Superior sewage sludge disposal with minimal greenhouse gas emission via fast pyrolysis in a fluidized bed reactor

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Abstract. In response to global carbon footprint reduction efforts, the promising waste-to-energy sludge disposal is assessed according to greenhouse gas emissions and biofuel production. Life cycle assessment and ⁶EsTABouses were used in quantifying the CO₂ eq emissions of sludge disposal routes. In energy content assessment, fast pyrolysis experiment was done using a fluidized bed reactor, and the energy contents of derived biofuels were accounted for. The result shows that sewage sludge disposal through fast pyrolysis is the most environmentally sustainable route with the lowest emissions (696.7 kg CO₂ eq) compared to liming and land application (833.3 kg CO₂ eq), composting and land application (756.3 kg CO₂ eq), and incineration with household wastes (2805.3 kg CO₂ eq) per ton of dried sludge. The fast pyrolysis supremacy is illustrated by net negative emission balance (−1070.9 kg CO₂ eq), manifesting its significant contribution to emission mitigation. Fast pyrolysis has a high bio-oil yield (35.68 wt%) with a high heating value of 36.43 MJ/kg. Energy contents per ton of dried sludge are: bio-oil = 13.0 GJ, biogas = 2.73 GJ, biochar = 1.75 GJ. Overall, this study demonstrated fast pyrolysis as a superior sludge disposal route contributing to the environment and energy sustainability.

1. Introduction

Sewage sludge is one of the special biomasses generated in high volume nowadays, which, if not handled carefully, poses hazards to human health and the environment. One green prospect of sludge waste is embracing its enormous potentials for energy generation while eliminating its taxing disposal burdens. The benefits of using wastes as a source of energy would address two pressing problems faced by society today, i.e., environment and energy sustainability.

First, wastewater treatment plant managers and operators are continually challenged in the increasing volume of sludge generated from the wastewater of enlarging communities [1]. The annual average generation of sewage sludge in Germany, England, France, and America are 22, 12, 8.5, and 71 million tons, respectively [2]. Common and generally acceptable disposal routes currently practiced include composting, landfilling, and incineration [3]. However, these disposal routes produce greenhouse gases (GHG), which contributed to the global warming phenomenon felt by most societies today. The exploitation of sludge for energy generation with efficient minimization of GHG emissions would significantly contribute to international environmental sustainability efforts.
Second, the imminent depletion of oil reserves worldwide is becoming a significant problem facing a world hungry for energy. The continuous production of primary energy from coal, natural gas, and petroleum resources resulted in the continued depletion of natural resources, the ecosystem's degradation, and the worsening problems of solid wastes, water pollution, and atmospheric pollution. In the USA alone, primary energy consumption increases at an annual average of 2.4%, with attached growing pollution and environmental degradation rates. In the transportation sector, high dependence on energy creates a volatile market with ever-increasing and dwindling prices of petroleum-derived fuels [4]. Utilization of sludge for the production of biofuels to augment, if not substitute, petroleum-based fuels would become a neat contribution towards global energy sustainability.

These two problems, combined, bring both challenges and opportunities for recovering the value of wastes for the environment and energy sustainability. One challenge is to reduce the environmental burden of pollution generation, GHG emissions, and waste disposal. Likewise, it is an opportunity for a waste-to-energy generation to augment the diminishing supply of petroleum-based fuels. Sludge is a special kind of biomass rich in an organic compound that can generate second-generation biofuels such as bio-oil, biogas, and biochar. The conversion of sludge waste, non-agricultural biomass rich in a volatile combustible matter [5], into bio-energy resources resolves the food shortage argument considering that it does not compete with food production [6,7]. It reduces the exploitation of agricultural lands from planting biomass sources [8]. More importantly, it would address the increased sludge generation problems from domestic wastewater treatment facilities [9,10].

Though sludge has enormous potential as a biofuel source, the option needs to be assessed considering GHG emissions during production. In this way, its viability and acceptability would be established. In this study, the GHG emissions, when sludge underwent fast pyrolysis for biofuels production, is assessed and compared to other reported conventional sludge disposal routes such as (1) liming and land application, (2) composting and land application, and (3) incineration with household wastes. The work used data in the previous report that quantified GHG emissions from sewage sludge using life cycle assessment and 

2. Materials and methods

2.1 Functional unit and scope of the study

A functional unit is a basis for comparison and computations. A functional unit of one ton of dried sludge was used in this work, and available secondary data were recomputed according to this base value.

The study focused on comparing different sludge disposal routes in terms of GHG emissions. In the calculation of the carbon footprint, it considered only processes after the sludge dewatering.

For energy recovery illustration, it did experimental runs using a fluidized bed reactor through fast pyrolysis technique. Experimental conditions, based on optimization study, were employed: temperature – 500 ºC, biomass particle size – 0.60 mm, vapor residence time – 1.95 s, and feed rate – 5 kg/h [12].

2.2 Sources of data

The GHG emissions of the three conventional sludge disposal routes were taken from the study using the 

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indirect, and avoided emissions reported, expressed in CO₂ eq, were recalculated according to a base functional unit of one ton of dried sludge.

Fast pyrolysis emission was quantified based on the life cycle assessment (LCA) of liquid sewage sludge [15]. The LCA analysis was structured considering technical frameworks such as goal and scope limitation, inventory analysis, impact assessment, and interpretation. This paper considered GHG emissions from sludge drying, fast pyrolysis operation, biochar transport, and avoided emissions (e.g., natural gas substitution, crude oil substitution, and fertilizer substitution). The LCA was made using the 500 m³ liquid sludge with 5% solid content. Conversion to dry sludge (92%) equivalent is computed (Eq. 1) using published dried sludge density of 0.566 ton/m³ [16].

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Mass \ of \ dried \ sludge = \frac{500 \ m^3 \times 0.05}{0.92} \times \left( \frac{0.566 \ ton}{m^3} \right) = 15.38 \ tons
\]

Direct, indirect, and avoided CO₂ eq emissions were recalculated by ratio and proportion to arrive values according to the base functional unit of one ton of dried sludge.

The bio-oil production through fast pyrolysis of dried sludge using an electrically heated fluidized bed reactor was modeled and optimized in the previous work [12,17]. The results of that prior investigation were used to establish the superiority of the fast pyrolysis route in the disposal of sewage sludge.

3. Results and discussion
Figure 1 summarizes the total direct emissions, emissions avoided, and global emission balance for each sludge disposal route using one ton of dried sludge equivalent (DSE). A graphical illustration (figure 2) compares the extent of GHG emissions of four (4) sludge disposal routes.

3.1 Greenhouse gas (GHG) emission analysis
As shown in figure 1, liming and land application routes produced more GHG (883.3 kg CO₂ eq/ton DSE) than avoided (713.8 kg CO₂ eq/ton DSE), leading to a positive GHG emission balance of 119.5 kg of CO₂ eq per ton of DSE used. This outcome means that around 120 kg of CO₂ eq can be emitted in every ton of DSE when disposed of via liming and land application route. The use of chemicals contributed much to GHG emissions (592.6 kg CO₂ eq/ton DSE) relatively because of the lime used in the treatment wherein much emission was generated during its production. Direct emission (132.7 kg CO₂ eq/ton DSE) came from the total N₂O generation after land application. The 97 kg CO₂ eq is the summation of transport emissions in bringing sludge from WWTP to land field and lime from store to WWTP. The avoided emissions of 713.8 kg CO₂ eq/ton DSE included non-use of mineral fertilizers and the carbon sequestered in the soil after sludge land spreading [11]. The GHG emissions from electricity and combustible were negligible.

Composting and land application tandem show positive GHG emissions of 86.3 kg CO₂ eq, which demonstrated that this route added this much GHG to the atmosphere for every ton of dried sludge. Of the total GHG emissions, 79.20% is contributed by direct emissions. This was due to high emissions during composting (567 kg CO₂ eq), which were emitted in the form of CH₄ (214.4 kg CO₂ eq) and N₂O (352.6 kg CO₂ eq). Land application direct emissions of 32.0 kg CO₂ eq completed the 599 kg GHG direct emissions. The 12% of the GHG emissions (119.8 kg CO₂ eq) were generated by sludge transport to the composting site and to the field [11]. Further, the avoided emissions of 670 kg GHG accounted for the non-use of mineral fertilizer and the carbon sequestered in the soil after compost land spreading.

Incineration of sludge with household wastes as co-substrate showed towering total emissions of 2805.3 kg CO₂ eq in every ton of dried sludge. Around 88% of total emissions (2455.4 kg CO₂ eq) was due to direct emissions in the form of CO₂ (2294.1 kg CO₂ eq) and N₂O (161.3 kg CO₂ eq) during the incineration process. Avoided emissions of 2062.6 kg CO₂ eq corresponds to the non-use of fuel in incinerating household wastes. A positive total emission balance of 737.4 kg CO₂ eq in every ton of
dried sludge incinerated means that this route could give a much GHG contribution to the atmosphere than liming/land application and composting/land application.

| Sewage sludge route                        | Global balance       |
|--------------------------------------------|----------------------|
| **Liming & Land Application** *             |                      |
| Total emissions: 833.3 kg CO₂ eq           |                      |
| Direct emissions: 132.7 kg                 |                      |
| Transport: 97.0 kg                         |                      |
| Electricity: 0.4 kg                        |                      |
| Chemicals: 592.6 kg                        |                      |
| Combustible: 7.1 kg                        |                      |
| Infrastructure: 3.5 kg                     |                      |
| Emission avoided: 713.8 kg CO₂ eq          | 119.5 kg CO₂ eq      |
| **Composting and Land Application** *      |                      |
| Total emissions: 756.3 kg CO₂ eq           |                      |
| Direct emissions: 599.0 kg                 |                      |
| Transport: 119.8 kg                        |                      |
| Electricity: 10.8 kg                       |                      |
| Combustible: 9.5 kg                        |                      |
| Infrastructure: 17.2 kg                    |                      |
| Emission avoided: 670 kg CO₂ eq            | 86.3 kg CO₂ eq       |
| **Incineration with Household Wastes** *   |                      |
| Total emissions: 2805.3 kg CO₂ eq          |                      |
| Direct emissions: 2455.4 kg                |                      |
| Transport: 92.4 kg                         |                      |
| Electricity: 10.2 kg                       |                      |
| Chemicals: 21.9 kg                        |                      |
| Combustible: 225.4 kg                      |                      |
| Infrastructure: 0.1 kg                     |                      |
| Emission avoided: 2062.6 kg CO₂ eq         | 737.4 kg CO₂ eq      |
| **Fast Pyrolysis** *                       |                      |
| Total emissions: 695.7 kg CO₂ eq           |                      |
| Sludge drying: 597.5 kg                    |                      |
| Fast pyrolysis operation: 96.9 kg          |                      |
| Biochar transport: 1.3 kg                  |                      |
| Total emissions avoided: 1766.6 kg CO₂ eq   |                      |
| Natural gas substitution: 1102.1 kg        |                      |
| Crude oil substitution: 637.2 kg           |                      |
| Fertilizer substitution: 27.3 kg           | -1070.9 kg CO₂ eq    |

*Data sources: [11], [15]*

**Figure 1.** GHG emissions of one-ton dried sewage sludge at different disposal routes.

The fast pyrolysis route demonstrated a negative emission balance of -1070.9 kg CO₂ eq. This negative balance is due to the total emissions of 695.7 kg CO₂ eq which exceeded the total avoided emissions of 1766.6 kg CO₂ eq. This net negative GHG emission means more reduction than GHG emissions to the atmosphere [15]. The GHG credit for using fast pyrolysis route at the disposal of every ton of dried sludge was 1070 kg CO₂ eq (1.07 t CO₂ eq). Regarding direct emissions, a higher percentage
(86%) was accounted for the drying of sludge (597.5 kg CO\textsubscript{2} eq). The fast pyrolysis process accounted for 14% of the total direct emissions.

Biofuels (syngas, bio-oil) produced during the fast pyrolysis process largely contributed to the total emission avoidance, with a contribution percentage of 98.45%. The remaining emission avoidance (1.55%) was due to biochar as soil fertilizer [15]. Overall, the fast pyrolysis disposal route of sludge did not carry the environmental burden in terms of climate change impact, considering the net negative GHG emissions to the atmosphere.

3.2 Comparison of the extent of GHG emissions

A clear illustration of the superiority of fast pyrolysis over the other three conventional sludge disposal routes is presented in figure 2. Fast pyrolysis showed the lowest GHG emissions than liming and land application, composting and land application, and incineration with household wastes methods. Similarly, the fast pyrolysis dominance over the other routes is illustrated by net negative emission balance manifesting its significant contribution to the mitigation of atmospheric GHG emissions.

Overall analyses of GHG emissions provided evidence for the substantial benefits of fast pyrolysis as an environmentally sustainable sewage sludge disposal strategy. Unlike the other three conventional approaches, sludge disposal through fast pyrolysis can avoid more GHG emissions than the emission burden they create [15].

![Figure 2. Comparison of GHG emissions of different sewage sludge disposal routes.](image-url)
3.3 Sewage sludge energy recovery potentials via fast pyrolysis

Fast pyrolysis is a thermochemical conversion of biomass in the absence of oxygen, desiring to maximize bio-oil yield. The use of digested sewage sludge from domestic wastewater, reported elsewhere [12], resulted in a relatively higher fast pyrolysis bio-oil (35.68 wt%) than biochar (23.52 wt%) and biogas (28.66 wt%) yields (table 1). Although the bio-oil yield is lower than those derived from wood biomass having 50-80 wt% recovery [18], the result is within the 26.7%-43.1% (daf) bio-oil recovery from different sewage sludge [19] and comparable to the 30-40% (db) recovery using second-generation sources [18] like corn stover [20]. Further, the result indicated an incredible high heating value of the sludge-derived bio-oil (36.43 MJ/kg), a value significantly higher than those derived from the wood of 16-19 MJ/kg [4,21] and those from agri-wastes with less than 23 MJ/kg such as sorghum bagasse [22], rice husk [23] and corn cobs [24]. Additionally, this sludge-derived bio-oil's heating value is nearly comparable to the 40 MJ/kg of heavy fuel oil [25,26]. The biochar and biogas respective high heating values are 7.43 MJ/kg and 9.42 MJ/kg, which are within the literature’s reported values [27].

| Particulars         | Product recovery (%) | HHV (MJ/kg) | Energy content (GJ/ton) | Tons of oil equivalent b |
|---------------------|----------------------|-------------|-------------------------|-------------------------|
| Dried sludge sample | 18.54±0.15           |             | 18.54±0.15              |                         |
| Fast pyrolysis products a |                   |             |                         |                         |
| bio-oil             | 35.68                | 36.43±0.15 | 13.0±0.05               | 0.311                   |
| biochar             | 23.52                | 7.43±0.13  | 1.75±0.04               | 0.042                   |
| biogas              | 28.66                | 9.52±0.49  | 2.73±0.14               | 0.065                   |
| Losses              | 11.82                | -           | -                       | -                       |

a Fast pyrolysis conditions: 500 °C temp, 0.6 mm dried sludge particle size, 0.95 s vapor residence time
b Conversion: 1 toe = 41.868 GJ

Considering one ton of dried sludge, the total energy of 17.48 GJ was extracted and elevated to fast pyrolysis products ready for various applications (table 1). The bio-oil took the highest energy content of 13.0 GJ/17.48 GJ (74.37%), which indicated that the sludge biomass's energy content was mostly elevated to the bio-oil product. In every ton of dried sludge, the fast pyrolysis process generated huge tons of oil equivalent (toe), amounting to 0.311. This result is desirable considering the high demand for liquid biofuel to augment petroleum-based fuel for energetic and transportation applications. The remaining energy content from pyrolysis products was elevated in the biochar of 1.75 GJ (±0.042 toe) and biogas of 2.73 GJ (±0.065 toe), respectively.

Because of the increasing volume of sludge needing a sustainable disposal route, this result promises a new and sustainable energy source that would substitute the conventional biomass sources such as wood and agri-wastes in making biofuels via thermochemical pathways. For energy sustainability, the result generally showed that exploitation of wastes like sludge for bioenergy production is very promising, a direction that most likely be taken when sources of petroleum fuels will be exhausted.

4. Conclusion

Environmental and energy sustainability are among the pressing concerns in the coming years as climate change, and energy security issues become more pronounced. There is a need to mitigate greenhouse gas (GHG) emissions to reduce environmental impacts and reverse ecological deterioration. Likewise, a concerted effort is needed to address the high worldwide dependence on energy that creates a volatile market with increasing prices of different petroleum-derived fuels. Combined, these two pressing problems are an inspiration for investigating the potential of using fast pyrolysis technology to dispose of sewage sludge generated from a wastewater treatment plant. The result highlighted the superiority of the fast pyrolysis route of producing significant energy content from bio-oil, biogas, and biochar and reducing GHG emissions. Compared to the other three conventional strategies, sludge conversion to an
energy source through fast pyrolysis is safe and environmentally friendly. It avoided more GHG emissions than the emission burden generated. This study proved that fast pyrolysis is the best sludge disposal option with enormous environmental and energy sustainability implications.

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