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Comparative Life Cycle Analysis of Poultry Manure Management Technologies

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As the growing world population drives demand for poultry meat and eggs, a surplus of poultry manure is produced, which, when applied to land, can lead to freshwater eutrophication and harmful algae blooms. To sustainably manage poultry manure, several waste-to-energy and soil amendment pathways have been developed, drawing from technologies such as pyrolysis, hydrothermal liquefaction, hydrothermal carbonization, and anaerobic digestion. To evaluate the “cradle-to-gate” life cycle impacts of the pathways, as well as how the introduction of these technologies affects the upstream and downstream markets for products, two different Life Cycle Assessments (LCA) methods are used. In an attributional LCA setting, direct land application has the lowest environmental impacts except prominently in the climate change and eutrophication categories, which are the categories for which its harms are most noticeable. In a consequential LCA setting, due to the consideration of offsets, direct land application only has the lowest energy resource use and ionizing radiation, while other technologies minimize all other impact categories. To meet environmental targets, the choice of management technology for poultry manure is significantly determined by the chosen system boundary, implying that careful consideration of environmental objectives is necessary for the circular economy.

1. Introduction

There is increasing demand for poultry products such as eggs and meat, with market forces leading to the consolidation and growth of poultry farms (OECD/FAO, 2022). A larger supply of poultry manure increases pressure to dispose of poultry manure via direct land application (Ma et al., 2019), which will lead to harmful environmental impacts such as freshwater eutrophication and harmful algae blooms (Moore et al., 1995), and increased global warming potential through the emission of greenhouse gasses once applied to land (Bora et al., 2020a). Thermochemical conversion technologies such as slow pyrolysis, hydrothermal liquefaction (HTL), and hydrothermal carbonization (HTC) (Yue et al., 2014); and waste-to-energy technologies such as anaerobic digestion (AD) have been used to process poultry manure into environmentally sustainable alternatives (Zhao et al., 2020). Pyrolysis consists of the exposure of a feedstock to temperatures between 300-600 °C without the presence of oxygen, yielding syngas, bio-oil, an aqueous phase (AP), and biochar (Lehmann et al., 2021), though these yields are also influenced by the inclusion of catalysts and variations in moisture content (Zsinka et al., 2023). Bio-oil has shown potential as a renewable fuel (Lee et al., 2014). Biochar’s increased stability makes it an excellent carbon sequestration agent (Lehmann et al., 2021), though that benefit is ignored if biochar is combusted as a fuel (Laird et al., 2009), leading to the broader implications of food-energy-water-waste nexus (Garcia et al., 2017). HTL and HTC are similar processes for converting biomass in water at pressures between 10 and 25 MPa, with HTL operating at temperatures of 280-370 °C (Toor et al., 2011) and HTC operating at temperatures of 180-220 °C (Funke and Ziegler, 2010). HTC produces hydrochar, AP, and a gaseous phase (GP) (Funke and Ziegler, 2010) with yields of hydrochar decreasing over the temperature range (Codignole Luz et al., 2023), and HTL additionally produces non-trivial amounts of bio-oil (Toor et al., 2011). Similar to biochar, hydrochar can be used as a soil amendment (Kammann et al., 2012) or as a coal replacement in power plants (Sharma et al., 2020). In AD, microorganisms transform organic material under oxygen-free conditions to yield biogas, a renewable fuel, and digestate, which contains nitrogen, phosphorus, and potassium – necessary nutrients for crop growth (Bora et al., 2020b). Current Life Cycle Assessment (LCA) modeling of poultry manure management pathways (Garcia et al., 2016) does not take into consideration system boundary expansion or

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different end product uses. There is a knowledge gap in comparing the environmental impacts of a holistic set of management technologies and end product uses. To decipher the environmental tradeoffs between direct land application and the conversion technologies, the first comparative consequential life cycle assessment (CLCA) and cut-off attributional life cycle assessment (ALCA) for poultry manure is evaluated.

2. Life cycle assessment

This LCA uses the standard life cycle assessment process, including the goal and scope definition, inventory analysis, impact assessment, and results interpretation, which can be found in the following sections.

2.1 Goal and scope definition

An ALCA is used to quantify the emissions generated by managing manure, while a CLCA quantifies the relevant upstream and downstream impacts of the management pathway construction and operation (Wernet et al., 2016). For example, in a CLCA, the electricity produced from poultry manure that is sold on the market would be considered an offset for grid electricity, whereas, in the attributional system model, this would not be present. Both LCAs are "cradle to gate," with the "cradle" indicating collected poultry manure, which is assumed to be burden free as poultry is not raised for its manure. Because the fate of products sold in the markets is unknown, the system boundary is drawn at the "gate" to sale on the market. The functional unit is 1 t of poultry manure, as the comparison of environmental impacts across technologies with disparate final products is facilitated by choosing the common input. A monetary functional unit is not chosen because estimating revenues from products and costs of production introduces unnecessary uncertainty into the environmental impacts.

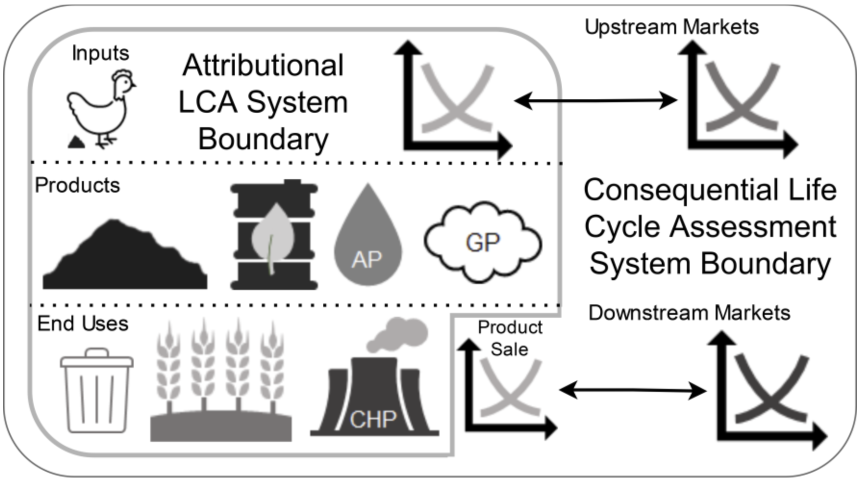

Figure 1: Attributional and consequential life cycle assessment system boundaries. Inputs besides poultry manure include products from markets such as fertilizer, diesel, electricity, and natural gas. Products include solids, bio-oil, aqueous phase (AP) and gaseous phase (GP). End uses include disposal, land application, combustion, and sale in markets. Abbreviations: LCA, life cycle assessment; CHP, combined heat and power

Seven scenarios are constructed for poultry manure management: direct land application (DLA), pyrolysis with direct land application of biochar and sale of bio-oil (P-DLA), pyrolysis with combustion of biochar and sale of bio-oil (P-CHP), HTC with direct land application of hydrochar (HTC-DLA), HTC with sale of hydrochar on markets (HTC-S), HTL with sale of bio-oil and combustion of hydrochar (HTL-CHP), and AD with land application of digestate and combustion of biogas (AD-DLA). Some of these processes, P-CHP, HTL-CHP, and AD-CHP, focus on generating energy from poultry waste, while direct land application processes emphasize nutrient recovery to close the circular economy.

2.2 Inventory analysis

Onondaga County produces 1,356 t/month of poultry manure, following county-level poultry sales and inventory figures from the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS, 2019) and estimates for annual poultry manure production amounts (Vest et al., 1994).

The process yields are taken from the literature and are as follows. For pyrolysis at 500 °C, the biochar yield is 54 %, the syngas yield is 19 %, the bio-oil yield is 16 %, and the AP yield is 12 % (Baniasadi et al., 2016). Biochar offsets 64.05 kg of N fertilizer, 17.06 kg of P fertilizer, and 27.37 t/t of K fertilizer per biochar (Enders et al., 2012). For combustion, syngas has an HHV of 10,000 MJ/t syngas, and biochar has an HHV of 11,900 MJ/t.

For HTL at 350 °C, the hydrochar yield is 17.1 %, the GP yield is 11.4 %, the bio-oil yield is 17 %, and the AP yield is 54.5 % on a mass basis, with hydrochar having an HHV of 25,400 MJ/t (Ekpo et al., 2016). For HTC, hydrochar is produced at 200 °C, yielding 54.9 % hydrochar, 5.6 % GP, and 39.4 % AP on a mass basis (Mau et al., 2016). For AD, 104.131 Nm^3 of methane and 0.831 t of digestate are yielded per 1 t manure (Bareha et al., 2022). To apply manure directly to the land, no conversion is necessary.

The majority of the inventory data comes from the EcoInvent database version 3.9.1 (Wernet et al., 2016), though processes are modified for land application and combustion in particular. The data for natural gas and water consumption comes from the EcoInvent processes for "heat and power co-generation, natural gas, conventional power plant, 100 MW electrical" and "market for water, decarbonized". For the disposal of aqueous phase, the "treatment of sewage sludge, 97 % water, WWT[R], WW from anaerobic digestion of whey, landfarming" process is used as there was insufficient data to characterize the wastewater from the various processes, but it is well documented that the AP from all phases is rich in organics. The impacts associated with the construction of the HTL, HTC, and pyrolysis plants are taken from the "market for chemical factory", for AD, "market for anaerobic digestion plant, agricultural", and for storage of solid products, "market for shed, large, wood, non-insulated, fire-unprotected – GLO". The offsets include N, P, and K fertilizer from "markets for inorganic fertilizer – US", grid electricity from "market for electricity, low voltage". In addition, it is assumed that bio-oil offsets soybean oil from the process "market for soybean oil, crude" as soybean oil comprises the plurality of bio-oil used as heating oil (BioHeat, 2018), and the offset for hydrochar sale is lignite from the process, "market for lignite – RoW", due to the higher atomic ratios for hydrochar (Ekpo et al., 2016).

The sources for inventory data for direct land application are reported below. For the climate impacts of biochar, it is calculated that biochar sequesters 2,460 kg $CO_{2\text{-eq}}$ after 100 y following regression estimates in the literature (Leng et al., 2019). N_2O emissions from soil are reduced by 0.132 kg/t biochar applied. No significant changes were reported for CH_4 and CO_2 emissions in the literature (Song et al., 2016). For hydrochar, changes in soil GHG emissions for CO_2, N_2O, and CH_4 are 18.29 kg/t, 0.584 g/t, and 0.0206 g/t, as reported in an experimental dataset (Kammann et al., 2012). The application of digestate to land results in emissions of 25.32 kg $CO_{2\text{-eq}}$/t digestate (Zeshan and Visvanathan, 2014). For spreading poultry manure on land, N_2O emissions are calculated at 0.1334 kg/t manure (IPCC, 2019a), with no significant impacts on soil CO_2 (Kreidenweis et al., 2021), and methane emissions of 1.8806 kg/t manure (IPCC, 2019b). Although emissions to surface water are affected by the application rate and tillage (Kaiser et al., 2009), they are assumed to be constant for poultry manure. P emissions to surface water from poultry manure are estimated at 0.5653 kg/t manure (Kaiser et al., 2009), while ammonium, nitrate, and organic nitrogen emissions to surface water are estimated at 0.1334 kg, 0.0208 kg, and 0.7226 kg/t manure (Diaz et al., 2010).

The sources for inventory data for combustion are reported below. Biochar has a low O/C ratio (<.1) and H/C ratio (< 0.5) (Baniasadi et al., 2016), which corresponds to the bituminous and anthracite coal types. For hydrochar, the comparable coal is lignite due to the higher O/C and H/C ratios of hydrochar (Ekpo et al., 2016). Syngas is assumed to cleanly combust to CO_2 (Lehmann et al., 2021), and the impacts for combustion of biogas come from the "heat and power co-generation, biogas, gas engine - US NPCC" EcoInvent process.

2.3 Impact assessment

ReCiPe 2016 midpoint indicators at a 100-y time horizon are chosen here to align with the 100-y stability assessment for biochar. OpenLCA (GreenDelta, 2023) is used to calculate the life cycle impacts.

3. Comparative life cycle assessment

In Figure 2, the functional unit-based comparative ALCA results are shown. HTL-CHP has the highest environmental impacts in most categories, followed by P-CHP, in part due to the high environmental impact associated with the combustion of solid products. Direct land application often has minimal impact, though it has the highest level of freshwater eutrophication of all technologies. Pyrolysis has a significant negative climate impact when applying biochar directly to land, which is negated when biochar is combusted (Gebreslassie et al., 2013). Despite combusting biogas, AD has a lower climate change impact than applying poultry manure and hydrochar to land, demonstrating its power as a renewable energy source.

Switching from direct land application to other technologies can be primarily justified from a eutrophication or climate change perspective – as its lack of reliance on complex facilities and combustion avoids a great deal of environmental impact in other categories. The production of energy from biochar is substantially worse than applying it to land, with every impact category showing higher values. However, for HTC, selling hydrochar on markets yields reduced environmental impacts than applying it to land, though in most cases, this is minor and likely due to reduced emissions from transportation.

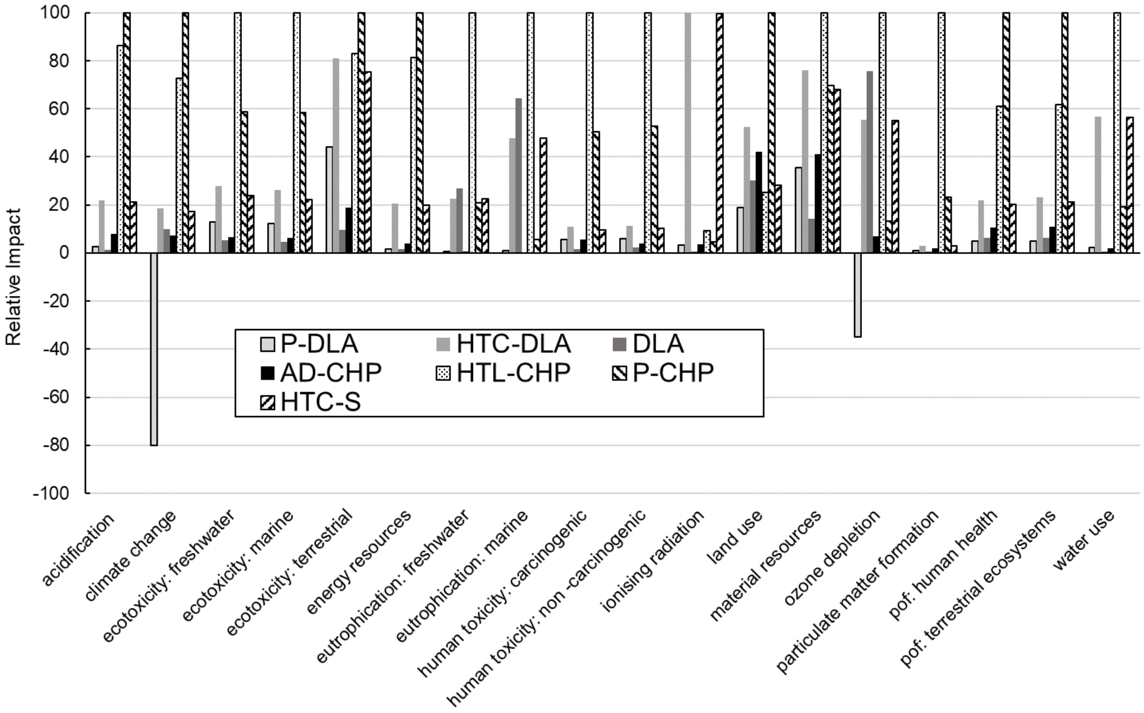

Figure 2: ALCA environmental impacts. The values for each impact category are scaled by the maximum value for that category. Abbreviations: pof, photochemical oxidant formation

In Figure 3, the functional unit-based CLCA environmental impacts are shown. AD has the largest environmental impact in acidification, climate change, ecotoxicity, energy resources, human toxicity, ionizing radiation, land use, material resources, ozone depletion, photochemical oxidant formation, and water use, the vast majority of impact categories. In the P-DLA scenario, environmental impacts are negative for acidification, marine eutrophication, land use, material resources, ozone depletion, particulate matter formation, photochemical oxidant formation, and water use due to the offsets for bio-oil not considered in the ALCA. HTL and HTC now share the highest impact for freshwater eutrophication, with direct land application having the highest marine eutrophication. Finally, HTL-CHP yields the highest particulate matter formation, though unlike in the ALCA, it has average values in most categories. Due to the inclusion of fertilizer offsets, direct land application now has a slightly negative impact in most impact categories. While the climate impact of direct land application can be reduced by switching to direct land application of biochar still remains, only selling hydrochar results in a smaller freshwater eutrophication impact due to the offsets for bio-oil.

The range of the environmental impacts is greater under a CLCA regime than an ALCA regime, primarily due to the large offsets that can occur. This is particularly apparent in the marine eutrophication and land use categories. AD had a significant increase in life cycle impacts from the ALCA to the CLCA, implying that the upstream and downstream processes used in the construction of anaerobic digesters have a significant adverse effect on the environmental impacts. This impact can be avoided by sustainability sourcing materials and components for an anaerobic digester.

4. Conclusions

Despite the significant potential of alternative waste management pathways for poultry manure, under an ALCA, direct land application has the lowest environmental impact in all categories except climate change, eutrophication, land use ozone depletion, and photochemical oxidant formation. However, by considering the upstream and downstream products and offsets involved, direct land application only minimizes energy resource consumption and ionizing radiation, which are not documented as important environmental targets for poultry manure management. The selection of system boundaries plays a crucial role in determining the level of life cycle impacts, a trend most noticeable in AD and HTL-CHP. The selection of technologies, whether pyrolysis to minimize climate change impact or HTC and AD to minimize eutrophication, requires careful consideration of environmental opportunities and targets. But additional factors, such as economics, may influence the adoption of these technologies for a sustainable future.

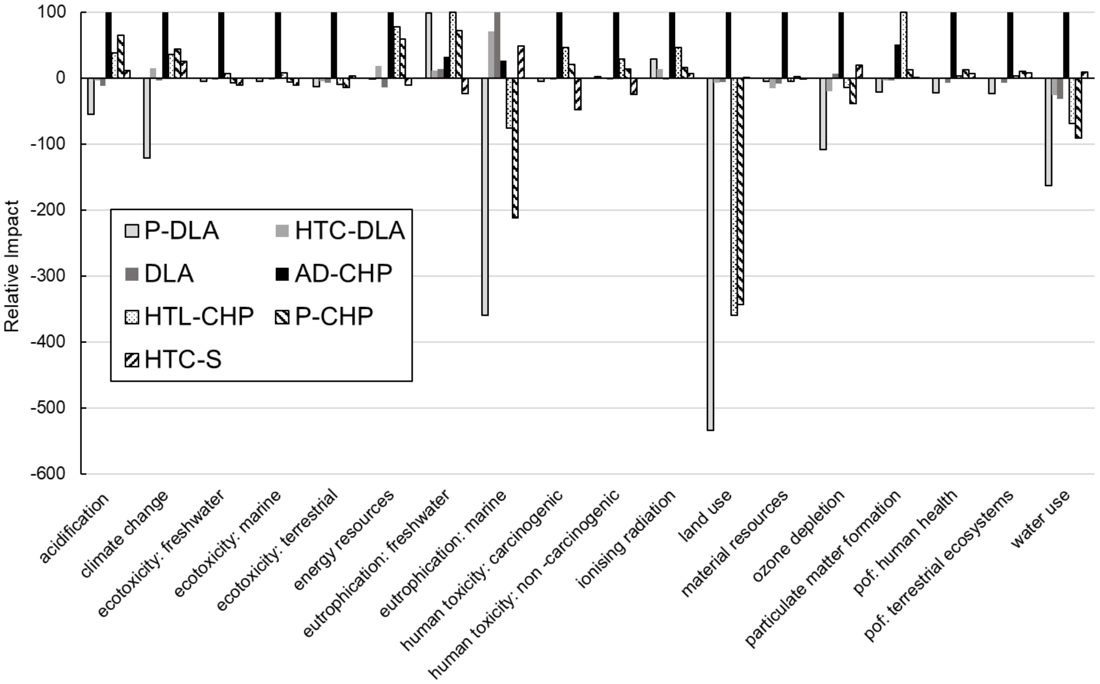

Figure 3: CLCA environmental impacts. The values for each impact category are scaled by the maximum value for that category. Abbreviations: pof, photochemical oxidant formation

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