SIMULATION AND ENERGY SELF-SUFFICIENCY ANALYSIS OF MUNICIPAL SEWAGE SLUDGE PYROLYSIS

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ABSTRACT

Municipal sewage sludge is a fast-growing waste stream that poses both environmental and energy management challenges. Pyrolysis is a promising thermochemical route because it reduces sludge volume, destroys pathogens, and yields energy-rich pyrolysis gas together with biochar. In this work, a complete pyrolysis-based sludge treatment plant was modeled in SuperPro Designer to evaluate energy efficiency under realistic feed conditions. The flowsheet couples a sludge dryer, a pyrolysis reactor, a gas cyclone, a burner that combusts the pyrolysis gas, and a heat-recovery exchanger. Nine scenarios were generated by combining three pyrolysis temperatures (400, 450, and 500 °C) with three initial moisture contents (60, 70, and 80 wt-%) at a fixed wet sludge feed of 5,000 kg/h. Energy efficiency ranged from 57.68% to 97.56%, with the best performance at 500 °C and 60 wt-% moisture, while the biochar yield reached 1,202.29 kg/h at 400 °C and 60 wt-%. Energy efficiency above 90% was achieved whenever the initial moisture was kept at or below 60 wt-%, indicating this value as a threshold for stand-alone operation.

Keywords: Sewage sludge, pyrolysis, process simulation, energy efficiency, biochar

1. INTRODUCTION

Continued urbanization and the expansion of wastewater treatment infrastructure have led to a sharp increase in the amount of municipal sewage sludge generated worldwide [1]. Traditional sludge management routes such as landfilling, agricultural application, and direct incineration are increasingly constrained by limited land availability, the presence of pathogens, heavy metals, and persistent organic pollutants, and by strict emission limits [1,2]. As a consequence, thermochemical conversion has received considerable attention as a means of simultaneously reducing sludge volume, destroying hazardous compounds, and recovering the energy stored in its organic fraction.

Among the available thermochemical routes, pyrolysis has several advantages: it operates in an inert atmosphere at moderate temperatures (typically 400 to 500 °C) and produces pyrolysis gas, bio-oil, and biochar with a relatively low burden of dioxins and heavy metals compared with direct incineration [1,2]. The pyrolysis gas can be combusted internally to supply the heat required for the drying and pyrolysis stages, whereas the biochar has a well-developed pore structure that makes it suitable for use as a soil amendment, an adsorbent, or a solid fuel [1]. Recent process-level studies have indicated that, when sludge with a dry-basis calorific value of approximately 10 MJ/kg or higher is processed, the energy released by the combustion of the pyrolytic off-gas can be sufficient to drive the entire system without external energy input [1].

Comparative assessments based on Aspen Plus and life-cycle analysis have further shown that integrated configurations such as gasification coupled with chemical looping combustion or supercritical water gasification followed by gas turbines can achieve net energy efficiencies in the range of 14 to 21% and exergy efficiencies of up to 17%, while keeping global-warming potential between 0.13 and 0.72 kg $CO_{2\text{-eq}}$ per kg of treated sludge [2]. Additional improvements have been reported when pyrolysis is coupled with anaerobic digestion and thermal hydrolysis, where apparent energy efficiencies of over 90% have been demonstrated owing to the simultaneous recovery of biogas, pyrolysis gas, and tar [3]. These results show that the overall energy balance depends strongly on operating variables such as pyrolysis temperature, sludge moisture content, and the routing of internal energy streams.

Despite the progress reported in the literature, most published process studies focus on a limited number of operating points and rarely systematically quantify the threshold conditions under which a municipal sewage sludge pyrolysis plant can become fully self-sufficient. The present study develops a flowsheet of

a municipal sewage sludge pyrolysis plant in SuperPro Designer and evaluates its energy efficiency under nine combinations of pyrolysis temperature and initial moisture content. The biochar production rate was also calculated for each scenario to identify the trade-off between energy recovery and solid by-product yield.

2. MATERIALS AND METHODS

A pyrolysis-based municipal sewage sludge treatment plant was modeled in SuperPro Designer. The flowsheet integrates the full processing chain, namely sludge feeding, drying, pyrolytic conversion, gas-solid separation, pyrolysis gas combustion, and internal heat recovery, and is solved over coupled mass and energy balances under steady-state conditions. The main unit operations included in the model are a sludge dryer, a pyrolysis reactor, a gas cyclone, a burner that combusts the pyrolysis gas as an internal heat source, and a heat exchanger that recovers thermal energy from the hot flue gas. A simplified schematic of the plant is shown in Fig. 1.

The wet sludge enters the dryer, where the moisture content is reduced before pyrolysis. The dried sludge is subsequently fed to the pyrolysis reactor, where thermochemical decomposition occurs in an oxygen-free atmosphere at 400, 450, and 500 °C, producing a mixture of syngas and biochar. The gas cyclone separates the biochar from the syngas; the resulting pyrolysis gas is then burned with ambient air in the burner, and the hot flue gas is routed to the heat exchanger. A water stream collects the residual low-grade heat at the heat exchanger's exit.

The total wet sludge feed was fixed at 5,000 kg/h. The overall energy efficiency was evaluated as the ratio of the useful energy output to the total energy input of the process. The useful energy term includes the chemical energy retained in the biochar and the sensible heat recovered in the water stream, whereas the total energy input includes the chemical energy of the dry sludge feed, auxiliary work, and the heat required for moisture evaporation in the dryer, as given in Eq. (1). Three pyrolysis temperatures (400, 450, and 500 °C) and three initial moisture contents (60, 70, and 80 wt-%) were combined in a full factorial design, giving the nine scenarios summarised in Table 1.

$$\eta_{energy} = \frac{\dot{m}_{char}(HHV)_{char} + \dot{m}_{w,out}\left(h_{w,out} - h_{w,in}\right)}{\dot{m}_{dry,s}(HHV)_{dry,s} + \dot{W}_{in} + \dot{Q}_{dryer,in}} \quad (1)$$

Several inputs that are not directly computed by the flowsheet were adopted from published experimental and modeling studies on municipal sewage sludge pyrolysis. The mass distribution of pyrolysis products among solid, liquid, and gaseous fractions is known to depend strongly on temperature. The product yield distributions for the three pyrolysis temperatures considered in this study (400, 450, and 500 °C) were obtained from the experimental data reported by Zhou et al. [1] for municipal sewage sludge slow pyrolysis. The composition of the bio-oil produced at the outlet of the pyrolysis reactor was specified in the simulator on the basis of the GC-MS characterization reported by Xu et al. [4] for sewage-sludge-derived pyrolysis oil, which identifies hydrocarbons, phenolic compounds, and nitrogen- and oxygen-containing species as the main constituents. The composition of the non-condensable pyrolysis gas (H_2, CH_4, CO, CO_2, C_2H_4, and C_2H_6) was likewise adopted from Zhou et al. [1], and the dry-basis higher heating value (HHV) of the sludge was set to 13.78 MJ/kg.

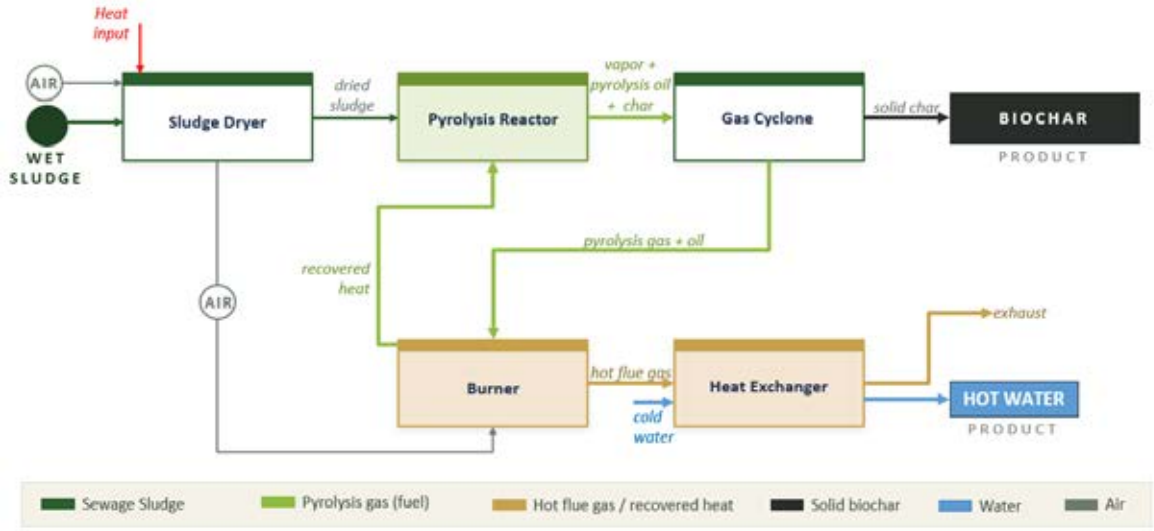


Fig. 1. Schematic of the simulated municipal sewage sludge pyrolysis plant.

Table 1. Scenario matrix used in the simulation study (3 pyrolysis temperatures × 3 initial moisture contents).

Initial moisture (wt-%)	500 °C	450 °C	400 °C
60	Scenario 1	Scenario 4	Scenario 7
70	Scenario 2	Scenario 5	Scenario 8
80	Scenario 3	Scenario 6	Scenario 9

3. RESULTS AND DISCUSSION

The simulated energy efficiency and the corresponding biochar mass flow rates obtained for the nine scenarios are reported in Table 2. Across the investigated parameter range, the energy efficiency ranges from 57.68% to 97.56%, while the biochar mass flow rate ranges from 520.85 to 1,202.29 kg/h.

Table 2. Energy efficiency and biochar flow rate obtained for the nine simulated scenarios.

Scenario	Pyrolysis temperature (°C)	Initial moisture (wt-%)	Energy efficiency (%)	Biochar flow rate (kg/h)
1	500	60	97.56	1041.70
2	500	70	86.38	781.27
3	500	80	65.42	520.85
4	450	60	93.66	1104.91
5	450	70	79.99	828.68
6	450	80	62.87	552.46
7	400	60	85.92	1202.29
8	400	70	73.85	901.72

Scenario	Pyrolysis temperature (°C)	Initial moisture (wt-%)	Energy efficiency (%)	Biochar flow rate (kg/h)
9	400	80	57.68	601.15

The highest energy efficiency of 97.56% is achieved in Scenario 1, where the pyrolysis temperature is set to 500 °C and the initial moisture content is maintained at 60 wt-%. At constant moisture, increasing the pyrolysis temperature consistently improves energy efficiency because higher temperatures shift the product distribution toward gaseous compounds, thereby increasing the heat released in the burner. Conversely, at constant temperature, the energy efficiency decreases markedly as the initial moisture content is raised from 60 to 80 wt-%, since a larger fraction of the available thermal energy must be diverted to water evaporation in the dryer. Energy efficiency above 90% was achieved whenever the initial moisture content was at or below 60 wt-%, indicating this value as a practical threshold for stand-alone operation without supplementary fuel.
The biochar production rate follows an opposite trend. The highest biochar flow rate of 1,202.29 kg/h is achieved in Scenario 7 (400 °C, 60 wt-%), whereas the lowest value of 520.85 kg/h corresponds to Scenario 3 (500 °C, 80 wt-%). At a given initial moisture content, lower pyrolysis temperatures favor the formation of solid char over the volatile and gaseous products. Likewise, at a fixed pyrolysis temperature, a higher initial moisture content reduces the amount of dry sludge entering the reactor and, consequently, the biochar yield. As a result, energy efficiency and biochar yield respond in opposite directions to changes in temperature, suggesting that an optimal operating window must balance both objectives, depending on whether the plant is operated primarily for energy recovery or for biochar valorization.

4. CONCLUSIONS

A municipal sewage sludge pyrolysis plant was simulated in SuperPro Designer to assess its energy efficiency across nine combinations of pyrolysis temperature (400-500 °C) and initial moisture content (60-80 wt-%), with a fixed wet sludge feed rate of 5,000 kg/h. The results showed that energy efficiency ranged from 57.68% to 97.56%, while biochar production rate ranged from 520.85 to 1,202.29 kg/h. Energy efficiency above 90% was achieved whenever the initial moisture was reduced to 60 wt-% or lower, and an inverse relationship between energy and biochar yields and temperature was observed, suggesting an optimal operating window. Future work will refine the unit operation models, validate them against pilot-scale data, develop an automated control layer linking dryer duty, pyrolysis temperature, and burner air supply, and add a second-law exergy analysis to identify the largest sources of irreversibility in the integrated plant.

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