Supporting Information

Life Cycle Assessment and Techno-economic Analysis of Thermochemical Conversion Technologies Applied to Poultry Litter with Energy and Nutrient Recovery

Raaj R. Bora,[1,†] Musuizi Lei,[1,†] Jefferson W. Tester,[1, 3] Johannes Lehmann,[2, 3] Fengqi You[1, 3,*]

[1] *Robert Frederick Smith School of Chemical and Biomolecular Engineering, Cornell University, Ithaca, New York 14853, USA*

[2] *Soil and Crop Sciences, School of Integrative Plant Science, College of Agriculture and Life Sciences, Cornell University, Ithaca, New York 14853, USA*

[3] *Atkinson Center for a Sustainable Future, Cornell University, Ithaca, New York 14853, USA*

This file contains: 27 pages, 5 sections, 9 tables and 5 figures.

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[*] Corresponding author. E-mail: fengqi.you@cornell.edu

[†] Raaj R. Bora and Musuizi Lei contributed equally to this work

List of Sections

List of Tables

List of Figures

S1. Description of thermochemical technologies

Table S1. Major components of each system considered in the analysis. The CHP is considered to have pollutant removal technology installed, with NO_x removal efficiency at the same level as that of the SCR (0.9). The gas phase for the hydrothermal technologies consists of the gases produced by the technologies themselves and from the AD used to treat their aqueous phases.

	Rearing of poultry	**Poultry litter collection**	**Drying**	**Main products**	**Gas phase**	**Oil phase**	**Aqueous phase**	**Solid phase**
Direct land application system	No	Tractor & trailer	No	N/A	N/A	N/A	N/A	Direct soil application of poultry litter
Slow pyrolysis system	No	Tractor & trailer	Yes	Gas, Bio-oil, Biochar	Combusted on site with SCR	Upgraded to fuels	N/A	Soil application of biochar
Fast pyrolysis system	No	Tractor & trailer	Yes	Gas, Bio-oil, Biochar	Combusted on site with SCR	Upgraded to fuels	N/A	Soil application of biochar
Gasification system	No	Tractor & trailer	Yes	Gas, Biochar	CHP	N/A	N/A	Soil application of biochar
HTC system	No	Tractor & trailer	No	Gas, Aqueous, Hydrochar	CHP	N/A	Digested (AD)	Soil application of hydrochar and digestate
HTL system	No	Tractor & trailer	No	Gas, Aqueous, Bio-crude, Hydrochar	CHP	Upgraded to fuels	Digested (AD)	Soil application of hydrochar and digestate
SCWG system	No	Tractor & trailer	No	Gas, Aqueous, Syngas	CHP	N/A	Digested (AD)	Soil application of digestate

S1.1. Pyrolysis of poultry litter

Pyrolysis is one among the thermochemical technologies that are considered in this analysis (Table S1). Pyrolysis is the process involving thermal degradation of organic matter at elevated temperatures in an inert atmosphere. Pyrolysis processes can be split into slow pyrolysis and fast pyrolysis depending on reaction temperature and duration[1]. Two typical studies are selected for slow pyrolysis and fast pyrolysis respectively as the basis to build mass and energy flows.[2-4] In both studies, the elements' fate and distribution among product fractions are provided in detail (as summarized in Table S2). In the 400-degree Celsius slow pyrolysis, 1 kg fresh feedstock results in 0.44 kg biochar, which contains 51% of feedstock energy, 63% carbon and 59% nitrogen. In the fast pyrolysis studies, nearly half of the primary energy, carbon and nitrogen go into bio-crude.

The process scheme for slow and fast pyrolysis is almost identical in our study. First, after collection, pre-treatment and drying, the biomass is sent to the reactor. The biochar produced is directly sent for soil application and the bio-oil is sent to a refinery plant to produce diesel and gasoline products. The syngas produced is burnt onsite in a boiler to supply energy for internal consumption. The low-energy content condensable vapor (aqueous phase), as well as the filtered water from the drying processes are regarded as wastes and are sent for wastewater treatment. The detailed emissions associated with each unit process are provided in Table S3.

S1.2. Gasification of poultry litter

Gasification is carried out at elevated temperatures and in a restricted oxygen environment. The fed biomass is converted into a gaseous energy carrier called "syngas" or "product gas". In the past, poultry litter has been regarded as an unconventional fuel to gasify, because the high ash content in poultry litter requires low reaction temperatures to avoid ash agglomeration, but low temperatures only lead to low gas yields. However, a recent study has successfully achieved an energy efficiency of up to 89% by blending poultry litter with limestone at 8% and setting the temperature to 800 degree Celsius. This great energy ratio is aided by calcite addition, which reduces the bed agglomeration risk and permits high operation temperatures. It deserves mention that this experiment is performed at a load rate of less than 1 kg/h and the large-scale production stability remains unknown.[5] This limestone does not serve as a CO_2 absorbent but as a means to improve the product yield. For gasification, all the available carbon in the feedstock would eventually be converted to CO_2. The emissions could be reduced either with some form of carbon capture, or as in the case of the pyrolysis technologies, through biochar which sequesters a part of the carbon.[6] Considering there are other poultry litter gasification studies which have successfully simulated the process with a load rate of 1500 kg/h, we assume the large-scale production is feasible.[7] In this LCA, the produced syngas from gasification (with air as the gasifying agent) is sent to an existing CHP by using a biogas truck, based on a typical transportation method in distributed biogas systems.[8, 9] For simplification, we assume that there are no stray gas emissions during the gasification process itself and the syngas transportation. The pre-drying water and gasification ash are regarded as industrial waste. The biochar produced from the gasification process is assigned a similar economic value as the pyrolysis biochars (and this may be conservative as the concentration of nutrients is comparatively higher than the other biochars). As with pyrolysis biochars, gasification biochar cannot be considered as a nitrogen fertilizer substitute owing to the low levels of plant-available nitrogen present in the biochar. We assume that the biochar is the source of some organic carbon to the soil as with pyrolysis biochars, though the quantity of biochar produced through gasification is much lower.[10]

S1.3. Hydrothermal methods for treatment of poultry litter

Hydrothermal processes are novel technologies to convert wet biomass into biofuels using sub-critical water as the solvent. Unlike in the "dry" thermal conversion technologies, water provides an excellent environment, and acts as a reactant and solvent for the typical reactions associated with the hydrothermal technologies. To ensure consistency, a comparative study for the three hydrothermal technologies on poultry litter is utilized and cited. Water is added to the poultry litter for diluting the feed. Since poultry litter is a relatively dry organic feedstock, this dilution is currently required to make it suitable for the hydrothermal technologies, which function best with wetter feeds. An alternative would be to consider recycled water streams for the dilution purposes if possible. It is interesting to note that over half of the mass, 60% of the Nitrogen (N), and 90% of the Potassium (K) go into the aqueous phase. In our process scheme design, all the aqueous primary products from hydrothermal processes are further sent to AD-CHP units to recover energy and nutrients. The hydrochar is sent for direct soil application. Bio-crude from HTC and SCWG are regarded as waste, and only HTL bio-crude goes through hydrotreatment to produce transportation fuels because of the comparatively larger volumes produced. Similarly, only the SCWG gas is sent to CHP, and the HTL and HTC gases are burnt on site for internal utilization of heat produced. This comes with its set of emissions too.[11]

S2. Mass and energy balances

The mass, energy, carbon, and nitrogen output distribution for the six technologies are represented through the following tables and figures (Table S2, Figure S1-S2). The feed for all of these processes is considered to have the same properties (as described in the main text).

Table S2. Product distribution and element fate for bioconversion technologies. The summed ratios do not necessarily add up to 100% because of measurement errors or heat losses.

Studies		ref[2]	ref[3, 4, 12]	ref[5]	ref[11]	ref[11]	ref[11]
Technology		**Slow pyrolysis**	**Fast pyrolysis**	**Gasification**	**HTC**	**HTL**	**SCWG**
Mass Distribution	**solids**	0.55	0.42	0.20	0.35	0.17	0.12
	bio oil/crude	0.15	0.27	-	0.03	0.17	0.02
	aqueous phase	0.10	0.18	-	0.50	0.54	0.55
	syngas	0.20	0.13	0.80	0.12	0.12	0.31
Energy Distribution	**solids**	0.48	0.32	-	0.70	0.31	0.18
	bio oil/crude	0.29	0.49	-	0.06	0.36	0.04
	aqueous phase	0.04	-	-	0.14	0.10	0.05
	syngas	0.06	0.03	0.70	0.05	0.05	0.50
Carbon Distribution	**solids**	0.63	0.30	0.11	0.27	0.28	0.18
	bio oil/crude	0.25	0.48	-	0.09	0.36	0.05
	aqueous phase	0.05	0.17	-	0.53	0.25	0.30
	syngas	0.07	0.05	0.89	0.11	0.11	0.47
Nitrogen Distribution	**solids**	0.59	0.24	0.25	0.30	0.12	0.07
	bio oil/crude	0.07	0.52	-	0.05	0.17	0.05
	aqueous phase	0.20	0.15	-	0.60	0.58	0.63
	syngas	0.16	0.10	0.75	0.02	0.02	0.20

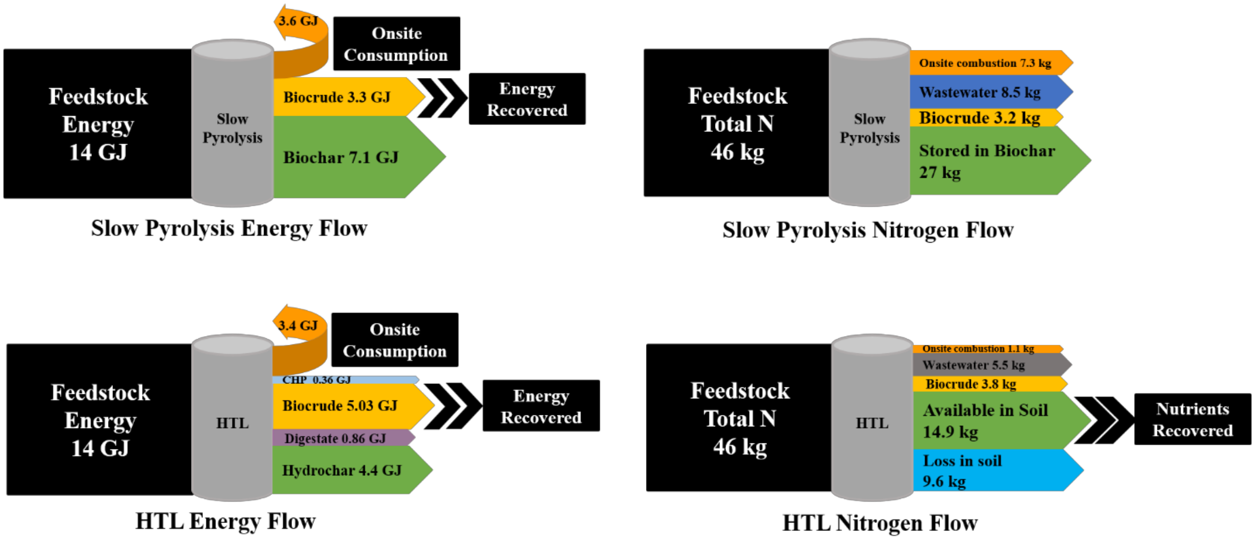


Figure S1. Energy and N flow for slow pyrolysis and HTL processes for 1000 kg wet poultry litter as a representation of the various balances used in this analysis.

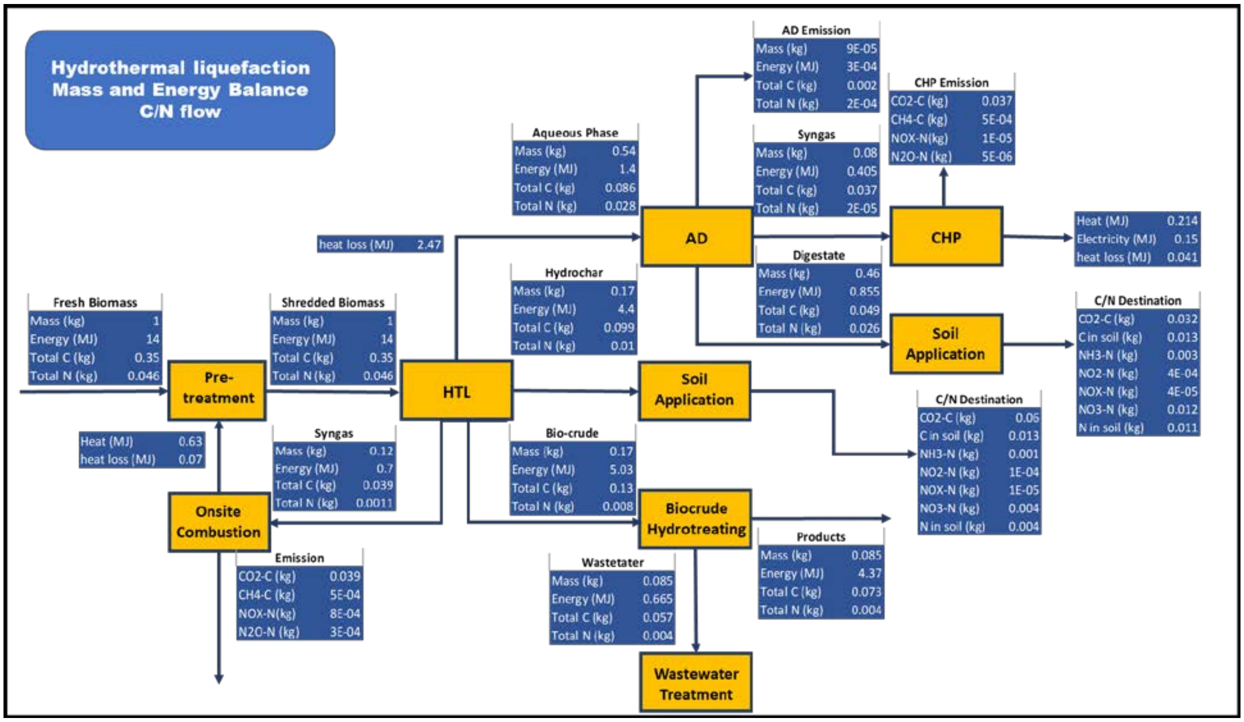


Figure S2. Mass and energy Balance and C/N flow for 1 kg wet biomass via HTL process. The external energy and material as well as emissions from other elements are not shown in this figure.

S3. Life cycle inventory (LCI) data and sensitivity analysis parameters

S3.1. Introduction

This section covers the LCI data and describes some of its sources as well as a brief description of the processes themselves. It also includes a list of parameters and assumptions used in the sensitivity analysis. Table S3 contains the LCI data used for calculating the LCIA scores. Each row in this table is derived from one or more processes, which have been grouped together, based on what they consume or produce.

Table S3. Life cycle inventory associated with 1000 kg of wet poultry litter treated

Item	Unit	Slow Pyrolysis	Fast Pyrolysis	Gasification	HTC	HTL	SCWG	Reference Case
Inputs from Technosphere								
trailer	t.km	5.00E+00	5.00E+00	5.00E+00	5.00E+00	5.00E+00	5.00E+00	5.00E+00
truck	t.km	7.80E+01	7.76E+01	0.00E+00	1.18E+02	1.21E+02	1.11E+02	0.00E+00
gas truck	t.km	0.00E+00	0.00E+00	6.43E+00	0.00E+00	0.00E+00	3.10E+00	0.00E+00
electricity	kWh	2.76E+02	2.97E+02	-7.50E+02	1.98E+02	2.49E+02	-3.19E+02	0.00E+00
heat	MJ	4.18E+02	9.08E+02	-3.49E+03	-8.05E+02	-1.07E+02	-1.31E+03	0.00E+00
natural gas	m^3	1.36E+01	2.50E+01	0.00E+00	0.00E+00	1.93E+01	0.00E+00	0.00E+00
tap water	kg	4.46E+01	8.18E+01	0.00E+00	0.00E+00	6.32E+01	0.00E+00	0.00E+00
limestone	kg	0.00E+00	0.00E+00	8.70E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
lubricating oil	kg	0.00E+00	0.00E+00	2.90E-01	1.00E-02	1.00E-02	1.60E-01	0.00E+00
steel	kg	8.00E-01	8.00E-01	8.00E-01	8.00E-01	8.00E-01	8.00E-01	0.00E+00
iron	kg	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	0.00E+00
aluminum	kg	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	1.00E-02	0.00E+00
concrete	kg	2.51E+00	2.51E+00	2.51E+00	2.51E+00	2.51E+00	2.51E+00	0.00E+00
AD	plant eq	0.00E+00	0.00E+00	0.00E+00	4.65E-06	3.33E-06	1.66E-06	0.00E+00
CHP	plant eq	0.00E+00	0.00E+00	1.15E-05	5.52E-07	3.94E-07	7.02E-06	0.00E+00
boiler	plant eq	1.62E-06	8.22E-07	0.00E+00	3.92E-06	1.73E-06	1.45E-06	0.00E+00
refinery plant	plant eq	4.92E-09	8.86E-09	0.00E+00	0.00E+00	5.58E-09	0.00E+00	0.00E+00
slurry spreading	m^3	4.60E-01	3.50E-01	0.00E+00	7.00E-01	6.40E-01	5.80E-01	1.67E+00

Direct Emission								
NMVOC	kg	2.15E-03	1.54E-03	8.00E-02	1.00E-02	6.69E-09	4.00E-02	0.00E+00
NH_3	kg	0.00E+00	0.00E+00	0.00E+00	3.19E+00	3.56E+00	3.96E+00	1.20E+01
CO_2	kg	6.40E+02	9.80E+02	1.17E+03	1.28E+03	1.28E+03	1.28E+03	1.20E+03
CH_4	kg	2.00E-02	2.00E-02	9.00E-01	9.10E-01	4.20E-01	9.60E-01	3.01E+01
NO_X	kg	1.79E+00	1.12E+00	1.30E-01	8.80E-01	3.20E-01	1.10E-01	1.90E-01
N_2O	kg	3.00E-01	1.90E-01	2.00E-01	8.00E-01	7.80E-01	8.80E-01	8.90E-01
CO	kg	5.00E-02	4.00E-02	1.88E+00	3.20E-01	1.60E-01	1.08E+00	0.00E+00
P to river	kg	0.00E+00	0.00E+00	0.00E+00	9.00E-01	3.21E+00	8.20E-01	1.36E+00
N to ground	kg	0.00E+00	0.00E+00	0.00E+00	8.30E+00	6.50E+00	6.45E+00	3.57E+01
Outputs from Technosphere: Avoided Products								
gasoline	kg	-2.56E+01	-4.69E+01	0.00E+00	0.00E+00	-3.63E+01	0.00E+00	0.00E+00
diesel	kg	-3.44E+01	-6.31E+01	0.00E+00	0.00E+00	-4.87E+01	0.00E+00	0.00E+00
fertilizer N	kg	-5.16E+00	-3.41E+00	-2.19E+00	-3.11E+01	-2.42E+01	-2.42E+01	-1.61E+01
fertilizer K_2O	kg	-2.41E+01	-2.33E+01	-1.98E+01	-5.78E+00	-5.62E+00	-4.15E+00	-4.98E+00
fertilizer P_2O_5	kg	-2.71E+01	-2.74E+01	-2.33E+01	-3.94E+00	-1.41E+01	-3.59E+00	-5.91E+00
electricity	kWh	0.00E+00	0.00E+00	-1.21E+03	-5.83E+01	-4.17E+01	-6.85E+02	0.00E+00
heat	MJ	4.62E+02	-2.12E+02	-6.27E+03	-1.25E+03	-6.34E+02	-4.17E+03	0.00E+00
Waste Treatment								
ash	kg	0.00E+00	0.00E+00	1.57E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
waste mineral oil	kg	0.00E+00	0.00E+00	2.90E-01	1.00E-02	1.00E-02	1.60E-01	0.00E+00
wastewater	kg	3.40E+02	4.54E+02	2.00E+02	0.00E+00	8.50E+01	0.00E+00	0.00E+00

S3.2. Soil Products

In the direct land application case, only collection and slurry spreading activities are involved. The environmental burdens mostly come from GHG emission and leaching.[13-19] It has been estimated that over 30% of N applied on land will be converted into ammonia,[20] and 35% will leach into groundwater. Additionally, land applied with organic fertilizer also tends to emit 32.2% more N_2O

than synthetic N fertilizer.[15] 21% of the Phosphorus (P) contained will leach into surface water. The remaining P is precipitated in the soil.[21, 22]

In this study, it is assumed that 90% of biochar carbon will be stably stored, all the biochar P and K will finally be taken up by plants and per ton, biochar will help mitigate 0.3933 kg N_2O emissions. The assumptions are consistent with other field studies conducted on biochar.[23-25] For the fertility improvement effect, instead of assuming short-term effects, here we assume biochar will keep this function for three years as a base scenario, which could finally save 14.6 kg N, 8.9 kg K_2O and 6.2 kg P_2O_5 fertilizers.[24-26]

In contrast, hydrochar and digestate receive far less attention as soil amendments principally due to their poor performance in carbon sequestration[27-29]. 68-88% and 48-77% hydrochar carbon were reported to be lost after one-year laboratory incubation and one-year field incubation study, respectively. There is no strong evidence that hydrochar will improve fertility except from the nutrients themselves.[30] Table S4 summarizes the properties of the different soil products considered in a comparative form.

Table S4. Comparison between soil products[23, 25, 27, 29]

	Biochar	**Hydrochar**	**Digestate**	**Fresh Poultry Litter**
Production process	High temperature "dry" pyrolysis and gasification	"Wet" pyrolysis, energy saving	From AD process or co-digestion	Directly from farms
Available of nutrients	N is unavailable, other nutrients are available	Most of nutrients are available, but certain parts cannot be utilized.	Most of nutrients are available, but certain parts cannot be utilized.	Most of nutrients are available, but certain parts cannot be utilized.
Emissions	CO_2 is stably stored, soil N_2O and NH_3 emissions are mitigated. No CH_4 emissions observed.	Risk of stimulating microbial activity and increase in N_2O emissions. Also C-based emissions.	N is highly unstable, with high NH_3 and N_2O emissions.	N is highly unstable, with high NH_3 and N_2O emissions. High CH_4 emissions observed.
Leaching	Slowly degradable, but leaching is not considered.	Excess P and N leaching to surface water and underground water.	Excess P and N leaching to surface water and underground water.	Excess P and N leaching to surface water and underground water.

S3.3. Energy production processes

The pre-treatment heat required for drying and the heat required to reach the reaction temperature is calculated based on the work by Wang et al.[31] The operation electricity demand for all the processes is assumed as 0.24 kwh per kg wet biomass.[32, 33] The onsite combustion of syngas and biocrude is assumed at an energy efficiency of 60%. Here we assume selective catalytic reduction (SCR) is present in the boiler, which reduces 90% N emissions. The ratio of C and N compounds emissions are mainly extracted from the Ecoinvent broiler emission data. Similarly, the CHP and AD data, including the energy consumption and emissions, are all from Ecoinvent.[34] The data concerning bio-oil upgrading and hydrotreating are mainly cited from a fuel upgrading study and a comparative study, where similar final product yields are achieved (but their components vary).[33] Although the system boundary ends with the diesel and gasoline ready to be sold, the carbon dioxide emissions from bio-fuel burning are still included from the perspective of maintaining carbon balance.

S3.4. Transportation, electricity and construction

The transportation distances are assumed as 50 km for all the facility-to-farm processes as well as the distances between the different facilities themselves. This value is higher than other studies and one reason is that poultry litter is produced in small volumes and the conversion plant is assumed as relatively centered. The distance estimated here is also suggested by poultry fertilizer spatial allocation analysis.[35] The systems end with the diesel and gasoline ready to be sold, and 50 km is taken as the value for plant to market distance.

The electricity produced from CHP is assumed to be consumed onsite, so no electricity transmission is involved. Data related to waste collection is hard to evaluate, and here we assume a small tractor and trailer for the collection of poultry litter on the farm. Every collection activity is estimated to last for 30 minutes based on the dairy manure collection system for reference.[36] The materials for construction of all the plants are assumed the same and the required materials for a gasification plant with a capacity of 10 ton/h are used as the reference case. Construction materials in different cases are then scaled according to capacity.

S3.5. Sensitivity Analysis Parameters

The following table specifies the selection of the values of various parameters for the sensitivity analysis and our assumptions involved, as not all the literature that is cited was exclusively based on poultry litter.

Table S5. Selected parameters along with their base values and ranges used for the sensitivity analysis. References for the values and ranges are provided in the parameter column. (In the units' column, feed is referred to on a dry basis).

Parameter	Technology	Base value	Range	Units
Electricity consumption	Slow pyrolysis	275	100–500	kWh
Biochar efficacy period	Slow pyrolysis	3	1–9	years
Biochar yield[37]	Slow pyrolysis	0.55	0.4–0.6	kg/kg feed
Bio-oil yield	Slow pyrolysis	0.12	0.06–0.2	kg/kg feed
Transportation distance[34]	Slow pyrolysis	78	0–150	km
Hydrochar yield	HTL	0.17	0.1–0.3	kg/kg feed
N-uptake amount[25]	HTL	0.75	0.25–1	kg/kg-N feed
Biocrude yield[33]	HTL	0.17	0.1–0.3	kg/kg feed
Transportation distance[34]	HTL	117.5	20–200	km
CHP energy efficiency[34]	Gasification	0.9	0.6–0.95	kg/kg feed
Syngas yield[29]	Gasification	0.8	0.7–0.9	kg/kg feed
Biomass transportation[34]	Gasification	10	5–100	km
Biochar value[26, 38, 39]	Slow pyrolysis	182	0–300	\$/1000 kg
CO_2 price[6]	Slow pyrolysis	20	0–500	\$/1000 kg CO_2-eq
Biogas transport[34]	Gasification	10	0–20	km

S4. Life cycle impact assessment (LCIA) categories and factors

S4.1. LCIA parameters

The IMPACT 2002+ framework consists of fifteen mid-point categories and four damage-oriented or end-point categories. The four damage-oriented impact categories considered (along with their units) are: human health (DALY), ecosystem quality (PDF*m^2*year), climate change (kg CO$_2$-eq) and resource depletion (MJ primary).[40] DALY (Disability-Adjusted Life Years) characterizes the disease severity, accounting for both mortality (years of life lost due to premature death) and morbidity (the time of life with lower quality due to an illness). PDF*m^2*y (Potentially Disappeared Fraction of species over a certain amount of m^2 during a certain amount of years) is the unit to measure the impacts on ecosystems. GWP (Global Warming Potential) of 100 years is measured in units of kg CO$_2$-eq for the climate change category. MJ (Mega Joules) measures the amount of energy extracted or needed to extract the resource.[41]

For human health, in DALY (disability adjusted life year), the mid-points are carcinogens, non-carcinogens, respiration inorganics, ionizing radiation, ozone layer depletion, respiratory organics. For ecosystem quality, which is presented as PDF*m^2*year, the mid-points include aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutri, aquatic acidification and aquatic eutrophication. The climate change category (in kg CO$_2$ eq) only consists of global warming, and the resources category (in MJ primary) includes non-renewable energy and mineral extraction.[40] The weights and normalization factors used for these categories can be found in Table S6-S7. In this study, the LCI data is initially utilized to calculate the values for each of the fifteen midpoint categories.[40] Then, the midpoint values are converted into the four damage categories by multiplying with the respective characterization factors. Ultimately, the endpoint category values are normalized into points by dividing them by the associated normalization factors.

Table S6. Characterization Factors (CF) used for the 15 mid-point categories.[41]

Category	Factor	Units	Category	Factor	Units
Carcinogens	2.80E-06	DALY/kg C2H3Cl eq	**Terrestrial acidification/nutrification**	1.04E+00	PDF•m^2•yr /kg SO2 eq
Non-carcinogens	2.80E-06	DALY/kg C2H3Cl eq	**Land occupation**	1.09E+00	PDF•m^2•yr /m^{2}org.arable land-yr
Respiratory inorganics	7.00E10-4	DALY/kg PM2.5 eq	**Aquatic acidification**	8.82E-03	PDF•m^2•yr /kg SO2 eq

Ionizing radiation	2.10E-10	DALY/Bq C-14 eq	**Aquatic eutrophication**	1.14E+01	PDF•m^2•yr /kg PO4 P-lim
Ozone layer depletion	1.05E-03	DALY/kg CFC-11 eq	**Global warming**	1.00E+00	kg CO2-eq/kg
Respiratory organics	2.13E-06	DALY/kg C2H4 eq	**Non-renewable energy**	1.00E+00	MJ primary/kg
Aquatic ecotoxicity	5.02E-05	PDF•m^2•yr /kg TEG water	**Mineral extraction**	1.00E+00	MJ surplus/kg
Terrestrial ecotoxicity	7.91E-03	PDF•m^2•yr /kg TEG soil			

Table S7. Normalization factors used for the damage categories.

Human Health (DALY/pt)	**Ecosystem Quality (PDF*m^2*yr/pt)**	**Climate Change (Kg CO_2-eq/pt)**	**Resource Depletion (MJ/pt)**
0.0071	13,700	9,900	152,000

S5. Techno-economic analysis parameters

S5.1. Capital costs

The methods to estimate the pyrolysis and gasification capital costs are derived from the studies by Bridgewater et al, where the capital costs and plant size relationships are separately provided for fast pyrolysis plants and gasification plants. These equations have considered the learning effects, which refers to the phenomenon that the cost reduces with more units built and more experience accumulated. In this study, a learning factor of 50% has been assumed, corresponding to 10 installations of a novel process. The plant costs are also updated according to CEPCI from 394.1 in 2000 to 567.5 in 2017. The pyrolysis (including slow and fast pyrolysis) and gasification plant costs are calculated by the following equations:

$$TPC_{pyrolysis} = 39.7 \times (Q \times 1000)^{0.6194} \tag{S1}$$

$$TPC_{gasification} = 92 \times (Q \times 1000)^{0.6384} \tag{S2}$$

Where, TPC is the total plant cost ($kUSD_{2018}$) and Q is the feedstock input rate (in dry ton/hour). In this study, the average plant size is set to be 30 ton/day, which was calculated by equally assigning the total amount of poultry litter in NYS into 10 plants. The capital cost calculated for pyrolysis and gasification plants are \$3.2MM and \$8.73MM, respectively. Besides, since the above equations do not include pretreatment modules, and the capital cost of pre-treatment part is around 27% of the main reactor capital cost according to the same study, the total capital costs for pyrolysis and gasification become \$4.17MM and \$11.1MM, respectively. The equivalent capital cost is calculated based upon a 20-year lifetime and a discount rate of 10%.

$$Annual\_capital = \frac{Total\_capital}{\frac{1}{r} - \frac{1}{r(1+r)^n}} \tag{S3}$$

The annual capital costs are \$0.49MM and \$1.31MM, and the costs for unit ton feedstock are \$44 and \$119 for pyrolysis and gasification, respectively. The capital cost calculations for the hydrothermal technologies follow the methods adopted by Van Doren et al. [42]

S5.2. O&M costs

The O&M costs include fixed operating costs and variable operating costs. The fixed part mainly consists of operation labor cost (a function of plant size), maintenance labor cost (1% the total capital cost), overheads (2%), maintenance materials (3%), taxes and insurance (2%) and other fixed costs (1%). The variable part primarily includes, in this case, the electricity and natural gas cost as well as waste handling. For gasification, there is limestone involved as catalysts. The wastewater cost is \$0.73/1000 kg, electricity price is \$0.06/kwh, natural gas is \$0.022/MJ, limestone price is \$30/1000 kg, and the labor rate for this size plant is 0.02 M\$/annum. The O&M costs for the six technologies are calculated to be \$62, \$102, \$155, \$86, \$59 and \$130 per 1000 kg wet poultry litter, respectively.[43-45]

S5.3. Secondary treatment

Secondary treatment refers to the processes converting primary products into final products including the AD process, CHP process, hydrotreating and oil upgrading. The hydrotreating plant and upgrading plants are considered as newly constructed plants in this study because the oil refinery plants are mostly built around oil wells and are not as abundant and widely distributed as AD and CHP. For AD and CHP, we consider utilization of existing facilities. However, in this study, we utilize existing ADs which are assumed to have spare capacity, and the government is assumed to be crediting a gate-fee for the AD plants to encourage co-digestion[42, 46]. Here, we assume the poultry litter plant stakeholders do not need to pay for AD digestate disposal. The cost for CHP is \$0.0077/MJ energy produced for a relatively large-sized unit.[27] It is interesting to observe that the cost for bio-oil upgrading is much higher than bio-crude hydrotreating according to a TEA study. The upgrading cost is \$10.3/GJ oil produced while the hydrotreating cost is \$2.4/GJ.[33] The low cost for bio-crude hydrotreating holds the key if hydrothermal technologies are to economically outweigh “dry” technologies in terms of the production costs. The costs for selective catalytic removal (SCR) implementation are also calculated. [47]

S5.4. Transportation

The road transportation costs follow the equation:

$$T_c = 4.8 + 0.094 * D \tag{S4}$$

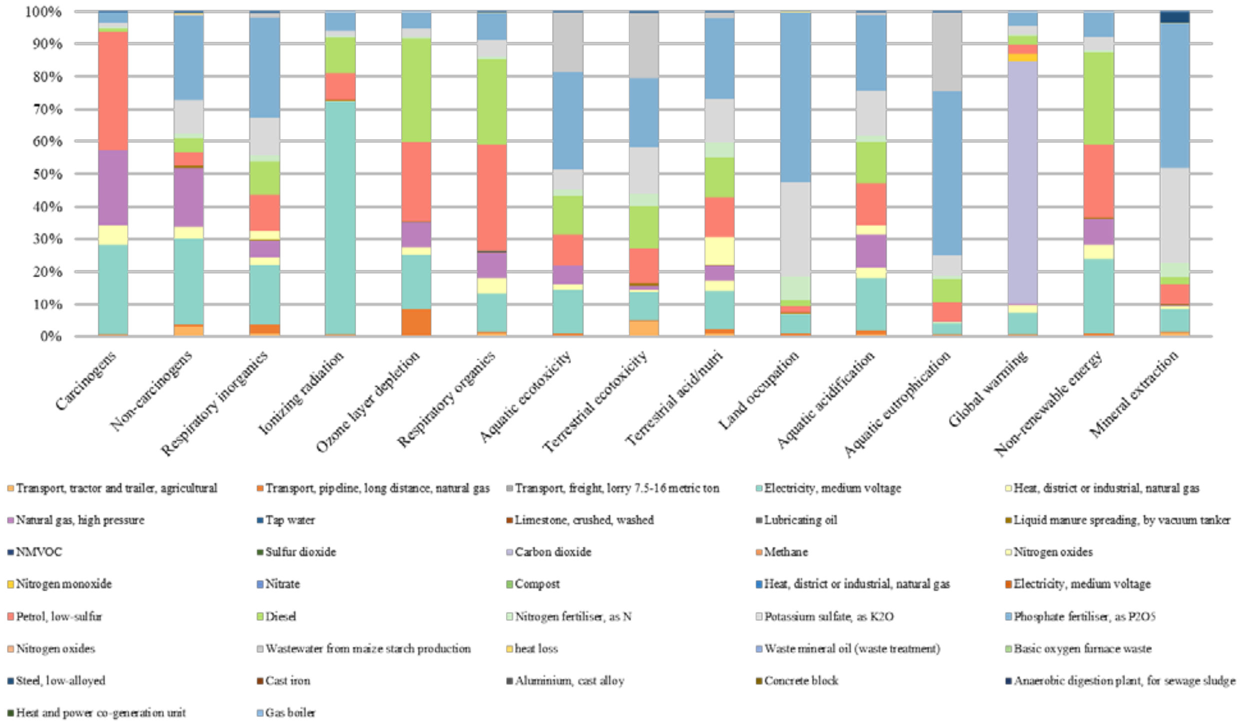
where 4.8 is the load and unload charge per ton, and 0.094 is the shipping cost per ton-km. All the value are in 2009 USD, and are converted to the corresponding 2017 values.[26] The biogas transportation cost is calculated to be \$0.07/Nm^3 per km.[48]

S5.5. Governmental credits

The governmental credits for carbon tax remain very low. In 2017 and 2018, the allowance was \$7/t CO_2e to \$16/t CO_2e, respectively in the European Union[49] and there were no credits in the USA. Here we estimate an average value of \$20/t CO_2e considering the predicted scenarios in the cited references. The avoided compost fees and the credits for CHP are not considered.

S6. Additional results

The LCA points results (Figure S3) along with their breakdown in terms of end-point category points is provided in this section. The representation of the end-point category scores in terms of their respective units is also provided (Table S8). Finally, the sensitivity analysis results for the three representative technologies - slow pyrolysis, gasification and HTL are provided (Figure S5).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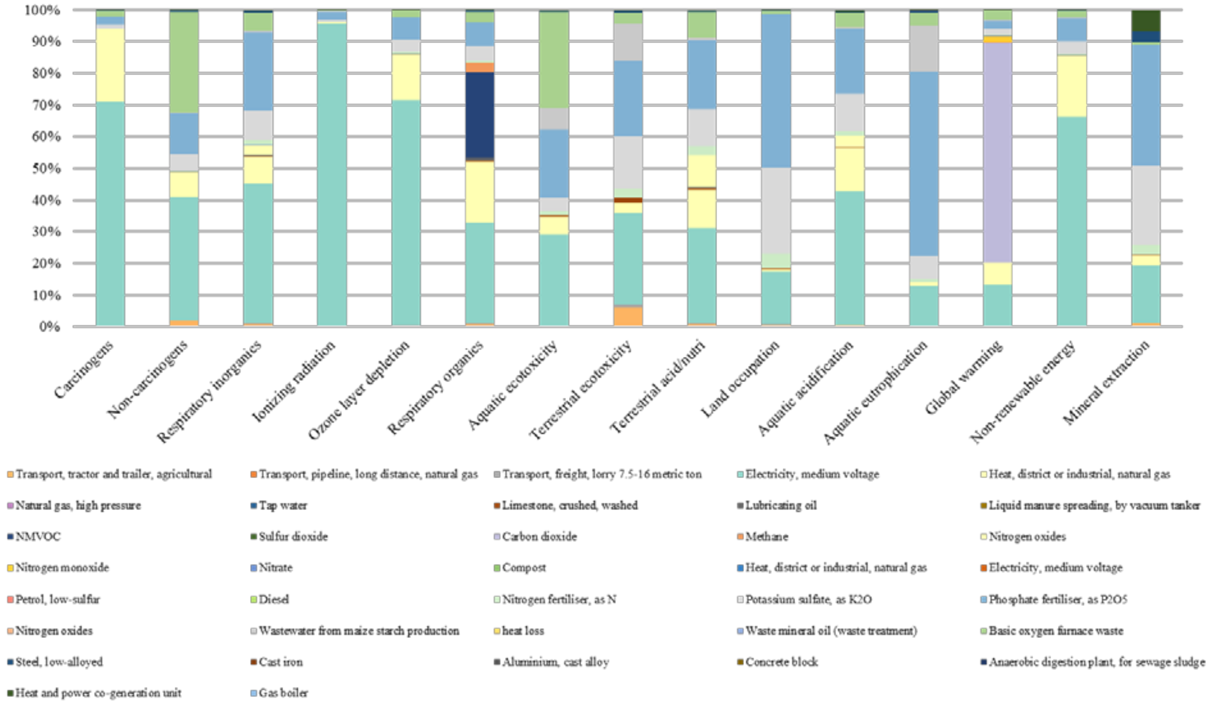
Ionizing radiation
Ozone layer depletion
Respiratory organics
Aquatic ecotoxicity
Terrestrial ecotoxicity
Terrestrial acid/nutri
Land occupation
Aquatic acidification
Aquatic eutrophication
Global warming
Non-renewable energy
Mineral extraction
Transport, tractor and trailer, agricultural
Transport, pipeline, long distance, natural gas
Transport, freight, lorry 7.5-16 metric ton
Electricity, medium voltage
Heat, district or industrial, natural gas
Natural gas, high pressure
Tap water
Limestone, crushed, washed
Lubricating oil
Liquid manure spreading, by vacuum tanker
NMVOC
Sulfur dioxide
Carbon dioxide
Methane
Nitrogen oxides
Nitrogen monoxide
Nitrate
Compost
Heat, district or industrial, natural gas
Electricity, medium voltage
Petrol, low-sulfur
Diesel
Nitrogen fertiliser, as N
Potassium sulfate, as K2O
Phosphate fertiliser, as P2O5
Nitrogen oxides
Wastewater from maize starch production
heat loss
Waste mineral oil (waste treatment)
Basic oxygen furnace waste
Steel, low-alloyed
Cast iron
Aluminium, cast alloy
Concrete block
Anaerobic digestion plant, for sewage sludge
Heat and power co-generation unit
Gas boiler

(a)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Respiratory organics
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Global warming
Non-renewable energy
Mineral extraction
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Transport, pipeline, long distance, natural gas
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Lubricating oil
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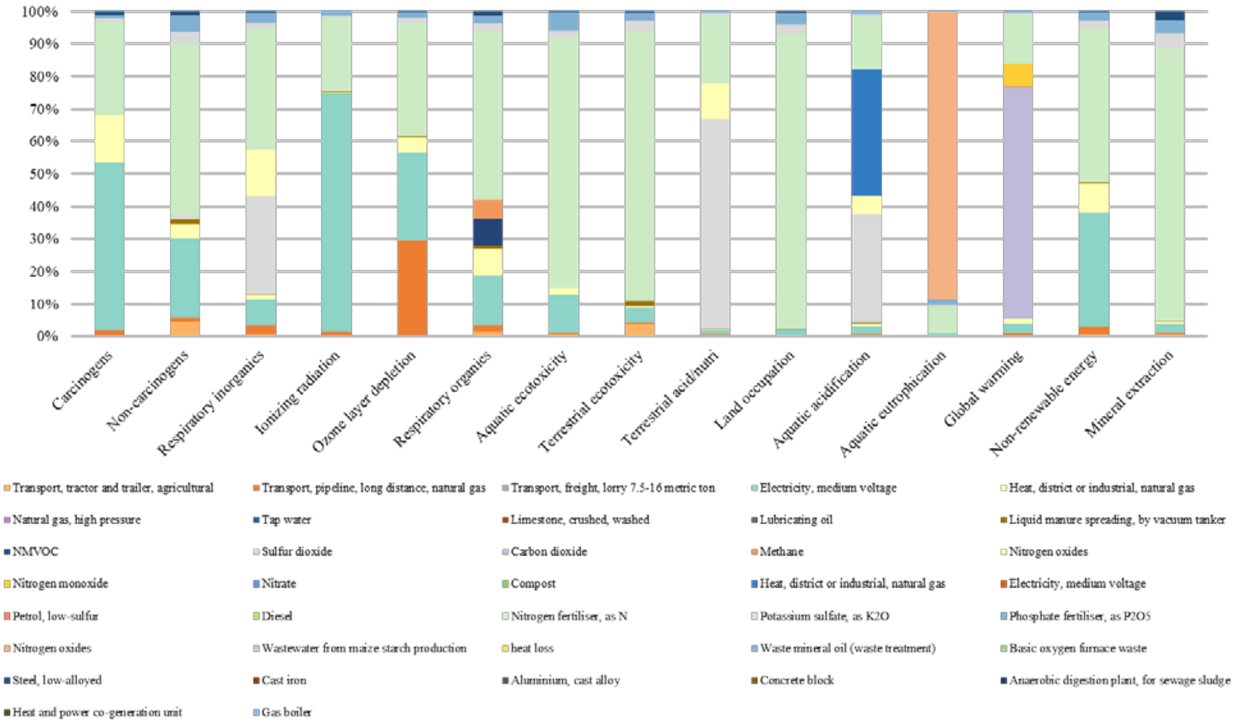
NMVOC
Sulfur dioxide
Carbon dioxide
Methane
Nitrogen oxides
Nitrogen monoxide
Nitrate
Compost
Heat, district or industrial, natural gas
Electricity, medium voltage
Petrol, low-sulfur
Diesel
Nitrogen fertiliser, as N
Potassium sulfate, as K2O
Phosphate fertiliser, as P2O5
Nitrogen oxides
Wastewater from maize starch production
heat loss
Waste mineral oil (waste treatment)
Basic oxygen furnace waste
Steel, low-alloyed
Cast iron
Aluminium, cast alloy
Concrete block
Anaerobic digestion plant, for sewage sludge
Heat and power co-generation unit
Gas boiler

(b)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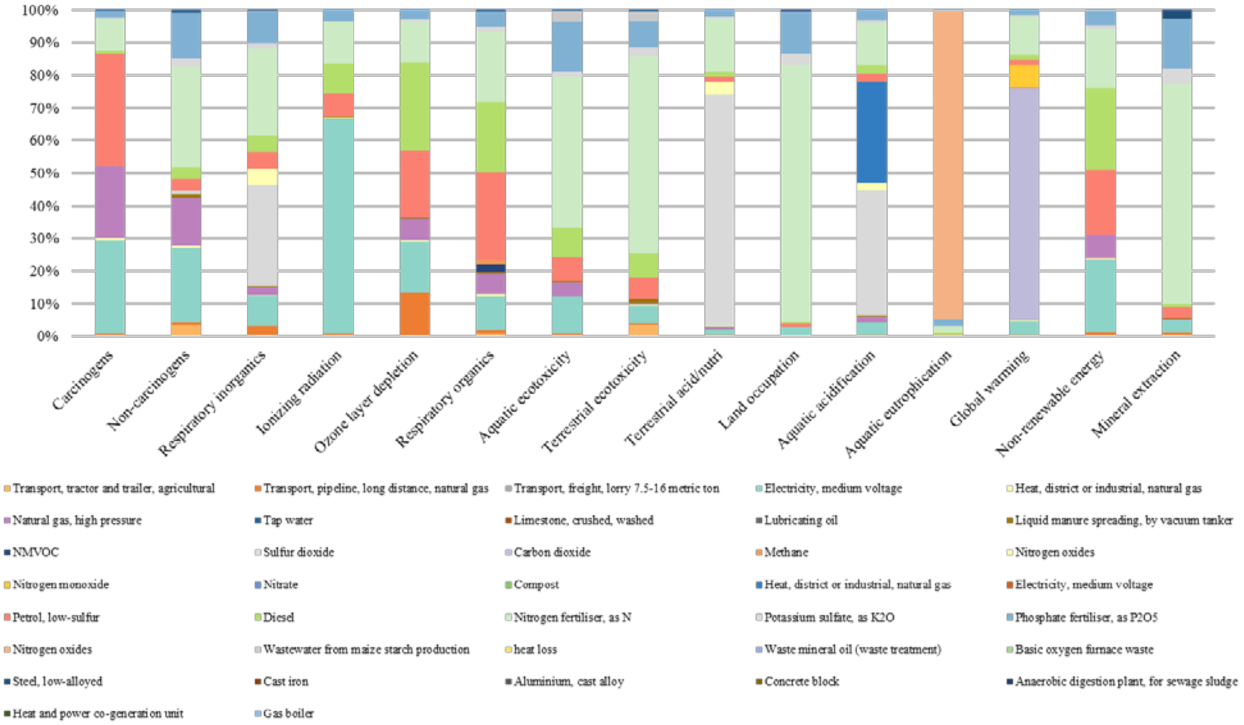
Wastewater from maize starch production
heat loss
Waste mineral oil (waste treatment)
Basic oxygen furnace waste
Steel, low-alloyed
Cast iron
Aluminium, cast alloy
Concrete block
Anaerobic digestion plant, for sewage sludge
Heat and power co-generation unit
Gas boiler

(c)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Natural gas, high pressure
Tap water
Limestone, crushed, washed
Lubricating oil
Liquid manure spreading, by vacuum tanker
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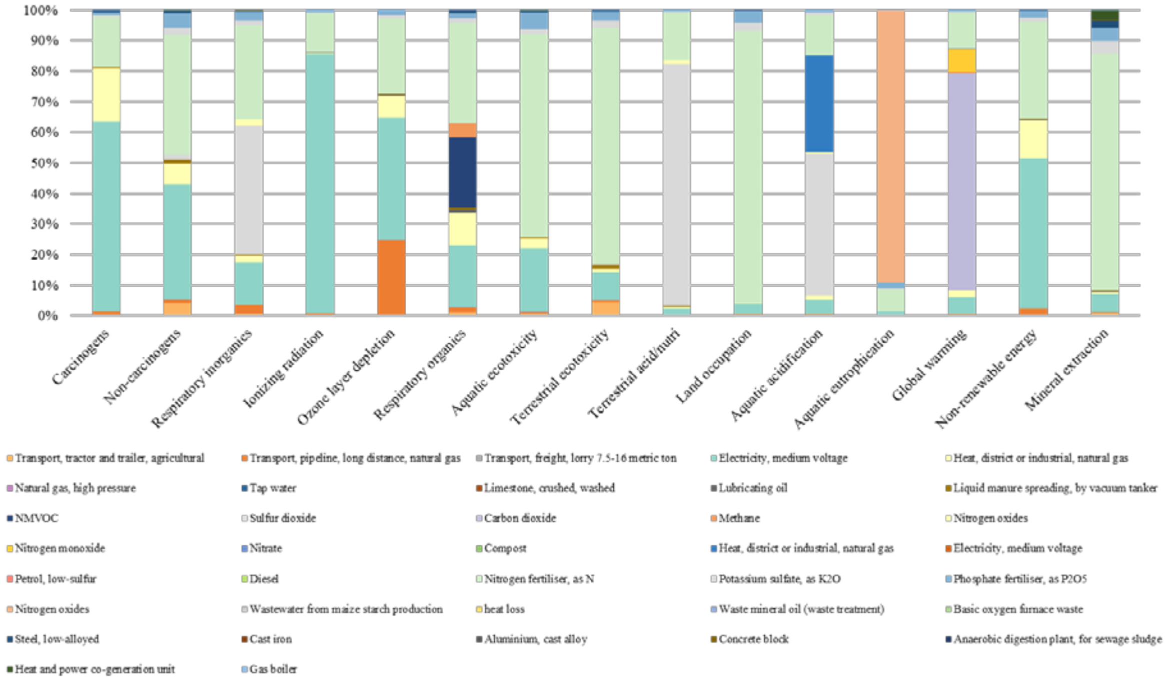
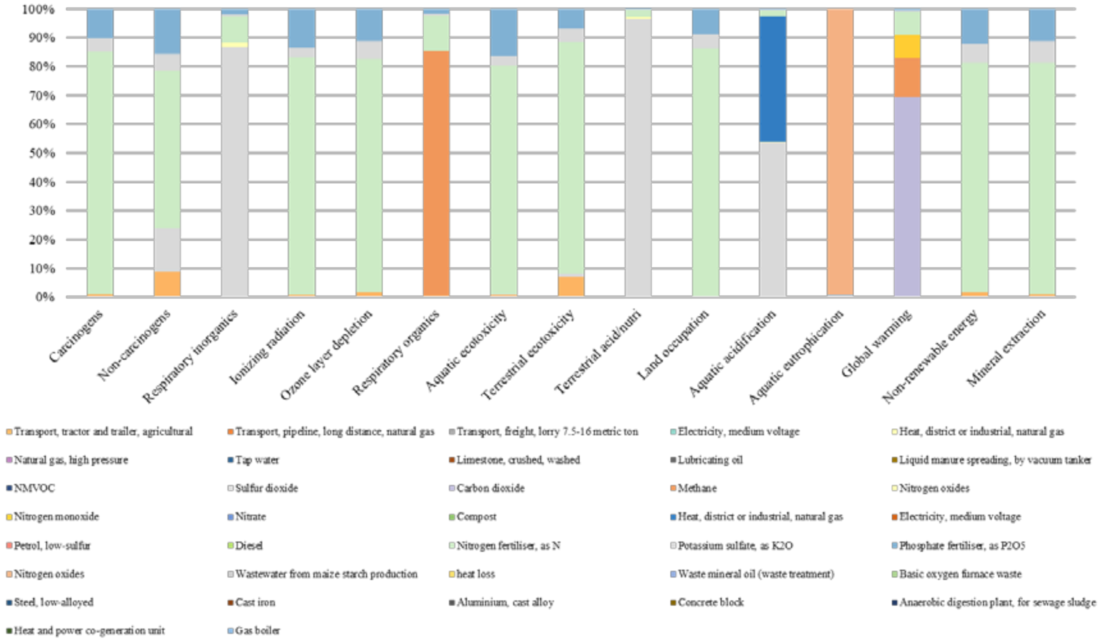
Sulfur dioxide
Carbon dioxide
Methane
Nitrogen oxides
Nitrogen monoxide
Nitrate
Compost
Heat, district or industrial, natural gas
Electricity, medium voltage
Petrol, low-sulfur
Diesel
Nitrogen fertiliser, as N
Potassium sulfate, as K2O
Phosphate fertiliser, as P2O5
Nitrogen oxides
Wastewater from maize starch production
heat loss
Waste mineral oil (waste treatment)
Basic oxygen furnace waste
Steel, low-alloyed
Cast iron
Aluminium, cast alloy
Concrete block
Anaerobic digestion plant, for sewage sludge
Heat and power co-generation unit
Gas boiler

(d)



(e)



(f)

Figure S3. Calculated LCIA midpoint contribution for the different technologies: (a) fast pyrolysis; (b) gasification; (c) HTC; (d) HTL; (e) SCWG; (f) Reference case of land application.

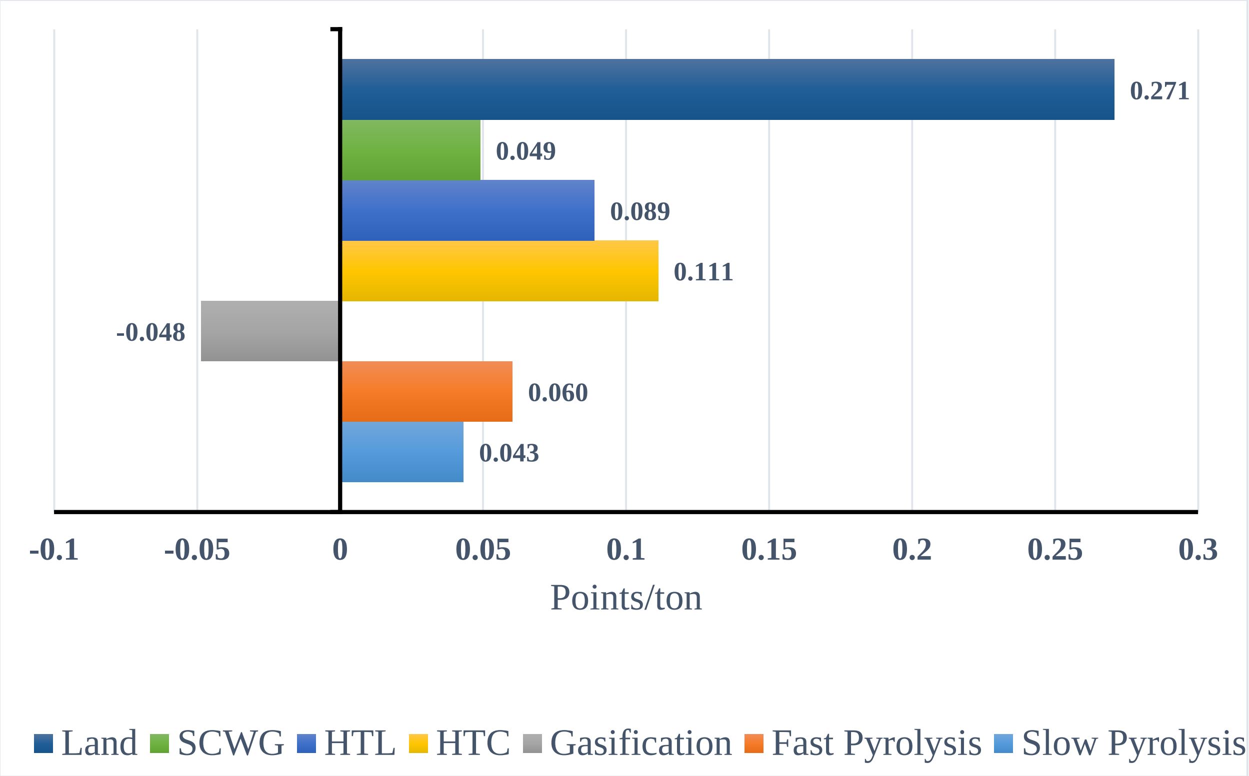


Figure S4. Calculated LCIA normalized points for the different technologies. Lesser value corresponds to better environmental performance.

Table S8. Life cycle impact assessment (LCIA) of thermochemical conversion of poultry litter (values given for wet poultry litter). Lower values correspond to better environmental performance, and we can see that the reference case of land application has the highest values for all five columns, indicating worst performance in each category. The values in the 'Human Health' category should be read by multiplying the values in the column by 10^{-3} (this was done to ensure consistency in the number of decimal digits). For example, the human health value for the reference case is 0.000882 DALY/1000 kg wet poultry litter.

	LCIA score (Points/1000 kg)	**Human Health (10^{-3} • DALY /1000 kg)**	**Ecosystem Quality (PDF • m^2 • year /1000 kg)**	**Climate Change (Kg CO_2-eq/1000 kg)**	**Resource Depletion (MJ primary /1000 kg)**
Reference case	0.271	0.882	204.6	1410	-1653
Slow pyrolysis	0.043	-0.071	-49.5	658	-1464
Fast pyrolysis	0.060	-0.089	-52.3	978	-3370
Gasification	-0.048	-0.433	-68.8	853	-10,412
HTC	0.111	0.072	-122.7	1170	-1247
HTL	0.089	0.022	-86.7	1192	-4287
SCWG	0.049	-0.095	-100	1079	-5975

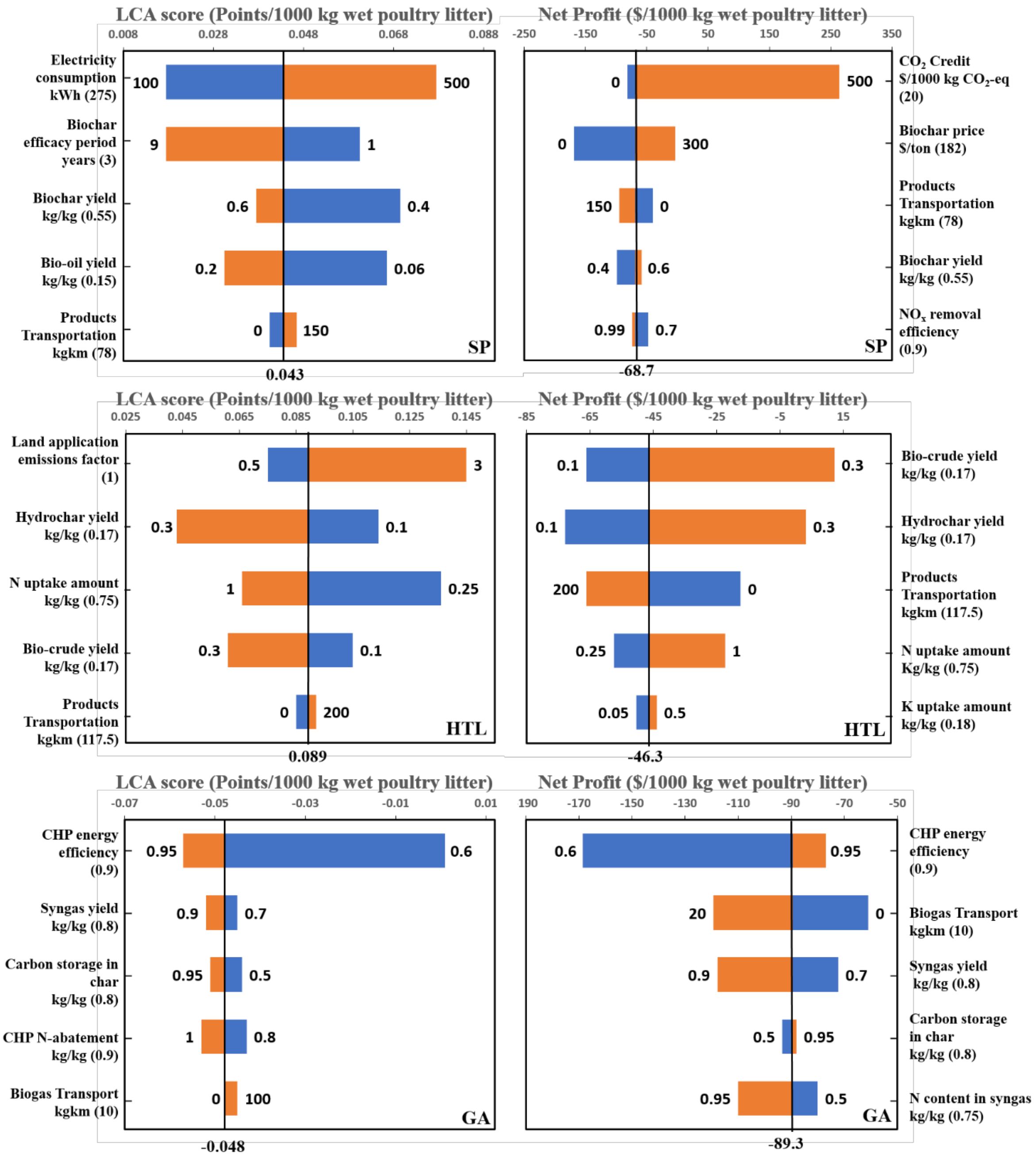


Figure S5. Sensitivity analysis of the LCA (left) and TEA (right) results for the three technologies - slow pyrolysis (SP), hydrothermal liquefaction (HTL) and gasification (GA). The centerline represents the base case results and the numbers in the brackets represent the base values of the input parameters used in our calculations. The numbers next to each bar represent the minimum and maximum values for the change in the input parameter, whereas the numbers on the x-axis represent the corresponding change in output. The orange and blue bars stand for the increase and decrease of input factors, respectively. For the LCA score, negative points mean better performance. For the TEA results, positive values refer to profits while negative values correspond to losses.

Table S9. Additional sensitivity analysis of the six technologies to highlight the uncertainty in the capital costs and the associated effects on the economic performance. The input variations for the capital costs are different for different technologies as shown in the table.[50, 51]

Technology	**Parameter**	**Low**	**Baseline**	**High**	**Change (%)**
slow pyrolysis	Capital cost ($/ton)	-35.84	-44.80	-53.76	±20
	Economic performance$/ton	-45.72	-68.70	-88.38	**±31.81**
fast pyrolysis	Capital cost ($/ton)	-61.33	-76.66	-91.99	±20
	Economic performance$/ton	-94.30	-130.80	-165.76	**±27.48**
gasification	Capital cost ($/ton)	-95.11	-118.89	-142.67	±20
	Economic performance$/ton	-40.52	-89.30	-138.08	**±54.62**
HTC	Capital cost ($/ton)	-38.82	-64.70	-90.58	±40
	Economic performance$/ton	-34.25	-94.62	-154.99	**±63.80**
HTL	Capital cost ($/ton)	-22.69	-37.81	-52.93	±40
	Economic performance$/ton	-10.39	-46.25	-82.11	**±77.54**
SCWG	Capital cost ($/ton)	-60.20	-100.34	-140.48	±40
	Economic performance$/ton	-14.29	-106.61	-198.93	**±86.60**

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