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Supply Chain Design of Poultry Waste Valorization through Pyrolysis: Economic and Spatial Analysis for New York State

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As an organic waste with high nutrient contents, the conventional landfill or incineration of poultry waste has led to growing concerns. This study applies spatial analysis to two scenarios of poultry waste valorization supply chain design in New York State (NYS). Ultimately, the optimal distribution of slow and fast pyrolysis biorefineries within NYS based on the operational and economic parameters, locations of major poultry farms, crude refineries and corn croplands is discerned and mapped. Additionally, the biochar transportation costs are distributed in the form of heat maps. The outcome indicates that building a single centralized biorefinery in NYS for both slow pyrolysis and fast pyrolysis is more economically feasible than building multiple smaller biorefineries for ten slow pyrolysis and eight fast pyrolysis distributed biorefineries in NYS.

1. Introduction

The explosive growth in global human population over the past few decades has urged the drastic increase in food supply (Kaza et al., 2018), and subsequently led to the waste flooding (Demirbas et al., 2011). Poultry litter, as one of the most common organic waste, if disposed by conventional disposal method such as land application, has brought various concerns about air pollution, nutrient loss (Osorio et al., 2017), water contamination and health risks (Seidavi et al., 2019). More sustainable alternatives are being considered for treating organic waste such as poultry litter (Kantarli et al., 2016), owing to their potentials to sequestrate biogenic carbon (Isemin et al., 2019), retain nutrients and recover energy through products such as biochar, bio-oil and pyrolysis gas (Skaggs et al., 2018). Specifically, slow and fast pyrolysis have been shown to be environmentally beneficial as a result of waste-to-energy conversion (Ning et al., 2019), as well as nutrient recycling and carbon sequestration through biochar (Nicoletti et al., 2019). In the United States, 50 Mt/y of poultry litter is produced, with most of it being either land applied or landfilled (Bolan et al., 2010). Some states have identified thermochemical technologies to treat a part of their wastes and they are actively investigating the large-scale application of these technologies (EIA, 2019). New York State (NYS) is a prime example with a number of policies being deliberated upon currently to tackle organic wastes and produce sustainable energy (EIA, 2019). Since the spatial data for the large poultry farms and the crop fields is also available for NYS, it provides a great opportunity to carry out a spatial analysis for the region to investigate the feasibility of implementing thermochemical technologies, along with the determination of optimal plant capacities (Garcia et al., 2017). Most techno-economic studies assessing thermochemical technologies are found to choose a predetermined downstream processing option for each technology (Yue et al., 2014), without investigating the impacts for other downstream processing options or locations (Satrio et al., 2010). In this study, by utilizing results and parameter values from a previous study, a spatial analysis to investigate how pyrolysis technologies would perform if implemented at different scales for NYS is conducted. Novel contributions of this study is a detailed spatial analysis scenario studies presenting the optimal plant locations and capacities for both pyrolysis technologies in NYS.

2. Material and methods

To illustrate the economics of both centralized and distributed design of the pyrolysis biorefineries, a scenario-based study for concentrated animal feeding operations (CAFOs) in NYS is presented. The following sections

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provide details about the technical and economic parameters and constraints used in this study, as well as the selection of different scenarios for NYS. The data are either available in the form of a county-level distribution or based on the CAFOs for poultry litter in NYS. The latter is selected for this study as the fourteen CAFOs are found to produce approximately 175 kt of poultry litter per year, 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.

2.1 Parameters and constraints

The poultry CAFO data including name, geographic information and annual capacities are collected from the NYS Organic Resource Locator, and presented in Figure 1 (RIT, 2019). It is assumed that the pyrolysis biorefineries can only be built on the CAFOs themselves to minimize transportation of the poultry litter as explained in an earlier section. Additionally, all the poultry litter feedstock generated by the 14 poultry CAFOs is utilized. The minimum capacity of a slow pyrolysis biorefinery (Zhao et al., 2020) and a fast pyrolysis biorefinery (Zhang et al., 2014) is assumed to be 4.38 and 8.76 kt/y, which corresponds to an input feed rate of 0.5 t/h and 1 t/h (Wright et al., 2010). Any biorefinery smaller than these minimum capacities for this study would prove to be economically infeasible. Along similar lines, the minimum capacity of a CHP unit in a slow pyrolysis biorefinery and a fast pyrolysis biorefinery is assumed as 4.60 and 3.68 kt/y (Zhao et al., 2014). These correspond to production of 0.5 MW and 0.25 MW of electricity in that order (Zhu et al., 2019). Based on these constraints, it is found that all fast pyrolysis biorefineries in our system can process the pyrolysis gas through CHP, to generate heat to offset part of the O&M cost, and to produce electricity to generate additional revenue. The bio-oil can either be upgraded on-site or sent to an existing crude refinery and the biochar is to be applied on corn cropland.

Figure 1: Map containing distribution, names, and annual poultry litter generation amounts (t/y) for the CAFOs in NYS, as well as existing crude refineries near the State.

Annual net revenue is calculated based on the difference between the sum of bio-oil income, biochar income, electricity income and carbon tax income and the sum of capital cost, O&M cost, poultry litter transportation cost and bio-oil transportation cost along with a fixed biochar price of $100 / t and without consideration of the biochar transportation cost (You et al., 2012). All the parameters needed for the annual net revenue calculations are assigned values based on the techno-economic analysis from a previous study (Bora et al. 2020). It is worth mentioning that due to the difficulty in estimating the transportation cost for biochar, it is excluded from the consideration of the biorefinery location and the annual net revenue is calculated with the premise of trading biochar without transportation. Biochar breakeven price is subsequently calculated to illustrate the biochar application throughout the NYS. It is worth mentioning that when annual net revenue turns out to be positive, a negative biochar breakeven price is obtained, and vice versa. Capital cost, O&M cost, biochar income, bio-oil income, electricity income and carbon tax income are found to be dependent on the capacity and technology choices for the biorefinery, while the poultry litter, bio-oil and biochar transportation costs are related closely with the location of the biorefineries and corn croplands. To determine the optimal locations of the biorefineries among the 14 CAFOs, the pairwise route distances between each crude refinery and CAFO, from one CAFO to another, and between corn cropland pixels and each CAFO are computed and integrated in the calculation of the breakeven price for biochar.

2.2 Choice of scenarios and cases for the spatial analysis

In this case study, two scenarios for both slow and fast pyrolysis technologies are chosen (Table 1). Scenario 1 involves building only one pyrolysis biorefinery for the entire NYS. According to the CAFO data, the overall estimated poultry manure generated through NYS's CAFOs is 175.3 kt/y, and that is chosen as the capacity for the pyrolysis biorefinery in Scenario 1. (RIT, 2019) This scenario takes advantage of the economy of scale that helps to reduce the unit production costs, but the transportation costs of both feedstock and products is expectedly higher. Scenario 2 is designed to minimize the transportation of poultry litter. Based on the previously defined cutoffs (minimum capacity) for building a pyrolysis biorefinery, the scales of some CAFOs are found to be too small to build a biorefinery, and it is still necessary to transport poultry litter from those CAFOs to their nearest biorefineries. Consequently, there are ten biorefineries for Scenario 2 of slow pyrolysis but only eight biorefineries for fast pyrolysis due to the different cutoffs (minimum capacity) for building slow and fast pyrolysis plants. The location of biorefineries in Scenarios 1 and 2 will be revealed and analyzed in Results and discussion section.

Table 1: Description of scenarios for spatial analysis in terms of number of plants, technology and capacity.

Scenario name	No. of plants	Technology	Capacity (kt/y)
SP Scenario 1	1	Slow	175.3
SP Scenario 2	10	pyrolysis	49.5, 39.4, 26.4, 17.3, 9.9, 8.3, 7.6, 7.1, 5.4, 4.6
FP Scenario 1	1	Fast	175.3
FP Scenario 2	8	pyrolysis	49.5, 39.4, 26.4, 17.3, 13.2, 9.97, 9.9, 9.7

3. Results and discussion

The spatial analysis results are presented based on the two different scenarios that are considered to treat NYS's poultry litter through either slow or fast pyrolysis. The location of poultry CAFOs is depicted using purple dots with their size proportional to the farm's capacity. A star is used to identify the optimal pyrolysis biorefinery built for each scenario, and its size represents the original capacity of the chosen CAFO. The capacity of the biorefinery is portrayed through the orange lines. In Figure 2, the arrows represent the transportation of poultry litter from CAFOs to the pyrolysis biorefineries. Similarly, the location and capacity of crude refineries is shown in the figures using a black rhombus with its size proportional to capacity. The arrows represent the transportation of bio-oil from pyrolysis plants to the crude refineries. Transportation volumes are also labeled besides the arrow or pointed out with lines.

3.1 Scenario 1: Building a single pyrolysis biorefinery in NYS

The heat maps of biochar transportation cost across NYS and the optimal supply chain design for SP Scenario 1 and FP Scenario 1 are illustrated in Figure 2a and 2b (where SP stands for slow pyrolysis and FP stands for fast pyrolysis). It can be observed that the CAFO named Wayne County Eggs (Figure 1) is chosen to be the location of the pyrolysis biorefinery for both SP Scenario 1 and FP Scenario 1. The large capacity (175.3 kt/y) helps satisfy the constraints associated with building the biorefineries and their downstream processing facilities, and both scenarios choose to process pyrolysis gas with a CHP unit. The FP Scenario 1 also chooses to upgrade the bio-oil instead of transporting and selling it to existing crude refineries. Under the given choice of technology and biorefinery capacity, the biorefinery location for FP Scenario 1 is only determined by the poultry litter transportation, while the biorefinery location for SP Scenario 1 is a result of the combined effect of poultry litter transportation and bio-oil transportation.

Transportation cost is based on the interaction between transportation distances and loads, so a biorefinery is more likely to be built on a large CAFO with low total turnover of transportation (calculated through the multiplication of load and distance), in order to avoid as much poultry litter transportation as possible. The 39.4 kt/yr capacity of Wayne County Eggs is the second highest among all the CAFOs and is not far from the 48.2 kt/y capacity of Giroux's Poultry Farm (ranked first). While Giroux's Poultry Farm is comparatively far from 12 of the CAFOs and the two crude refineries, Wayne County Eggs is closer to most CAFOs, among which there are two CAFOs - Kreher's Farm Fresh Eggs and Whitesville Farms, whose capacities are the third and fourth highest. Consequently, the summation of poultry litter capacity of the three CAFOs, namely Wayne County Eggs, Kreher's Farm Fresh Eggs and Whitesville Farms, accounts for 47 % of all poultry litter feedstock from the 14 CAFOs. Since the remaining CAFOs do not have capacities comparable to the four largest ones, the fast pyrolysis biorefinery is most likely to be built at Wayne County Eggs.

While considering bio-oil transportation for slow pyrolysis, a biorefinery located towards the lower half of NYS would be preferable, such as at Whitesville Farms and Ace Farms (Figure 1). However, the amount of bio-oil produced from slow pyrolysis (33 kt/y) is much less than the amount of poultry litter to be transported (127 to 175 kt/y), and the bio-oil transportation distance for each CAFO is not significantly higher than the average poultry litter transportation distance. The bio-oil transportation did not prove to be an influential factor on the choice of biorefinery location in SP Scenario 1. As a consequence, Wayne County Eggs is chosen to be the optimal location to build the pyrolysis biorefinery for both scenarios and the bio-oil from slow pyrolysis is transported to both crude refineries, since the closest crude refinery is not able to accommodate all the produced bio-oil based on the cutoff for the maximum bio-oil permissible in a conventional crude refinery.

For both scenarios, the radial color pattern of the heat map arising from the biorefinery represents the biochar transportation cost varying from lower to higher values (Figure 2). The biochar breakeven price is found to vary from \$59 / t to \$96 / t for slow pyrolysis while it changes from -\$128 / t to -\$91 / t for fast pyrolysis (summarized in Table 2). The differences can be explained through the breakdown analysis of the economics (Figure S6 in the Supporting Information). All the costs and sources of revenue are considered on an annual basis, and the revenue generated through bio-oil, biochar, carbon tax and electricity account for 31.6 %, 47.0 %, 20.6 % and 0.8 % of the total income for the SP Scenario 1. In contrast, the FP scenario 1 has the bio-oil, biochar, carbon tax and electricity account for 76.7 %, 17.3 %, 5.7 % and 0.3 % of the total income. Due to higher biochar production in slow pyrolysis, its biochar and carbon tax revenues are found to be \$6.98 M and \$4.06 M more than that of fast pyrolysis. On the other hand, since the diesel (\$3.26/gallon) and gasoline prices (\$2.79/gallon) are much higher than the bio-oil price (\$45/barrel), the upgraded fast-pyrolysis bio-oil is able to generate \$30.9 M more than the slow pyrolysis bio-oil.

In terms of fixed and variable costs, the capital cost, O&M cost, poultry litter transportation cost and bio-oil transportation cost account for 16.6 %, 59.8 %, 18.0 % and 5.6 % of the total costs in SP Scenario 1. For FP Scenario 1, the capital cost, O&M cost and poultry litter transportation cost account for 18.2 %, 72.4 % and 9.4 % of the total costs with the poultry litter transportation cost having the same values for both scenarios. As a result of the additional bio-oil upgrading equipment required for fast pyrolysis, FP Scenario 1 has \$16.85 M higher annual O&M costs and \$3.91 M higher annualized capital costs compared to SP Scenario 1. The resultant net revenues (derived from the earlier techno-economic analysis) are \$13.42 M and \$13.60 M for SP Scenario 1 and FP Scenario 1.

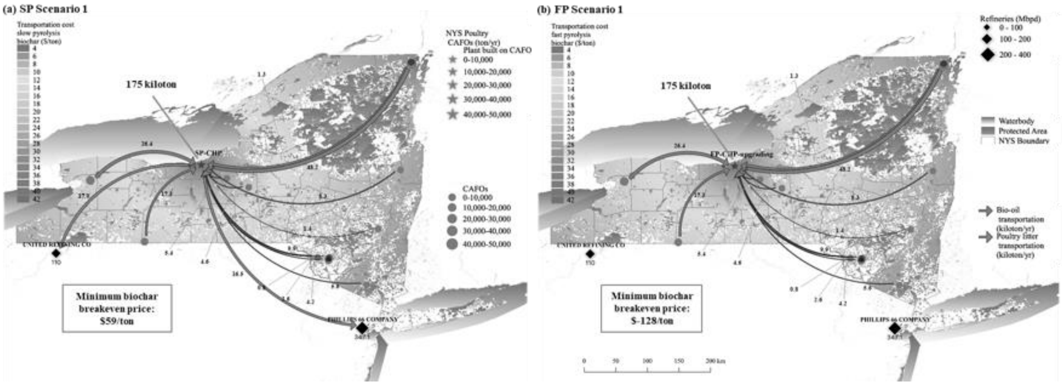

Figure 2: Transportation cost of biochar and illustration of biorefinery location, technology selection, capacity, transportation of feedstocks and products in Scenario 1 for a. slow pyrolysis and b. fast pyrolysis.

3.2 Scenario 2: Building multiple pyrolysis biorefineries for NYS

The heat maps of biochar transportation cost distributed across NYS, and the optimal supply chain design for SP and FP Scenario 2 are illustrated in Figures 3a and 3b. Under this scenario, we aim to build biorefineries on all CAFOs. However, some CAFOs are too small to construct a pyrolysis biorefinery on, and poultry litter from these CAFOs is transported to the nearest biorefinery and further processed. Ten CAFOs (namely Kreher's Farm Fresh Eggs, Whitesville Farms, Wayne County Eggs, Hudson Egg Farms, Smith Quality Eggs, Harold Brey & Sons, Bella Poultry, Ace Farm, Tomas Poultry Farm of Schuylevil and Giroux's Poultry Farm) are chosen as slow pyrolysis biorefineries with annual capacities of 26.4, 17.3, 39.4, 5.4, 4.6, 9.9, 7.6, 7.1, 8.3 and 49.5 kt/y. Among these, only Smith Quality Eggs processes its pyrolysis gas with a combustor due to the minimum capacity limitation for CHP units, while the other biorefineries could utilize CHP units. Eight CAFOs are chosen as fast pyrolysis biorefineries, namely, Kreher's Farm Fresh Eggs, Whitesville Farms, Wayne County Eggs, Hudson Egg Farms, Harold Brey & Sons, Bella Poultry, Tomas Poultry Farm of Schuylevil and Giroux's Poultry Farm with annual capacities of 26.4, 17.3, 39.4, 9.97, 9.9, 13.2, 9.7 and 49.5 kt/y. Among these, all biorefineries process their pyrolysis gas with a CHP unit. Three biorefineries, namely Hudson Egg Farms, Harold Brey & Sons and Tomas Poultry Farm of Schuylevil, transport and sell their bio-oil to crude refineries while the others satisfy the capacity constraint to upgrade bio-oil onsite.

In terms of bio-oil transportation, all slow pyrolysis biorefineries have to transport and sell bio-oil to their nearest crude refineries. Some biorefineries have geographic advantages while the others do not. For fast pyrolysis, only biorefineries which do not have sufficient capacity for the upgrading facilitites to be feasible would have to transport and sell bio-oil to their nearest crude refineries. As mentioned previously in Scenario 1, the radial color pattern of the heat map arising from all biorefineries represents biochar transportation cost varying gradually from low to high value. As shown in Table 2, the biochar breakeven price varies from $76 / t to $91 / t for slow pyrolysis, while it ranges from $74 / t to $93 / t for fast pyrolysis. Notably, the variance of biochar breakeven price becomes less compared to that under Scenarios 1, suggesting that the biochar transportation cost does not vary much for each pixel of corn cropland across NYS. This benefits from the sparse distribution of biorefineries and greatly reduces the minimum transportation distance between corn cropland and biorefineries. However, the distributed design of biorefineries leads to economic infeasibility here. Total annual biochar income, carbon tax income and O&M costs are the same for all scenarios of slow pyrolysis or fast pyrolysis. Under SP Scenario 2, annual electricity income is $7,620 less than that in SP Scenario 1 as a result of pyrolysis gas combustion on Smith Quality Eggs. Under FP Scenario 2, annual electricity income is the same as that in FP Scenario 1. Bio-oil income does not change for SP Scenario 2, compared to SP Scenario 1. Fast pyrolysis, in contrast, earns 8.5 % or $3.27 M less revenue through bio-oil than that earned in FP Scenario 1, suggesting that the distributed design of biorefineries is economically infeasible when CAFOs with small capacities exist.

Table 2: Range of biochar breakeven price for Scenarios 1 and 2 of slow and fast pyrolysis across NYS

Scenario name	No. of plants	Technology	Range of biochar breakeven price ($ / t)
SP Scenario 1	1	Slow	59 - 96
SP Scenario 2	10	pyrolysis	76 - 91
FP Scenario 1	1	Fast	-128 - -91
FP Scenario 2	8	pyrolysis	74 - 93

Total annualized capital costs for SP and FP Scenario 2 are much higher compared to Scenario 1. To be specific, the total annualized capital cost in Scenario 2 is 131.4 % and 99.7 % higher than that in Scenario 1 for slow and fast pyrolysis. In contrast, the poultry litter transportation cost in Scenario 1 is 95 and 28 times higher than that in Scenario 2 for slow and fast pyrolysis. Bio-oil transportation costs in Scenario 2 are slightly higher than that of Scenario 1. The annual net revenue for Scenario 2, which is calculated with a fixed biochar price of $300 / t and without biochar transportation cost, is found to be $12.48 M and $15.65 M less than those in Scenario 1 for slow and fast pyrolysis. The reduction in biochar transportation cost is found to offset part of the reduction in the net revenue, bringing the range of biochar breakeven price for slow pyrolysis lower and comparable to that in SP Scenario 1. However, for fast pyrolysis, the reduction in net revenue is too much to be offset significantly. Particularly, only two out of eight fast pyrolysis biorefineries show slightly positive annual net revenues, while the others all possess negative net revenues. The biochar breakeven price is brought up significantly from previous negative values to the range of $74 / t to $93 / t.

4. Conclusions

The poultry litter supply chain in NYS illustrates the variability in transportation of feedstock and products associated with real practice. The centralized treatment of poultry litter is found to outperform the distributed system for fast pyrolysis in NYS by a large margin, revealing the advantage that large-scale facilities possess. For slow pyrolysis on the other hand, the differences in the biochar breakeven price between the two systems are much smaller, portraying that either of the two could be suitable for NYS based on policy and market demand. Fast pyrolysis is found to outperform slow pyrolysis under both centralized and distributed supply chain design, emphasizing the tremendous economic value that bio-oil currently possesses. The proposed model provides a basis for decisions regarding the choice of technologies in the future, as a particular pathway would be more suitable in some cases as compared to the others depending on scale, feedstock, operating conditions, products desired, finances, and geospatial distribution of the entities involved.

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