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SUSTAINABLE STRATEGIES FOR SEWAGE SLUDGE MANAGEMENT: CHALLENGES, OPPORTUNITIES, AND INTEGRATED APPROACHES

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Abstract: Within the European Union, the treatment and recovery of sludge from wastewater treatment plants have become a critical topic, due to their environmental, economic, and social implications. Proper management of this material requires a coordinated approach that combines technical solutions, regulatory compliance, and institutional oversight to ensure safe disposal or beneficial reuse. Effective sludge management covers the organization of all stages, including collection, treatment, transport, recovery, and final disposal, while protecting both public health and the environment. Processes must be adapted to local conditions and the specific properties of the sludge, considering applicable national and EU legislation. A regional water utility continuously generates sludge from its wastewater treatment operations This highlights the need for a sustainable management plan that incorporates recovery methods—such as agricultural or forestry applications—as well as safe disposal alternatives. Current recovery practices involve using sludge as a natural fertilizer when it meets legal quality standards, application on degraded soils, or co-incineration in industrial facilities like cement plants. Ensuring compliance also requires ongoing monitoring of sludge quality in accordance with regulatory requirements, such as those outlined in Order no. 344/2004. Ultimately, the main goal of sludge management is to implement treatment and disposal strategies that minimize environmental impact while recovering valuable resources, aligning with sustainable development principles.

Keywords: Wastewater treatment plant, Sludge management, Sustainable management, Agricultural application

1. INTRODUCTION

Efficient sludge management requires attention to its environmental impact and the implementation of sustainable recovery solutions. Achieving this demands an integrated approach that includes preventing excessive sludge formation, controlling its composition, and reducing its volume through optimized technological processes.

In Romania, sludge management is governed by a structured institutional framework. The Ministry of Environment, the National Environmental Protection Agency, and their subordinate institutions (ARPM, APM) have clearly defined responsibilities, including approving agricultural use of sludge, monitoring its quality, preparing annual reports, and ensuring compliance with environmental legislation.

The National Administration "Romanian Waters" plays a key role in authorizing activities and monitoring their impact on water resources, while the Ministry of Agriculture is responsible for analysing soil quality and assessing the suitability of sludge for agricultural applications.

Before sludge is applied to land, agrochemical studies must be carried out by specialized institutions, such as the Research Institute for Pedology and Agro chemistry. Operators must also ensure traceability and maintain high quality standards. Agricultural use is allowed only if all parameters established by Order no. 344/2004 and other applicable regulations are met.

In conclusion, proper sludge management requires not only adequate technological treatment but also close inter-institutional collaboration to ensure the responsible and sustainable use of these residues.

2. SLUDGE MANAGEMENT STRATEGY

The main aim of the sludge management strategy is to achieve long-term improvements in environmental quality by minimizing the negative consequences of improper sludge handling. The strategy proposes practical and sustainable approaches, including viable methods for sludge recovery and reuse, stronger stakeholder participation in recovery activities, and raising awareness about the safe and effective use of sludge in agriculture.

The overall goal is to provide practical tools for managing sludge and other residues produced by wastewater treatment plants.

In southern of Romania, the strategy sets out the following objectives:

- Assessing and balancing the quantity and quality of sludge generated.
- Identifying suitable disposal and recovery routes, prioritizing agricultural use, while also considering alternative applications such as energy production.
- Promoting regional recovery strategies, including concentration measures and combined treatment with other waste streams.
- Supporting the operational capacity of companies that handle sludge from treatment plants to ensure safe and legally compliant recovery or disposal. This includes recovery for agriculture, energy production, and other uses that provide both economic and

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ecological benefits, such as rehabilitating degraded lands or closing existing landfills.

The specific application of disposal and recovery principles will depend on local economic, social, climatic, and geographical conditions.

Finally, successful implementation of the strategy requires effective public communication and engagement, ensuring community support for proposed solutions and addressing potential resistance or reluctance.

3. LEGISLATIVE FRAMEWORK

The management of sludge from wastewater treatment is governed by European directives and national regulations that protect the environment, public health, and natural resources. In this context, the legal framework establishes clear obligations for operators, public authorities, and end-users of sludge.

At the European level, key directives such as Directive 86/278/EEC (on the protection of soil when sludge is used in agriculture), Directive 91/271/EEC (on urban wastewater treatment), and Directive 2008/98/EC (on waste) form the legal basis in this field. These directives are complemented by regulations covering the storage, incineration, transfer, and environmental monitoring of waste.

In Romania, the transposition of these directives has been achieved through normative acts such as:

- Law no. 211/2011 on the waste regime.

Government Decision no. 349/2005 on waste disposal.

- Joint Order no. 344/708/2004 on technical norms for the use of sludge in agriculture.
- Law no. 188/2002 on the conditions for the discharge of wastewater into the aquatic environment.
- Decision no. 1061/2008 on the transport of waste within Romanian territory.

These regulations establish requirements regarding the composition of sludge, recovery methods, authorization procedures, monitoring and reporting obligations, as well as sanctions applicable in case of non-compliance.

It is essential that any local sludge management strategy aligns with the legal provisions in force and that technical documents, including feasibility studies, include explicit references to the applicable normative acts.

Thus, the legislative framework underpins sludge management activities, ensuring compliance with European standards and safeguarding the public interest. Current quantities of sludge from wastewater treatment plants

4. STUDY CASE

The quantities of sludge generated in wastewater treatment plants in the operating area analysed are shown in the table below. The dehydrated sludge has a dry matter content of 18-22%.

Table 1. The quantities of sludge

Nr crt	Capacity	Amount of sludge produced
	(EI)	**tone/year**
1	125800.00	3610.00
2	20400.00	2370.00
3	4443.00	21.80
4	1800.00	10.90
5	1800.00	9.81
6	4500.00	19.08
7	3750.00	16.35
8	2000.00	10.90
EI	equivalent inhabitants	

The quality of sludge resulting from wastewater treatment processes is a fundamental criterion in determining the appropriate method of recovery or disposal. It is determined by the physicochemical and biological composition of the sludge, which must comply with the limits imposed by the regulations in force to be used, for example, in agriculture.

According to Order no. 344/2004, the use of sludge in agriculture is permitted only if the maximum allowed concentrations for heavy metals and other contaminants—such as cadmium, lead, mercury, copper, zinc, nickel, arsenic, and chromium—are respected. Parameters such as dry matter content, pH, nutrient concentrations (nitrogen, phosphorus, potassium), and the level of organic matter are also considered.

Analyses performed on sludge samples from the wastewater treatment plants indicate. compliance with the values set by national legislation for most of the relevant parameters. However, continuous monitoring is important, as seasonal variations, plant load types, and industrial influences can significantly alter sludge quality.

The interpretation of laboratory results is essential for selecting the recovery option: if the sludge complies with the standards, it can be used in agriculture or forestry; otherwise, it must undergo further treatment or be disposed of under controlled conditions (e.g., final disposal or co-incineration).

In conclusion, the assessment of sludge quality is not merely a matter of legal compliance but a strategic step in the integrated waste management process within the water sector, contributing to environmental protection and efficient resource recovery. According to the results of the analyses, all sludge samples fall within the provisions of Order no. 344/2004 and, as a result, the sludge produced can be used in agriculture.

Disposal to ecological waste landfills is not an option, since one of the acceptance requirements for sludge is a dry matter content of at least 35%.

The sludge can be used in agriculture if the regional operator obtains an Application Permit from the County Agency for Environmental Protection, based on a special Agrochemical Study prepared by the Office for Pedological Studies and Agro chemistry and approved by the Directorate for Agriculture and Rural Development.

Currently, sludge from existing treatment plants is utilized in agriculture.

The quality of agricultural land includes both soil fertility and the influence of other environmental factors on plants. From this perspective, agricultural land is divided into five quality classes, differentiated by the bonitation score (Class I: 81–100 points; Class V: 1–20 points), as follows:

Class I (very good): land without limitations for arable use;

Class II (good): land with minor limitations for arable use;

Class III (medium): land with moderate limitations for arable use;

Class IV (poor): land with severe limitations for arable use;

Class V (very poor): land with extremely severe limitations, unsuitable for arable use, vineyards, or orchards.

Land quality classes determine their suitability for agricultural purposes.

The share of agricultural land by quality classes in 2024 within the analysed area is as follows:

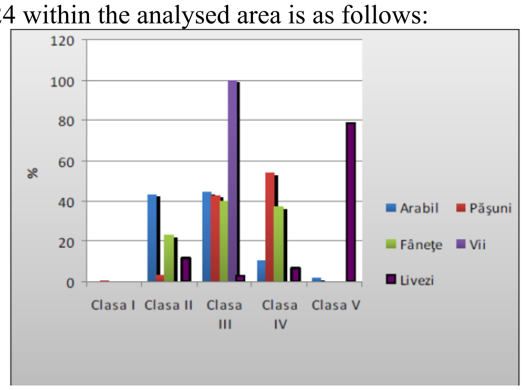

Fig. 1. Share of agricultural land

The share of types of use in total agricultural land in 2024 is presented in the graph below:

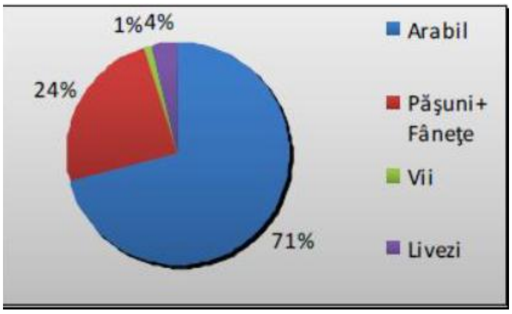

Fig.2 . Types of use in total agricultural land in 2024

As can be seen from the above information, the share of agricultural land is 71% of the total land fund, so the option of valorising sludge from sewage treatment plants in agriculture is a feasible one.

In the options regarding the valorisation/disposal of sludge, priority is always given to using the fertilizing potential of sewage sludge, because if the quality standards of sewage sludge are met, this is the most sustainable solution.

In addition to the option of valorisation in agriculture, the second feasible solution is energy recovery through incineration or in industrial processes, depending on local conditions.

The advantages and disadvantages of the most common ways of valorising/disposing of sludge are briefly presented in the following table.

Table 2. advantages and disadvantages

Options for Sludge Recovery/Disposal		
Recovery/Disposal Option	Advantages	Disadvantages
Land application (agriculture, forestry, and soil quality improvement)	Environmentally sustainable solution Benefits for both the sludge producer and the end user	Relatively limited experience in Romania Complex option from a logistical and administrative point of view Strict monitoring and control required for application Seasonal constraints (application periods)
Incineration with energy recovery (mono- or co-incineration)	Significant volume reduction Recovery of sludge calorific value Continuous solution	High investment and operational costs Need for ash disposal in specially designed landfills
Combustion (as supplementary fuel in industry)	Complete destruction of sludge Recovery of calorific value Continuous solution	Limited number of industries capable of using sludge as an alternative fuel

Regarding Sludge Management, the following potential options for sludge recovery and disposal are considered:

- Recovery as fertilizer in agriculture
- drying and disposal at the Ecological Landfill
- drying and co-incineration at the Cement Factory
- drying/incineration and thermal recovery.

Investment costs refer to:

• purchase and installation of sludge treatment equipment (centrifuges, belt filters, drying systems);

• arrangement of composting platforms or temporary storage basins.

• construction of infrastructure for energy recovery or controlled storage.

Agricultural recovery, although one of the cheapest methods in terms of disposal costs, involves a series of expenses for agrochemical analyses and specific logistics. Co-incineration involves higher costs but brings benefits through energy recovery.

In contrast, final storage is considered the least sustainable option and involves environmental taxes, high transport costs and ecological risks, which makes it increasingly less economically and legally viable.

For effective planning, it is essential to carry out a comparative analysis of the available options, which includes all short- and long-term costs, but also indirect benefits, such as reducing the impact on the environment and increasing the degree of resource reuse.

Sludge recovery and disposal costs

• In order to ensure sustainable and efficient management of sludge resulting from wastewater treatment, it is necessary to implement integrated solutions, adapted to the local context and legal requirements. Among the most relevant proposed solutions are:

1. Modernization of treatment infrastructure – replacing outdated equipment with modern sludge dewatering and stabilization technologies, which would ensure a significant reduction in volume and an improvement in the quality of the final product.
2. Creation of local partnerships – between wastewater treatment plant operators and farmers or local authorities, to facilitate the controlled application of sludge in agriculture and its use in land rehabilitation projects.
3. Diversification of recovery methods – by integrating co-incineration, composting and use in forestry, depending on the characteristics of the sludge and local market requirements.
4. Implementation of traceability systems – to accurately monitor the quantities of sludge produced, transported and recovered, ensuring transparency and compliance with environmental regulations.
5. Information and training campaigns – aimed at operators, farmers and local decision-makers, to promote good practices and encourage social acceptance of sludge reuse.
6. Access to European funds – for investments in modern equipment, innovative recovery projects and the development of the infrastructure necessary for sustainable management.

These measures, applied coherently and coordinated, can contribute to reducing the negative impact on the environment, to the recovery of the resources contained in sludge and to the achievement of the sustainable development objectives assumed at national and European level.

Financial analysis of sludge strategy options

The management of sludge resulting from treatment plants is an essential component of the environmental protection and responsible use of resources strategy. The analysis carried out in this paper highlights the fact that sludge, although considered waste, can become a valuable resource if it is treated, monitored and used appropriately.

By applying modern treatment and recovery methods, such as use in agriculture, co-incineration or composting, both the volume of waste generated and the negative impact on the environment can be significantly reduced.

At the same time, the economic and ecological benefits of these methods justify the necessary investments in management infrastructure.

To ensure sustainable management, collaboration between public authorities, economic operators and local communities is essential. Clear policies, access to financing and awareness of the advantages of a circular approach to the resources resulting from wastewater treatment are needed.

In conclusion, sludge can be integrated into an efficient circular economy, provided that appropriate technical solutions are applied, supported by a coherent legislative framework and rigorous implementation. Thus, sludge management is no longer just an environmental obligation but becomes an opportunity for sustainable development.

5. CONCLUSIONS

This paper aimed to identify and analyse the optimal methods for managing sludge from 8 wastewater treatment plants. By researching relevant legislation, analysing technical data and evaluating current practices, a clear picture of the challenges and opportunities in the field was created.

The main conclusions are:

• Sewage sludge can represent a reusable resource, not just a waste, if it is treated and recovered appropriately.

• The most sustainable direction of use is agricultural recovery, complemented by methods such as co-incineration or composting.

• There is an obvious need to modernize treatment equipment and expand transport and recovery infrastructure.

• The involvement of local authorities and collaboration between institutions is vital for the success of any strategy.

• Compliance with the legislative framework and accessing European funds are essential conditions for the development of an efficient and sustainable system.

Therefore, the approach proposed in the paper provides a coherent direction for improving sludge management in the study area, with the possibility of extending it to the national level.

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