

# Catalysing water treatments: A Comprehensive Examination of sludge, its treatment and Energy Valorisation Solutions

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**Abstract.** The escalating production of sewage sludge in WasteWater Treatment Plant (WWTP) due to urban population growth and its management poses a substantial risk to the energetic and environmental efficiency of WWTP. This paper aims to explore the potential for sludge as a renewable energy source to reduce reliance on traditional energy through a systematic literature review of peer-reviewed articles and case studies. This overview demonstrated that various treatment methods such as anaerobic digestion, incineration, gasification, and pyrolysis are the most used and the most promising in terms of their energy outputs and effectiveness. The paper discussed the complexity of sludge composition, its financial burden on WWTP, and the crucial role in the success of these systems. Moreover, a comparative analysis of the different valorisation techniques was conducted that highlighted the energy production potential existing within each method and its underlying constraints while emphasising on the proper sludge management for overall efficiency. Finally, this paper recommended the need for sustainable, cost-effective approaches, considering legal standards for efficient WWTP.

## 1 Introduction

The global rise in urban population, accompanied by the expansion of WWTP, has led to a significant increase in the production of sewage sludge [1]. Sludge management is a critical aspect of sustainable waste treatment, particularly due to the challenges associated with its disposal.

This by-product of WWT poses significant environmental and health challenges if not properly managed [1]. In addition, in the dawn of an ever-increasing energy bills due to geopolitical conflicts and disturbance to the supply chain, the sludge can represent a renewable energy capable of reducing the dependence of WWTP to electricity and fossil fuels [2]. Therefore, it is crucial to explore innovative and sustainable approaches for sludge treatment and valorisation to minimise its adverse impacts and harness its benefits. This paper presents a comprehensive overview conducted to evaluate sludge treatment and valorisation methods generating energy therefore providing valuable insights for policymakers and stakeholders, enabling them to make informed decisions and implement effective strategies for sludge management.

The disposal of sludge derived from wastewater treatment facilities presents a demanding endeavour that plays a major role in the efficiency and success of a WWTP [2]. The significance of this practice was highlighted in Agenda 21, which outlines a set of directives to implement the three Rs-Reduce/Reuse/Recycle sludge from WWTP [4]. Conventional methods such as incineration, landfilling or ocean disposal lack environmental sustainability [5].

However, exploring sludge to energy processes offers a promising alternative.

Therefore, this paper strives to elucidate the multifaceted approaches in sludge management, focusing on innovative treatment technologies and their potential for energy recovery. It aims to bridge the gap between current sludge treatment practices and the pressing need for sustainable, efficient, and cost-effective solutions that not only minimize environmental impacts but also contribute to energy valorisation.

## 2 Methodology

The methodology adopted to achieve this objective relied on a literature review, focusing on the nexus between sludge treatment technologies and energy valorisation processes. This involves the aggregation and synthesis of peer-reviewed articles and case studies that highlight innovative methodologies, efficiency outcomes, and sustainability impacts of various treatment solutions. Critical to this process is the application of a multidisciplinary lens, integrating insights from environmental engineering, chemistry, and renewable energy studies to offer a holistic analysis of sludge treatment and its potential for energy recovery.

Subsequently, a comparative analysis framework was adopted, evaluating the efficacy, cost-effectiveness, and environmental sustainability of different sludge treatment technologies. This analysis will benefit from the inclusion of quantitative metrics, such as energy yield, greenhouse gas emissions, and operational costs, derived from meta-analysis of existing studies.

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### 3 Results and discussion

Organic pollutants in wastewater have the potential to be an energy source for treatment plants. Assessing various energy considerations in these plants, a chemical oxygen demand (COD) mass balance is deemed the most suitable method [7]. One kilogram of COD holds an energy equivalent of approximately 14 megawatt-seconds (MWs) [7,8].

Current mathematical models for activated sludge treatment are primarily founded on COD balances [9]. Assuming typical wastewater contains 220 grams of biodegradable COD per inhabitant per day, the average "power input" from municipal wastewater is roughly 35 watts per inhabitant [10]. Efficient nutrient removal plants generally consume power in the range of 5–20 watts per inhabitant, implying that energy self-sufficient treatment plants are feasible if some of the COD can be converted into methane through anaerobic sludge digestion [3].

To better extract energy from WWTP by-product, a deeper dive into this material and its components is

required. Indeed, the by-product of waste water treatment process most communally known as sludge can be defined as the solid particles not retained by the pre-treatment and water treatment processes [11,12]. This by-product is made of non-degraded organic matter, mineral matter, microorganisms and water. However, the composition, chemical attributes, and thermal characteristics of sludge are contingent upon various factors, including the employed stabilisation techniques, the engineering aspects of WWTP, and the pollution load of wastewater effluents [12]. Consequently, sludge is a complex amalgamation of diverse constituents, encompassing organic materials (OMs), inorganic substances, and microorganisms in both dissolved and suspended states. Furthermore, it encompasses valuable inorganic components such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), sulfur (S), and magnesium (Mg), in addition to potential contaminants and hazardous substances like heavy metals (HMs), dioxins, furans, and pathogenic microorganisms [11,12].

**Table 1.** Characteristics of the sludge produced and wasted from the liquid phase (directed to the sludge treatment) [12].

Wastewater treatment system	kgSS/ kgCOD applied	Dry solids content (%)	Mass of sludge (gSS/ inhabitant-d) (a)	Volume of sludge (L/ inhabitant-d) (b)
<b>Primary treatment (conventional)</b>	<b>0.35–0.45</b>	<b>2–6</b>	<b>35–45</b>	<b>0.6–2.2</b>
<b>Primary treatment (septic tanks)</b>	<b>0.20–0.30</b>	<b>3–6</b>	<b>20–30</b>	<b>0.3–1.0</b>
<b>Facultative pond</b>	<b>0.12–0.32</b>	<b>5–15</b>	<b>12–32</b>	<b>0.1–0.25</b>
<b>Anaerobic pond – facultative pond</b>				
• Anaerobic pond	0.20–0.45	15–20	20–45	0.1–0.3
• Facultative pond	0.06–0.10	7–12	6–10	0.05–0.15
• Total	<b>0.26–0.55</b>	–	<b>26–55</b>	<b>0.15–0.45</b>
<b>Facultative aerated lagoon</b>	<b>0.08–0.13</b>	<b>6–10</b>	<b>8–13</b>	<b>0.08–0.22</b>
<b>Complete-mix aerated – sedim. pond</b>	<b>0.11–0.13</b>	<b>5–8</b>	<b>11–13</b>	<b>0.15–0.25</b>
<b>Septic tank + anaerobic filter</b>				
• Septic tank	0.20–0.30	3–6	20–30	0.3–1.0
• Anaerobic filter	0.07–0.09	0.5–4.0	7–9	0.2–1.8
• Total	<b>0.27–0.39</b>	<b>1.4–5.4</b>	<b>27–39</b>	<b>0.5–2.8</b>
<b>Conventional activated sludge</b>				
• Primary sludge	0.35–0.45	2–6	35–45	0.6–2.2
• Secondary sludge	0.25–0.35	0.6–1	25–35	2.5–6.0
• Total	<b>0.60–0.80</b>	<b>1–2</b>	<b>60–80</b>	<b>3.1–8.2</b>
<b>Activated sludge – extended aeration</b>	<b>0.50–0.55</b>	<b>0.8–1.2</b>	<b>40–45</b>	<b>3.3–5.6</b>
<b>High-rate trickling filter</b>				
• Primary sludge	0.35–0.45	2–6	35–45	0.6–2.2
• Secondary sludge	0.20–0.30	1–2.5	20–30	0.8–3.0
• Total	<b>0.55–0.75</b>	<b>1.5–4.0</b>	<b>55–75</b>	<b>1.4–5.2</b>
<b>Submerged aerated biofilter</b>				
• Primary sludge	0.35–0.45	2–6	35–45	0.6–2.2
• Secondary sludge	0.25–0.35	0.6–1	25–35	2.5–6.0
• Total	<b>0.60–0.80</b>	<b>1–2</b>	<b>60–80</b>	<b>3.1–8.2</b>
<b>UASB reactor</b>	<b>0.12–0.18</b>	<b>3–6</b>	<b>12–18</b>	<b>0.2–0.6</b>
<b>UASB + aerobic post-treatment (c)</b>				
• Anaerobic sludge (UASB)	0.12–0.18	3–4	12–18	0.3–0.6
• Aerobic sludge (post-treatment) (d)	0.08–0.14	3–4	8–14	0.2–0.5
• Total	<b>0.20–0.32</b>	<b>3–4</b>	<b>20–32</b>	<b>0.5–1.1</b>

The table displayed shows that the stabilization ponds yield a relatively smaller sludge volume, while conventional activated sludge systems generate the largest. This can be explained from the fact that in ponds, sludge accumulates at the bottom over an extended period, allowing for natural digestion and thickening processes that significantly reduce its volume [13]. In contrast, in the conventional activated sludge process, the sludge is not digested within the aeration tank due to its relatively short residence time (sludge age) [13,14].

The treatment of sludge is cost-intensive and, in certain cases, may surpass the expenses associated with treating the entire wastewater stream. While sludge constitutes a mere 1% to 2% of the total volume of treated wastewater, its management typically accounts for a significant proportion, ranging from 20% to 60%, of the overall operational expenditures incurred by WWT facilities [14,15]. Hence, selecting an appropriate treatment method and valorising sludge to minimize losses emerges as a pivotal consideration for WWTP.

The most established methods for the secure treatment and harnessing of energy from sludge encompass anaerobic digestion (AD) and Thermal Oxidation that includes incineration, pyrolysis, and gasification [15]. It is worth noting that there are alternative pathways, such as wet air oxidation and hydrothermal treatment; however, these have seen limited practical application and are thus not the primary focus of this paper.

On one hand, incineration, also known as Advanced Thermal Oxidation (ATO) in sludge treatment, involves a multi-step process. It commences with the drying of sludge cake. The incineration process necessitates a minimum temperature of 700°C, and an excess air supply ranging from 20% to 100% above the stoichiometric air requirement [16]

The heating value of both digested and raw sludge typically falls within the range of 12,000 to 25,000 kJ/kg [16]. To ensure self-sustaining incineration, the feed sludge must contain a minimum of 15–25% solids. Additionally, the use of natural gas or fuel oil as auxiliary fuel is essential for ignition and to maintain the appropriate combustion temperature [17]. The combustion by-products primarily comprise of carbon dioxide (CO<sub>2</sub>), water (H<sub>2</sub>O) and ash [17].

On the other hand, the gasification process involves the conversion of organic materials into a fuel gas, often referred to as syngas [18]. This operation occurs within a temperature range spanning from 590°C to 980°C while maintaining a controlled air supply below the stoichiometric requirement [18]. The resultant syngas comprises nitrogen (N<sub>2</sub>), carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), hydrogen (H<sub>2</sub>), and methane (CH<sub>4</sub>). Syngas possesses a heating value of approximately 4500–5500 kJ/m<sup>3</sup>, which is approximately 10–15% of that of natural gas [18].

Last treatment method is the Pyrolysis, also referred to as destructive distillation that involves the controlled heating of organic matter within an oxygen-starved environment [19]. Under temperatures ranging from 200–590°C, this organic matter undergoes a process of

thermal decomposition, resulting in the generation of combustible gases, oil, tar, and charcoal [19]. These resultant by-products serve as valuable energy sources. Presently, pyrolysis of Municipal Solid Waste (MSW) is recognized as an effective approach for Waste-to-Energy (WTE) initiatives; however, the environmental consequences necessitate comprehensive assessment. An alternative avenue involves the co-pyrolysis of biosolids with MSW, offering a viable strategy. Gasification or pyrolysis may both function as integral components within a comprehensive Combined Heat and Power (CHP) system [20].

Anaerobic digestion, also known as methanisation, is a naturally occurring process in which microbial flora break down organic matter under anaerobic conditions [21]. This process comprises three stages, although they often occur concurrently; Hydrolysis, Acidogenic and Methanogenic phase.

This process takes place within controlled enclosures known as digesters, where fermentation reactions are meticulously managed and optimised. The outcome is the generation of biogas, primarily consisting of 60–70% methane, accompanied by 30–40% carbon dioxide and trace quantities of other gases like hydrogen, hydrogen sulfide, and nitrogen [21]. It possesses a relative density of approximately 0.85 and a calorific value ranging from 13–21 MJ kg<sup>-3</sup>, which is lower than that of coal (15–27 MJ kg<sup>-3</sup>) but comparable to lignite (12–16 MJ kg<sup>-3</sup>) [21,22].

We can argue that anaerobic digestion (AD) remains a prevalent sludge disposal method, resilient to high sludge water content, yet challenged by long processing times, incomplete organic matter (OM) removal, and relatively low efficiency [22]. In contrast, incineration demonstrates remarkable efficiency and power generation capabilities but demands costly treatment of flue gases before atmospheric release [15]. Other thermal treatments, such as gasification and pyrolysis, offer substantial advantages by producing syngas and bio-oil for versatile applications, albeit with lower efficiency and higher costs associated with waste activated sludge pretreatment to reduce moisture content [16].

## 4 Conclusion and Recommendations

These technologies, including AD coupled with pyrolysis, co-combustion, and co-incineration, require further development to mitigate the energy penalty and enhance economic feasibility. Crucially, real-world application poses challenges in meeting stringent air quality and emissions standards, while limitations encompass financial risk acceptance, limited operational experience, and the economics of capital-intensive plant and equipment [1]. The focus on resource conservation and tangible benefits stands as an ongoing challenge in advancing sludge treatment and disposal technologies. Moreover, future WWTP will face the challenge of meeting increasingly stringent legal requirements, encompassing pathogen disinfection, micropollutant discharge, and greenhouse gas emissions. These developments raise concerns related to heightened

energy demand and the need for establishing a consensus on new requirements and indicators, which may entail competing priorities. While the reduction of energy consumption and increased energy recovery are essential objectives, they should not overshadow the primary goal of achieving reliable and highly efficient wastewater treatment [3]. This remains fundamental for effective water protection and conservation at a reasonable cost.

Finally, in addressing the urgent need for sustainable sludge management practices, it is paramount to explore the integration of renewable energy sources within the framework of sludge treatment processes. This recommendation pivots on the imperative to mitigate the environmental footprint associated with conventional sludge treatment methodologies, which are often energy-intensive and contribute significantly to greenhouse gas emissions. By harnessing renewable energy sources such as solar, wind, or bioenergy, sludge treatment facilities can significantly reduce their reliance on fossil fuels, thereby decreasing carbon emissions and enhancing the sustainability of wastewater management systems. Furthermore, the integration of renewable energy can also improve the economic viability of sludge treatment operations by reducing energy costs and potentially generating surplus energy that can be fed back into the grid or used to power other processes. This strategic approach not only aligns with global sustainability goals but also propels the wastewater treatment sector towards a more circular economy model, where waste products are valorised and resources are efficiently utilized, thereby contributing to the overall resilience and sustainability of urban water systems.

## References

1. D. Giacomo, Gabriele, and P. Romano. "Evolution and Prospects in Managing Sewage Sludge Resulting from Municipal Wastewater Purification." *Energies* 15.15 (2022)
2. Metcalf & Eddy, AECOM, *Wastewater Engineering: Treatment and Resource Recovery*, 5th ed., McGraw-Hill, New York, NY, (2014)
3. Campana, P. Elia, et al. "100% renewable wastewater treatment plants: Techno-economic assessment using a modelling and optimization approach." *Energy Conversion and Management* 239 (2021):
4. Aid, Graham, D. Lazarevic, and A. Kihl. "Waste to resources: Moving toward the 2030 sustainable development goals." *Linnaeus Eco-Tech 2016*, 21–23 November 2016, Kalmar, Sweden. (2016).
5. Makarichi, Luke, W. Jutidamrongphan, and K. Techato. "The evolution of waste-to-energy incineration: A review." *Renewable and Sustainable Energy Reviews* 91 (2018)
6. V.K. Tyagi, S.-L. Lo, Sludge: A waste or renewable source for energy and resources recovery ?, *Renewable and Sustainable Energy Reviews* 25 708-728 (2013)
7. Xin, Xiaodong, et al. "An integrated approach for waste activated sludge management towards electric energy production/resource reuse." *Bioresource technology* 274 225-231 (2019).
8. Jiménez, Blanca, et al. "Wastewater, sludge and excreta use in developing countries: an overview." *Wastewater irrigation and health* : 3-27 (2009).
9. Gernaey, V. Krist, et al. "Activated sludge WWTP modelling and simulation: state of the art." *Environmental modelling & software* 19.9 763-783. (2004):
10. Svardal, Karl, and H. Kroiss. "Energy requirements for waste water treatment." *Water Science and Technology* 64.6 : 1355-1361 (2011).
11. V. Sperling, M., and R. F. Gonçalves. "Sludge characteristics and production." *Sludge treatment and disposal*. IWA Publishing London, UK, 4-28 (2007).
12. Yan, S., et al. "Wastewater sludge characteristics." *Sustainable Sludge Management: Production of Value Added Products*. American Society of Civil Engineers, Reston, Virginia, USA : 6-36 (2009)
13. S. Qasim. *WWTPs: Planning, Design and Operation*, Holt, Rinehart and Winston (1985)
14. EPA Design Manual – Dewatering Municipal Wastewater Sludges. EPA/625/1– 87/014, United States Environmental Protection Agency (1987)
15. Andreoli, C. Vitorio, M. Von Sperling, and Fernando Fernandes. *Sludge treatment and disposal*. IWA publishing, (2007)
16. U.S. Environmental Protection Agency, *Biosolids Technology Fact Sheet: Heat Drying*, EPA 832-F-06-029, Office of Water, Washington, DC, September (2006)
17. Zemmermann, *Wet air combustion*, *Industrial Water and Wastes*, 6(4), 102–106 (1961).
18. Siemens, *Zimpro Wet Air Oxidation Systems: The Cleanest Way to Treat the Dirtiest Water*, <http://www.siemens.com>, (2011).
19. B. Khiari, F. Marias, F. Zagrouba, J. Vaxelaire, Analytical study of the pyrolysis process in a wastewater treatment pilot station, *Desalination* 167 39-47 (2004).
20. N. Gao, C. Quan, B. Liu, Z. Li, C. Wu, A. Li, Continuous pyrolysis of sewage sludge in a screw feeding reactor: products characterization and ecological risk assessment of heavy metals, *Energy & Fuels* 31 5063-5072 (2017).
21. D. Deublein, A. Steinhauser, *Biogas from Waste and Renewable Resource* (Weinheim, WileyVCH Verlag GmbH & Co. KgaA, (2008).
22. D. Devlin, S. Esteves, R. Dinsdale, A. Guwy, The effect of acid pretreatment on the anaerobic digestion and dewatering of waste activated sludge, *Bioresource Technology* 102 4076- 4082 (2011).