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Improving Anaerobic Digestion Process of Sewage Sludge in Terms of Energy Efficiency and Carbon Emission: Pre- or Post-Thermal Hydrolysis?

Yawen Ye [1], Azizi Selemani Msuya [1], Xiaohu Dai [1,2], Xiaoli Chai [1,2] and Boran Wu [1,2,*]

[1] State Key Laboratory of Water Pollution Control and Green Resource Recycling, College of Environmental Science and Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China; 2050607@tongji.edu.cn (Y.Y.); 2393403@tongji.edu.cn (A.S.M.); daixiaohu@tongji.edu.cn (X.D.); xlchai@tongji.edu.cn (X.C.)

[2] Shanghai Institute of Pollution Control and Ecological Security, Shanghai 200092, China

* Correspondence: author: boranwu@tongji.edu.cn

Abstract

Sewage sludge, a by-product of biological wastewater treatment, poses significant environmental and health risks if not properly managed. Anaerobic digestion (AD), widely used as a stabilization technology for sewage sludge, faces challenges such as rate-limiting hydrolysis steps and difficult dewatering of residual digestate. To address these issues, thermal hydrolysis (TH) has been explored as a pretreatment or post-treatment method. This study systematically analyzes the typical sludge treatment pathways incorporating TH either as a pretreatment step to AD or as a post-treatment step, combined with incineration or land application for the final disposal. The mass balance algorithm was applied to evaluate the chemical consumption, and energy input/output calculations were conducted to assess the potential effects of TH on energy recovery. Carbon emissions were estimated using the Intergovernmental Panel on Climate Change (IPCC) methodology, considering direct, indirect, and compensated carbon emissions. The results indicate that applying TH as a post-treatment significantly reduces the carbon emissions by 65.94% compared to conventional AD, primarily due to the enhanced dewaterability and reduced chemical flocculant usage. In contrast, TH as a pretreatment step only moderates the emission reduction. The combination of post-TH with land application results in the lowest carbon emissions among the evaluated pathways, highlighting the environmental benefits of this approach. All the findings here are expected to provide insights into optimizing the technical combination mode of sludge processing pathways in terms of minimizing carbon emission.

Keywords: sewage sludge treatment; anaerobic digestion; thermal hydrolysis; sludge disposal; carbon emission estimation

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1. Introduction

Sewage sludge is an inevitable by-product of biological wastewater treatment processes [1], and contains pathogens, heavy metals, and substantial amounts of organic compounds. If improperly treated and disposed of, sewage sludge would pose significant risks to the natural environment and human health. Considering both the environmental impact and economic costs, it is essential to focus on reduction, being harmless, stabilization, and resource utilization in the proper treatment of sewage sludge [2].

The predominant technologies employed during the sewage sludge treatment stage include minimization, thickening, dewatering, drying, and stabilization [3]. Anaerobic digestion (AD) is one of the stabilization technologies that effectively achieves reduction, stabilization, and resource utilization. Due to its ability to generate methane—a highly promising biomass energy—AD is increasingly being employed in sewage sludge treatment [4,5]. The complex biological process of AD generally involves four stages: hydrolysis, acidification, acetic acid production, and methane production. In conventional AD processes, the hydrolysis of macromolecules, i.e., extracellular polymeric substances (EPS), into small-molecule organic compounds—enabling their subsequent conversion—is often considered as the rate-limiting step [6]. Meanwhile, the residual material (digested sludge) from the AD process is difficult to dewater, thus bringing a negative impact on subsequent disposal measures such as land application. To address these two major challenges, a growing number of treatment methods have been developed, with TH being the most widely used.

Thermal hydrolysis (TH) is a chemical process that breaks down the molecular structure of organic matter through the intense thermal motion of water molecules under high temperature and pressure [7]. Our previous studies have shown that TH can greatly promote the biodegradability of sludge in AD processes and also can improve the dewatering performance of residual materials [8–11]. Targeting the rate-limiting step of AD, TH is commonly applied as a pretreatment method to disrupt cell structures, enhance the dissolution and hydrolysis rates of organic matter, and thereby provide more favorable substrates for subsequent AD [12]. With TH as the pretreatment step, AD can increase the organic conversion rate and improve the methane yield from the sludge [13]. Accordingly, more energy can be recovered from AD biogas, which enhances the self-sustainability of the anaerobic digestion process by reducing the need for external energy and chemical inputs. Regarding the dewaterability improvement of anaerobic digestate, TH could crack the entrapped cells and the hydrophilic structure units of EPS, which facilitates the reduction and resource utilization of anaerobic digestate [8,14]. It was reported that the water content of anaerobic digestate treated by TH can be directly decreased below 60 wt.% only by the mechanical pressing process without thermal drying [8]. As a result, the energy and materials required by the anaerobic digestate disposal can be minimized. Therefore, as discussed above, whether TH is employed as a pretreatment step to enhance the biogas yield or as a post-treatment to reduce the disposal burden of the anaerobic digestate, it contributes to improving the overall efficiency of the AD-based sludge treatment process. Consequently, associated energy and chemical consumption—and thereby carbon emissions—can be reduced. However, there is still ongoing debate regarding the optimal point of integration for the TH process, i.e., whether it should be applied as a pretreatment or post-treatment step of AD, to achieve the most efficient sludge treatment strategy with minimal carbon emissions and maximum energy recovery.

This study presents an innovative comparative analysis of energy consumption and carbon emissions between two distinct thermal hydrolysis (TH) process configurations for sewage sludge treatment. Through systematic evaluation of mass flow characteristics, energy efficiency, and carbon emissions in TH-assisted AD systems, this work establishes fundamental insights for optimizing TH integration strategies within sludge treatment processes. Primarily, the mass balance algorithm was adopted to evaluate the functional targets and handling capacity of different units in the sludge disposal process; then, the energy input and output of the representative processes were calculated to clarify the potential effects of TH operation on the energy recovery efficiency of sludge treatment; finally, the carbon emission was estimated to assess the low-carbon attributes of TH-assisted sludge treatment processes. All the findings here are expected to provide a basis

for determining the optimal integration mode of TH with other unit operations, e.g., AD, mechanical dewatering, and thermal drying, from the perspectives of energy conservation and carbon emission reduction.

2. Materials and Methods

2.1. Functional Units and Accounting Boundaries

This study analyzed six scenarios for sewage sludge treatment with AD as the core process. Regarding the disposal following AD, sewage sludge can be disposed of with incineration, utilized for land application, and incorporated into building materials [1]. The land application of sludge has certain economic and biological outcomes due to the full utilization of nutrient elements in sludge [15,16]. Also, incineration technology, known for its significant reduction and being completely harmless, is extensively utilized in economically developed regions [1]. Although the use of sludge in building materials offers potential benefits, the associated environmental, technical, economic, and regulatory challenges have limited its widespread adoption [17,18]. Therefore, this study specifically focused on the sludge treatment pathways with different combination modes of TH, AD, incineration, and land application. Specifically, the following six different scenarios listed in Table 1 were analyzed:

Table 1. Process flow of different sludge treatment pathways L1–L6.

Pathway	Step 1 Thickening	Step 2 AD and TH Sequence	Step 3 Dewatering	Step 4 Final Disposal
L1 (N/A TH)	Included	AD	Included	Drying → Incineration
L2 (Pre-TH)		Pre-TH → AD		Drying → Incineration
L3 (Post-TH)		AD → Post-TH		Drying → Incineration
L4 (N/A TH)		AD		Land Application
L5 (Pre-TH)		Pre-TH → AD		Land Application
L6 (Post-TH)		AD → Post-TH		Land Application

The starting point of the carbon emission calculation was municipal sewage sludge with a water content of 98% after gravity settling; meanwhile the endpoint was product output or energy recovery, including greenhouse gas (GHG) directly or indirectly generated during the sludge treatment and disposal process and expressed as CO_2-equivalents ($CO_{2\text{-eq}}$) per unit mass of sludge.

2.2. Calculation Method

The carbon emission estimation was conducted based on the method provided in the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (hereinafter referred to as the IPCC method) [19–21]. Although it provides a calculation method for CH_4 and N_2O emission from biological waste treatment, the calculation method for CO_2 emission from energy sources is not provided directly [22]. Based on the specific treatment processes involved in the sludge treatment pathways studied in this paper, corresponding extensions have been made on the basis of the IPCC method.

The specific calculation content was as follows: (1) Direct carbon emission refers to the GHG emitted during the sludge treatment, as well as the energy source CO_2 released from primary energy consumption [23,24]; (2) Indirect carbon emission refers to the GHG emission caused by the production or use of secondary energy consumed during the treatment and disposal process [25]; (3) Carbon compensation is due to the power generation or heat generation caused by the collection and utilization of methane produced during anaerobic digestion, as well as the incineration of biogas residue, which can replace the consumption

of primary or secondary energy with corresponding calorific value. The greenhouse gas emission of these alternative energy or substances during production or use are deducted in the calculation in the form of negative values. Finally, these three types of carbon emission were normalized and compared in the form of CO_2 equivalents ($CO_{2\text{-eq}}$) [1,26]. The specific calculation formula reads as follows:

2.2.1. Direct Carbon Emission

In this study, direct carbon emissions include the CO_2 emission caused by primary energy consumption and CH_4 and N_2O generated from sludge treatment.

The calculation of the CO_2 emission caused by primary energy consumption was based on Equation (1) [21].

$$CO_2 = W\left(DC \cdot f_{DC} + NGC \cdot \frac{f_{NGC}}{\eta_{NGC}}\right) \quad (1)$$

where W is the sludge amount, measured by the dry weight; DC is the equipment fuel consumption, calculated as diesel oil; f_{DC} is the CO_2 emission factor of diesel oil; NGC is the heat consumption of different processes, calculated as natural gas; f_{NGC} is the CO_2 emission factor of natural gas; η_{NGC} is the energy utilization rate of natural gas.

The calculation of the CO_2 emission caused by CH_4 and N_2O generated from sludge incineration is based on Equation (2) [21].

$$GHG = W \cdot EF \cdot GWP \quad (2)$$

where EF is the CH_4 and N_2O emission factors from sludge incineration, with values based on the IPCC method; GWP is the global warming potential of CH_4 or N_2O, taken as 21 or 310, respectively [27].

2.2.2. Indirect Carbon Emission

Indirect carbon emission is mainly CO_2 equivalent emission caused by electricity consumption, which also includes N_2O emissions during the land application process.

The calculation of the CO_2 equivalent emission caused by electricity consumption was based on Equation (3) [21].

$$CO_2 = W \cdot EC \cdot f_{EC} \quad (3)$$

where EC is the electricity consumption of the equipment; f_{EC} is the CO_2 emission factor of electric energy.

N_2O emissions during the sludge land application process include those resulting from the atmospheric deposition of volatile nitrogen compounds into the soil, as well as from nitrogen leaching and runoff. These emissions were calculated based on Equation (4) [21].

$$N_2O = W_N \cdot Frac \cdot EF \quad (4)$$

where W_N is the amount of nitrogen from sludge added to the soil, measured in kg N; $Frac$ is the proportion of nitrogen evaporated in the form of NH_3 and NO_X, or the proportion of nitrogen applied through nitrogen leaching and runoff loss in soil management.

2.2.3. Carbon Compensation

Among the sludge treatment processes involved in this study, carbon compensation refers to the carbon offsets achieved through energy and resource recovery. The calculation of carbon compensation was based on Equation (5) [21].

$$CO_2 = W\left(EC^{'} \cdot f_{EC} + NGC^{'} \cdot \frac{f_{NGC}}{\eta_{NGC}}\right) \quad (5)$$

where EC' represents the electricity generated from heat recovery or the electricity consumption offset by alternative fertilizer production; and $NGC^{'}$ denotes the recovered heat, expressed in terms of equivalent natural gas.

2.3. Parameter Selection

Based on the existing studies, the parameter values used in the calculation process mainly including the consumption of electricity, steam, and chemicals, are summarized in Table 2. Also, the biogas production of the anaerobic digestion process and the nitrogen/phosphorus/potassium production of land application used during the calculation can be obtained according to Table 2.

Table 2. Parameters used in calculation of carbon emissions.

Processing Unit	Parameter	Unit	Value L1/L4	Value L2/L5	Value L3/L6	Emission Factor	Emission Factor Unit
Thickening	Energy consumption	kW·h/tDS		15		0.68	kg CO_2/kW·h
	PAM dosage	kg/tDS		4		25	kg CO_2/kgPAM
AD [28,29]	Biogas production	m^3/tDS	200	350	200	0.056	kg CO_2/MJ
	Energy consumption	kW·h/tDS	100	50	100	0.68	kg CO_2/kW·h
TH [30,31]	Energy consumption	kW·h/tDS	N/A	260	260	0.68	kg CO_2/kW·h
	Steam consumption	tSteam/tDS	N/A	1.6	1.6	193.39	kg CO_2/tSteam
Dewatering [29]	Energy consumption	kW·h/tDS	55	40	40	0.68	kg CO_2/kW·h
	PAM dosage	kg/tDS	3	1	N/A	25	kg CO_2/kgPAM
	$FeCl_3$ dosage	kg/tDS	120	50	N/A	8.3	kg CO_2/kg$FeCl_3$
Drying [32]	Energy consumption	kW·h/kgH_2O		0.125		0.68	kg CO_2/kW·h
Incinerate [33–35]	Energy consumption	kW·h/tDS		300		0.68	kg CO_2/kW·h
	Auxiliary fuel consumption	m^3/tDS		12.25		1.879	kg CO_2/m^3
Land application [36]	N	kg/tDS		30		7.759	kg CO_2/kgN
	P	kg/tDS		15.75		2.332	kg CO_2/kgP
	K	kg/tDS		2.4		0.660	kg CO_2/kgK
Biogas slurry treatment [37]	Energy consumption	kW·h/m^3		2		0.68	kg CO_2/kW·h

3. Results and Discussion

3.1. Mass Flow Analysis of Typical Sludge Disposal Pathways

Sludge treatment pathways incorporating TH, AD, thermal drying, incineration, and land application as core operational units were selected as the focus of this study, during which PAM and $FeCl_3$ are applied as the most common sludge conditioning agents. The different process combinations, also the chemical consumption and generation of recyclable resources at each stage of these pathways, are illustrated in Figure 1. As shown, compared with the conventional AD pathway without TH pretreatment (L1), the biogas production increased by 70.63% when TH was introduced as a pretreatment step (L2), which is consistent with previous research findings [7,13,38].

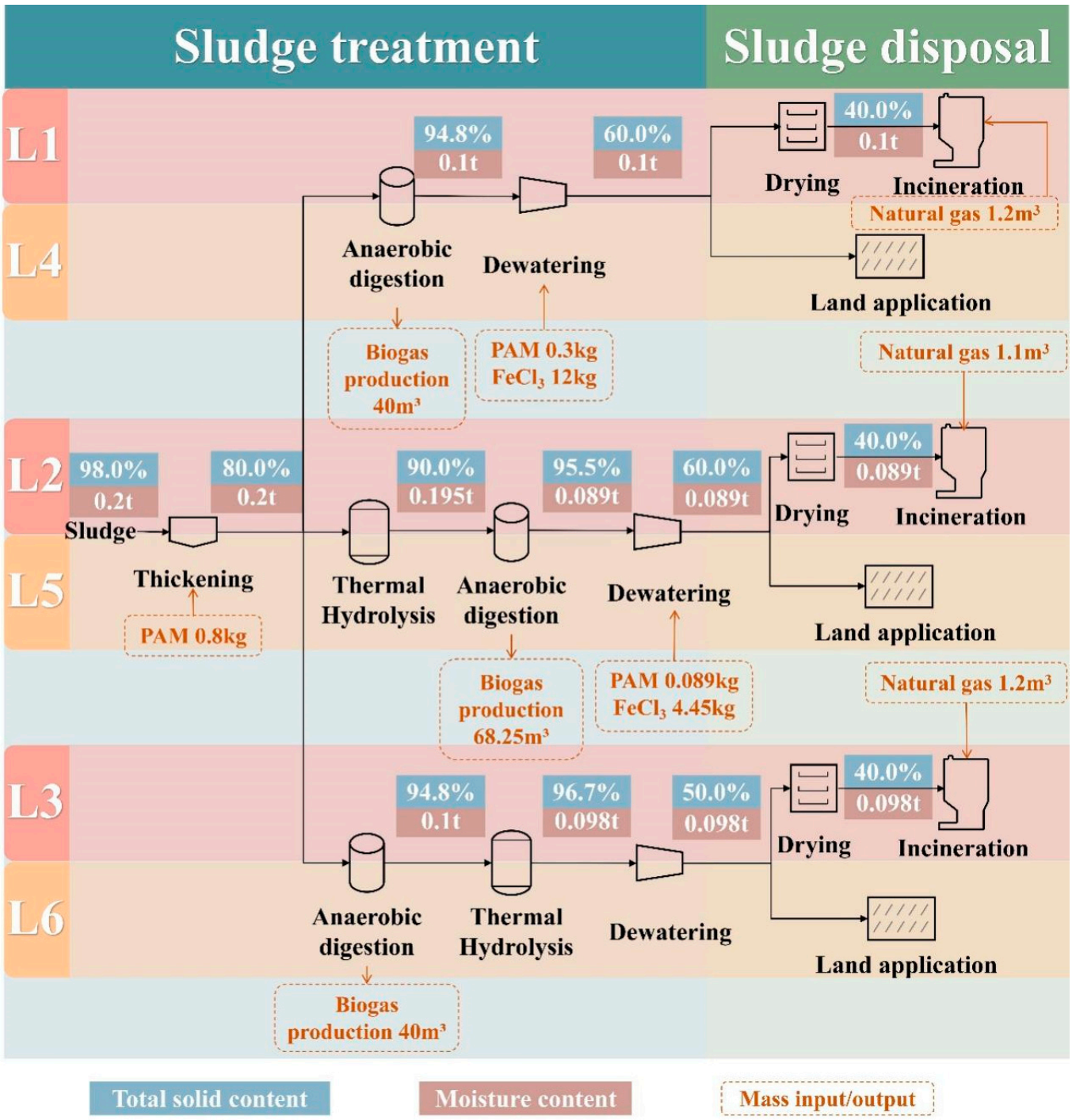


Figure 1. Mass flow of typical sludge treatment processes (sludge with the initial water content: 98 wt.%) with AD as the core unit. (Scenarios: L1 represents conventional AD followed by incineration; L2 represents pre-TH AD followed by incineration; L3 represents post-TH AD followed by incineration; L4 represents conventional AD followed by land application; L5 represents pre-TH AD followed by land application; L6 represents post-TH AD followed by land application).

Meanwhile, using TH as a pretreatment can also improve the dewaterability of anaerobic digestate. A comparison between pathways L1 and L2 shows that incorporating TH before anaerobic digestion reduces the dosage of PAM and $FeCl_3$ in the dewatering unit by 70.33% and 62.92%, respectively. Additionally, applying TH as a post-treatment to anaerobic digestate significantly enhances the dewatering performance, enabling mechanical dewatering to reduce the moisture content to below 50% without requiring chemical

additives. Improved dewatering efficiency also lowers the energy demand of subsequent thermal drying.

However, it is noteworthy that although pre-TH enhances the efficiency of the AD process and reduces the organic content in the digestate, it may negatively affect the incineration stage by requiring additional fuel to sustain combustion. In other words, the gain in energy recovery from AD may come at the expense of reduced energy recovery from incineration. Thus, the total energy recovery efficiency of TH-integrated sludge treatment pathways should be comprehensively evaluated.

Furthermore, comparing L1/L2/L3 with L4/L5/L6, it is evident that land application, as a disposal method, does not require additional material inputs like drying and incineration. Consequently, land application can offer the lowest carbon emissions, making it a suitable option when nearby land application sites are available.

3.2. Evolution of Energy Input and Output of Typical Sludge Disposal Pathways

As discussed above, TH as the pretreatment approach can enhance the organic conversion of the AD process and improve the energy recovery from an increased amount of biogas. However, the enhanced reduction of organic matter would decrease the energy recovery from the incineration of residual anaerobic digestate and even increase the extra fuel requirement for self-sustained incineration [39]. Therefore, the energy efficiency of sludge disposal pathways with TH integrated should be systematically analyzed.

Figure 2 illustrates the power consumption associated with each step of the six selected sludge treatment pathways. The total energy consumption for pathway L1 is 7.227 kW·h per ton of sludge (initial water content: 98 wt.%) [33–35], with the added fuel of incineration accounting for the largest proportion (4.042 kW·h/t), followed by AD (2 kW·h/t). For the same sludge input, the total energy consumption of the L2 pathway (pre-TH + AD) reaches 10.815 kW·h/t, where TH alone accounts for 5.2 kW·h/t. The L3 pathway (AD + post-TH) consumes 9.185 kW·h/t in total, primarily from incineration (3.348 kW·h/t) and TH (2.6 kW·h/t).

It is evident that integrating TH as a post-treatment process results in lower total energy consumption than using it as a pretreatment. Although TH pretreatment enhances the performance of AD, the overall energy utilization efficiency of the integrated AD + incineration system is not improved. Due to the inherently high energy demand of the TH process itself, the total energy consumption in pathways incorporating TH (L2 and L3) exceeds that of the conventional AD followed by incineration (L1).

Land application is commonly regarded as the low-carbon and low-energy consumption way to dispose of sludge because it retains the major part of carbon-containing compounds in the digested sludge instead of directly releasing it into the atmosphere by incineration [40,41]. Comparing the pathways L4, L5, and L6, with the pathways L1, L2, and L3, it can be found that using land application as the final disposal method generally saves more energy consumption than by using incineration as the final disposal method. Also, the total energy consumption of pathway L6 with post-TH is 5.837 kW·h/t, which is significantly lower than that of pathway L5 with pre-TH (7.218 kW·h/t). This also reflects the obvious advantage of integrating post-TH to improve the overall energy efficiency of the sludge treatment process.

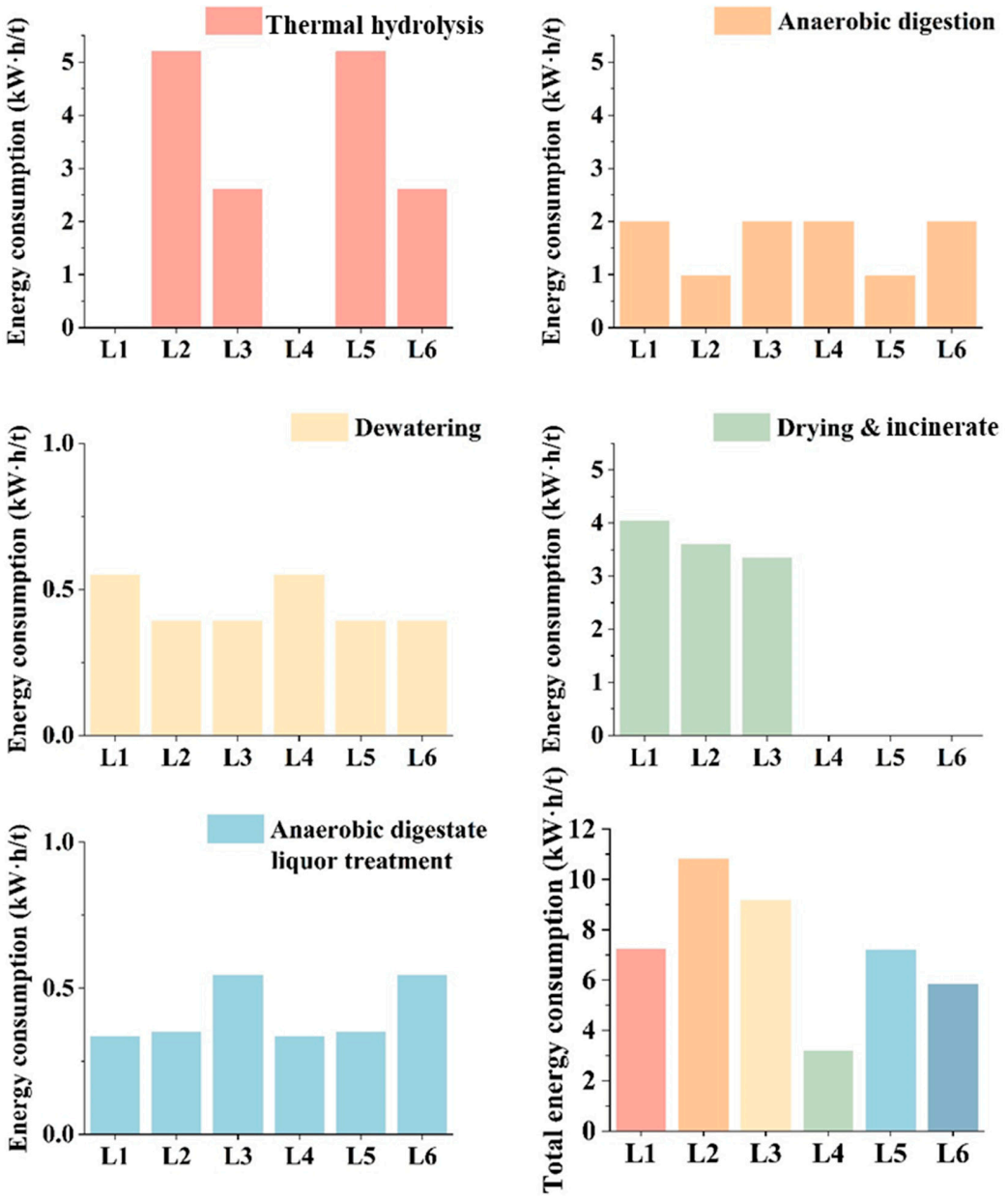


Figure 2. Energy consumption of typical sludge treatment unit and total energy consumption of each sludge treatment pathway with AD as core unit (Calculation unit: per ton of sludge with initial water content of 98 wt.%).

3.3. Carbon Emission and Reduction Potential Analysis for Typical Sludge Disposal Pathways

Figure 3 presents the carbon emissions of each step associated with municipal sewage sludge treatment and disposal across six different pathways. For comparative purposes, the summary of calculation results on the material consumption, energy consumption, and carbon emissions of different processing units in L1–L6 are also displayed in Figures S1–S6. The total carbon emission for the conventional AD followed by incineration (L1) is 465.45 kg CO_2-eq per ton of total solids (t TS), with the primary contributor being the electricity consumption of the enhanced dewatering unit (554.20 kg CO_2-eq/t TS). For the pathway incorporating TH as a pretreatment (L2), the total carbon emission is 407.95 kg CO_2-eq/t TS. This value shows a reasonable agreement (16% deviation) with the 350.98 kg CO_2-eq/t TS reported by Yang et al. [42] for similar systems. The pretreatment implementation resulted in significant carbon compensation from the AD process, reaching −412.5 kg CO_2-eq/t TS in our study. This finding aligns well with Ruan et al.'s [43] reported net energy

consumption reduction (equivalent to approximately −448 kg CO_2-eq/t TS in carbon compensation) for the AD systems with thermal pretreatment. In contrast, the pathway utilizing TH as a post-treatment (L3) exhibits a significantly lower total carbon emission of 158.50 kg CO_2-eq/t TS, primarily due to the emissions from electricity consumption and gas release during drying and incineration (253.65 kg CO_2-eq/t TS).

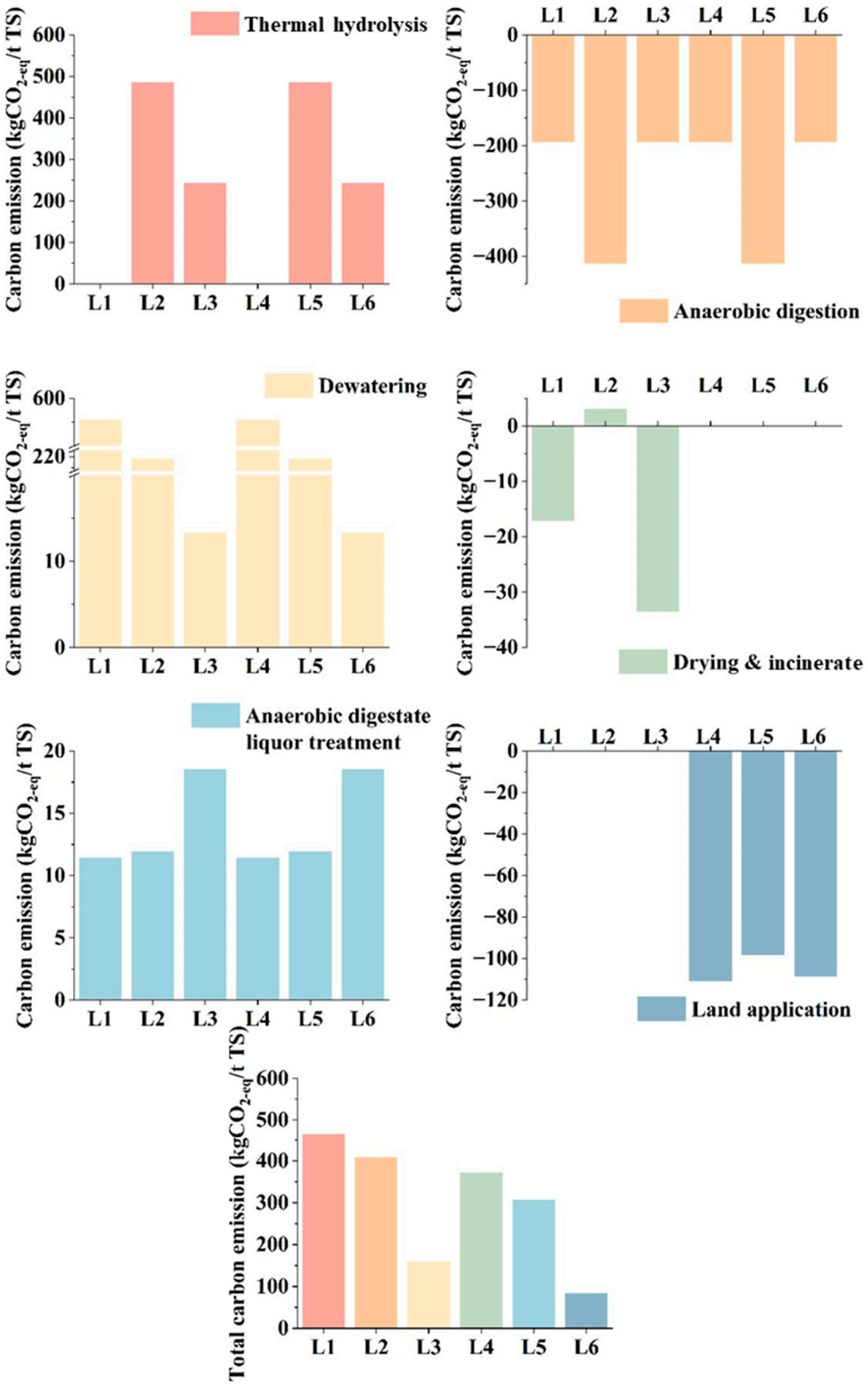


Figure 3. Carbon emission of typical sludge treatment processes and total carbon emission of each sludge treatment pathway with AD as core unit (Calculation unit: per ton of dry matter of sludge).

The total carbon emission for the conventional AD followed by thermal drying and incineration (L4) is 371.85 kg CO_2-eq/t TS, with the enhanced dewatering unit again being the major emission source (554.20 kg CO_2-eq/t TS). When TH-AD is combined with land application (L5), the total emissions drop to 306.90 kg CO_2-eq/t TS, predominantly from the heating requirements of the TH unit (486.20 kg CO_2-eq/t TS). The lowest carbon emission is observed in the L6 pathway (AD + post-TH + land application), at only 83.45 kg CO_2-eq/t TS, mainly due to the heating consumption in the TH unit (243.10 kg CO_2-eq/t TS). Our results demonstrate a substantial improvement over the results reported by Piippo et al. [22], who suggested that the GHG emission of anaerobic digestion route were 120–180 kg CO_2-eq/t TS, where biogas is used for producing heat and electricity, and digested sludge is used in the fields.

Comparing L1, L2, and L3 pathways from the perspective of total carbon emissions, both L2 and L3 demonstrate emission reductions with the integration of TH. Notably, L3 achieves a 65.94% reduction in the total carbon emissions compared to L1, which is significantly greater than the 12.35% reduction observed in L2. Analyzing emissions from individual process steps, the dewatering stage in L3 shows a reduction of 97.59% and 93.62% in carbon emissions relative to L1 and L2, respectively. This highlights the substantial enhancement in the dewatering performance brought about by TH, which directly contributes to reduced carbon emissions.

While using TH as a pretreatment process in pathway L2, this demonstrates a significant 51.25% reduction in emissions from the subsequent AD step compared to pathway L1. This environmental benefit is counterbalanced by the substantial carbon footprint of the TH unit itself. This analysis reveals that the net emission reduction achieved by L2 remains limited when considering the complete system. These results indicate that although TH used as a pretreatment process effectively enhances the AD performance by reducing process emissions, its overall carbon footprint negates these advantages at the system level. Furthermore, this analysis suggests that implementing TH in both the pretreatment and post-treatment configurations may not yield meaningful net emission reductions, as the cumulative energy demands and associated emissions of a dual-stage TH application would likely outweigh the incremental gains in AD efficiency. Consequently, from a carbon emission perspective, implementing TH as a post-treatment unit in sludge processing routes appears more environmentally favorable than its application as a pretreatment technology.

By comparing land application with drying and incineration as final disposal methods, it is evident that, under identical treatment conditions, land application results in significantly lower total carbon emissions—achieving reductions ranging from 20.1% to 47.4%. As illustrated in Figure 3, the lowest total carbon emission is observed when TH is applied as a post-treatment process, coupled with land application as the final disposal route. This outcome is primarily attributed to the carbon-negative nature of land application, wherein its total carbon emissions are approximately half of the carbon offsets generated through energy and resource recovery.

4. Conclusions

This study aims to elucidate the impact of integrating TH into sewage sludge treatment pathways, focusing on improvements in energy efficiency and carbon emission reduction. A mass balance framework, coupled with an assessment of energy input/output evolution and carbon emission accounting, was applied to six representative treatment pathways. The research provides the first systematic comparison of TH implementation strategies, specifically examining its differential impacts when deployed either as a pretreatment unit

prior to AD, or a post-treatment step following AD, within complete sludge processing systems. The key conclusions drawn from this comparative analysis are as follows:

- Compared with conventional anaerobic digestion, applying TH as a post-treatment process leads to a substantial reduction in carbon emissions by 65.9–77.6%, while pretreatment integration yields only moderate improvements.
- Post-treatment TH significantly enhances the dewaterability of anaerobic digestate, and the elimination of chemical flocculants in the dewatering stage and the energy consumption in the drying stage plays a pivotal role in reducing carbon emissions.
- The combination of TH as a post-treatment step with land application as the final disposal method yields the lowest overall carbon emission (83.45 kg CO_2-eq/t TS) among the evaluated pathways.

These findings provide clarity on the debated role of TH in improving sludge treatment efficiency. By systematically comparing pre- and post-TH configurations, the results show that the post-treatment unit can be the optimal positioning of TH within the sludge treatment pathways, no matter the land application or thermal treatment used as the final disposal methods. These findings might offer theoretical guidance for optimizing sludge treatment system design, particularly in determining the optimal integration of TH with common sludge treatment operations—including anaerobic digestion, mechanical dewatering, and thermal drying—from the perspectives of energy conservation and carbon mitigation. Also, compared with the process using thermal approaches, e.g., incineration, as the final disposal method, the sludge disposal method dominated by land application generally shows the more significant potential in carbon emission reduction. Future sludge treatment operations should endeavor to maximize the sustainability with resource recovery and adapting to ecological restoration.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17136147/s1, Figures S1–S6: The material consumption, energy consumption, and carbon emissions of different processing units in L1–L6.

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