry. Also, through the graphic representation in the temperature-time coordinates, it is possible to see how the holding time for drying influences the evaporation of water under conditions where the working temperature doubles. The results align with findings from other researchers, who reported that proper air circulation prevents water vapor from recondensing on sludge, enhancing drying efficiency (Santos et al., 2020).

Table 2 shows the values resulting from the calculations according to the calculation formula (1), results obtained for the three samples subjected to drying in a non-ventilated space, at a temperature of 100°C, for time intervals of 30, 60 and 100 minutes.

Table 2. Results for 100°C - unventilated

Time [min]	Initial mass m_1 [g]	Final mass m_2 [g]	Petri dish [g]	Evaporation rate [%]
30	16.32	12.06	36.2	26.10
60	16.58	10.15	36.2	38.78
100	17.05	5.21	36.2	69.44

Table 2 shows that, in the case of the sample subjected to the thermal treatment of 100°C, after 30 minutes, the percentage of moisture decrease is 26.10%. After 60 minutes, the humidity decreases by 38.78%; after 100 minutes, the decrease reaches 69.44%.
The graphical representation in Figure 1 illustrates the evolution of evaporation as the temperature increases from 50°C to 100°C. Thus, water evaporation rises from 7.57% after 30 minutes at 50°C, reaching 21.59% after 100 minutes.

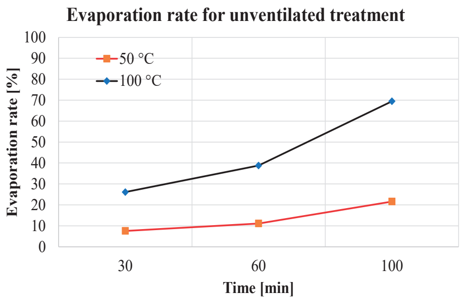

Figure 1. Evaporation rate for unventilated treatment.

The evaporation phenomenon significantly intensifies when the temperature is increased from 50°C to 100°C, reaching 26.10% after 30 minutes and 79.44% after 100 minutes.

The dehydrated sludge at 50°C under ventilation conditions

In order to highlight the influence of ventilation on the drying process, experiments were carried out under the same temperature and time conditions, replacing the non-ventilated drying space with a ventilated one.
The three samples were simultaneously introduced into the drying space at a temperature of 50°C. The first sample was left in the drying space for 30 minutes, the second was dried for 60 minutes, and the third was dried for 100 minutes. After each time interval, each sample was weighed to compare the weight of the dried sample with its weight before drying. The difference in weight was considered equal to the weight of the amount of water evaporated following drying.
Table 3 shows the values obtained by calculation, according to formula (1), for the three samples subjected to drying in a ventilated space at 50°C for 30, 60, and 100 minutes.

Table 3. Results for 50°C - ventilated

Time [min]	Initial mass m_1 [g]	Final mass m_2 [g]	Petri dish [g]	Evaporation rate [%]
30	16.77	13.26	36.2	20.93
60	17.12	10.13	36.2	40.83
100	18.02	7.11	36.2	60.54

Table 3 shows the decrease in humidity after 30 minutes, at a temperature of 50°C, in a ventilated space, by 20.93% for the first sample. After 60 minutes, under the same conditions, the degree of evaporation increases to 40.83%, and after a period of 100 minutes in the drying space, the evaporation reaches 60.54%.
These experiments highlight how the phenomenon of water evaporation from the dewatered sludge is influenced by the holding time, under the conditions of a ventilated drying space, at a temperature of 50°C.

The dehydrated sludge at 100°C under ventilation conditions

The research was conducted under the same conditions (ventilated closed space), but the working temperature increased from 50°C to 100°C. Three other samples were used for the second set of experiments (at a temperature of 100°C).
In these experiments, the conditions of the first set were kept unchanged, the only change being

the temperature increase from 50°C to 100°C. The purpose of these experiments was to highlight how temperature influences the evaporation of water during the heating process.
Table 4 shows the values obtained by calculations, according to formula (1), for the three samples subjected to drying in a ventilated space at a temperature of 100°C for 30, 60, and 100 minutes. The results presented in Table 4 indicate that, under the conditions of drying in a ventilated space, at a temperature of 100°C, the evaporation of water is 47.76% after 30 minutes. After 60 minutes, at the same temperature, the degree of evaporation reaches 62.43%, and after 100 minutes, at a temperature of 100°C, in the ventilated space, the degree of evaporation reaches 78.24%.

Table 4. Results for 100°C - ventilated

Time [min]	Initial mass m_1 [g]	Final mass m_2 [g]	Petri dish [g]	Evaporation rate [%]
30	15.62	8.16	36.2	47.76
60	16.29	6.12	36.2	62.43
100	16.13	3.51	36.2	78.24

Ventilation of the drying space significantly increases the efficiency of the drying process. Figure 2 shows that the drying differences between 50°C and 100°C (which are very large in the case of drying without ventilation) are greatly reduced when using ventilated spaces. Proper ventilation of the space can reduce the drying temperature while maintaining the efficiency of the drying process.

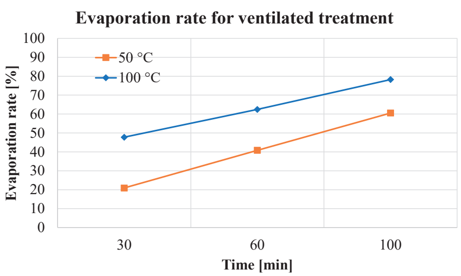

Figure 2. Evaporation rate for ventilated treatment

Interpreting the results offers multiple solutions and combinations of temperatures, drying spaces, and time that can optimize the drying process. One can analyze the degree of increase in evaporation percentage under different temperature conditions and the same time conditions to identify the most efficient settings. The results in Figures 3 and 4 highlight the optimal conditions of time, temperature, and drying space necessary to ensure efficient drying of the dehydrated sludge originating from the wastewater treatment process in the treatment plants.
Moreover, in the case of non-ventilation of the drying space, a progressive increase in the percentage of evaporation was observed, which increased as the heat treatment progressed. This phenomenon suggests that, in the absence of ventilation, the evaporation process continues progressing as the drying time increases, but with a lower efficiency than in ventilated conditions.

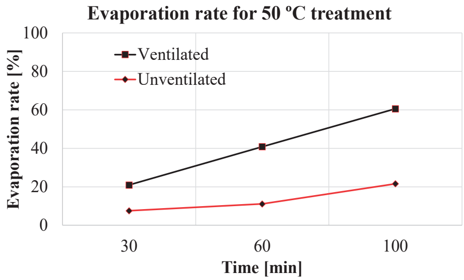

Figure 3. Evaporation rate for 50°C treatment.

The investigated dewatered sludge samples were subjected to a chemical analysis to determine the composition of the elements in the sludge, to identify the presence of heavy metals, which may constitute a risk of environmental pollution (Suciu et al., 2008).

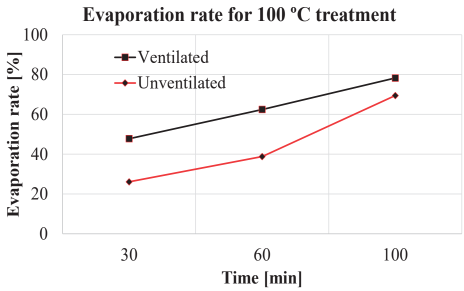

Figure 4. Evaporation rate for 100°C ventilated treatment

The dewatered sludge was chemically analyzed for heavy metals in accordance with ISO 11047:1998.

Table 5 shows the results of the analyses. Chemical: dry matter, organic matter, heavy metals (ISO 11047:1998), total nitrogen (ISO 13878:1998). The analyses were mainly conducted to determine the heavy metals in the dewatered sludge. The percentage of these elements in the dewatered sludge is essential in determining the final destination of the dewatered and dried sludge.

The nutrient content of experimentally determined sludge (ISO 11047:1998) is of remarkable importance when the sludge is utilized as an agricultural fertilizer or used to improve soil conditions. They enrich the soil with substances essential for plant growth, making dewatered sludge a useful resource in agriculture. Also, the use of sludge in agriculture is conditioned by the presence and amount of heavy metals (copper, zinc, lead, chromium, etc.), which have a high degree of toxicity and accumulate in the soil (ISO 11047:1998).

Table 5. Chemical analyses performed on the sludge sample

Determined parameters	UM	The value obtained	Analysis method	Maximum limit*
Dry substance (DS)	[%]	17	STAS12586-87	
Organic Substance	[%]	82,5	STAS12586-87	
Manganese	[mg/kg DS]	283	ISO 11047/1999	
Copper	[mg/kg DS]	337	SR EN ISO 11047/1999	*500
Zinc	[mg/kg DS	988	SR EN ISO 11047/1999	*2000
Crom	[mg/kg SU]	181	SR EN ISO 11047/1999	*500
Lead	[mg/ kg DS]	34	SRENISO 11047/1999	*300
Total nitrogen	[% DS]	5.19	ISO 13878:1998	-
Cobalt	[mg/kg DS]	110	SR EN ISO 11885:2009	*50
Calciu	[%]	2.88	EPA7000B	-
Potasiu	[%]	0.61	EPA7000B	-

Suppose urban sludge contains low amounts of heavy metals, generally below the permissible limits. In that case, sludge resulting from the combined treatment of domestic and industrial water may have higher concentrations of heavy metals, depending on the industry profile. Therefore, periodic chemical analysis of sludges is required to monitor and control their levels.

CONCLUSIONS

The comparative graphic representation of the results of drying the samples at a temperature of 50°C and 100°C (without ventilation) shows a linear increase in water evaporation from 7.57% after 30 minutes at 50°C, reaching a value of 21.59% after 100 minutes. The phenomenon of evaporation intensifies as the temperature increases from 50°C to 100°C. After 30 minutes, the percentage of evaporation is 26.10%. After 100 minutes, the value is 79.44%.

Following these experiments, it was highlighted how the evaporation of water is influenced by the temperature and the time allocated to the drying process in the conditions of a non-ventilated drying space. The increase in the degree of evaporation from 7.57% to 26.10% after 30 minutes, with the increase in temperature from 50°C to 100°C, represents a 3.4-fold increase. After 60 minutes, the increase is from 11.10% to 38.78%, representing a 3.4-fold increase. After 100 minutes, the evaporation percentage increases from 21.59% to 69.44%, a 3.2-fold increase.

The drying process is carried out in the non-ventilated drying space without evenly distributing the heat throughout the sludge mass. Lack of ventilation causes water vapor released during drying to condense and return to the dried sludge.

The ventilation of the drying space significantly increases the efficiency of the drying process. The drying differences between 50°C and 100°C, which are very large in the case of drying in non-ventilated spaces, are greatly reduced when using ventilation spaces with an increasing trajectory, but a linear trajectory.

In contrast, in the ventilated drying space, at a temperature of 50°C and a drying time of 30 minutes, the degree of dehydration is 20.93%. Raising the temperature to 100°C and keeping the drying time the same results in an evaporation rate of 47.76%, a 2.2-fold increase. After 60 minutes, the degree of dehydration increases from 40.83% to 62.43%, a 1.5-fold increase. After 100 minutes, the degree of evaporation is 60.54% at 50°C, and at 100°C it increases to 78.24%, a 1.3-fold increase. The rate of increase in evaporation remains relatively constant, and the increase is more uniform in the case of ventilation of the drying space, as opposed to drying in unventilated spaces.

Water vapor returning to the sludge negates dewatering efforts. Moreover, these vapors can be toxic and, by accumulation, become dangerous. Sludge drying should only be done in properly ventilated areas that allow evaporation to be controlled and vapors to be directed to safe areas for condensation and disposal without endangering the safety of the work area.

Experiments carried out in unventilated spaces have shown that sludge drying is possible with higher temperatures and longer times. Still, the uncontrolled presence of vapors in the working space constitutes a significant risk and prevents the process from being carried out on an industrial scale. The degree of evaporation remains relatively constant during drying. The lack of homogeneity of temperature in the drying space, caused by the absence of ventilation, leads to high evaporation rates.

The values obtained from these experiments highlighted the correlation between temperature, drying time, and the degree of evaporation.

With the increase in the drying temperature, a constant increase in the evaporation percentage was observed, which increased as the heat treatment increased. This phenomenon indicates that evaporation continues to occur in the absence of ventilation as drying time increases, but at a lower efficiency compared to ventilated drying conditions. Following the analysis of the chemical substances from the sludge samples from the Arad Wastewater Treatment Plant, especially the heavy metals, it was proven that they are far below the limits allowed by the standards in force (Directive 86/278/CEE), which means that it can be used as a fertilizer for plants and used on agricultural land, without affecting the ecological balance.

Future research will focus on finding safe areas for the use of dewatered and dried sludge so that in the near future, sludge will be viewed not as a colossal waste but as an inexhaustible resource.

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