Modeling of Wastewater Sludge Treatment with Thermal Hydrolysis Processing: Example of Seyhan Wastewater Treatment Plant

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Rapid urbanization and industrialization have led to a substantial increase in sewage sludge production at wastewater treatment plants (WWTPs). WWTP sludge poses significant challenges for municipalities, not only due to the environmental damage caused by existing disposal methods, but also due to energy consumption in storage, drying, and incineration processes, as well as transportation costs. Integrating Thermal Hydrolysis Process (THP) technology into municipal WWTPs offers a sustainable solution by enhancing waste management efficiency and mitigating greenhouse gas emissions (GHGE), while simultaneously yielding eco-friendly byproducts. This study evaluates the characteristics of sludge generated at the Seyhan WWTP in Adana, Turkey—which currently processes approximately 100 tons of sludge daily—with operational projections extending to 2025. The findings indicate that by 2025, THP technology is projected to emit approximately 12,957 kgCO_2eq/ton of GHG, achieving a nine-fold greater emission reduction compared to traditional incineration. Furthermore, the implementation of THP is expected to generate an additional 54 m^3/h of biogas and reduce annual dewatered sludge volume by 4,886 tons, resulting in approximately $122,150 in annual operational savings.

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INTRODUCTION

Industrialization, along with economic development, has led to significant environmental challenges such as water pollution, global climate change, and increased waste. To transition toward sustainable development, modern society must minimize its ecological footprint by implementing reliable and innovative technological solutions (Sebile 2022). According to the International Energy Agency (IEA 2017), fossil fuels—specifically coal (28.1%), oil (31.7%), and natural gas (21.6%)—dominate the global primary energy supply. Consequently, integrating renewable energy sources is vital to reducing the environmental degradation associated with fossil fuels. Among these resources, biomass stands out as a versatile precursor for the production of energy, fuels, and chemicals through various conversion methods (Başakçılardan Kabakcı and Koca

2019). From a sustainability perspective, converting waste into renewable resources is essential for enhancing environmental quality and public health (Giglio *et al.* 2013).

Wastewater treatment plants (WWTPs) are critical infrastructure for protecting water resources by removing pollutants from domestic and industrial effluents (Bharathiraja *et al.* 2014; Yüksekdağ *et al.* 2020). However, the final sludge generated during these processes—varying in consistency from liquid to solid—presents a complex management problem due to its high volume and hazardous nature. Historically, a large portion of sewage sludge was disposed of in landfills. However, this practice is no longer preferred due to operational difficulties, stringent legal restrictions on storage, and the increasing demand for resource recovery.

Environmental pollution remains a primary threat to human health, largely driven by anthropogenic activities such as mining, industrialization, and urbanization. Traditional treatment methods, such as open burning, contribute significantly to ecological damage through greenhouse gas emissions (GHGE) and air contamination (Wang *et al.* 2018). The rising volume of WWTP sludge has intensified the need for safer, more sustainable management strategies and stricter quality standards (Volpe *et al.* 2020). Currently, sludge management is one of the most pressing technical and ecological challenges for WWTPs. While biological processes are fundamental to wastewater treatment, the resulting sludge remains an undesirable byproduct that requires efficient disposal. Studies indicate that sludge management can account for up to 30% of capital costs and 50% of total operating costs in WWTPs, reaching approximately €80 per ton (Jiang *et al.* 2014; Prestigiacomo *et al.* 2019).

Recent research suggests that sewage sludge should be viewed not merely as waste, but as a valuable raw material for energy recovery and material production. Key techniques for energy recovery include incineration (Kijo-Kleczkowska *et al.* 2015; Gao *et al.* 2020), anaerobic digestion (Khanh Nguyen *et al.* 2021), pyrolysis (Mphahlele *et al.* 2021), gasification (Chen *et al.* 2020), wet oxidation (Baroutian *et al.* 2016), hydrothermal processing (Ün 2024), and thermal hydrolysis (Suárez-Iglesias *et al.* 2017). Additionally, sludge is utilized in the production of building materials (Chang *et al.* 2020), cement (Świerczek *et al.* 2021), and biodiesel (Liu *et al.* 2021). The push to minimize carbon footprints and enhance energy efficiency has driven the adoption of these innovative technologies.

Discharging untreated sewage sludge onto agricultural land poses severe risks, including the leaching of heavy metals into soil and water, pathogen transmission, and increased GHGE (Zhang *et al.* 2017; Djandja *et al.* 2021). However, hydrothermal processes can effectively reduce sludge volume and transform it into valuable, stabilized products (Tasca *et al.* 2019). While the accumulation of industrial and municipal waste continues to exacerbate global warming (Christodoulou and Stamatelatou 2015; Tshemese *et al.* 2023), these impacts can be mitigated through heightened environmental awareness, stricter regulations (Jiao *et al.* 2024), and the promotion of cleaner production methods that prioritize waste minimization and sustainable resource management (Luttenberger 2020).

Despite the availability of various disposal technologies, there is need to evaluate their performance specifically for regional facilities. This study addresses this gap by modeling the integration of Thermal Hydrolysis Process (THP) at the Seyhan WWTP. By comparing THP with incineration, pyrolysis, and landfilling, this research provides a novel assessment of emission reductions and economic feasibility, offering a sustainable roadmap for regional sludge management.

MATERIALS AND METHODS

Materials

The volume of sewage sludge generated at wastewater treatment plants (WWTPs) in Adana, Turkey, has exhibited a consistent annual increase. This study evaluates the characteristics and disposal potential of sludge produced at the Seyhan WWTP through the integration of the Thermal Hydrolysis Process (THP). The geographical location of the facility is illustrated in Fig. 1.

Fig. 1. Seyhan WWTP in Adana province

The operational parameters of the Seyhan WWTP and the characteristics of the dewatered sludge are summarized in Table 1 (ASKI 2026).

Table 1. Main Parameters and Projections for Seyhan WWTP

Project Year	2010	2025
Total Equivalent Population	1,156,006 E.N. 48	1,760,958 E.N. 55
Daily Flow (m³/day)	227,346 m³/day	311,973 m³/day
Inlet BOD5 Concentration(mg/L)	243 mg/L	310 mg/L
Total BOD5 (kg/day)	55,251 kg/day	96,853 kg/day
	Input	Output
TSS (mg/L)	201	14 to 20
BOD (mg/L)	224	12 to 15
pH	7.4	7.3
COD (mg/L)	442	48 to 55
TN (mg/L)	62	15 to 20
TP (mg/L)	6	0-3
Wastewater Sludge Amount After Dewatering (tons/day)	~100	
Dry Solids	The pre-thickening sludge typically contains approximately ~3% solids by weight.	

The facility serves the Cukurova and Seyhan districts, utilizing anaerobic digestion (AD) to produce biogas for electricity generation. The plant meets 70% of its energy demand through this process. On average, the plant produces 100 tons of dewatered sludge daily (25% to 30% dry solids content), which is temporarily stored on-site. It is estimated that approximately 900,000 tons of sludge have accumulated in the storage area to date.

The process flow of the Seyhan WWTP is presented in Fig. 2. For the THP experiments, sludge cake samples were collected post-dewatering and stored at 4°C to maintain stability. The proximate and elemental compositions of the raw sludge are detailed in Table 2.

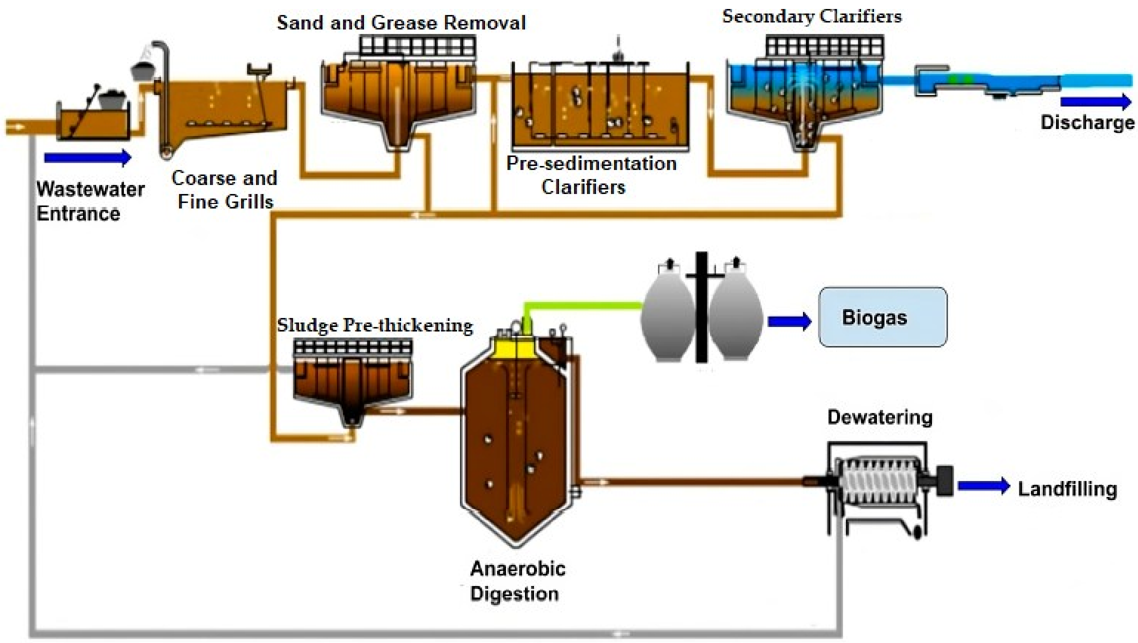

Fig. 2. Flow chart of the WWTP in Seyhan

Table 2. Approximate and Elemental Analysis Results of Raw Treatment Sludge from Seyhan WWTP

Approximate (Proximate) Analysis Results					Elemental Analysis Results (%)				
Total Solids (%)	Moisture Content (%)	Volatile Solids (%)	Ash Content (%)	Energy Value (MJ/kg)	C	H	N	S	O
16.4	83.6	73.6	26.4	17.8 ± 0.14	37.4	5.9	6.3	1.0	49.3

When examining the population data for Adana province in 2025, according to the latest census data, the population of Seyhan district in Adana is 807,420 and the population of Cukurova district is 456,918. Accordingly, in 2025, 60,984,923 m^3 of wastewater generated in the Seyhan district service area of Adana will be treated at the Seyhan WWTP (details regarding the amount of treated wastewater obtained from the Seyhan WWTP in Adana between 2005 and 2025 are given in Fig. 3) (ASKI 2026).

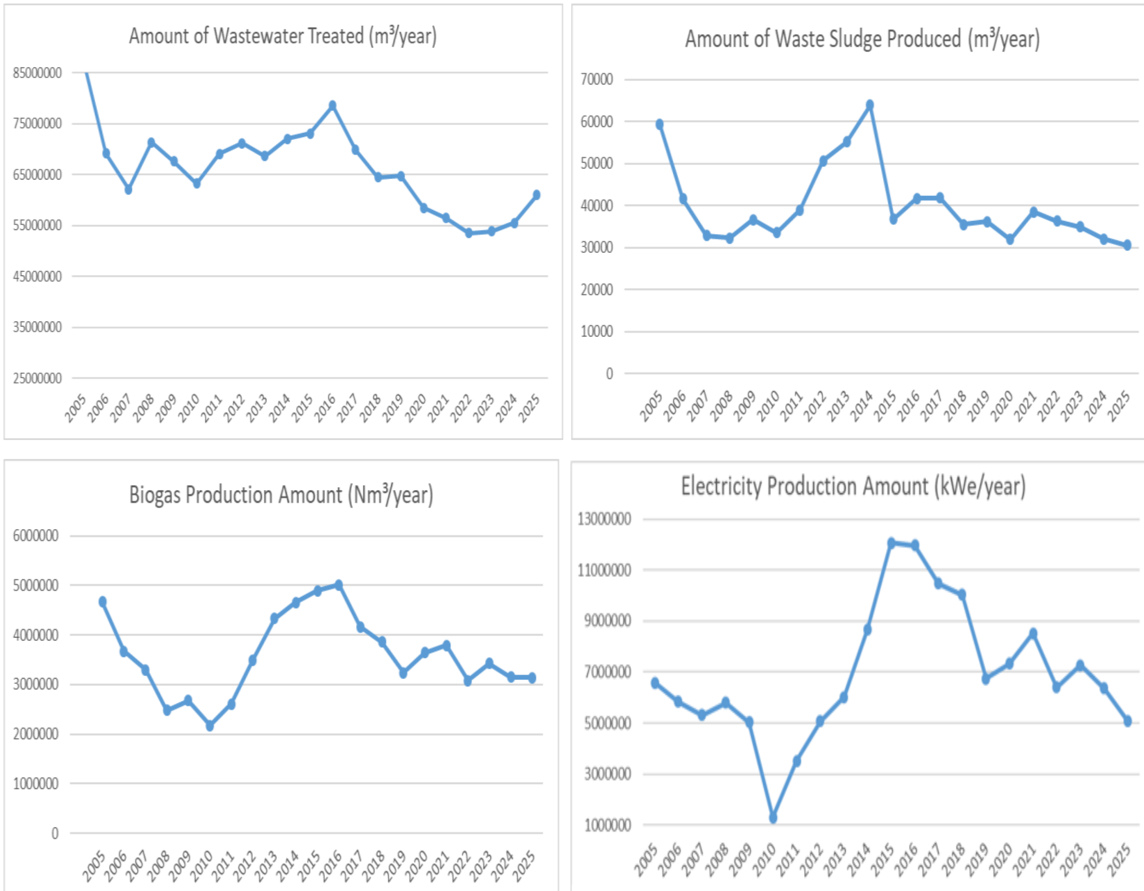

Fig. 3. Amounts of treated wastewater, sludge produced, biogas produced and electricity generated by year

This study analyzes both the quantity and quality of wastewater treatment sludge from the Seyhan WWTP in Adana province. It also examines various methods used for the disposal of this sludge. This research evaluates and compares various wastewater treatment sludge disposal methods, appraising their performance and ecological impacts. This study also examines disposal options for Seyhan WWTP sludge treatment in Adana province and provides forward-looking information for reducing future environmental impacts.

Methods

The digestion performance has been significantly improved by the optimum integration of THP technology before anaerobic digestion of biological sludge in a WWTP. The THP systems reduce GHGE by directly drying the sludge without pre-drying, thus saving energy (Vardon *et al.* 2012). In this study, the sludge from the dewatering unit at Seyhan WWTP was examined. This study compared the environmental outputs and efficiency of THP technology against established disposal methods: incineration, pyrolysis, and landfilling. Sludge moisture content is a critical variable in these comparisons; while incineration and pyrolysis require pre-drying the sludge to below 10% moisture—a process with a high energy consumption rate (ECR)—THP can process wet materials directly.

Treatment Technologies

Thermochemical methods are fundamental to modern sludge management (Seiple *et al.* 2017). The study investigated how integrating THP (a rapid-reaction technology) into the existing AD system at Seyhan WWTP can enhance gas yield and operational efficiency. The ECR for sludge disposal technology is 0.22 for THP (pyrolysis, incineration), while in the conventional method, it is calculated as 0.52 for pyrolysis and 59.0 for incineration, highlighting THP's superior energy efficiency. THP subjects the sludge to high temperature and pressure, accelerating the decomposition of organic matter, which increases methane (CH_4) production and reduces the decontamination load (Li *et al.* 2023).

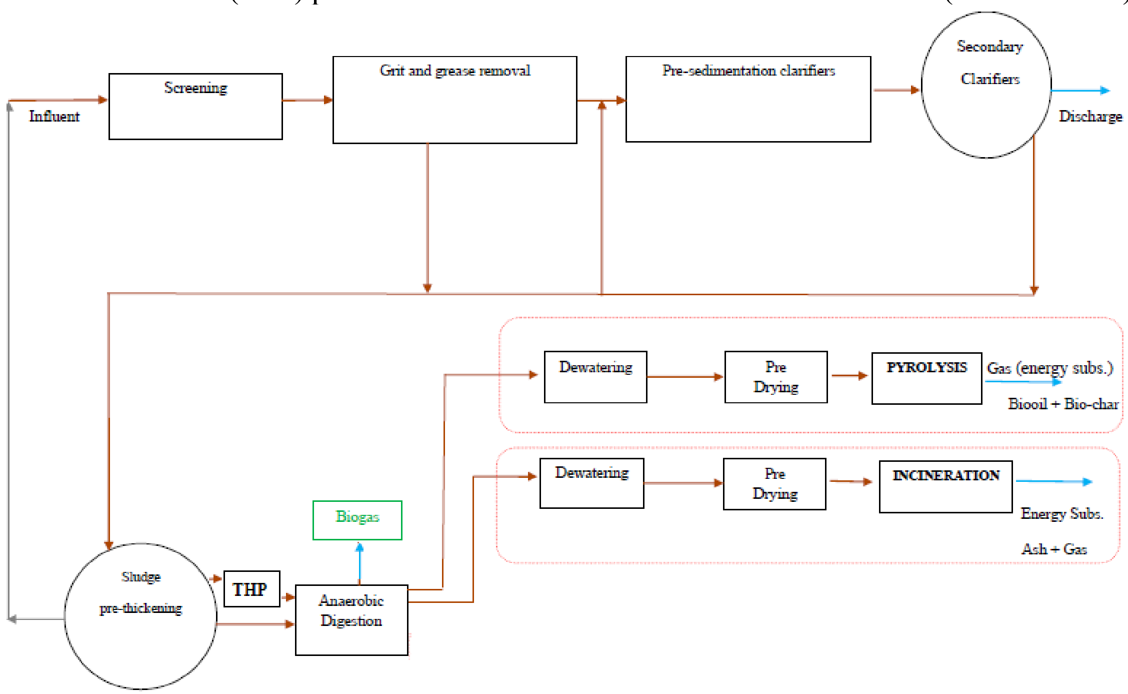

Fig. 4. The framework for comparing the four disposal technologies

THP emerges as an innovative technology for converting AD sludge, offering significantly faster reaction times and high conversion efficiencies (more than 50%). Due to its high-temperature operation, THP has demonstrated significant advantages in terms of both its ability to dispose of wet raw materials without pre-drying and the sterilization of sludge. The THP method provides an eleven-fold increase in energy recovery and up to an 85% reduction in GHGE compared to landfilling and other disposal methods (Si *et al.* 2019). This study highlights the potential of integrating THP technology into an anaerobic digester (AD). Study evaluated four different sludge disposal methods that have been previously studied. The THP technology of the sludge resulted in production of biogas phase. The gas products were released untreated, while the solid phase was sent to a landfill. Another technology is pyrolysis; in this method, sewage sludge is dried to a moisture content of up to 7% to obtain bio-oil, biochar, and gas for energy. The incineration, which involves pre-drying the sludge to a moisture content of up to 10%, has also been evaluated in terms of energy and environmental impact. The landfill disposal method requires storage of sludge with approximately 25% moisture content in designated areas. From a sustainable environmental perspective, incineration, compared to other disposal technologies (THP, pyrolysis, and landfilling), is dependent on fossil fuels, which increases GHGE and therefore poses environmental risks. In contrast, converting THP sludge into biogas increases the use of renewable energy sources and provides benefits by reducing GHGE. However, there is no energy recovery in the storage of wastewater treatment sludge, and it can lead to emissions and groundwater pollution. Pyrolysis and incineration processes require pre-drying of the sludge, which leads to increased energy use and GHGE. The framework for comparing the disposal technologies is shown in Fig. 4 (Ün 2024).

Thermal Hydrolysis Process (THP) Mechanisms

THP technology is a pretreatment method that enables the physical and chemical breakdown of biological sludge generated in WWTPs by subjecting it to high temperature and pressure before anaerobic digestion. This process makes organic matter more easily decomposable and significantly improves anaerobic digestion performance. THP technology is considered the most efficient method in terms of energy efficiency and increasing the amount of biogas produced, which are the most important expectations in WWTP facilities, as existing processes are open to improvement. This system will present a technologically superior process. Within the scope of THP, there will be a thermal hydrolysis process with high efficiency, capable of increasing energy production per unit mass, with a very short processing time, capable of continuous operation, and with a compact design. The thermal hydrolysis process should be applied to obtain energy from wastewater sludge with high efficiency. In terms of increasing efficiency in energy production from sludge, the limiting factor is the hydrolysis stage of biomass. Certain processes are applied to eliminate this limiting factor.

THP serves as a pretreatment stage where biological sludge undergoes physical and chemical breakdown via two primary mechanisms:

- ✓ *Thermal Mechanism:* Controlled by specific temperature-time profiles to enhance degradability without compromising biomass structure.
- ✓ *Vapor Explosions:* Rapid pressure reduction causes water within cell walls to flash into steam, effectively rupturing the cell structure and making organic matter more accessible for digestion.

Application of Thermal Hydrolysis Technology to Achieve Advanced Anaerobic Digestion

Anaerobic digestion is a biological process in which microorganisms break down organic waste in an oxygen-free environment, thereby producing biogas in the form of CH_4 and CO_2. Traditional AD systems face some challenges because of slow biodegradation; the main problem is that the limiting stage of AD mechanisms is the hydrolysis (dissolution) process of solid organic waste. Various pretreatment methods have been attempted to overcome this limitation and achieve advanced AD. Among these, THP, where organic waste is subjected to high temperature and pressure, is the preferred pretreatment method owing to its technical and economic advantages. The first stage of traditional AD (Standard) is hydrolysis, where complex organic substances are broken down into simpler compounds by enzymes. These simpler compounds then proceed to subsequent stages where methanogenic microorganisms produce biogas. The performance of traditional AD systems is limited by the following factors. *Slow hydrolysis rate:* The initial decomposition of complex organic matter occurs slowly, limiting the overall efficiency of the digestive system. *Low biogas yield:* Slow hydrolysis and subsequent methanogenic stages reduce biogas yield. *Long retention times:* Conventional AD requires long processing times for waste, leading to larger and more expensive digestion tanks. Advanced AD can be applied to overcome the limitations of conventional AD. Waste is typically subjected to heat and high pressure, usually between 140 and 160 °C, before entering the digester.

Advantages of Thermal Hydrolysis Process

Short hydraulic retention times (HRT) and high organic loading rates significantly reduce capital costs by using smaller digestion tanks. Short HRT leads to less foaming in digesters with special designs that facilitate optimum integration into WWTP. The size and cost of the mixer and construction costs are reduced. The approach reduces sludge handling, transportation costs, and sludge processing costs. It provides high-speed digestion. Its plug-and-play module design requires minimal space. As shown in Fig. 5, THP integration can increase biogas yield by 30% to 50% while reducing final biosolids volume by up to 50%. The resulting residue is pathogen-free (EPA Class A), making it suitable for high-grade agricultural applications.

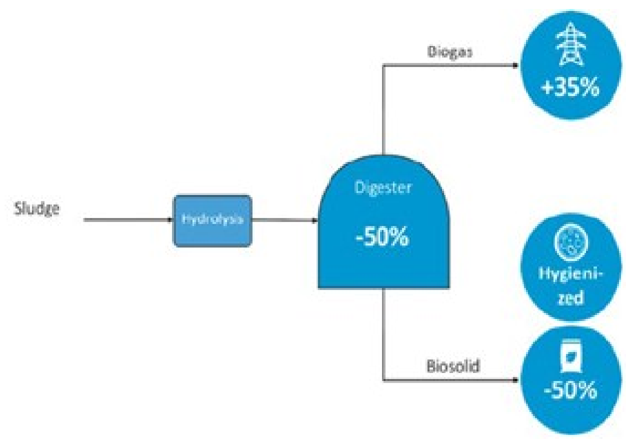

Fig. 5. Model of biogas production and final sludge quantity in plants using thermal hydrolysis

Technical Characteristics and Modeling

To ensure steady-state operation and compact design, the THP system consists of three functional modules:

- ✓ *Feed Module:* Preheats, pressurizes, and homogenizes the incoming biomass.
- ✓ *Hydrolysis Module:* Operates at high temperatures with short retention times to prevent secondary reactions that could reduce efficiency.
- ✓ *Heat Recovery Module:* Recaptures steam from cell wall evaporation to return energy to the system.

The flowchart of the thermal hydrolysis process is given in Fig. 6, and the application of the THP system to WWTP is given in Fig. 7.

Dry Matter and Calorific Value

The sewage sludge samples from the Seyhan WWTP were collected for analysis. To prevent contamination, samples were prepared at the facility in accordance with TS 9546 EN 12880 (TSI 2002), following safety protocols. Dry residue (%) and humidity content (%) were computed using predetermined formulas. The reliability of the findings and meaningful comparisons of different samples depend on adherence to the standards.

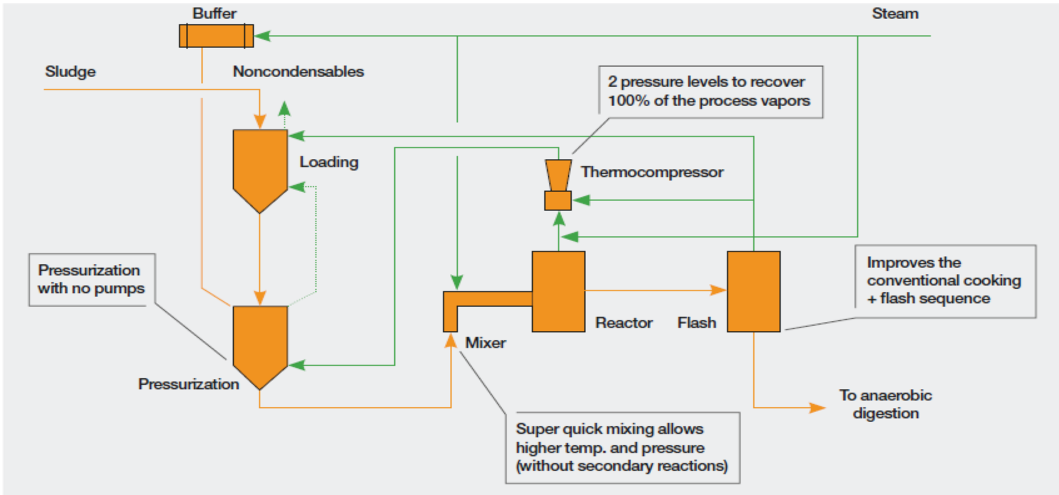

Fig. 6. Flow diagram of the thermal hydrolysis system

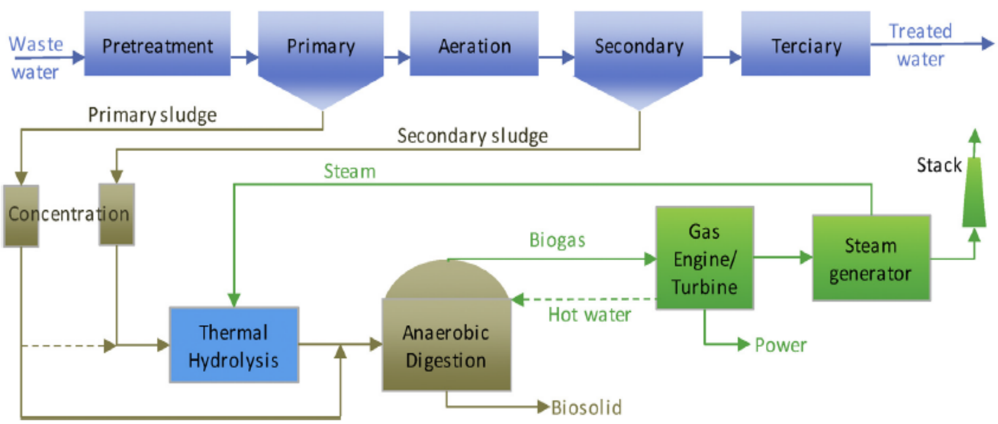

Fig. 7. Application of thermal hydrolysis plant to wastewater treatment plant

Greenhouse Gas (GHG) Calculations

GHGE for landfilling, incineration, pyrolysis were calculated using conventional and THP equations (Chen and Kuo 2016),

$$GHG_{\text{landfill}} = T \times EF_{\text{electricity}} + \sum m_{\text{i}} \times EF_{\text{i}} + \sum D_{\text{i}} \times EF_{\text{di}} \quad (1)$$

$$GHG_{\text{incineration/pyrolysis}} = M \times EF_{\text{GHGi}} + T \times EF_{\text{electricity}} + \sum m_{\text{i}} \times EF_{\text{i}} \quad (2)$$

where T is the total electricity consumption (kWh/tonne of sludge); $EF_{\text{electricity}}$ is the emission factor of GHGs from electricity consumption (kgCO_2eq/kWh); m_{i} is the amount of material "i" consumed at neutralization for per tonne of sludge (kg); EF_{i} is the emission factor of GHGs from material "i" consumption (kgCO_2eq/kg); D_{i} is the amount of diesel consumption for transportation (L/per tonne of sludge); EF_{di} is the emission factor of GHGs from diesel consumption (kgCO_2eq/L); M is the total amount of sewage sludge incinerated, pyrolyzed, or converted with THP (tonne); and EF_{GHGi} is the emission factor of GHGs (kg CO_2eq/tonne).

For greenhouse gases from landfills, emissions from landfills have been measured at 60.6 kg of CH_4 per ton (Yin *et al.* 2010). Landfill operations typically require 70 kWh of electricity, 3.10 L of diesel, and 5.65 kg of polymer per ton for maintenance and repair. Emission factors for diesel consumption are based on their default values, specifically 0.74 $\times 10^{-1}$ kg of CO_2, 0.25 $\times 10^{-4}$ kg of CH_4, and 0.45 $\times 10^{-3}$ kg of N_2O/L (IPCC 2006).

For incinerate pyrolysis and THP (incinerate, pyrolysis) greenhouse gases calculation is achieved as follows: The process operates in an oxygen-rich environment to facilitate the combustion of organic matter, which in turn emits greenhouse gases (GHG). This high-temperature process requires approximately 200 kWh of electricity per ton and approximately ~45 kg of NaOH/ton to reduce moisture content. Typically, sludge incineration results in the production of approximately ~10 kg of CH_4/ton. The incineration, pyrolysis, and their THP factors used to predict off-location GHGE in study were adapted from both Chen and Kuo (2016) and Chen *et al.* (2020).

This study addressed three GHGs specified in the Kyoto Protocol: CO_2, CH_4, and N_2O. As stated by the IPCC in 2006, their global warming potentials (GWP) over a 100-year period are 1, 25, and 298 CO_2 equivalents, respectively. This means that one ton of CH_4 emissions is equal to 25 tons of CO_2 emissions, and one ton of N_2O emissions is equal to 298 tons of CO_2 emissions. In this study, the CO_2 emission coefficient for electricity was reported as 0.4261 kg CO_2/kWh (Carbon Footprint 2023).

This study estimates the GHGE of one ton of sewage sludge produced during WWTP activities (including activities such as aeration tanks, decanters used for sludge removal, pumps, various chemicals, fuels, *etc.*). Here the GHGE was generated because of WWTP activities was computed in tons.

Modeling of the THP Pilot Plant

The THP pilot plant modeling for the Seyhan WWTP is detailed in Fig. 8 and Fig. 9. The configuration data for the primary sedimentation tanks and anaerobic digesters are provided in Tables 3 and 4.

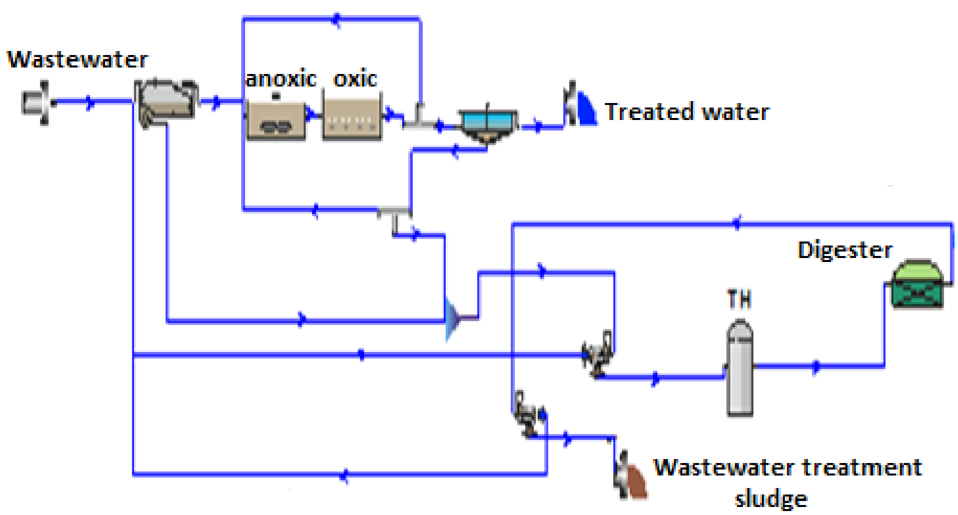

Fig. 8. Flowchart of modeling the THP pilot plant at Adana Seyhan wastewater treatment plant

Table 3. Configuration Information for All Ideal Primary Sedimentation Tank Units

Physical Data				
	Number	Volume (m^3)	Area (m^2)	Depth (m)
Ideal primary settling tank1	3	1200	254.57	4.00
Operating Data Average (Flow/Time Weighted as Required)				
	% removal	Blanket fraction	Average Split specification	
Ideal primary settling tank1	55	0.10	50	

Table 4. Configuration Information for All Anaerobic Digester Units

Physical Data				
	Number	Volume (m^3)	Area (m^2)	Depth (m)
Digester	6	9000	314.29	39.40
Operating Data Average (Flow/Time Weighted as Required)				
	Average Temperature	Pressure (kPa)	pH	
Ideal primary settling tank1	35	309	7	

The modeling of THP pilot plant at Adana Seyhan WWTP is given in Fig. 9.

a) General view and control unit

b) Feeding module

c) Hydrolysis reactor

d) Heat recovery unit

Fig. 9. Modeling of the THP pilot plant at Adana Seyhan WWTP

The modeled system (Fig. 9) is designed for continuous operation with direct steam injection and automatic control. It features a compact 20 m² footprint and a 1.5 m³ reactor volume. The process operates at 170 ºC with a hydraulic retention time (HRT) of less than 15 minutes, processing 3,000 kg DM/h (14% ST) to serve a population equivalent (p.e.) of 400,000.

RESULTS AND DISCUSSION

Characterization of Sewage Sludge

The physicochemical properties of the dewatered sludge obtained from the Seyhan WWTP are summarized in Table 5. The sludge exhibits a high moisture content (73.5%) and a relatively low dry matter proportion (26.5%). The measured calorific value is 3330 cal/g, with a neutral pH of approximately 7.0.

Table 5. Physical and Thermal Properties of Dewatered Seyhan WWTP Sludge

Plant Name	Moisture (%)	Dry Matter (%)	Heat Value (cal/g)	pH
Seyhan WWTP	73.5	26.5	3330	7

While conventional disposal methods such as incineration and pyrolysis necessitate energy-intensive pre-drying to compensate for low dry matter content (25% to 30%), THP technology operates efficiently under high temperature and pressure. This allows THP to process wet sludge directly, enhancing biogas yields by 30% to 50%. The ability of THP to handle high moisture content while yielding products with superior energy potential demonstrates its operational superiority over traditional anaerobic digestion (AD) and thermal disposal.

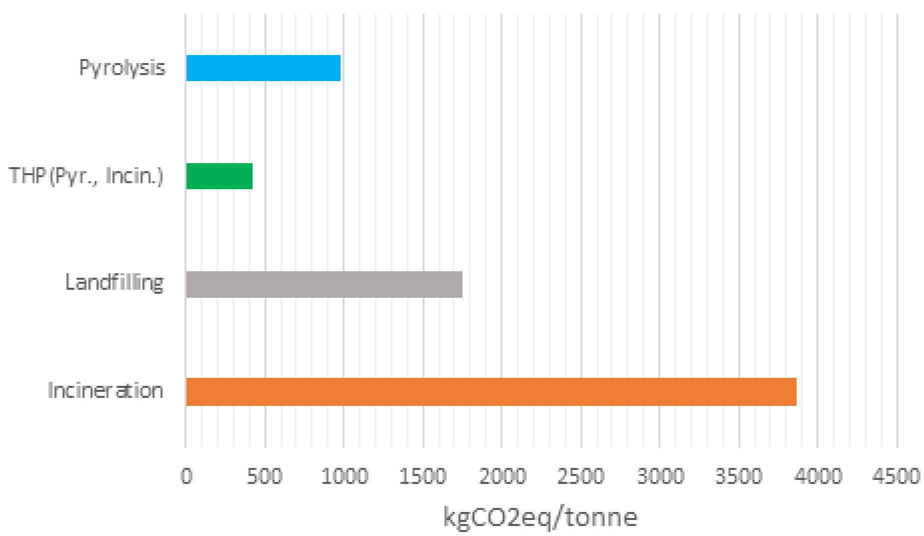

Fig. 10. Greenhouse gas emissions from conventional pyrolysis, incineration, landfill, and their THP methods

Comparative Analysis of Greenhouse Gas Emissions (GHGE)

The environmental impact of different disposal technology was quantified in terms of GHGE, as illustrated in Fig. 10. The total emissions for the THP (pyrolysis, incineration) technology and for conventional pyrolysis, incineration, and landfill were found to be 425, 985, 1752, and 3869 kgCO2eq/ton, respectively.

These results underscore the ecological advantages of integrating THP into AD systems. Specifically, THP (pyrolysis, incineration) technology achieves a GHGE reduction of approximately 57% compared to conventional pyrolysis, 89% compared to lincineration, and 76% compared to landfilling. Such a significant reduction exemplifies a sustainable and eco-friendly approach to sludge management, significantly lowering the overall carbon footprint of municipal WWTPs.

Long-term Projections and Environmental Implications

Projections for the Seyhan WWTP through 2025 (Fig. 11) indicate that THP (pyrolysis, incineration) technology will consistently remain the most sustainable option, with the lowest cumulative emissions (approx. 12,957 kgCO_2eq/ton). In contrast, incineration reached a peak emission value of 247,388 kgCO_2eq/ton in 2014, highlighting its disproportionate impact on climate change and human toxicity.

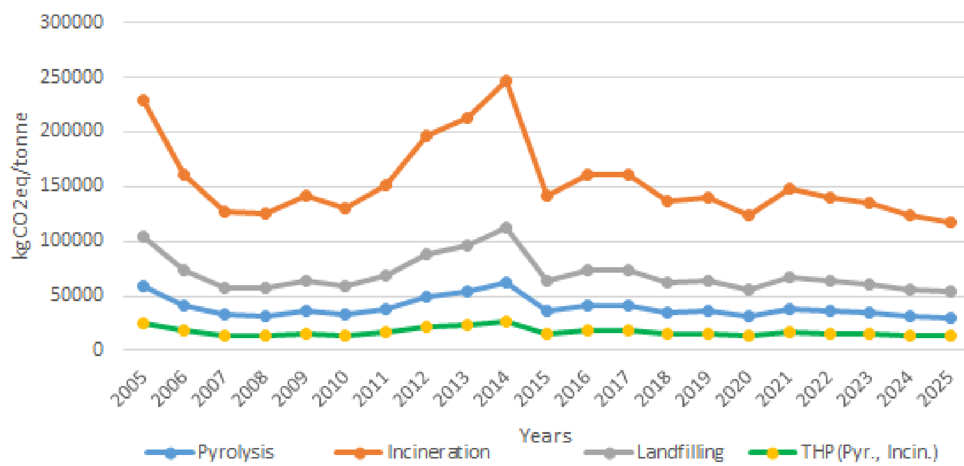

Fig. 11. GHGE values for various technology models at Seyhan WWTP in Adana until 2025

Furthermore, the existing 900,000 tons of sludge currently stored in the Seyhan WWTP landfill represent a staggering emission potential of approximately 1,576,800 kgCO_2eq/ton. Transitioning to THP technology not only addresses the management of annually generated sludge but also provides a viable pathway for processing accumulated waste with minimal carbon output. By converting sludge into a renewable energy source, THP transforms a management burden into an economically valuable raw material, thereby improving local air quality and supporting global decarbonization goals.

Economic and Operational Feasibility of THP Integration

Modeling results for the integrated THP-digester system at Seyhan WWTP reveal substantial operational gains:

- ✓ *Energy Recovery:* THP is projected to produce an additional 54 m^3/h of biogas (473,040 m^3/year). This is equivalent to 1,087,992 kWh/year of electricity. At a unit price of $0.13/kWh, this generates a direct revenue of $141,438/year.
- ✓ *Waste Reduction:* The process reduces the final sludge volume by 4,886 tons/year. Given a disposal cost of $25/ton (covering maintenance, heating, investment, and personnel), this yields an additional saving of $122,150/year.
- ✓ *Total Economic Impact:* Assuming that the heat generated by Combined Heat and Power (CHP) technology covers the operational heating requirements for THP, the total projected annual benefit is approximately $263,588.

Currently, the Seyhan WWTP operates two cogenerators with a total capacity of 2,400 kWh. The findings suggest that the heat produced is sufficient to maintain both the digesters and the THP system, creating a self-sustaining energy loop. This highlights THP as not only an environmental necessity but also a financially robust investment for modernizing wastewater infrastructure.

CONCLUSIONS

This study calculated, modeled, and evaluated the greenhouse gas emissions (GHGE) and operational performance of Thermal Hydrolysis Process (THP) technology for sludge disposal at the Seyhan wastewater treatment plants (WWTP) in Adana, Türkiye. The following conclusions were drawn from the analysis:

1. *Environmental Performance*: By 2025, the GHGE from THP (pyrolysis, incineration) technology is projected to be approximately nine times lower than that conventional of incineration. Considering the existing 900,000-ton sludge stockpile and the increasing annual sludge volume at the Seyhan facility, THP technology offers a significantly lower environmental impact compared to conventional methods such as landfilling, incineration, and pyrolysis.
2. *Sustainability and Decarbonization:* THP technology minimizes environmental degradation and reduces reliance on fossil fuels by providing a sustainable alternative with substantially lower GHGE. By shifting away from landfilling, this approach effectively mitigates methane emissions and prevents potential groundwater contamination. The adoption of THP technology represents a critical step toward eco-friendly sludge management, offering superior benefits in pollution prevention over traditional disposal routes.
3. *Enhanced Energy Recovery:* Field-scale modeling indicates that the integration of thermal hydrolysis can increase biogas production by at least 35%, while simultaneously reducing the final sludge volume by up to 50%. This synergy maximizes energy recovery from waste streams.
4. *Product Quality and Disposal Efficiency:* Thermal hydrolysis ensures the production of a pathogen-free, high-hygiene final product (Class A biosolids) suitable for agricultural applications even under stringent regulatory frameworks. Additionally, the process significantly improves sludge dewaterability, leading to a marked reduction in transportation and disposal costs.

5. *Operational and Economic Optimization:* By reducing hydraulic retention times (HRT), THP technology allows for more efficient utilization of anaerobic digester volumes, effectively reducing digester capacity requirements by up to 50%. This optimization lowers initial investment costs and provides a cost-effective solution for increasing the capacity of existing facilities.
6. *Additional Advantages:* Beyond energy and emission benefits, the THP technology offers several operational advantages, including significant odor reduction, a compact design for space-constrained sites, and overall lower long-term operational expenditures.

Conflict of Interest

The authors declare no conflict of interest.

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