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Techno-economic Feasibility of Thermochemical Conversion Pathways for Regional Agricultural Waste Biomass

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This study examines four prominent thermochemical conversion technologies such as slow pyrolysis (SP), fast pyrolysis (FP), gasification (GA) and hydrothermal liquefaction (HTL), for treating poultry litter in New York State (NYS). Nine cases involving various combinations of the four technologies and different downstream processing options such as bio-oil upgrading, Fischer-Tropsch conversion and combined heat and power generation are chosen based on the product composition and distribution. High-fidelity process simulations for each technological platform are performed to derive the mass and energy balance information. Calculations and breakdown of the equipment costs, capital costs, operating and maintenance costs and utilities are provided and compared extensively for each of the nine cases. The economic performance is further analyzed by calculating and comparing the resultant net present values (NPV), ranging from \$10 M to \$170 M (SP), \$89 M to \$314.5 M (FP), \$28 M to \$196 M (HTL) and \$25 M to \$234 M (GA). The greenhouse gas emission inventories are also compiled to understand the corresponding impacts of different downstream processing choices (ranging from 217 to 494.5 kg CO_2-eq/t feedstock with both the pyrolysis technologies outperforming the others in most cases) and to highlight the trade-off with economic performance. Through sensitivity analysis, the influential factors requiring further investigation are identified and it is found that plant capacity and bio-oil yield are the most important parameters for the fast pyrolysis systems, biochar price for SP is the single most important parameter.

1. Introduction

There has been a surge in the consumption of resources and generation of organic waste streams around the world over the past few decades (Garcia et al., 2017), and this can be directly linked to the exponential rise in human population during that period (Demirbas et al., 2011). Some of the major waste streams include wastewater sludge, municipal solid waste (MSW) (Tokmurzina et al., 2019), dairy manure and poultry manure (Zhao et al., 2019), among others (Mills et al., 2014). The global MSW production in 2018 was 2.01 Gt (Kaza et al., 2018). Most solid waste streams are either landfilled or incinerated with an associated transportation and disposal cost (Cao et al., 2017), in addition to environmental concerns, such as air pollution, leaching of toxic elements, soil fertility reduction, and nutrient losses (Seidavi et al., 2019). Alternatively, organic fecal wastes with high nutrient contents (nitrogen (N), phosphorus (P), and potassium (K)), are often directly applied to croplands owing to their potential benefits in terms of soil fertility, contributing to the food-energy-water nexus considerations (Garcia et al., 2019). Recent studies have shown that this method of disposal does not fare better than the other conventional methods, with over-application of wastes such as dairy manure and poultry litter leading to eutrophication of water bodies (Zhao et al., 2020), and the risk of bio-magnification of antibiotics or other harmful chemicals in the food chain (Bolan et al., 2010). There is an urgent need to find a more sustainable option for disposing organic wastes like poultry litter and minimizing public health risks through possible pathogens in the wastes, while ensuring maximum recovery of valuable products simultaneously (Isemin et al., 2019).

Thermochemical technologies (Bora et al., 2020), such as slow pyrolysis (SP), fast pyrolysis (FP), hydrothermal liquefaction (HTL) and gasification (GA) are now being considered as alternatives to conventional biological and thermal methods for treating organic waste streams (Nicoletti et al., 2019), owing to their potential to do so with

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minimum environmental impact (Kantarli et al., 2016). They have proven to be conducive to nutrient recycling and energy generation as a result of their valuable products (Skaggs et al., 2018). The kinetics and reaction pathways for these technologies have been developed extensively and this provides an opportunity for modeling these processes (Moldoveanu 2019). Despite the various options available and the multiple products produced (Bora et al., 2020), the conditions under which thermochemical technologies would be capable of providing clean, energy-efficient and reliable alternatives to current biomass-to-energy conversion processes are yet to be determined (Yue et al., 2014). Most of the poultry litter produced in the United States is either land applied or landfilled currently (Bolan et al., 2010). Consequently, certain states are searching for solutions to tackle organic wastes and produce sustainable energy simultaneously (Ning et al., 2019). Most techno-economic studies assessing thermochemical technologies are found to choose a predetermined downstream processing option for each technology without investigating the impacts for other downstream processing options or locations (Swanson et al., 2010).

To address some of the challenges mentioned above, this study involves high-fidelity process simulations for nine different cases based on different downstream processing options for the four prominent thermochemical conversion technologies to treat poultry litter (SP FP HTL, GA) (Cavalaglio et al., 2018). This is followed by a thorough economic analysis with the primary objective to compare the performance of the different technologies. Novel contributions of this study include the simulation of thermochemical technologies with flexible downstream processing options for poultry litter in NYS.

2. Materials and Methods

The simulations for the studied thermochemical conversion technologies—SP, FP, GA, and HTL—along with their respective cases based on the downstream processing choices are carried out using the Aspen Plus software version 9. More than one case is associated with each of the technologies depending on the proven feasibility and compatibility of a particular processing option with the main products from the individual technologies (Table 1). For instance, the cases for both HTL and FP are based on the best possible pathways for the bio-oil that is produced (Peterson et al., 2008)). Similarly, the cases for SP and GA revolve around the processing of biochar and syngas (Zhang et al., 2014). Based on this approach, nine valid cases are identified from these four technologies. Fischer-Tropsch (FT) processing involves the conversion of the gases from GA into liquids that can be converted to fuels (Wang et al., 2013)), and the other downstream processes are described in the footer of Table 1. The simulations as well as the analysis of each of these cases in terms of economic performance, greenhouse gas emissions and variability involves numerous parameters and assumptions, as not all data is available at the commercial scale for these technologies. Some of these values are derived through the simulations, others are based on technical government reports and additional literature (Tews et al., 2014).

Table 1: The different cases analyzed in this study based on choices for downstream processing options. The entries in the columns for the phases represent their ultimate utilization mode.

Abbreviation	Output from main reactor	Gas phase	Oil phase	Solid phase	Main revenue generators
GA-FT	syngas, biochar	fuel	N/A	land application	fuels
GA-CHP	syngas, biochar	power	N/A	land application	heat, electricity
GA-COMB	syngas, biochar	heat	N/A	land application	heat
SP-COMB	gas, bio-oil, biochar	heat	existing refinery	land application	biochar, electricity
SP-CHAR	gas, bio-oil, biochar	heat	existing refinery	land application	heat, biochar
FP-SELL	gas, bio-oil, biochar	heat	existing refinery	land application	bio-oil, biochar,
FP-UPGRADE	gas, bio-oil, biochar	heat	upgraded to fuels	land application	bio-oil, biochar,
HTL-SELL	gas, oil phase, biochar	heat	existing refinery	land application	bio-oil, hydrochar
HTL-UPGRADE	gas, oil phase, biochar	heat	upgraded to fuels	land application	fuels, hydrochar

**GA stands for gasification, SP for slow pyrolysis, FP for fast pyrolysis, HTL for hydrothermal liquefaction, FT for Fischer-Tropsch processing, CHP for combined heat and power generation, COMB for combustion, CHAR for biochar, SELL for selling bio-oil to existing crude refineries, UPGRADE for bio-oil upgrading plant and AD for anaerobic digestion.*

2.1 System boundaries and assumptions

Since the primary objective of this study is to simulate and analyze different thermochemical processing schemes, the considered systems only involve the processes themselves along with the associated products. Steps involving the rearing of poultry and the production and collection of poultry litter or the photosynthesis capturing the CO_2 through plant growth of the feed are not applicable to this study. Indirect and embedded environmental impacts of these processes are not analyzed, and only the greenhouse gas emissions for each system are compiled, as they could be attributed to a form of revenue or an economic burden either now or in the future (such as carbon credit/tax).

2.2 Consideration of different operating scales

The plant capacities and the input feed flowrates for the simulations are based on the available poultry litter data for NYS. The data are either available in the form of a county-level distribution or based on the concentrated animal feeding operations (CAFOs), (which are defined as large farms with more than 1,000 animal units or 125,000 broiler chickens) for poultry litter in NYS. The latter is selected for this study as the fourteen CAFOs are found to produce approximately 175 kt/y of poultry litter, which accounts for roughly 63 % of the total production in the state. Additionally, they are found to be hotspots in terms of poultry litter density distribution, providing ideal locations to build a plant, as against the county centers which would not always have the highest densities owing to much smaller, distributed farms. The absolute values presented in the results are all calculated assuming a centralized plant with a capacity of 175 kt/y.

2.3 Economic parameters

The estimation of capital cost and operating and maintenance (O&M) cost is carried out based on the process economics analysis results from the Aspen economic analyzer, as well as literature and government reports. Various assumptions are made to accurately calculate these values and other associated costs by allocating certain percentages of the capital costs to land cost, installation cost, start-up cost and other operating costs (Wright et al., 2010). Utility costs and product market prices are determined based on the simulation results, and the current industrial market pricing for NYS (Zhu et al., 2014). In order to analyze the overall economic performance of the cases, the method of net present value (NPV) is selected with an assumed plant life of 20 years and an annual discount rate of 5 % (which has some uncertainty associated with it and has been included later in the sensitivity analysis) (Swanson et al., 2010). It is also important to note here that there are different levels of uncertainties in terms of the capital, startup and O&M costs for the various technologies considered. For instance, given the immaturity and the lack of full-scale commercial plants for HTL relative to GA and fast and SP, the estimated costs for HTL are obviously much more uncertain, and this should be considered while interpreting the results.

3. Results and discussion

Once the Aspen Plus simulations were completed and found to be comparable with experimental studies, the results of those simulations were used as the basis for the economic analysis. It is important to note that the results and the values shown in the figures are base-case values without uncertainties indicated, and that the uncertainty ranges for the estimated costs for an immature technology such as HTL would be much larger as compared to the other technologies. The sensitivity analysis results are discussed in Section 3.4.

3.1 Equipment costs

Based on the equipment cost analysis (Figure 1), the GA case (GA-FT) is found to have the most expensive equipment ($72 M), and the SP case (SP-COMB) has the lowest equipment cost ($41 M) for a plant of capacity 175 kt/y. The reactors and hydroprocessing units are found to be the most prominent factors, with contributions in the range of 20 - 41 % for the reactors and in the range of 15 - 36 % for the hydroprocessing units. Dryers are found to be responsible for 85 - 90 % of the ‘heat exchangers’ group cost for SP, FP, as well as GA. However, as expected, this cost is absent in the HTL case which does not require the feed to be dried. Similarly, compressors and pumps are found to dominate the ‘others’ equipment group (59 - 90 %), and this could be attributed to the high pressures involved as well as the pumping of viscous feed and bio-oil.

3.2 Annualized production costs

The fixed and variable annualized costs for each case shows the large impacts that downstream processing options can have on the capital and operating costs. The three most expensive combinations are GA-FT ($35.2 M/y), HTL-UPGRADE ($32.5 M/y) and FP-UPGRADE ($31.2 M/y), and each of these technologies involve utilization of downstream processing for the respective major products. GA-FT is 39 % and 60 % more expensive compared to the other two cases for GA involving CHP (GA-CHP) and combustion (GA-COMB). SP-CHAR is the cheapest among all cases ($16.8 M/y) owing to lesser capital and operating costs. Similarly, the cases involving upgrading for both HTL (HTL-UPGRADE) and FP (FP-UPGRADE) are approximately 65 % times more expensive than the cases without any downstream processing. For SP, interestingly, the two cases of SP-COMB ($20.3 M/y) and SP-CHAR ($16.8 M/y) only have a difference of 20 % as both of them are considered to employ very similar processes.

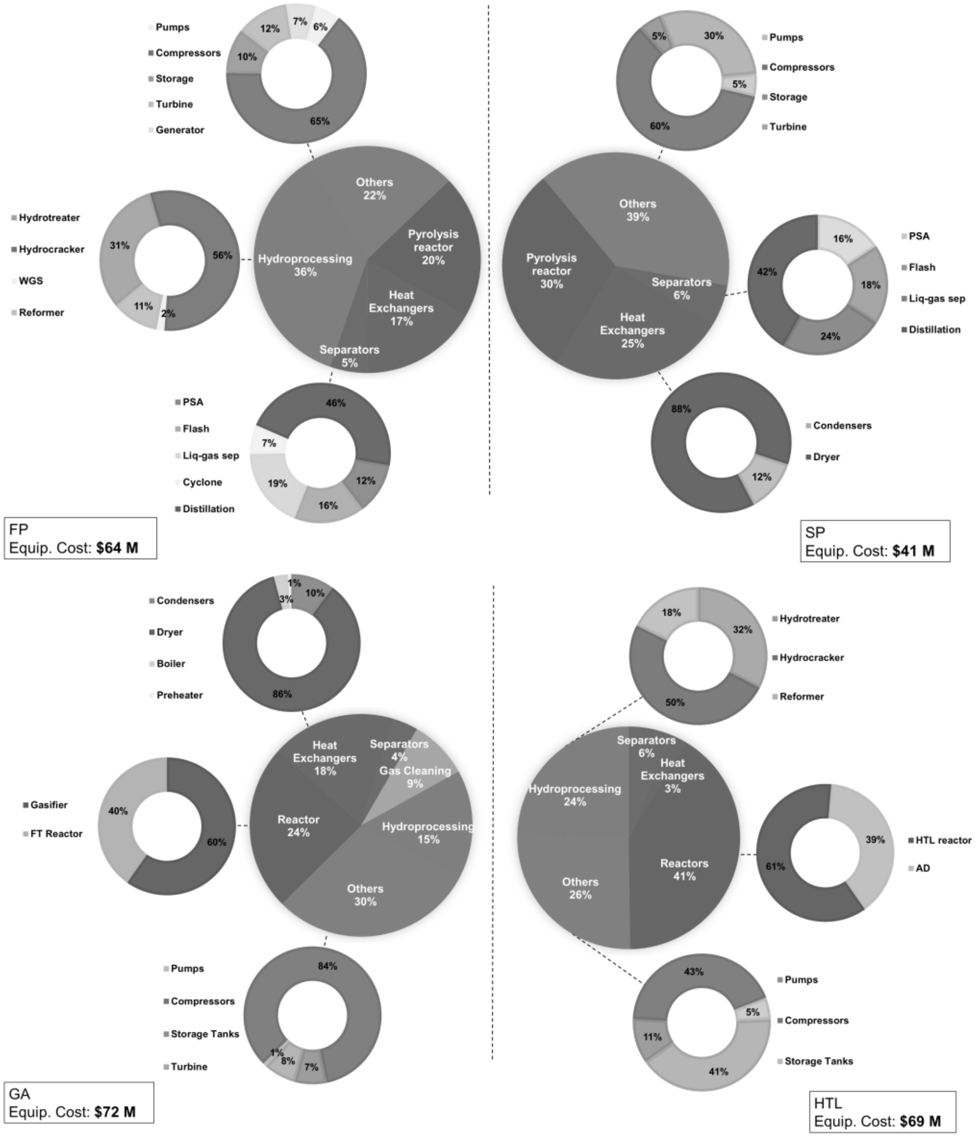

Figure 1. Equipment cost breakdown. This figure shows the major contributors to the equipment cost for each of the four technologies (in the pie-charts) with a capacity of 175 kt/y while considering the respective cases with downstream options. Fast pyrolysis (FP) and slow pyrolysis (SP) on the upper side; gasification (GA) and hydrothermal liquification (HTL) on the lower side).

3.3 Net present value (NPV) results

Apart from analyzing the costs associated with the different cases and technologies, their net present values (NPV) are also calculated based on our assumptions to incorporate the revenue streams. Based on the calculations for a plant of size 175 kt/y, it is found that the FP case involving the upgrading of bio-oil (FP-UPGRADE) has the highest NPV ($315 M) at the end of the 20-year horizon and a discount rate of 5 % (Wright et al., 2010). The other two cases with the highest NPVs are the GA-FT and HTL-UPGRADE cases. The results highlight the influential role that diesel and gasoline prices have on the overall economic performance of the processes. The cases with lower NPV values are the ones with minimal downstream processing and those that utilize their products internally. As an example, SP-COMB with the lowest NPV of $10 M involves the combustion of biochar to produce energy, which could otherwise have been sold to generate much higher revenue, such as in the SP-Char case with an NPV of $170 M.

3.4 Sensitivity analysis results

Through the sensitivity analysis for both the SP and FP cases, parameters which would have a major impact on the NPV values for each case are identified. For the FP case (FP-UPGRADE), the plant capacity is the dominating factor with a negative NPV of -\$32 M (decrease of 110 %) on moving from the existing capacity (175 kt/y) to a lower capacity (25 kt/y). This could be explained by the fact that the building of an upgrading facility dedicated solely to process bio-oil would be a very expensive proposition if the scale is not large enough. Both bio-oil yield (ranging from -49.0 % to +38.2 %) and diesel price (-47.4 % to +30.8 %) are other influential parameters, further establishing the importance of optimizing the utilization and processing steps of bio-oil for FP. For SP on the other hand, the biochar price (with a base value of \$100/t) is found to be capable of dictating the overall economic performance of the plant, with a meagre NPV of \$12 M at \$0/t biochar, and a substantial NPV of \$298 M at \$500/t biochar. Towards the higher end of the biochar price spectrum, it is found that the SP system could compete with the FP system in terms of NPV and even surpass it if in combination with a high carbon credit value (+73 % for \$500/t CO_2-eq). The biochar and carbon credit prices could play a huge role in dictating the better technology to be deployed at a larger scale.

3.5 Greenhouse gas emission results

Apart from the NPV, it is also important to look at the corresponding environmental impacts while making a decision to choose a certain processing technology over another. A greenhouse gas inventory for each case including the sum of all the greenhouse gases (CO_2, N_2O, CH_4) emitted directly through the initial reactions, as well as in the downstream processing steps is compiled. On comparing these values against the corresponding NPVs for the cases, there is a clear identification of the trade-offs associated with the two parameters. The cases with GA and HTL seem to have an average value of emissions higher than the corresponding slow and FP cases. The top three cases with high NPVs (FP-UPGRADE, GA-FT, HTL-UPGRADE) are also among the biggest emitters of greenhouse gases (greater than 300 kg CO_2-eq/t feedstock), the ones with minimal or no downstream processing have correspondingly lower emissions.

4. Conclusions

In this paper, the techno-economic analysis for nine cases involving combinations of the four thermochemical technologies with different downstream processing options is achieved with the aid of rigorous process simulations. The resultant net present values for the base-cases, ranging from \$10 M to \$170 M (SP), \$89 M to \$315 M (FP), \$28 M to \$196 M (HTL) and \$25 M to \$234 M (GA) highlight the potential benefits of implementing these technologies, and the sensitivity analysis portrays the impact that parameters with high variability such as biochar price (\$0/t to \$1,900/t), carbon credits (\$0/t to \$500/t) and plant capacity (25 kt/y to 175 kt/y) can have on the economic performance (this can be directly linked with policy too). Since the cases with the highest NPV generation also seem to be the ones with the highest GHG emissions it further emphasizes the need for spatial analysis and supply chain optimization to aid in determining the optimal choices for specific regions to deal with their waste biomass efficiently.

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