Systems & Control Transactions

Research Article
Foundations of Computer Aided Process Design (FOCAPD 2024)
Breckenridge, Colorado, USA. July 14-18, 2024
Peer Reviewed Conference Proceeding

PSE PRESS

Industrial Biosolids from Waste to Energy: Development of Robust Model for Optimal Conversion Route – Case Study

Hesan Elfaki[a*], and Dhabia M. Al-Mohannadi[b]

[a] Texas A&M University, Texas Sea Grant College Program, College Station, Texas, United States
[b] Texas A&M University at Qatar, Chemical Engineering Program, Education City, Doha, Qatar
* Corresponding Author: h.elfaki@tamu.edu

ABSTRACT

Utilizing sustainable energy sources is crucial for expanding the range of solutions available to meet the growing energy demand and reducing reliance on environmentally damaging and depleting conventional fuels. Biosolids, a type of biomass, are generated as secondary effluent during wastewater treatment process in municipal and industrial sites. These solids possess the potential to serve as a sustainable energy source due to their richness of carbon. For an extended period, biosolids have been landfilled, even though it can be considered a wasteful use of a precious resource and a possible mean for contamination to the food supply chain. This has served as an extra impetus to investigate the potential for harnessing the capabilities of these substances. While many research studies have looked at different ways to put biomass waste to use, very little has been written on biosolids, especially those derived from industrial sources. This research assesses the feasibility of transforming GTL derived biosolids into value-added commodities that can serve as raw materials in chemical manufacturing or be employed energy generation. The study primarily examines widely recognized thermal conversion processes, pyrolysis and gasification. An evaluation is carried out to analyze the economic, technological, and environmental aspects of the treatment methods utilizing these technologies. The aim is to demonstrate the potential of GTL biosolids conversion and to determine associated costs and environmental impacts. The ASPEN simulation tool is utilized to model thermal treatment pathways, allowing for the generation of economic and environmental estimations for each route.

Keywords: Biosolids, Energy, Utilization, Simulation

INTRODUCTION

Biosolids are a significant waste stream that is discharged from wastewater treatment plants and water management facilities around the world. Although biosolids have traditionally been regarded as a waste by-product and disposed of in landfills for many years, current research has demonstrated that they possess significant value as a result of their nutrient and energy content [1, 2]. They are now formally classified as renewable sources of energy because of the energy value derived from their organic component [3, 4]. The utilization of biosolids for energy generation has a significant potential to promote a circular economy and reduce environmental waste [4]. Possible uses for the recovery of mass and energy from biosolids include using them as fertilizer for land, composting, anaerobic digestion, combustion, gasification, pyrolysis, and hydrothermal treatment. These applications transform biosolids into valuable resources, such as composts for nutrients or biofuels and char for energy. Each of these uses necessitates a designated preliminary treatment to prepare the biosolids stream. The treatment of biosolids is a significant obstacle in water management and treatment plants due to the substantial electrical and operational expenses involved. These costs make up 20% and 53% respectively of the total wastewater treatment process [1]. Pyrolysis and gasification are two thermal conversion methods that have great potential for transforming biosolids into products that have increased value.

Pyrolysis is a process that involves the combination of thermal cracking and catalytic conversion. It is conducted at relatively moderate temperatures (400 – 700 °C) and atmospheric pressure [5]. The process of producing bio syngas, oil, and fuel char from biosolids involves heating them in an oxygen-free environment [6, 7]. Gasification is a combustion process that involves burning biosolids with a limited amount of oxygen or air at very high temperatures that can reach up to 1200 °C and 0.6-2.6 MPa. Conceptually, this technology has resemblance to pyrolysis, albeit it differs by utilizing a sub-stoichiometric oxygen input and operating at considerably higher temperature settings [8].

Considerable research is readily accessible that examines the costs and economic evaluations of treating and reusing biosolids. AlNouss et al. performed a techno-economic assessment of biomass gasification for hydrogen production[9]. Ghiat et al. provided a comprehensive economic analysis of a biomass gasification system that is combined with power generation and carbon dioxide recovery. The analysis was conducted using aspen simulation software [10]. [11] conducted a study on the techno-economic factors of power generation using biogas produced by gasifying biosolids, utilizing actual data from a facility [11]. However, there is a scarcity of research that has examined the process of converting biosolids produced by industrial facilities in oil and gas sector.

This study assesses the feasibility of transforming GTL industrial biosolids into high-value products through gasification and pyrolysis processes. Analytical investigation is conducted to compare the technological, economic, and environmental aspects of two treatment methods in order to identify the demonstrate efficient paths for treating GTL derived biosolids. The conversion processes are simulated using Aspen process simulation tool.

PROBLEM STATMENT

Gas-to-liquids (GTL) technology transforms natural gas, which is the most environmentally friendly fossil fuel, into premium liquid products that are typically derived from crude oil. The process produces biosolid waste streams that need to be treated to uncover their energy potential and reduce the need for solid waste management.

To assess the feasibility of treating a continuous flow of GTL biosolids, which includes information on flowrate, solid content, and moisture content, it is necessary to examine the viability of employing thermal pyrolysis and gasification methods. Additionally, it is crucial to quantify the costs and environmental impacts associated with these treatment approaches.

ASPEN MODEL

Process Flowsheet

The diagram in Figure 1 depicts the process of converting GTL biosolids through pyrolysis and gasification, as simulated using Aspen Plus. The primary feed stream consists of GTL generated biosolids. The thermo-chemical parameters of the GTL biosolids have been determined using proximate and ultimate analysis, as described in the study by Zuhara et al. [12]. The characteristics are succinctly outlined in Table 1. Figure 1 describes the pyrolysis flowsheet. The initial step involves the treatment of biosolids in a decomposition unit, which is simulated using the Ryield reactor model in Aspen Plus. The device disassembles the non-conventional flow of biosolids into its primary elemental components, namely hydrogen, oxygen, carbon, nitrogen, and sulfur. The output of this unit is sent to the pyrolysis reactor, which is simulated using the RGibbs reactor model. This model uses Gibbs energy minimization to estimate the products produced by the reactions. Subsequently, the pyrolysis products are sent to a separator, where the resultant gas is isolated from the solid phase products, namely ash and char. After the separation process, the gas undergoes a cooling process, which leads to the retrieval of biogas as the final outcome.

Table 1: GTL biosolids proximate and ultimate analysis [12]

Proximate Analysis	
Moisture	12.29
Volatile matter	47.47
Ash	26.07
Fixed carbon	14.16
Ultimate Analysis	
C	33.69
H	6.18
O	29.03
N	5.03
S	-

The gasification flow sheet illustrated in Figure 2, diverts the elemental components produced in the decomposition unit to an alternative treatment pathway. Post decomposition, a solid separation unit is used to initially separate ash and char products from the gas stream. Subsequently, the gas stream leaving the separation unit is combined with steam and air before being introduced into the gasification reactor. Steam and air act as gasification agents in this process. The gasifier is simulated using the RGibbs reactor model. The gasifier products undergo a cooling process and are subsequently separated in a solid separation unit to obtain biogas and char products.

The simulation utilized thermodynamic calculations employing the Peng Robinson property method with the Boston modification to improve the accuracy of estimating the properties of non-conventional inputs, specifically GTL biosolids and Ash. The operational parameters are concisely outlined in Table 2.

RESULTS AND DISCUSSION

The simulation model was constructed under the assumption of steady-state operation under atmospheric pressure, disregarding pressure variations throughout unit operations and heat dissipation in gasification and pyrolysis units.

Table 2 Pyrolysis and Gasification flowsheet operation conditions

Parameter	Unit	Value
Biosolids Feed		
Feed flowrate	Kg/hr	2000
Temperature	°C	25
Pyrolysis		
Inert flowrate	Kg/hr	40
Inert temperature	°C	65
Pyrolysis unit temperature	°C	700
Decomposer temperature	°C	700
Gasification		
Air flowrate	Kg/hr	40
Air temperature	°C	65
Gasifier temperature	°C	800
Decomposer temperature	°C	700

The model presupposes that the char consists entirely of solid carbon.

The simulation model was executed using a feed flowrate of 2000kg/hr of GTL biosolids, as described by the provided approximate and ultimate analysis. Prior to being sent to the conversion units, pyrolysis and gasifier, the decomposition unit transformed the nonconventional biosolid material into its primary components. After the conversion has taken place, The solid splitters were used to separate the ashes and char, while the resulting biogas was pre-cooled to recover heat before being collected as the end product. The composition of the biogas stream was analyzed to determine the amounts of syngas and methane generated during the process. These gases are commonly used for energy production or as raw materials in downstream petrochemical processes. The accumulated ash can be beneficial in several applications for material utilization, such as in the manufacturing of cement. Char, in its solid state, is a useful energy source that can be used for carbon sequestration and land reclamation, depending on its specific properties [13]. The production rate of each of these components is illustrated in Figure 3.

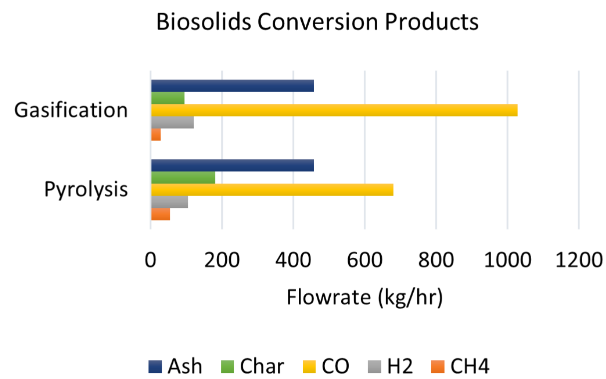

Figure 3. Production rate of various thermal conversion products for GTL biosolids feed

The findings exhibited total transformation of the biosolids into biogas, char, and ash. Upon analyzing the syngas composition in the effluent of the two processes, it is observed that gasification yields 1029 Kg/hr of carbon monoxide (CO) and 121 Kg/hr of hydrogen (H_2). The generation of CO has increased by approximately 50%, while the production of H_2 has increased by approximately 15% compared to pyrolysis. The increase in syngas creation was achieved at the cost of a 48% decrease in CH_4 output during gasification. The overall quantity of ash exiting the process remains constant in both process outlets, as they possess identical characteristics and receive the same amount of biosolids feed with a predetermined nonconventional ash content, according to the approximate and ultimate analysis of GTL biosolids. Gasification is preferred over pyrolysis when considering the use of biosolids as an extra feedstock stream for a petrochemical plant.

Post process simulation, Aspen program was used to conduct a technoeconomic and environmental assessment of the two processes. The model employs the integrated economic analyzer and environmental analysis tool. The tool provided estimates for the financial expenses, capital and operational costs of both scenarios and presented the greenhouse gas (GHG) emissions as carbon equivalents, measured in terms of their ability to contribute to global warming (GWP) [14]. The capital cost encompassed equipment cost estimation via an integrated unit operation mapping and equipment sizing methodology. Figure 4 below provides a concise summary of the cost estimation analysis and the CO_2 equivalent emissions for the two conversion scenarios.

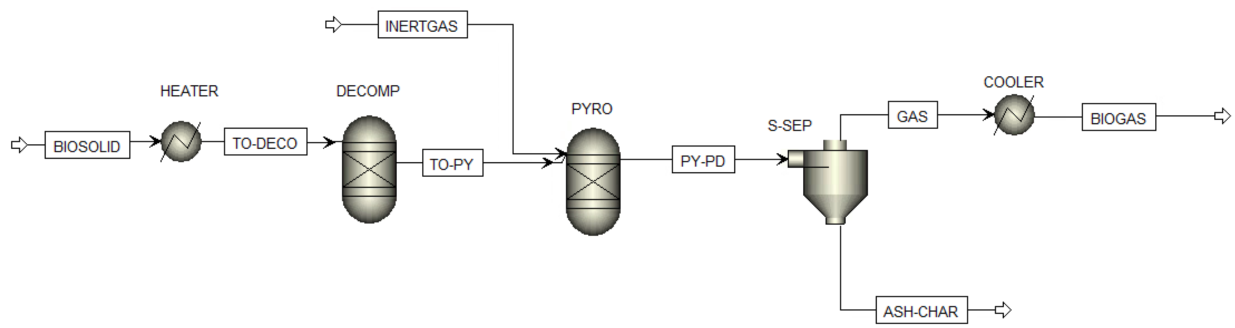

Figure 1: Biosolids pyrolysis flowsheet developed in Aspen Plus

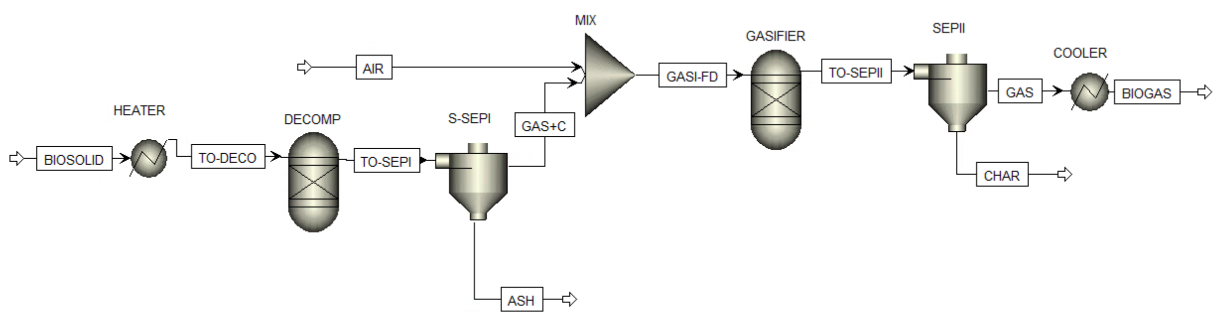

Figure 2: Biosolids gasification flowsheet developed in Aspen Plus

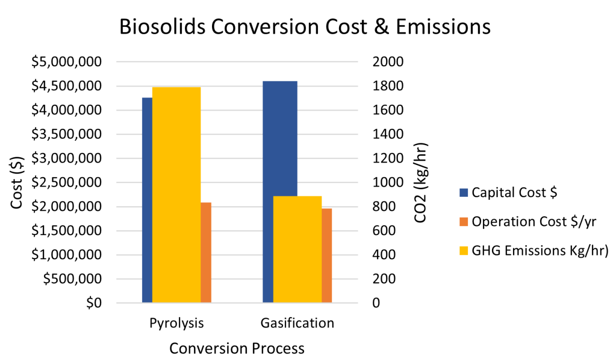

Figure 4. Cost estimation and GHG emissions from biosolids pyrolysis and gasification processes

The results indicate that the capital cost for biosolids gasification is around $4.6 million, which slightly exceeds the capital required for pyrolysis by 8%. The discrepancy can be rationalized by the disparity in unit operations employed in each scenario's flowsheet and the chosen materials capable of withstanding the operational temperatures of the conversion units. The model allocated suitable utilities to the various unit operation as per the required duties and pressure and temperature ranges. In order to meet the conversion process requirements in both scenarios, three primary utility categories were chosen: fuel, cooling water, and power. The overall operational cost, with utility expenses being the primary factor, showed an insignificant variance between the two scenarios. The anticipated cost for pyrolysis was $2.09 million per year, while the cost for the other method was $1.97 million per year. The CO_2 emissions depicted in Figure 4 exhibit a significant disparity in emissions between pyrolysis at a rate of approximately 1800 kg/hr and gasification 900 kg/hr. According to this model, pyrolysis results in double the amount of gasification GHG emissions. In gasification, the conversion process results in the production of additional CH_4 and CO_2. However, these gases are then further converted into H_2 and CO products, which helps to reduce greenhouse gas emissions from the process side of operation.

CONCLUSION

Biosolids are a valuable byproduct that must be effectively treated in order to be utilized. There is a dearth of research exploring the possibilities of utilizing industrial biosolids in literature. This study focuses on examining the transformation of biosolids derived from GTL (Gas-to-Liquid) into biogas products, specifically hydrogen (H_2), carbon monoxide (CO), and methane (CH_4). The investigation is conducted through the utilization of an Aspen simulation flowsheet that has been specifically developed for this purpose. Two primary thermal conversion pathways have been developed, which involve the integration of gasification and pyrolysis processes. Gasification emerges as the ideal method for treating biosolids and using them as an additional source of feedstock in a petrochemical plant. The results suggest that gasification produces greater amounts of carbon monoxide (CO) and hydrogen (H_2) in comparison to pyrolysis, which is beneficial for specific industrial uses. Gasification reduces methane (CH_4) emissions, while maintaining effective conversion of biosolids into biogas, char, and ash.

The Aspen software allows for technoeconomic and environmental studies, which offer additional insights. Although gasification has a somewhat larger initial investment compared to pyrolysis, the ongoing expenses for both techniques are practically the same. This implies that although the initial cost for gasification may be slightly greater, the operational effectiveness and long-term advantages compensate for this disparity. The environmental impact connected with each activity is of paramount significance. Gasification exhibits a notable superiority over pyrolysis in relation to greenhouse gas emissions since it leads to reduced emissions of carbon dioxide (CO_2) equivalents. The decrease in emissions is credited to the transformation of excess methane and carbon dioxide into hydrogen and carbon monoxide, effectively reducing greenhouse gas emissions from the operational process.

Ultimately, when it comes to utilizing biosolids as an extra input for petrochemical operations, gasification proves to be a beneficial choice. Gasification, despite having somewhat higher initial costs, has better conversion efficiency, similar running expenses, and reduced environmental effect when compared to pyrolysis.

In conclusion, this study demonstrates the capacity to transform industrial biosolids wastes into a viable energy source or valuable raw material, while simultaneously reducing the amount of solid waste generated. These findings provide valuable insights for decision-making processes as it enables well-informed judgments regarding biosolids treatment strategy that achieves a balance between the efficiency of conversion efficiency, economic feasibility, and environmental impacts.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge funding provided by Qatar Shell Research and Technology Centre (QSTRC).

REFERENCES

1. Zhao, G., Garrido-Baserba, M., Reifsnyder, S., Xu, J.C., Rosso, D. Comparative energy and carbon footprint analysis of biosolids management strategies in water resource recovery facilities. *Science of the Total Environment*. 665, 762–773 (2019).
2. Wang, H., Brown, S.L., Magesan, G.N., Slade, A.H., Quintern, M., Clinton, P.W., Payn, T.W. Technological options for the management of biosolids, *Environ Sci Pollut Res* 15:308–317 (2008)
3. Edwards, J., Othman, M., Crossin, E., Burn, S. Anaerobic co-digestion of municipal food waste and sewage sludge: A comparative life cycle assessment in the context of a waste service provision. *Bioresour Technol.* 223, 237–249 (2017).
4. Egan, M. Biosolids management strategies: An evaluation of energy production as an alternative to land application. *Environ Sci Pollut Res* 20:4299–4310 (2013)
5. Spinosa, L. From sludge to resources through biosolids. *Water Sci Technol.* 50 (9): 1–9 (2004)
6. He, W., Yang, H., Han, D. Thermodynamic investigation and optimization of a heat pump coupled open-air, open-water humidification dehumidification desalination system with a direct contact dehumidifier. *Desalination.* 469: 114101 (2019).
7. Liu, Z., McNamara, P., Zitomer, D. Autocatalytic Pyrolysis of Wastewater Biosolids for Product Upgrading. *Environ Sci Technol.* 51, 9808–9816 (2017).
8. Winchell, L.J., Ross, J.J., Brose, D.A., Pluth, T.B., Fonoll, X., Norton, J.W., Bell, K.Y. Pyrolysis and gasification at water resource recovery facilities: Status of the industry, *Water Environ Res.* 94:e10701(2022)
9. AlNouss, A., McKay, G., Al-Ansari, T. Enhancing waste to hydrogen production through biomass feedstock blending: A techno-economic-environmental evaluation. *Appl Energy.* 266 (2020).
10. Ghiat, I., AlNouss, A., McKay, G., Al-Ansari, T. Biomass-based integrated gasification combined cycle with post-combustion CO2 recovery by potassium carbonate: Techno-economic and environmental analysis. *Comput Chem Eng.* 135 (2020).
11. Carlos, L., Villalba, O., Acevedo, E.R. Technical and

economical assessment of power generation technologies firing syngas obtained from biosolid gasification. *Prod. Limpia* 9: 31-43 (2014)
12. Zuhara, S., Pradhan, S., Pasha, M., McKay, G.Potential of GTL-Derived Biosolids for Water Treatment: Fractionization, Leachate, and Environmental Risk Analysis. *Water (Switzerland)*. 14 (2022).
13. Collivignarelli, M.C., Canato, M., Abbà, A., Carnevale Miino, M. Biosolids: What are the different types of reuse? *J. Clean. Prod.* 238: 117844, (2019)
14. Shahbaz, M., Alnouss, A., Parthasarathy, P., Abdelaal, A.H., Mackey, H., Mckay, G., Al-Ansari, T. Investigation of biomass components on the slow pyrolysis products yield using Aspen Plus for techno-economic analysis. *Biomass Convers. Biorefin.* 12:669–681 (2022)