Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/2025.28065

Sewage Sludge-to-Energy Conversion Based on the Combination of Anaerobic Digestion and Pyrolysis Process: Energy Efficiency and Economy Assessment

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Abstract. Sewage sludge is a residual produced as a wastewater treatment byproduct. With the intensifying global waste and energy crisis, energy demands are accelerating quickly. Sewage sludge, as a byproduct of wastewater treatment, largely contributes to pollution when disposed via traditional means. To reduce the waste burden and detrimental pollutions to the environment, directly converting sewage sludge to wastewater is one of the effective ways. This paper focuses on an optimized model in the conversion of sewage sludge to energy with increased energy efficiency and economic cost to solve currently existing worldwide problems. By combining practices of pyrolysis and anaerobic digestion, a model with increased energy efficiency and cost is created. Three functions are targeted, including the levelized cost of energy (LCOE), energy efficiency (EE) and the biochar production.

Keywords: Anaerobic digestion, pyrolysis, sewage sludge, waste to energy conversion, biochar.

1. Introduction

The global waste and energy crisis is intensifying as the amount of waste materials and energy demand are increasing. Over 2 billion tons of municipal solid trash are produced worldwide each year, and by 2050, experts predict that this amount will rise by 70%. Addressing this interrelated crisis is critical for sustainable development and global environment protection. Sewage sludge, a major byproduct of wastewater treatment, significantly contributes to environmental pollution when disposed of via traditional means such as landfilling and incineration, which causes environmental degradation due to the occupation of land areas and the emission of greenhouse gases. However, scientists have discovered the potential of sewage sludge to reverse its negative environmental impact, turning a waste problem into a generation of renewable energy.

In response to these challenges, converting sewage sludge into energy has become a practical and optimistic solution, which aligns with sustainability goals and the principles of a circular economy,

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DOI: 10.54254/2755-2721/2025.28065

providing a dual benefit of waste minimization and renewable energy production. The integrated process of anaerobic digestion (AD) and pyrolysis is particularly notable for its ability to recover energy efficiently while reducing the overall environmental impact.

This study is driven by three primary objectives: 1. To assess the energy recovery potential of sewage sludge in the treatment process 2. To promote environmental sustainability through the combined treatment of AD and pyrolysis 3. To evaluate the economic feasibility of these methods to achieve a better economic opportunity compared to traditional practices. The research focuses on optimizing the energy efficiency and economic feasibility of the combined AD and pyrolysis process, employing genetic algorithms and multi-objective optimization models to maximize energy output and minimize costs, also ensuring it is environmentally conscious.

This paper demonstrates an in-depth analysis of the combined treatment process of sewage sludge-to-energy conversion and a comprehensive model designed for an energy-efficient and economically viable approach. By evaluating the energy output, levelized cost of energy (LCOE), and environmental impact, this study seeks to offer a sustainable alternative to conventional waste management systems and contribute to global efforts in the face of the waste and energy crisis.

2. Methodology

2.1. Description of process flow diagram

In order to realize the effective use of sewage sludge and improve the energy efficiency of sewage treatment system, this study constructs the flow chart through extensive research and data analysis. The chart illustrates the key stages of converting sludge into energy within the integrated framework of sewage treatment and resource recovery.

The research involves a variety of treatment technologies such as anaerobic digestion, pyrolysis and energy recovery systems to optimize wastewater treatment and extract its valuable resources. The method provides a clear pathway for the conversion of sludge into bioenergy and reusable materials, thereby contributing to promoting environmental sustainability and a circular economy.

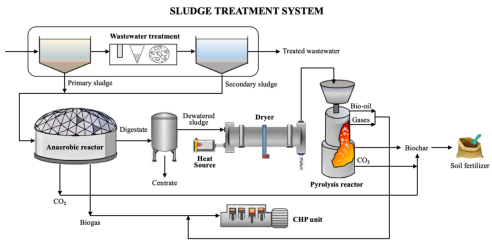


Figure 1. Flow chart of sludge treatment system

The untreated wastewater will go to the primary sludge tank, where it is mainly used to remove large particles of impurities from the water. The treated wastewater flows into secondary sludge tanks for further removal of fine suspended particles, thus ensuring that the water quality meets certain standards and that this part of the treated water can be safely discharged or used for other non-drinking purposes.

The sludge produced during the treatment process will be fed into an anaerobic reactor. At this stage, the sludge is decomposed in the absence of oxygen and the main product produced is biogas, which is mainly composed of methane and carbon dioxide and can be used as energy sources in other industrial processes. The digestion residue from the anaerobic reactor is fed to a dewatering plant, where it is separated from solid and liquid to produce dehydrated sludge and centrate. The

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dehydrated sludge is then fed into the dryer to further reduce humidity, while the centrate is separated for subsequent treatment or returned to the system.

The dried sludge is fed into a pyrolysis reactor, where it is converted into bio-oil, combustible gas and biochar at high temperatures and without oxygen. The resulting biochar can be used to store carbon dioxide produced in anaerobic reactors and pyrolysis reactors, and the excess biochar can be further used as soil fertilizer. At the same time, the biogas produced by the anaerobic reactor and the bio-oil and biogas produced by the pyrolysis reactor can be used as raw materials for the cogeneration unit to further generate electricity and heat.

In conclusion, the whole process not only realizes the purification of wastewater and the resource utilization of sludge, but also effectively recovers energy through the combined heat and power unit (CHP unit) and improves the efficiency of energy utilization.

2.2. Process analysis from chemical and mathematical perspectives

2.2.1. Chemical reactions on each stage

Table 1. Reactions during anerobic digestion process

Phases	Reaction	Rates
I	$C_6H_{10}O_5 + H_2O = C_6H_{12}O_6$	$S_0 = l_0\,[C_6H_{10}O_5][H_2O]$
II	$C_6H_{12}O_6 = C_4H_8O_2 + 2CO_2 + 2H_2$	$S_1 = l_1\,[C_6H_{10}O_6]$
III	$C_4H_8O_2 + H_2O + \frac{1}{2}\ CO_2 = 2C_2H_4O_2 + \frac{1}{2}\ CH_4$	$S_2 = l_2\,[C_4H_8O_2][H_2O]\,[CO2]^{\frac{1}{2}}$
IV	$\frac{1}{2}\ CO_2 + 2H_2 = \frac{1}{2}\ CH_4 + H_2O$	$S_3 = [CO2]^{\frac{1}{2}}\ [H_2]^2$
V	$2C_2H_4O_2 = 2CH_4 + 2CO_2$	$S_4 = l_4 = [C_2H_4O_5]^2$

Reactions during pyrolysis process.

$$C_6H_{10}O_5 \xrightarrow{\text{Heat}} 6C + 5H_2 + 5CO + 2CO_2 + 2H_2O + \text{Char}$$

2.2.2. Formulation and data considerations

Table 2. Characteristics of the sludge feedstock and pyrolysis product

	PS[a]	WAS[a]	ADS[a]
Sludge feedstock			
VS[a] content (wt.%)	84	69	59
CV[a] (MJ/kg)	23	19	17
Process yield of the sludge pyrolysis			
Bio-oil (%)	42	31	26
Biochar (%)	33	43	53
CV of the pyrolysis products			
Bio-oil (MJ/kg-bio-oil)	37	37	37
Biochar (MJ/kg)	17	13	10

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a. PS = Primary Sludge, WAS = Waste Activated Sludge, ADS = Anaerobically Digested Sludge, VS = Volatile Solids, CV = Calorific Value.

3. Results and discussion

3.1. Bioenergy production

There are three types of sludge: primary sludge (PS); waste activated sludge (WAS)/secondary sludge; anaerobically digested sludge (ADS), presence in different stages of the process. Assumed that the amount of raw sewage sludge (RSS) is 200 tons, and TS content is 4.5%, which is 9 tons. In this study, the main factor to be considered is different values of VS content in original sludge. Additionally, all the outputs (Electricity, AEE, LCOE) are changing with different VS contents. The VS content range is assumed from 0.65% to 0.85%.

The following equations are shown to calculate for AEE (apparent energy efficiency)

$$W_{ADS} = \frac{W_{RSS} \times (1 - VS_{RSS})}{1 - VS_{RSS}} \quad (1)$$

The (kg) and the (kg) are the dry matter amounts in the RSS and the ADS, the (wt.%) and the (wt.%) are VS contents in the RSS and the ADS.

According to Cao Y et al. [1], VS value of ADS and RSS can be found, which are 59% and 84%.

$$CV_{sludge} = 24.21 \times VS_{sludge} + 2.56 \left(R^2 = 0.9944\right) \quad (2)$$

The Y_{biogas} (m^3) is the biogas yield, and SBP_{biogas} is the specific biogas production (SBP), which is expressed as the proportion of the biogas amount produced to the amount of the VS degraded. For SBP, it is Specific biogas production (m^3 biogas/kg VS-destroyed). According to the Cao Y et al. [1], range of value is from 0.8 to 1.2 [1]. In this case, the calculation will use the typical value 1.0.

$$Y_{biogas} = SBP_{biogas} \times (W_{RSS} - W_{ADS}) \quad (3)$$

The $Y_{bio-oil}$ is the bio-oil yield (%), the VS_{sludge} is the volatile solids content in sludge (%), the CV_{sludge} is the calorific value of sludge (MJ/kg).

$$Y_{bio-oil} = 63.684 \times VS_{sludge} - 11.337 (R^2 = 0.9982) \quad (4)$$

For the total yield of products (Bio-oil, Biogas), according to the Cao Y et al. [1], The CV (calorific value) of biogas is 25.8 MJ/m3. After calculating the yield of biogas through the equations above, it can calculate the energy (electricity) produced by biogas by multiplying its CV value. Meanwhile, the CV (calorific value) of bio-oil is presented as 37 MJ/kg [1]. The thermal efficiency of CHP plants can vary significantly, often reported about 35% for electricity production.

$$Electricity\ produced_{biogas} = Y_{biogas} \times \frac{25.8 MJ}{m^3} \times 35\% \quad (5)$$

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$$Electricity\ produced_{bio-oil} = \mathrm{Y}_{bio-oil} \times \frac{37MJ}{\mathrm{kg}} \times 35\% \tag{6}$$

According to the calculations of the biogas and biooil, the total energy produced based on the combined process (AD combines pyrolysis) can be calculated by:

$$E_{total} = Electricity\ produced_{biogas} + Electricity\ produced_{bio-oil} \tag{7}$$

The efficiency with which a system makes use of the apparent energy it receives is known as apparent energy efficiency. Reactive and actual power are combined to form apparent energy. The useful output energy to total apparent input energy might be considered the ratio of apparent energy efficiency. The power factor, which gauges how well current is transformed into productive activity, has an impact on it. The system's efficiency in utilizing electricity for productive tasks increases with the AEE's proximity to 1. The targeted-product of AD process is biogas, after pyrolysis, the bio-oil will also be produced. Therefore, separately calculate the AEE of each process (AD and pyrolysis) Then, add them together to calculate total AEE through the whole process. $\mathrm{CV}_{targeted-product}$ and $W_{targeted-product}$ are the calorific value (CV) and yield of targeted biofuel products, CV_{sludge} and W_{sludge} are the calorific value and dry matter amount of feedstock.

$$AEE = \frac{\mathrm{CV}_{targeted-product} \times W_{targeted-product}}{CV_{sludge} \times W_{sludge}} \tag{8}$$

When comparing the overall energy output from a process's products to the energy present in the input (sludge), the Gross Energy Efficiency (GEE) offers a ratio. A higher GEE suggests a more energy-efficient process since it shows that a greater percentage of the sludge's energy is being transformed into usable goods. Also, the GEE can be calculated by the below equation, the $CV_{products}$ and the $W_{products}$ are the CV value and yield of all process products (biogas, bio-oil, biochar and Py-gas).

$$GEE = \frac{\sum(CV_{products} \times W_{products})}{CV_{sludge} \times W_{sludge}} \tag{9}$$

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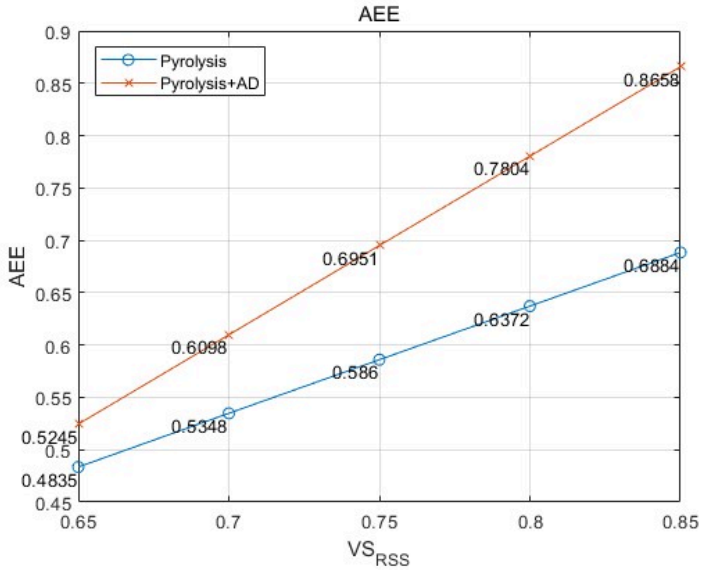


Figure 2. AEE affected by different values of VSRSS

According to the figure above, the AEE values of the combined system (the pyrolysis combines anerobic digestion system) are always larger than the AEE values of the pyrolysis system. Additionally, the AEE values of two different systems both become greater with the higher VS_{RSS} content of sludge. According to the definition, the system's efficiency increases with the AEE's proximity to 1. In this case, the efficiency of the combined system is greater than the efficiency of the pyrolysis system.

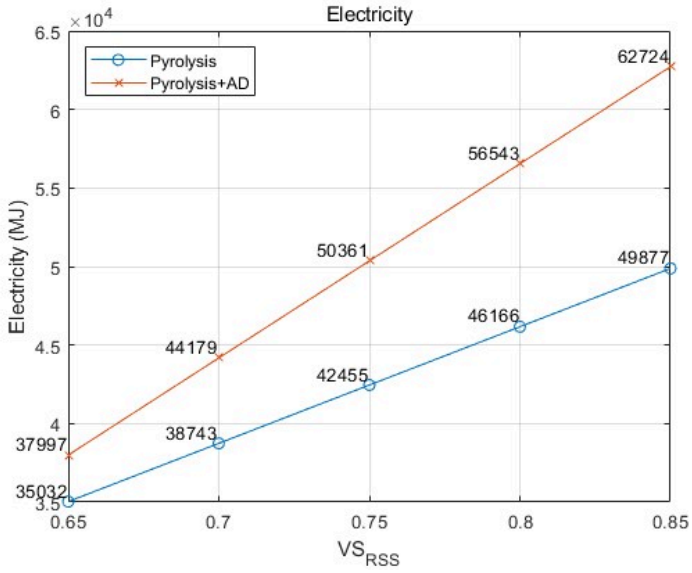


Figure 3. Electricity output affected by different values of VSRSS

According to the figure above, the electricity outputs of the combined system are always larger than the electricity outputs of the pyrolysis system. Additionally, the AEE values of two different systems both become greater with the higher VS_{RSS} content of sludge. In this case, the electricity output of the combined system is greater than electricity output of the pyrolysis system.

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3.2. Levelized cost of energy

To assess the economics of various power production systems, the energy sector frequently uses the Levelized Cost of Energy (LCOE) statistics. It shows the average cost throughout the course of a project per unit of energy, often measured in megawatt hours, or MWh. To put it briefly, Life Cycle Assessment of Energy (LCOE) offers a methodical way to evaluate the expenses of power production projects across their whole life cycle, assisting decision makers in comparing the prices of various energy sources.

First, assume the lifespan is 10 years. The equation of LCOE is:

$$LCOE = P = \frac{\sum_{t=0}^{T}\left[\left(Cap_t + FO_t + VO_t\right)(1+r)^{-t}\right]}{\sum_{t=0}^{T} E_t (1+r)^{-t}} \tag{10}$$

T : Number of years of economic life
t : Power output in year t
P : Price of electricity to balance cost
Cap_t : Capital investment
FO_t : Fixed operation (FO) cost in year t
VO_t : Variable operation (VO) cost in year t
r : Discount rate (Assumed the discount rate is 10%)
E_t : The total yield of products (Bio-oil, Biogas)

3.2.1. Equipment and operation cost for pyrolysis system

For the thermal drying - pyrolysis (TD-Py) system, converting cost data from Clack et al. Supplementary Table 34, the capital investment (CAPEX) is $68,694 per tonne TS per day. The fixed operation cost and variable operation are $936.24 per tonne TS in total, it is also called OPEX [2]. Also, for the sludge TS percentage, it is 2% to 7% of the raw sludge [3]. In this case, this passage uses the average value, which is 4.5% as the TS percentage of primary sludge.

$$\text{Total Solid (kg)} = 200 \times 10^3 \times 0.045 = 9000\text{kg} \tag{11}$$

The above equation indicates the TS value we calculated.

$$Plant's\ Total\ CAPEX\ =\ Ref_{CAPEX} * TS\ =\ 68694 \times 9 = 618246\ USD \tag{12}$$

$$Plant's\ OPEX\ per\ day\ =\ Ref_{OPEX} * TS\ =\ 936.24 \times 9 = 8426.16\ \frac{USD}{day} \tag{13}$$

$$Plant's\ OPEX\ per\ year\ =\ N\ *\ Ref_{OPEX} * TS\ =\ 300 \times 936.24 \times 9 = 2527848\ \frac{USD}{yr} \tag{14}$$

(N is the number of days in operation, often assumed to be ~300 days for such processes, 7.09 CNY can be exchanged for 1 USD (Xe.com, 2019))

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3.2.2 Equipment and Operation Cost for AD+Pyrolysis System

For the pyrolysis combines anerobic digestion system, according to Li, H. et (2017), the CAPEX of the anerobic digestion part can be calculated by equation (15) [4].

$$\frac{125\times10^4 CNY}{t\times day} \times 1day \times 9t \times \frac{1USD}{7.09CNY} = 1586741.89\ USD \tag{15}$$

According to Barry, D. et al. (2017), the CAPEX of the pyrolysis part can be calculated by equation (16) [5].

$$\frac{167.85\times10^4 CNY}{t\times day} \times 1day \times 9t \times \frac{1USD}{7.09CHY} = 2130677.01\ USD \tag{16}$$

In this case, the total CAPEX can be calculated by:

$$1586741.89USD + 2130677.01USD = 3717418.9\ \text{USD} \tag{17}$$

For the pyrolysis combines anerobic digestion system, according to Li, H. et al. (2017), the OPEX of the anerobic digestion part can be calculated by:

$$\left(\frac{3.4CNY}{t\times D} + \frac{29.6CNY}{t\times D}\right) \times 9t \times \frac{365D}{yr} \times \frac{1USD}{7.09CNY} = \frac{15289.84USD}{yr} \tag{18}$$

According to USDA (2007), the OPEX of the pyrolysis part can be calculated by:

$$2130677.01 \times 0.03 = \frac{63920.31USD}{yr} \tag{19}$$

In this case, the total OPEX can be calculated by:

$$\frac{15289.84USD}{yr} + \frac{63920.31USD}{yr} = 79210.2\ USD/yr \tag{20}$$

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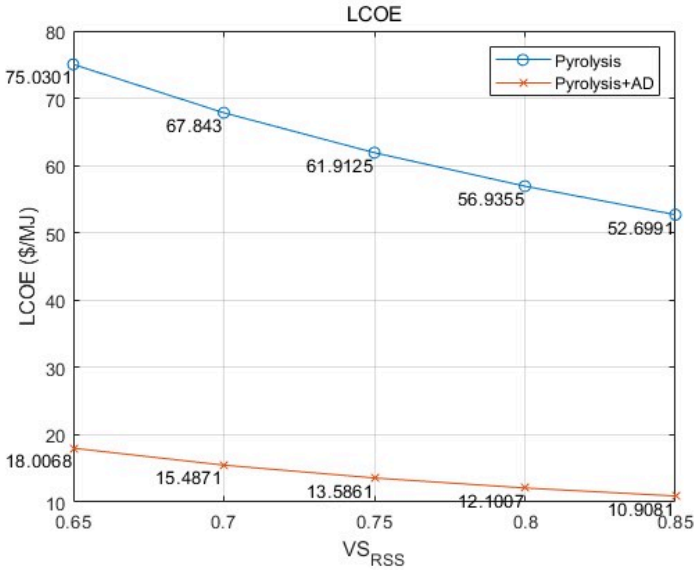


Figure 4. LCOE affected by different values of VSRSS

According to the figure above, the LCOE of the combined system is always lower than the electricity outputs of the pyrolysis system. Additionally, the AEE values of two different systems both become lower with the higher VS_{RSS} content of sludge. According to the definition, the lower the LCOE, the lower the price of electricity to balance cost is. Moreover, the LCOE decreases with the increased of the values of VS_{RSS} . In this case, the electricity output of the combined system is greater than electricity output of the pyrolysis system.

3.3. Carbon sequestration of biochar

Unlike bio-oil, which is the main product of pyrolysis that commonly be used as bioenergy to generate electricity, in terms of biochar, an earlier focus on its energy production has been turned to the current focus on its potential ability in soil improvement and carbon sequestration [6]. Compared with biomass (anaerobic digested sludge) before pyrolysis, the carbon is finally fixed in biochar after pyrolysis and is more difficult to be degraded by microorganisms. In this case, carbon could not be released again into atmosphere in the form of carbon dioxide. In this study, biochar is the py-product of pyrolysis, the moderate - temperature pyrolysis (400-500˚C) is the relatively optimal option that could consider all products generated from this process including bio-oil, biochar and py-gas. Because a pyrolysis process with this temperature range is more likely to produce all three products with a certain proportion. Not like slow pyrolysis, which operates with a slow heating rate and with a long residence time, is usually used to produce biochar rather than energy products such as bio-oil or py-gas. Neither like the high-temperature pyrolysis (around 1000˚C) which aimed to produce py-gas as much as possible rather than bio-oil or biochar [7-9].

The biochar yield is inversely proportional to the VS content of raw sludge. The main reason is based on the higher yield of bio-oil due to the increasing VS content. The higher bio-oil production will cause the lower biochar production because the product produced from pyrolysis is 100% total. According to Previous study, the char yields from primary, TWAS, and digested sludges ranged between 33 and 85, 43 and 77 and 53 and 87 wt.%, respectively [10]. Figure 5 reveals the biochar yield for two different treatment processes (combined process and pyrolysis only) versus the sludge type. Overall, it not only demonstrates that the higher yield of biochar is attributed to the lower VS

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content in the raw sludge feedstock, but also points out that biochar yield generated solely by pyrolysis is consistently higher than that from the combined process. The data of biochar yield percentage of two types of sludge (PS and WAS) was found in Table 2.

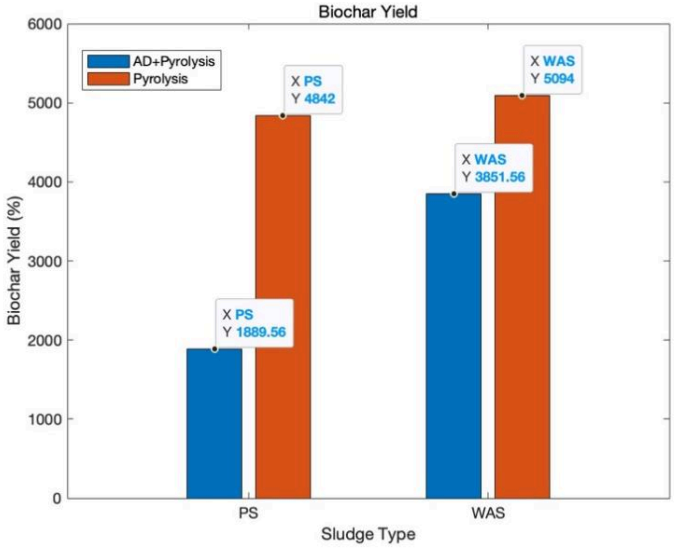


Figure 5. Comparisons of biochar yield from two treatment processes

Besides, temperature is also another key factor that could affect the yield of both biochar and bio-oil. The figure below presents the biochar yield for different types of sludge versus pyrolysis temperature. The x-axis represents the common temperature range of moderate-temperature pyrolysis, and y-axis indicates the biochar yield of different sludges including primary sludge (PS), waste activated sludge (WAS) and anaerobically digested sludge (ADS). Based on the figure, it indicates that the lower biochar produced with the increasing pyrolysis temperature as increased amount of VS content. As the temperature remains constant, the yield of biochar derived from PS with the highest VS content (84%) is the least, and the yield of biochar derived from ADS with the lowest VS content (59%) is the most. The maximum biochar yield is produced at 400˚C for three sludges (PS, WAS, ADS), which is 53.8%, 56.6% and 66.6%.

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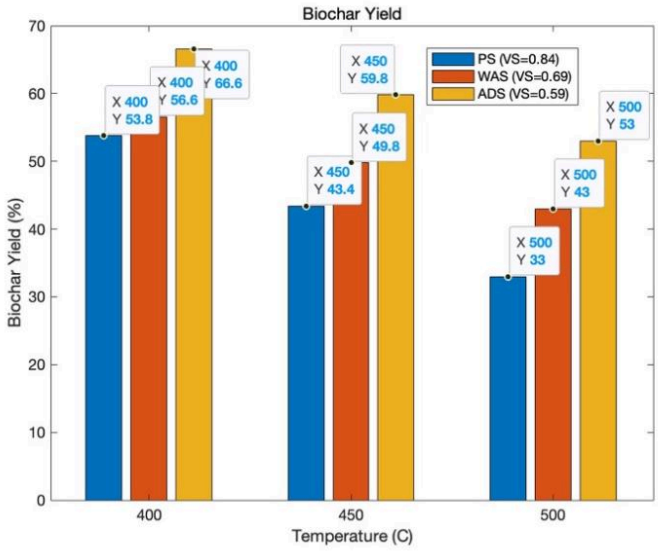


Figure 6. Biochar yield based on different temperature

3.3.1. Negative carbon emissions

The amount of carbon content in biochar is depending on the characteristic of original biomass. Based on the previous study, Sewage sludge biochar commonly has high ash content (65.61 wt%) and low carbon content (24.27 wt%) [11]. Then, the carbon dioxide fixed in 1kg biochar based on the quantities of carbon atoms in biochar mass is calculated by the equation below, which is 0.8899kg.

$$1kg \times \frac{44}{12} \times 0.2427 = 0.8899kg \tag{21}$$

The chart below presents the differences between carbon dioxide released and carbon fixed in biochar for WAS treated by each process (AD+pyrolysis and pyrolysis only). As mentioned above, biochar produced from WAS with a VS content of 69% could fix about 3427.5kg of carbon dioxide. The CO2 released from digestion process is a part of biogas, which contains 35% of CO2 and 65% of CH4. After anaerobic digestion, the ADS will firstly go through the drier and then process in pyrolysis reactor. There is no doubt that CO2 would still be produced due to the incompletely combustion of pyrolysis but not as much as that released in AD. Previous study has found the volume proportion of CO2 in the py-gas reaches 40–60% [12].

In this case, we assume that the carbon dioxide reaches approximately 50% of py-gas, which has a 21% mass of original biomass. Hence, the total CO2 emissions through the combined process could be calculated as 2105.41kg. It figures out that some of the solid carbon in original biomass is still released into the atmosphere in the form of carbon dioxide during the combined sewage sludge treatment process. In terms of pyrolysis, biochar is directly produced by pyrolysis without the presence of anaerobic digestion. The results reveal the higher proportion of CO2 fixed in biochar with much lower CO2 emissions. However, the released CO2 originally comes from the atmosphere and just back to the atmosphere at this phase. In other words, it indicates that the CO2 emissions from the sewage sludge treatment process could be ignored. Therefore, it concludes that pyrolysis is a more optimal process option for CDR (Carbon Dioxide Removal) in sewage sludge treatment.

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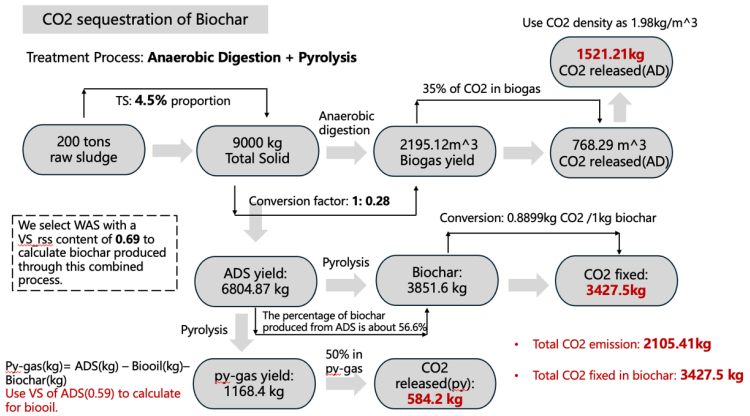


Figure 7. CO2 fixed via combined treatment process

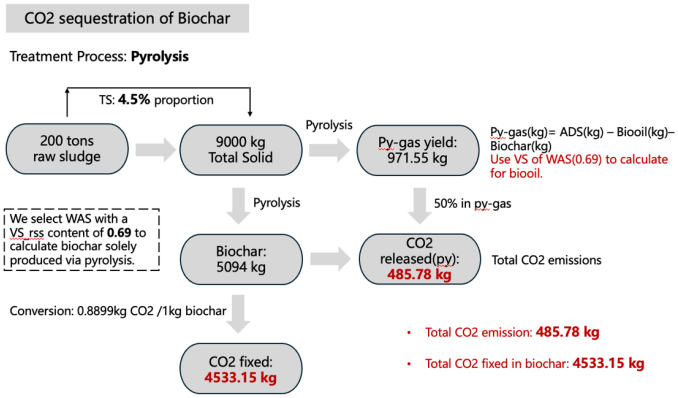


Figure 8. CO2 fixed via pyrolysis treatment process

4. Conclusion

Renewable and sustainable energy resources are the best choices to substitute environmentally threatening energy production systems. Sewage sludge is one of the major byproducts of wastewater treatment plants, and with traditional methods such as landfilling or incineration contributing to greenhouse gas emissions, transforming such products to energy is the most advantageous way. Especially when the accumulation of sewage sludge creates environmental problems, it is vital to look for a solution. Such an approach not only converts waste into valuable resources, but also aligns with sustainable goals and circular economy principles. A multi-objective optimization model with increased energy efficiency and economic advantages were developed based on the reactions of anaerobic digestion and pyrolysis for the process of sewage sludge to energy conversion. The model was designed to find the best solution for increased energy and economic efficiency when converting sewage sludge to usable energy in the daily basis. Based on the discussions and results presented above, the conclusions are obtained as below:

(1). Energy efficiency (EE) is measured by a power function between 0 and 1, the closer the power function is to 1, the more efficient the system will be. Results show the value of EE for pyrolysis + AD can reach up to 86.58%, and the value of EE for pyrolysis can reach to 68.84%, showing a very efficient value. The hybrid process (anaerobic digestion + pyrolysis) produces more

DOI: 10.54254/2755-2721/2025.28065

product yields, and the energy efficiency is higher than the only pyrolysis. Data also show that energy output and energy efficiency increase with the increase of VS content in raw sludge.

(2). A lower value of LCOE (Levelized cost of energy) represents an economic advantage. Results show a decreasing trend, with the value of pyrolysis + AD being 10.9081, and the value of pyrolysis being 52.6991. The combination of pyrolysis and anaerobic digestion shows a relatively better economic efficiency when applied.

(3). The third objective function measured is carbon sequestration of biochar. In this study, biochar is the byproduct of pyrolysis. Biochar yield is inversely proportional to the VS content of raw sludge. A higher biooil production causes lower biochar production, the higher yield of biochar is attributed to the lower VS content in raw sludge feedback. The lower biochar production with the increasing temperature of pyrolysis changes along with the increased amount of VS content. Biochar yield generated solely by pyrolysis is consistently higher than that from the combined process. The combination of anaerobic digestion and pyrolysis shows a total of 2105.41kg of CO2 emissions, and total CO2 fixed in biochar to be 3427.5kg. While in the process of only pyrolysis, total CO2 emissions to be 485.78kg, and total CO2 fixed in biochar to be 4533.15kg.

The model efficiently addresses problems stated throughout the essay. It demonstrates the potential to recover energy, minimizing environmental impacts. In addition, the combined practice of anaerobic digestion and pyrolysis maximizes energy efficiency and minimizes cost.

Future studies may include further simulating the process through experiments, specifically, exploring whether a more significant reduction of CO2 emissions can be achieved by adding carbon capture and storage (CCS) systems with carbon sequestration of biochar. At the same time, further evaluating the cost and energy efficiency, ensuring the applications in real life to be more practical.

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