Title

Bioresource Production from Wastewater Biosolids: A Snapshot in Time and Future Perspectives for a Circular Economy

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Publication Date

2022

UNIVERSITY OF CALIFORNIA

Los Angeles

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A Snapshot in Time and Future Perspectives for a Circular Economy

A thesis submitted in partial satisfaction

of the requirements for the degree of Master of Science

in Civil Engineering

by

Kevin Eaton Clack

2022

ABSTRACT OF THE THESIS

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Master of Science in Civil Engineering
University of California, Los Angeles, 2022
Professor Eric M.V. Hoek, Chair

Thermo-chemical bioresource recovery technologies present an opportunity to reduce environmental impacts and improve economic performance of municipal biosolids management operations. In this study, a uniform grading framework was established and findings from techno-economic and lifecycle assessments of wastewater biosolids management processes were synthesized into harmonized system boundaries to evaluate their environmental and commercial viability. It was found that while conventional wastewater biosolids management practices such as anaerobic digestion, landfilling, land application, and incineration are commercially mature, they pose significant environmental concerns and large economic burdens on municipalities. Furthermore, state-of-the-art thermochemical bioresource recovery technologies such as hydrothermal liquefaction, gasification, and pyrolysis showed potential to provide economic and environmental benefit through the recovery of carbon and nutrients in wastewater biosolids as biofuels, fertilizers, and other niche products that lessen demand for fossil-based resources and provide additional sources of revenue for wastewater utilities. Hydrothermal liquefaction paired with existing wastewater infrastructure was found to provide the greatest economic and environmental benefit.

The thesis of Kevin Eaton Clack is approved.

Shaily Mahendra

David Jassby

Eric M.V. Hoek, Committee Chair

University of California, Los Angeles

2022

I dedicate this thesis to my wife, my family, and my closest friends who have encouraged me to seek and find. Your love and support are the greatest gift.

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ACKNOWLEDGEMENTS

This work is in preparation for publication with Eric M.V. Hoek as the principal investigator. Funding for this study was provided in part by Oceankind, NSF NRT: Graduate Traineeship in Integrated Urban Solutions for Food, Energy, and Water Management (INFEWS)–DGE-1735325, and the California NanoSystems Institute.

1. Introduction and Background

In the United States, it is estimated that almost 13 million dry metric tons of municipal wastewater biosolids (or sludge) are produced and managed annually from 15,014 publicly owned treatment works (POTW).[1] While much effort has been invested to recover energy and nutrients from wastewater biosolids, conventional management practices (namely anaerobic digestion, incineration, land application, and landfill disposal) still result in significant energy consumption, greenhouse gas emissions, economic burden, and the release of valuable carbon, nitrogen, and phosphorus compounds into the environment as pollutants.[2] Alternative bioresource recovery technologies have recently emerged, which may improve the economic and environmental performance of wastewater biosolids management processes by closing the loop of nutrient emissions, GHG emissions and energy expenditure associated with conventional practices. However, these technologies must be thoroughly vetted before they may be widely applied at municipal scale.

To mitigate the stress placed on fossil-based phosphorus, nitrogen, and fuel resources by linear "take-make-dispose" economies, the European Commission introduced the concept of the circular "cradle-to-cradle" economy that aims to recover, restore and maintain resources at their highest utility.[2,3] The circular economic model contributes to the achievement of the United Nations Sustainable Development Goals (SDGs). Specifically SDG 11: "Making cities and human settlements inclusive, safe, resilient, and sustainable," SDG 12: "Ensuring sustainable consumption and production patterns," and SDG 13: "Taking urgent action to combat climate change and its impacts."[4,5] For much of recorded history, wastewater biosolids and human feces have existed within a circular economy, perceived as valuable fertilizer for agricultural applications.[6] This is evidenced by the conveyance of wastewater to agricultural fields from 300

BC to 500 AD in ancient Greece and beginning in 1189 AD by “rakers” and “gongfermors” in London, England. By 1300 AD, wastewater solids known as “night soil” were sold to farmers outside of the walls of Norwich, England, and in 14th century Florence, Italy, the “votapozzi” sold cesspit sludge to farmers for use as fertilizer.[6] Despite efforts by the United Nations and the European Commission to foster circular economies and sustainable development, the reuse of wastewater biosolids has become limited in the last century and has shifted towards a linear economy as regulations have been established to protect the public from exposure to wastewater-borne pathogens.[2]

Conventionally, wastewater biosolids are anaerobically digested to produce combustible biogas, incinerated in combined heat and power (CHP) units, land applied as a fertilizer supplement, or landfilled. [7] According to Seiple et al.[1] 21.1% of all raw wastewater biosolids (2.65 million dry metric tons) produced in the United States are converted into CO_2 and methane through anaerobic digestion. Of the remaining 9.91 million dry metric tons of digestate and raw wastewater biosolids, 1.87 million dry metric tons (14.9%) are incinerated, 3.78 million dry metric tons (30.1%) are landfilled and 6.91 dry metric tons (55%) are land applied for agricultural purposes.[1] Wastewater treatment accounts for about 3% of the entire US electrical consumption as well as about 0.4% of the total US greenhouse gas (GHG) emissions.[8–11] For a conventional municipal wastewater treatment facility, wastewater biosolids management accounts for up to 30% of the total energy demand, 40-50% of the total operating costs, and 40% of the total GHG emissions.[3,11,12] Therefore, the recovery of energy and renewable substitutes for fossil-based products may have a significant impact on the energy demand, carbon footprint, and economic performance of municipal wastewater treatment facilities.

Several state-of-the-art technologies including gasification (Gs), pyrolysis (Py), torrefaction (Torr), hydrothermal liquefaction (HTL), hydrothermal carbonization (HTC), transesterification (Trans), and alternative fermentation have been developed, which rely on biochemical and thermochemical processes to convert organic waste into value-added end-products such as biofuels, fertilizers, and bioplastics.[3,13] Conventional and state-of-the-art biosolids management processes may be implemented individually or in combination to recover energy and value-added products (Figure 1). However, the value derived from upcycling wastewater biosolids must be balanced with the economic and environmental impacts of processing and final disposal.[14]

To assess economic and environmental implications of a process or technology, the concept of the techno-economic assessment (TEA) and life-cycle assessment (LCA) were created, respectively. Do et al[15] described a TEA as a method of evaluating economic feasibility in terms of both technology and economics and explained that to estimate the total capital investment (CAPEX) and operating costs (OPEX) a process flow diagram (PFD) must be constructed, the equipment type and size must be determined, and the mass and energy balances calculated. According to the Web of Science, the oldest publication discussing the term "techno-economic assessment" was published in 1983, which described the recovery of chemical elements from seawater and brine.[16,17] Thomassen et al[18] described an LCA as an assessment of the environmental impacts of a specific product or process, which accounts for its entire life cycle. The first LCAs were conducted in the 1960s to assess the energy requirement for chemical production as well as the environmental impacts of packaging, and they varied widely in their methodologies.[19]

Several TEAs and LCAs have been published assessing conventional and state-of-the-art biosolids management practices. However, most focus on comparisons of either techno-economic or environmental implications and lack integration of the two with harmonized system boundaries. Multiple authors have emphasized the need for harmonized techno-economic and environmental assessments with uniform system boundaries to avoid varied results when assessing the sustainability of a technology, product or process.[16,20] Therefore, the primary objective of this analysis is to synthesize the findings from existing LCAs and TEAs into a uniform framework with harmonized system boundaries to assess the environmental and techno-economic implications of conventional and state-of-the-art wastewater biosolids management processes.

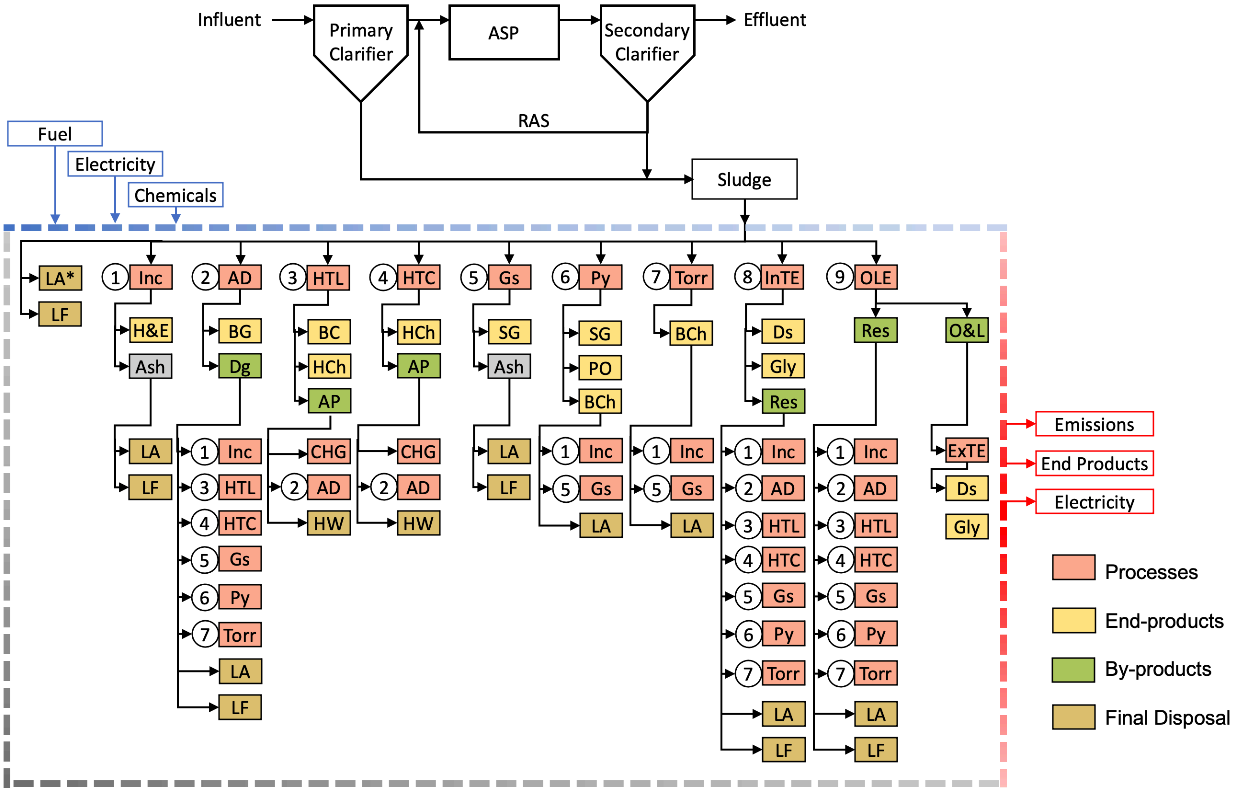

Figure 1: System boundaries and components for the different scenarios considered in this techno-economic and lifecycle analysis. The reactors, product separation, and product distribution for each process are different. Activated Sludge Process (ASP), Anaerobic Digestion (AD), Aqueous Phase (AP), Biochar (BCh), Biocrude (BC), Biogas (BG), Diesel (Ds), Digestate (Dg), Gasification (Gs), Glycerol (Gly), Heat & Electricity (H&E), Hydrochar (HC), Hydrothermal Carbonization (HTC), Hydrothermal Liquefaction (HTL), Incineration (Inc), Inorganic Ash (Ash), Insitu-Transesterification (InTE), Land Application (LA), Landfill (LF), Lignocellulosic

Residuals (Res), Oil and Lipids (O&L), Oil & Lipid Extraction (OLE), Py-oil (PO), Pyrolysis (Py), Return Activated Sludge (RAS), Syngas (SG), Wastewater Treatment Plant Headworks (HW).

2. Wastewater Biosolids Characterization and State-of-the-Art Management Practices

Untreated wastewater biosolids have a total solids (TS) content of 0.8-3.3%, consisting of 59-88% volatile organic solids, 1.5-5% nitrogen, 0.17-2.3% phosphorus, 7.0-15% cellulose, 2-65% fats, oils, and grease (FOG), 20-41% protein, and have an energy content of 19-23 MJ/kg TS. [3,12,21] The volatile organic solids contain 50-55% carbon, 25-30% oxygen, 10-15% nitrogen, 6-10% hydrogen, 1-3% phosphorus, and 0.5-1.5% sulfur.[12,22] Bioenergy, biofuels and other value-added products such as fertilizers, surfactants, bioplastics and certain cosmetic products can be produced from wastewater biosolids to recover saleable products.[3,13] State-of-the-art technologies that may be used in place or in combination with conventional anaerobic digestion and incineration processes are described below.

Gasification is a thermochemical process at extreme temperatures ranging between 500-1400°C, nominal pressure (~33 bar), and a low-absent oxygen atmosphere in the presence of a gasification agent and catalyst.[23] Gasification requires a dry feedstock with a moisture content lower than 10%.[24] Although this process requires dry feedstock, it has been proposed and evaluated for the recovery of combustible syngas and inorganic ash from wastewater biosolids, municipal solid waste, construction and demolition (C&D) waste, agricultural residues, animal manure, and forestry residues.[24–33] Gasification requires a significant amount of energy due to the endothermic behavior of the reaction and energy consumption is a major constraint on the thermal efficiency and on the design of the gasifier.[24] The benefits to this process are that carbon monoxide is catalytically converted into methane and due to its high operating temperatures.[23]

Pyrolysis is a thermochemical process characterized by the thermal decomposition of biomass in the absence of oxygen at temperatures ranging from 350-550°C and up to 700°C and at moderate pressures up to 10 bar.[23] This process requires a dry feedstock with a moisture content lower than 10%. Depending on the temperature, pressure, and feedstock residence time, pyrolysis can be manipulated to produce any combination of pyrolysis oil (py-oil), syngas, and biochar.[23] Although this process requires a dry feedstock, it has been evaluated using several different organic wastes including wastewater biosolids, municipal solid waste, C&D waste, agricultural residues, animal manure, and forestry residues.[25,34–44] An advantage of this process is that it produces a high yield of py-oil, which can be easily stored and transported, although it requires significant upgradation before it can act as a substitute for conventional crude oil in refineries.[23]

Torrefaction, a mild form of pyrolysis, is a dry thermochemical process characterized by relatively low temperatures (200-300°C) under atmospheric pressure in the absence of oxygen. This process requires a dry feedstock with a moisture content lower than 10%. The primary product of torrefaction is biochar, of which the H/C and O/C ratios are reduced towards those of coal due to the release of CO_2 and water.[15] Biochar is primarily used as a substitute for coal, as an adsorptive filter media, or as an agricultural soil amendment.[45] Although this process requires a dry feedstock, it has been evaluated using wastewater biosolids, municipal solid waste, C&D waste, agricultural residues, animal manure, and forest residues.[15,46–50] An advantage of this process is that only mild operating conditions are required to produce the saleable biochar.

Hydrothermal liquefaction is a wet thermochemical process characterized by the decomposition of biomass into biocrude oil, non-combustible gas, phosphorus-rich solids and nitrogen-rich aqueous co-product at moderate temperatures between 180-330°C, pressures ranging between 40-220 bar, and residence times between 30-60 minutes.[23,51] Reddy et al.[51] and Qian et al.[52] both found that hydrothermal liquefaction is most efficient with wet feedstocks with up to 85% moisture and that the highest yields of biocrude (47.5%) were attained at operating temperatures of 300°C with a residence time of 30 minutes. Typically, 65-70% of the nitrogen in the feedstock is retained in the aqueous co-product as ammonia, making it potentially favorable for use in agriculture or fertilizer production.[23] Most of the phosphorus is maintained in the remaining solid residues making it potentially favorable for use in agriculture as a fertilizer.[53] Because hydrothermal liquefaction is a wet process, it is ideal for recovering value from moist organic matter. This process has been proposed and evaluated for wastewater biosolids, municipal solid waste, agricultural residues, animal manure, and forestry residues.[52,54–62] Some advantages of hydrothermal liquefaction are that minimal dewatering is required, reducing the required energy input by up to 30%.[23] An important disadvantage is that 20-40% of the carbon in the feedstock is retained in the aqueous co-product, which must be managed downstream.[23,53]

Hydrothermal carbonization is another wet process that operates at moderate temperatures between 180-260°C, autogenous pressures of 1-5 bar, for prolonged residence times between 3-8 hours to produce a carbonaceous hydrochar, hydrochar liquor and noncombustible gas.[63] Hydrochar typically retains 55-90% of the initial mass of feedstock and 80-95% of its energy content with a higher heating value of approximately 29.2 MJ/kg.[63] The aqueous phase derived from hydrothermal carbonization primarily consists of organic acids, furans and phenols, which can be extracted and sold for industrial uses.[63] Because hydrothermal carbonization can operate using feedstocks of varied moisture content, it has been proposed and evaluated for its ability to process wastewater biosolids, municipal solid waste, agricultural residues, animal manure, and forestry residues.[63–72]

Transesterification is a conventional process for producing biodiesel from soybeans, corn, and other high-lipid crops through the production of fatty acid methyl esters (FAME). Conventionally, lipids and oils are extracted from the cells of the biomass through physical, chemical, or enzymatic means.[73] Because this process requires high concentrations of lipids to produce FAME, this process has only been proposed and evaluated for its ability to synthesize biodiesel from wastewater biosolids and animal manure.[73–76] Much recent research has studied the ability to produce biodiesel from algae grown in treated wastewater.[77,78]

Alcoholic fermentation is the production of ethanol and butanol from lignocellulosic matter. Ethanol and butanol are produced when saccharification of a lignocellulosic feedstock occurs followed by microbial fermentation and product recovery.[79] Because alcoholic fermentation requires saccharification of lignocellulosic material, municipal wastewater biosolids are not suitable. However, bioethanol and biobutanol synthesis from municipal solid waste, construction and demolition residues, agricultural residues, animal manure, and forestry residues has been evaluated.[79–89]

Several alternative fermentation processes exist that produce bio-pesticides, enzymes, detergents, bio-flocculants, fertilizers, and bioplastics.[13,90] Voort et al.[91] proposed the idea of a pyramid of value, which suggests that from a unit of biomass a high volume of low-value products or a low volume of high-value products can be derived (Figure 3). At the bottom of the pyramid, low-value high-volume products include biofuels, fertilizers, and industrial chemicals. At the top of the pyramid, high-value low-volume products include nutraceutical, pharmaceutical, and cosmetic products. Few techno-economic and lifecycle assessments have been prepared for these processes and many of these technologies are very early in their commercial maturity.

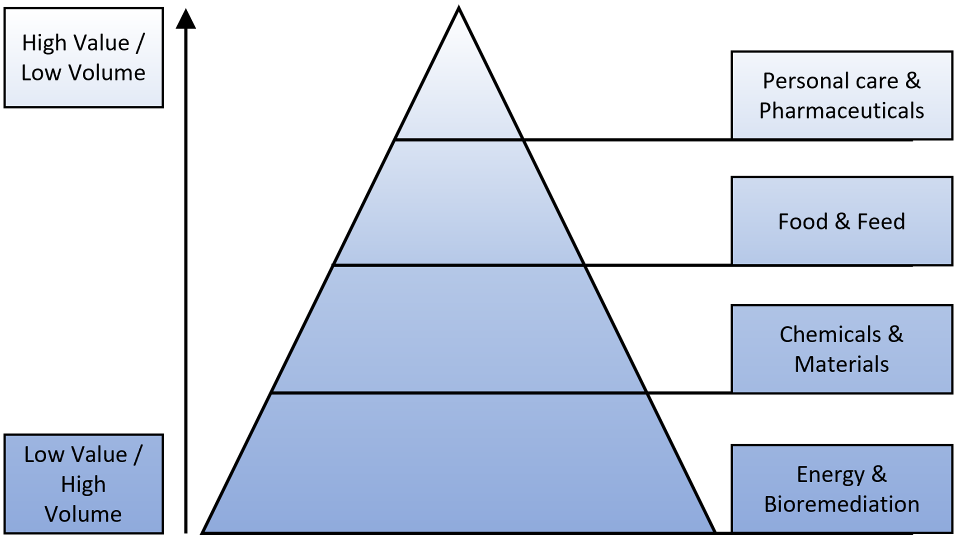

Figure 2: Pyramid of value with high value, low volume products at the top and low value, high volume products at the base. Modified from Voort et al. 2015.

3. Framework and Methodology

This study establishes a uniform grading framework to compare the environmental and commercial benefit provided by conventional and state-of-the-art biosolids management processes (Figure 3). Analyses from ten techno-economic and lifecycle assessments were synthesized into the uniform boundaries presented in Figure 1 to produce 35 distinct process scenarios. Environmental and commercial benefit were each graded along a 0-9 scale comprising of the summation of three equally weighted grading sub-categories. Data synthesized for each grading sub-category was linearly scaled between 0-3, with 0 being the least beneficial and 3 being most beneficial. Environmental benefit was graded as an equally weighted function of wet weight of final residues, net energy balance, and net CO_2e emissions. Commercial benefit was graded as an equally weighted function of CAPEX, net operating profit, and technology readiness level (TRL).

Environmental Benefit: (0-9)
+ *Wet weight of residuals disposed (0-3)*
+ *Net energy balance (0-3)*
+ *Net CO_2e emissions (0-3)*

Commercial Benefit: (0-9)
+ *CAPEX (0-3)*
+ *Net operating profit (0-3)*
+ *Technology Readiness Level (TRL) (0-3)*

Figure 3: Grading criterion for environmental and commercial benefit of wastewater biosolids management options.

Wet weight of final residues per mass of total dry solids processed (WS_f/TS_i) was calculated based on Eq. (1):

$$\frac{WS_f}{TS_i} = \frac{TS_f}{TS_i} \times \frac{1}{1 - MC_f} \qquad (1)$$

where WS_f is the total wet weight of the final residual solids sent to disposal ($t \cdot d^{-1}$); TS_i is the dry weight of initial solids managed ($t \cdot d^{-1}$); TS_f is the dry weight of final residual solids remaining after processing ($t \cdot d^{-1}$); MC_f is the fraction of moisture in the final residual solids. Process scenarios that did not incorporate drying steps were assumed to dewater final residues to a moisture content of 80% before transporting to final disposal. Processes that do not incorporate biochemical or thermochemical conversion steps yield large quantities of final residues due to low total solids reduction and high moisture content. To avoid over-optimistic scoring, processes that produced more wet residues than conventional anaerobic digestion (> 2.5 WS_f/TS_i) were given a score of 0. Processes that produced less final wet residues than conventional anerobic digestion (< 2.5 WS_f/TS_i) were graded linearly from 0-3.

The net energy balance was calculated to include energy imports and exports of the process, energy equivalence of end-products, and fuel requirements for transportation as expressed by Eq. (2):

$$E_{NET} = E_{elec,out} + E_{LFG} + E_{prod} - E_{trans} - E_{elec,in} - \frac{E_{NG,in}}{3.412 \times 10^{-3}} \tag{2}$$

where E_{NET} is the net energy balance a process scenario (kWh/t TS_i); $E_{elec,out}$ is the electric energy export of a process (kWh/t TS_i); E_{LFG} is the electric energy export from LFG combustion (kWh/t TS_i); E_{prod} is the lower heating value (LHV) of derived biofuel products normalized over the total solids managed (kWh/t TS_i); $E_{elec,in}$ is the electric energy input required for a process (kWh/t TS_i); $E_{NG,in}$ is the energy import from natural gas (MMBtu/t TS_i); 3.412E10^{-3} is a standard conversion factor from MMBtu to kWh; E_{trans} is the energy required for transportation of waste residues to final disposal (kWh/t TS_i). Electricity imports and exports, natural gas imports were calculated on a paper-by-paper basis due to the nonuniformity in data reporting in literature. Detailed calculations are included in the Tables S1-S36. It was assumed that final waste residues were transported 160 km (~100 mi) to final disposal sites, which is aligned with the distances to final disposal for large municipal wastewater treatment facilities in the US.[1,92] The energy demand for transportation to final disposal was not included in the system boundaries of most TEAs and LCAs and was therefore included in this synthesis using Eq. (3):

$$E_{trans} = \frac{\dot{m}_{diesel} \times e_d \times \frac{WS_f}{TS_i} \times d_t \times 2.2046}{\rho_d \times 3{,}412} \tag{3}$$

where E_{trans} is the energy demand for transportation to final disposal (kWh/t TS_i); $\dot{m}_d$ is the consumption rate of diesel provided by Suh and Rousseaux[93] (0.0635 kg/km-t WS_f); e_d is the energy density of diesel fuel provided by the U.S. Energy Information Administration (EIA) (137,381 Btu/gal); d_t is the distance transported to final disposal (km); 2.2046 is the conversion of kg to lbs; ρ_d is the density of diesel fuel (6.66 lb/gal); 3,412 is the conversion of BTU to kWh. For applicable process scenarios, it was assumed that landfill gas was captured and combusted for electricity generation at the final landfill disposal site. The landfill gas production rate was determined using methods established by Zhao et al. 2019[92] and was calculated using Eq. (4):

$$P_{LFG} = \frac{TS_f}{TS_i} \times VS_{LF} \times DOC_F \times \frac{16}{12} \times MCF \times (1 - OX) \times F_{CH_4} \tag{4}$$

where P_{LFG} is the amount of CH_4 produced per metric ton of total solids managed (kg CH_4/t TS_i); VS_{LF} is the volatile solids fraction of the waste residues landfilled; DOC_F is the fraction of volatile solids converted to biogas, which was assumed to be 0.5; 16/12 is the ratio of molar masses of methane and carbon; MCF is the methane conversion factor, which was assumed to be 1; OX is the factor of methane oxidized by the landfill soil cover, which was assumed to be 0.25; F_{CH4} is the fraction of methane in the landfill gas, which was assumed to be 0.5.[92] The effective electricity generation was calculated using Eq. (5):

$$E_{LFG} = P_{LFG} \times R_{LFG} \times H_{LFG} \times \eta_{comb} \tag{5}$$

where E_{LFG} is the effective electricity generation and export from captured landfill gas per metric ton of total solids managed (kWh/t TS_i); R_{LFG} is the landfill gas recovery efficiency (%). The landfill gas recovery efficiency was assumed to be 80% according to Zhao et al. 2019.[92] H_{CH4} is the lower heating value of methane, which was reported to be 55.048 MJ/kg by McAllister et al.

2011.[94] η_{comb} is the conversion efficiency for electricity generation from landfill gas, which was assumed to be 55% according to Storm 2020.[95]

Net CO_2e emissions were calculated from electricity and fuel imports, transportation fuel consumption, fugitive CH_4 emissions from landfilling, fugitive N_2O emissions from land application and incineration, and avoided emissions from fossil-based products displaced by bioderived fuel, electricity, and fertilizers. Biogenic CO_2 emissions were not considered to have any impact on global warming potential and were therefore excluded from this analysis. Net CO_2e emissions were calculated using Eq. (6):

$$\begin{aligned} CO_2e_{NET} = {} & \left(E_{elec,out} + E_{LFG} - E_{elec,in}\right) \times 0.416 + E_{NG,in} \times 52.91 + CO_2e_{trans} \\ & + CO_2e_{LFG,rel} + CO_2e_{N_2O,LA} + CO_2e_{N_2O,Inc} \\ & - CO_2e_{disp,fuels} - CO_2e_{disp,fertilizers} \end{aligned} \tag{6}$$

where 0.416 is the mass (kg) of CO_2e emissions per kWh of electricity produced in the U.S. in 2019 as reported by the U.S. Energy Information Administration (EIA);[96] 52.91 is the mass of CO_2e emissions per MMBtu of natural gas combusted (kg CO_2e/MMBtu) as reported by the EIA[97]; CO_2e_{trans} is the CO_2e emissions from transportation fuel consumption; $CO_2e_{LFG,rel}$ is the CO_2e of CH_4 emissions from fugitive landfill gas; $CO_2e_{N2O,LA}$ is the CO_2e of fugitive N_2O emissions from land application; $CO_2e_{N2O,Inc}$ is the CO_2e of fugitive N_2O emissions from incineration; $CO_2e_{disp,elec\_LFG}$ is the CO_2e emissions displaced by exported electricity from landfill gas combustion; $CO_2e_{disp,fuels}$ is the CO_2e emissions avoided from the displacement of fossil-based products with biofuels; $CO_2e_{disp,fertilizers}$ is the CO_2e emissions avoided from the displacement of fossil-based fertilizers with biosolids soil amendment. All values were normalized to the CO_2e emissions per metric ton of solids managed (kg CO_2e/t TS_i). Transportation emissions and fugitive CH_4 and N_2O emissions from final disposal practices were determined using methodologies established by Zhao et al.[92] CO_2e emissions from the transportation of waste residues to final disposal were calculated using Eq. (7):

$$CO_2e_{trans} = \frac{WS_f}{TS_i} \times d_t \times 0.179 \tag{7}$$

where 0.179 is the CO_2 emission factor per metric ton of sludge per kilometer transported as was used Zhao et al. 2019;[92] d_t is the distance to the final disposal site and was assumed to be 160 km. CO_2e of fugitive CH_4 emissions from landfilled waste residues were calculated using Eq. (8):

$$CO_2e_{LFG,rel} = P_{LFG}(1 - R_{LFG}) \times 25 \tag{8}$$

where, R_{LFG} is the landfill gas recovery efficiency, which was assumed to be 80% for process scenarios that incorporated LFG collection at final disposal; 25 is the CO_2e of CH_4 global warming potential.[92] CO_2e of fugitive N_2O emissions from land applied waste residues were calculated using Eq. (9):

$$CO_2e_{N_2O,LA} = \frac{TS_{f,LA}}{TS_i} \times TN_{LA} \times EF_{N_2O,LA} \times \frac{44}{28} \times 298 \tag{9}$$

where $TS_{f,LA}$ is the mass of land applied residues, TN_{LA} is the nitrogen fraction in $TS_{f,LA}$, which is assumed to be 0.04. EF_{N2O} is the fraction of TN_{LA} emitted as N_2O, which is assumed to be 0.012. 44/28 is the ratio of molar masses of nitrous oxide and nitrogen; 298 is the CO_2e of N_2O global warming potential.[92] CO_2e of fugitive N_2O emissions from incinerated waste residues were calculated using Eq. (10):

$$CO_2e_{N_2O,INC} = \frac{TS_{INC}}{TS_i} \times TN_{INC} \times EF_{N_2O,INC} \times \frac{44}{28} \times 298 \tag{10}$$

where TS_{INC} is the total solids incinerated (metric ton); TN_{INC} is the nitrogen fraction in TS_{INC}, which was assumed to be 0.04. $EF_{N2O,INC}$ is the fraction of TN_{INC} emitted as N_2O, which is assumed to be 0.388 per Zhao et al. 2019.[92] CO_2e emissions avoided from the displacement of fossil-derived fertilizers with biosolid soil amendment was estimated to be 130 kg CO_2e/t TS_i based on Zhao et al. 2019.[92] CO_2e emissions avoided from the displacement of fossil fuels ($CO_2e_{disp,fuels}$) was calculated for the biofuels derived from each process scenario on a paper-by-paper basis and used conversion factors to normalize all values to the unit mass CO_2e displaced per metric ton of solids managed. Detailed calculations are included for each process scenario in Tables S1-S36. Generally, the CO_2e of the biofuel was estimated by its respective lower heating value (LHV) in comparison to that of the fuel it displaced according to Eq. (11):

$$CO_2e_{disp,fuels} = \frac{LHV_{bio}}{LHV_{fossil}} \times CO_2e_{fossil} \tag{11}$$

where LHV_{bio} is the LHV of the biofuel as reported in literature; LHV_{fossil} is the LHV of the displaced fossil fuel; CO_2e_{fossil} is the CO_2e of the displaced fossil fuel. To avoid over-optimistic scoring, processes that produced higher net CO_2e emissions than conventional anaerobic digestion followed by landfill application (> 1.9 t CO_2e/t TS_i) were given a score of 0. Processes that produced less net CO_2e emissions than conventional anaerobic digestion followed by landfill application (<1.9 t CO_2e/t TS_i) were graded linearly from 0-3.

CAPEX included only the total installed cost of equipment as reported for each process scenario in literature and excluded other direct costs such as site development, and indirect costs such as project contingency, startup permits, working capital, and land requirements. The cost of land and equipment associated with landfill infrastructure was not included as part of CAPEX. All CAPEX values reported in literature were adjusted to the 2019 economic year and normalized to the respective plant capacity (USD/t $TS_i \cdot d$). State-of-the-art catalytic hydrothermal gasification processes had a significantly higher CAPEX than other processes. To avoid skewed scoring of the rest of the process options all CAPEX values higher than 1-million USD/t TS_i were given a score of 0. All other CAPEX values were graded linearly between 0-3 linearly between CAPEX values of 0 and 1-million USD/t TS_i.

Net operating profit included the deduction of all operating expenses from the revenues produced by each process and was calculated using Eq. (12):

$$NOP = R - OPEX - TDC \tag{12}$$

Where *NOP* is net operating profit normalized to the initial dry mass of solids managed (USD/t TS_i); *R* is the revenue from the sale of end-products and electricity exports. Revenues from the sale of end-products was included as reported for each process. Revenue values used in in this analysis are included in Tables S1-S35. Although the net present value (NPV) of a process configuration may be calculated as a function of CAPEX and net operating profit, these variables were considered separately in the commercial benefit grading framework because high CAPEX has been observed to be a deterring factor for municipalities despite potentially improved NPV from increased net operating profits.[3] *OPEX* is operating expenses normalized to the initial dry mass of solids managed (USD/ t TS_i). Operating expenses were included as reported for each process scenario in literature and included all variable and fixed operating expenses normalized to the initial dry mass of solids managed (USD/t TS_i). *TDC* is transportation and disposal costs normalized to the initial dry mass of solids managed (USD/t TS_i). Transportation and disposal costs were often not reported for each respective process scenario and were therefore calculated using Eq. (13) derived from Marufuzzaman et al. 2015:[98]

$$TDC = \frac{TS_f}{TS_i} \times \frac{\left(TF + FC + \frac{VC}{1.61} \times d_T\right)}{\rho_s} \times 1{,}000 \times 1.08 \tag{13}$$

where *TDC* is transportation and disposal cost normalized to the initial dry mass of solids managed (USD/t TS_i); *TF* is the tipping fee, which was reported to have a median cost of 45 USD per wet metric ton in 2015 California by CalRecycle.[99] *FC* and *VC* are the fixed and variable trucking costs, respectively, associated with transportation of sewage sludge to final disposal. *FC* was assumed to be 3.42 USD/m^3 of wastewater biosolids transported and VC was assumed to be 0.058 USD/m^3·mi as reported by Marufuzzaman et al. 2015.[98] 1.61 is the standard conversion from miles to kilometers. d_T is the distance to final disposal and was assumed to be 160km. ρ_s is the density of solids used to convert cubic meters to kilograms, which was assumed to be 1100 kg/m^3. 1,000 is the standard conversion from metric tons to kilograms. 1.08 is a multiplier to account for the 8% inflation between FY 2015 and 2019. The net operating profits calculated for thermal drying followed by pyrolysis was significantly higher than all other process scenarios. To avoid skews scoring of other processes scenarios, net operating profit values higher than 400 USD/t TS_i were given a score of 0. All other net operating profit values were graded linearly between 0-3. Although carbon credits and carbon taxes may have a significant impact on the net operating profit of both high and low CO_2e emitting processes, these assessed separately from this analysis due to rapidly evolving implementation globally.

Technology readiness levels (TRL) were reported based on the commercial maturity of each respective technology according to methodologies established by NASA.[100,101] TRL 1 was assigned to process scenarios that were early in development, but the basic principles have been observed and reported. TRL 2 was assigned to process scenarios for which the technology concept and/or application has been formulated. TRL 3 was assigned to process scenarios for which active research and development is initiated to study the critical function and/or proof-of-concept. TRL 4 was assigned to process scenarios that have been validated in a lab scale. TRL 5 was assigned to process scenarios that have been validated in a relevant environment. TRL 6 was assigned to process scenarios that have demonstrated a prototype in a relevant environment. TRL 7 was assigned to process scenarios that have been demonstrated near the scale of the planned operational system. TRL 8 was assigned to processes that have been successfully qualified through tests and demonstrations in the expected operational environment. TRL 9 was assigned to conventional processes that are fully mature and widely used.

To compare the effect of carbon credits and carbon taxation on the NPV each process configuration included in Table 1, a separate analysis was conducted based on a reference case. NPV was calculated according to Eq. (14):

$$NPV = \sum_{t=1}^{n} \frac{NOP}{(1+i)^t} - CAPEX \tag{14}$$

where *NOP* is the net operating profit including any applicable carbon credits or taxes; *t* is the expected project life expectancy; *i* is the discount rate. The reference case included a system solids loading rate of 100 metric tons of dry solids per day (t TS_i/day), 330 operating days per year, a discount rate of 10%, and a project life expectancy of 20 years. According to the California Air Resources Board (CARB) Low Carbon Fuel Standard (LCFS) Credit Bank and Transfer System (CBTS), credits may be sold at prices as high as 200 USD per metric ton of net negative CO_2e emissions.[102] Although carbon taxes are not currently established in the US, there are several proposals to do so. According to the Center for Climate and Energy Solutions, a carbon tax could cost approximately 50 USD per metric ton of net positive CO_2e emissions.[103]

Boundaries for analysis presented in Figure 1 assumed combined primary and secondary wastewater biosolids entered the system at a moisture content of 97-99%.[3] CO_2 equivalence (CO_2e) and costs of natural gas and electricity imports for heat and power, respectively, were taken into consideration as inputs to the system boundary. The costs of required chemical usage for each process was also taken into consideration as an input to the system boundary. At the exit of the system boundary CO_2e displaced by electricity and end-product exports and their respective revenues were accounted for. Transportation and disposal costs for non-saleable residues, including land-applied biosolids, were accounted for at the exit boundary. Transportation emissions and fugitive CH_4 and N_2O emissions associated with final disposal practices were accounted for at the exit boundary. Process-specific calculations used to synthesize data extracted from literature into the boundary conditions are provided in Tables S1-36.

The selection and analysis of scientific literature was made considering the following criteria. Bibliometric sources such as Web of Science, Google Scholar, and Science Direct were used to retrieve articles, book chapters, and conference proceedings. Keywords used in different combinations to identify relevant articles included: wastewater, biosolids, sludge, techno-economic, and lifecycle. The initial search resulted in 139 articles that were filtered down to those that specifically discusses domestic wastewater biosolids and/or sludge and included integrated techno-economic and lifecycle assessments with harmonized system boundaries for energy and mass balances, and capital and operating expense breakdowns. 10 studies were finally identified, which included 35 process scenarios including conventional and state-of-the-art biosolids management processes. The literature survey in Table 1 presents the operating conditions of the

35 process scenarios. In total, the relevant content of this paper includes 119 articles (in journals and conference proceedings), reports, books, and databases. Most references (91.6%) are used to give background and discuss the findings of this study. Most references (92.4%) are from 2011 to 2021 (110 of the total 119 references). The remaining references (7.6%) are from 1983 to 2010.

Table 1: Summary of techno-economic analyses (TEA) of physical, thermochemical, and biological pathways.

Source	Process	Plant Capacity	Operating conditions	End-product(s)
[92,104]	LF	80 MT/day	Dewatered via belt press to 80% MC and disposed in landfill w/o landfill gas capture.	Biosolids
[92,104]	LF_LFG	80 MT/day	Dewatered via belt press to 80% MC, and disposed in landfill, 80% CH4 emissions captured from landfill gas and combusted.	Biosolids, Electricity
[92,104]	TD-LF	80 MT/day	Dewatered via belt press to 80% MC, Thermal dried to 50% MC, disposed in landfill w/o landfill gas capture.	Biosolids
[92,104]	TD-LF_LFG	80 MT/day	Dewatered via belt press to 80% MC, Thermal dried to 50% MC, and disposed in landfill, 80% CH4 emissions captured from landfill gas and combusted.	Biosolids, Electricity
[92,104]	LA	80 MT/day	Dewatered via belt press to 80% MC, Land applied in agricultural setting	Land applied biosolids
[92,104]	TD-LA	80 MT/day	Dewatered via belt press to 80% MC, Thermal dried to 50% MC, Land applied in agricultural setting	Land applied biosolids
[92,104]	TD-INC-LF	80 MT/day	Dewatered via belt press to 80% MC, Thermal dried to 57.7% MC, Incinerated at 800-900°C, disposed in landfill.	Electricity, Ash
[92,104]	AD-CHP-LF	80 MT/day	Thicken to 97% MC, Mesophilic anaerobic digester, Dewatered via belt press to 80% MC, disposed in landfill w/o landfill gas capture.	Electricity, Biosolids
[92,104]	AD-CHP-LF_LFG	80 MT/day	Thicken to 97% MC, mesophilic AD, Belt press to 80% MC, 80% CH4 emissions from landfill captured and combusted	Electricity, Biosolids
[92,104]	AD-CHP-LA	80 MT/day	Thicken to 97% MC, mesophilic AD, Belt press to 80% MC	Electricity, Land applied biosolids
[92,104]	AD-CHP-TD-LF	80 MT/day	Thicken to 97% MC, mesophilic AD, Belt press to 80% MC, Thermal dry to 41.3 % MC	Electricity, Biosolids

Table 1 continued: Summary of techno-economic analyses (TEA) of physical, thermochemical, and biological pathways.

Source	Process	Plant Capacity	Operating conditions	End-product(s)
[92,104]	AD-CHP-TD-LF_LFG	80 MT/day	Thicken to 97% MC, mesophilic AD, Belt press to 80% MC, Thermal dry to 41.3 % MC, 80% CH4 emissions from landfill captured and combusted	Electricity, Biosolids
[92,104]	AD-CHP-TD-LA	80 MT/day	Thicken to 97% MC, mesophilic AD, Belt press to 80% MC	Biogas, Land applied biosolids
[92,104]	AD-CHP-TD-INC-LF	80 MT/day	Thicken to 97% MC, mesophilic AD, Belt press to 80% MC, Incineration at 800-900°C	Biogas, Electricity, Ash
[92,104]	TH-AD-CHP-LF	80 MT/day	Belt press to 80% MC, Thermal hydrolysis, mesophilic, AD, Best press to 80%	Biogas, Biosolids
[92,104]	TH-AD-CHP-LF_LFG	80 MT/day	Belt press to 80% MC, Thermal hydrolysis, mesophilic, AD, Best press to 80%, 80% CH4 emissions from landfill captured and combusted	Biogas, Biosolids
[92,104]	TH-AD-CHP-LA	80 MT/day	Belt press to 80% MC, Thermal hydrolysis, mesophilic, AD, Best press to 80%	Biogas, Land applied biosolids
[92,104]	TH-AD-CHP-TD-INC-LF	80 MT/day	Belt press to 80% MC, Thermal hydrolysis, mesophilic, AD, Best press to 80%, Thermal dry to 41.3% MC, Incineration at 800-900°C	Biogas, Electricity, Ash
[105]	HTL-CAS_BC	99.8 MT/day	HTL Residence time: 17 minutes HTL Pressure: 205 bar HTL Temperature: 347°C	Biocrude
[105]	HTL-CAS_FP	99.8 MT/day	HTL Residence time: 17 minutes HTL Pressure: 205 bar HTL Temperature: 347°C	Diesel, Naphtha, Gasoline
[106]	HTL-NH3-CAS_BC	99.8 MT/day	HTL Residence time: 17 minutes HTL Pressure: 205 bar HTL Temperature: 347°C	Biocrude
[106]	HTL-NH3-CAS_FP	99.8 MT/day	HTL Residence time: 17 minutes HTL Pressure: 205 bar HTL Temperature: 347°C	Diesel, Naphtha, Gasoline
[107]	SupCrit HTL-CAS_BHO	20 MT/day	HTL Temperature: 375°C HTL Pressure: 230 bar HTL Residence Time: Not reported	Bioheavy Oil
[107]	SubCrit HTL-CAS_BHO	20 MT/day	HTL Temperature: 325°C HTL Pressure: 120 bar HTL Residence Time: Not reported	Bioheavy Oil
[108]	HTL-AD-CHP_BC	4.8 MT/day	HTL Temperature: 350°C HTL Pressure: 200 bar HTL Residence Time: Not reported	Biocrude
[108]	HTL-AD-Boiler_BC	4.8 MT/day	HTL Temperature: 350°C HTL Pressure: 200 bar HTL Residence Time: Not reported	Biocrude

Table 1 continued: Summary of techno-economic analyses (TEA) of physical, thermochemical, and biological pathways.

Source	Process	Plant Capacity	Operating conditions	End-product(s)
[108]	HTL-CHG-CHP_BC	4.8 MT/day	HTL & CHG Temperature: 350°C HTL & CHG Pressure: 200 bar HTL Residence Time: Not reported	Biocrude, Electricity
[108]	HTL-CHG-Boiler_BC	4.8 MT/day	HTL & CHG Temperature: 350°C HTL & CHG Pressure: 200 bar HTL Residence Time: Not reported	Biocrude
[109]	TD-AirGs-CHP	5 MT/day	Gs Temperature: 850°C Gs Pressure: atmospheric	Electricity
[109]	TD-StmGs-CHP	5 MT/day	Gs Temperature: 850°C Gs Pressure: atmospheric	Electricity
[15]	FD-Torr-CHP_BSF	9 MT/day	Oil Temperature: 370°C Torr Pressure: atmospheric	Biochar, Electricity
[15]	FD-Torr_BSF	9 MT/day	Oil Temperature: 370°C Torr Pressure: atmospheric	Biochar
[110]	TE-PBR-TD-MWPy	265 MT/day	Solvent for lipid extraction: Methanol Hydrothermal Dewatering Temperature: 180°C Hydrothermal Dewatering Pressure: 60 bar MWPy Temperature: 500°C	Biodiesel, Bio-oil, syngas, Phosphorus Fertilizer
[111]	TD-Py	1.2 MT/day	Py Temp: 200-1000°C Py Pressure: atmospheric	Biochar, Bio-gas, Bio-oil
[112]	HTC-AD-CHP-LA	20.6 MT/day	HTC Temperature: 208°C HTC Residence Time: 1h HTC Pressure: 20 bar	Hydrochar,

4. Results and Discussion

It is well documented in literature that it is difficult to compare the findings of different TEAs and LCAs due to a large disparity in scope and system boundaries utilized.[16,20] Furthermore, the process capacity of each system may vary significantly between studies as seen in Table 1. Therefore, the findings from 10 peer-reviewed studies were synthesized into a uniform grading framework with harmonized system boundaries to assess the environmental and commercial benefit of 35 bioresource recovery process options for wastewater biosolids management.

Table 2 presents the inputs for the environmental benefit grading framework. Conventional biosolids management practices are typically associated with the transportation of large amounts of waste residues to final disposal, modest net energy benefit, and high CO_2e emissions. Conventional practices yield between 2 and 5 metric tons of wet residuals per metric ton of total dry solids (TS) processed and have a net energy benefit ranging between -737 and 1,197 kWh/t TS. CO_2e emissions from conventional processes range between -480 and 5,168 kg CO_2e/ t TS with TH-AD-CHP-LA and TH-AD-CHP-LF_LFG being the most favorable while also producing a modest net energy benefit of 698 and 1,197 kWh/t TS, respectively. State-of-the-art thermochemical processes have shown potential to improve the environmental implications of wastewater biosolids management through the recovery of bioresources such as fuel products, soil amendments, and other more valuable products.[3] State-of-the-art processes tend to yield less waste residuals that must be transported to final disposal (0 – 2 t/t TS) while producing a substantial net energy benefit (464 – 4,813 kWh/t TS) and attaining net negative CO_2e emissions (-195 – -1,182 kg CO_2e/t TS). Process options that include HTL attain the most favorable net energy benefit (up to 4,813 kWh/t TS) and lowest net CO_2e emissions (as low as -1,182 kg CO_2e/t TS). Furthermore, HTL paired with catalytic hydrothermal gasification (HTL-CHG) produces the most favorable net energy benefit (4,419 – 4,813 kWh/t TS) and net CO_2e emissions (-1,142 – -1182 t CO_2e/t TS) largely attributed to improved energy recovery from CHG while also limiting the waste residuals sent to disposal (0.13 wet t/t TS).[53,105,108] Processes that utilize gasification, pyrolysis, and torrefaction also effectively reduce the yield of waste residuals (0-0.05 t/t TS) but have lower net energy benefit (464 – 3,472 kWh/t TS) and higher net CO_2e emissions (-1,024 – -195 kg CO_2e/t TS) due to the energy requirements for pre-drying of the feedstock.[109]

Table 2: Results of environmental benefit grading framework

Process	Final wet-weight of residuals		Net energy benefit		Net CO_2e emissions		Total Grade
	(Wet t/t TS)	Grade (0-3)	(kWh/t TS)	Grade (0-3)	(t CO2/t TS)	Grade (0-3)	(0-9)
LF*	5.00	0.00	-737	0.82	5.17	0.00	**0.82**
LF_LFG*	5.00	0.00	486	1.30	0.66	1.16	**2.46**
TD-LF	2.00	0.60	-2831	0.00	5.53	0.00	**0.60**
TD-LF_LFG	2.00	0.60	-1607	0.48	1.02	0.79	**1.87**
LA*	5.00	0.00	-737	0.82	0.26	1.55	**2.38**
TD-LA	2.00	0.60	-2831	0.00	0.63	1.19	**1.79**
TD-INC-LF	0.11	2.87	-123	1.06	6.82	0.00	**3.94**
AD-CHP-LF*	3.40	0.00	22	1.12	1.81	0.00	**1.12**
AD-CHP-LF_LFG*	3.40	0.00	521	1.32	-0.03	1.84	**3.16**
AD-CHP-LA*	3.40	0.00	22	1.12	-0.20	2.02	**3.14**
AD-CHP-TD-LF	1.36	1.37	-2161	0.26	2.20	0.00	**1.63**
AD-CHP-TD-LF_LFG	1.36	1.37	-1662	0.46	0.36	1.46	**3.28**
AD-CHP-TD-LA	1.36	1.37	-2161	0.26	0.18	1.63	**3.26**
AD-CHP-TD-INC-LF	0.11	2.87	-338	0.98	4.44	0.00	**3.85**
TH-AD-CHP-LF*	3.40	0.00	698	1.38	1.54	0.28	**1.66**
TH-AD-CHP-LF_LFG*	3.40	0.00	1197	1.58	-0.30	2.12	**3.70**
TH-AD-CHP-LA*	3.40	0.00	698	1.38	-0.48	2.30	**3.68**
TH-AD-CHP-TD-INC-LF	0.11	2.87	-327	0.98	4.39	0.00	**3.86**
HTL-CAS_BC	0.26	2.70	2466	2.08	-0.64	2.46	**7.23**
HTL-CAS_FP	0.26	2.70	1979	1.89	-0.64	2.46	**7.04**
HTL-NH3-CAS_BC	0.26	2.70	2324	2.02	-0.56	2.38	**7.10**
HTL-NH3-CAS_FP	0.26	2.70	1686	1.77	-0.56	2.38	**6.85**
SupCrit HTL-CAS_BHO	0.35	2.58	2131	1.95	-0.77	2.59	**7.12**
SubCrit HTL-CAS_BHO	0.35	2.58	2323	2.02	-0.84	2.66	**7.27**
HTL-AD-CHP_BC	0.13	2.85	4554	2.90	-1.16	2.97	**8.72**
HTL-AD-Boiler_BC	0.13	2.85	4766	2.98	-1.17	2.98	**8.82**
HTL-CHG-CHP_BC	0.13	2.85	4419	2.85	-1.18	3.00	**8.69**
HTL-CHG-Boiler_BC	0.13	2.85	4813	3.00	-1.18	3.00	**8.85**
TD-AirGs-CHP	0.05	2.94	594	1.34	-0.25	2.07	**6.35**
TD-StmGs-CHP	0.08	2.91	464	1.29	-0.20	2.01	**6.21**
FD-Torr-Comb_BSF	0.01	3.00	1403	1.66	-0.47	2.28	**6.94**
FD-Torr_BSF	0.01	3.00	1364	1.65	-1.02	2.84	**7.48**
TE-PBR-TD-MWPy	0.00	3.00	2198	1.97	-0.99	2.81	**7.78**
TD-Py	0.00	3.00	3472	2.47	-0.88	2.70	**8.18**
HTC-AD-CHP-LA	1.70	0.96	1007	1.51	-0.31	2.13	**4.59**

*Conventional biosolids management process

Table 3 presents the inputs for the commercial benefit grading framework. Conventional biosolids management practices are typically associated with low CAPEX (35 – 644 thousand USD/t TS·d), poor net operating profit (-311 – -189 USD/t TS), and high commercial maturity (TRL 9). Conventional biosolids management practices that implement anaerobic digestion have improved net operating profit from biogas recovery and reduced transportation and disposal costs but have higher CAPEX, which result in a low net present value (NPV). State-of-the-art thermochemical processes have shown potential to improve net operating profits of wastewater biosolids management operations by limiting the amount of waste residues sent to final disposal and by enabling the recovery of higher value products such as biofuels. However, state-of-the-art technologies often suffer from high CAPEX (up to 1.6 million USD/t TS·d) and lack commercial maturity (TRL 3 – 7). While in some cases the CAPEX of state-of-the-art technologies may be economically justified by the improved NPV, resource-limited municipalities may have difficulty fronting such a large expenditure.[3] HTL processes that utilize existing conventional activated sludge (CAS) infrastructure to manage aqueous co-products have a relatively moderate CAPEX (196 – 448 thousand USD/t TS·d) while also producing improved net operating profits (-196 – 76 USD/t TS) without government subsidies or carbon credits.[105] Gasification, pyrolysis, and torrefaction processes also benefit from modest CAPEX (69 – 444 thousand USD/t TS·d) but suffer from a negative net operating profit (-776 – -135 USD/ t TS) due to increased costs associated with drying influent feedstock.[109]

Table 3: Results of commercial benefit grading framework

Process	CAPEX		Net operating profit		TRL		Total Grade
	(USD/t TS·d)	Grade (0-3)	(USD/t TS)	Grade (0-3)	(1-9)	Grade (0-3)	(0-9)
LF*	$35,805	2.89	-$311	0.56	9	3.00	**6.46**
LF_LFG*	$35,805	2.89	-$311	0.56	9	3.00	**6.46**
TD-LF	$260,865	2.22	-$288	0.71	9	3.00	**5.92**
TD-LF_LFG	$260,865	2.22	-$288	0.71	9	3.00	**5.92**
LA*	$35,805	2.89	-$311	0.56	9	3.00	**6.46**
TD-LA	$260,865	2.22	-$288	0.71	9	3.00	**5.92**
TD-INC-LF	$562,650	1.31	-$266	0.85	9	3.00	**5.16**
AD-CHP-LF*	$465,465	1.60	-$189	1.33	9	3.00	**5.93**
AD-CHP-LF_LFG*	$465,465	1.60	-$189	1.33	9	3.00	**5.93**
AD-CHP-LA*	$465,465	1.60	-$189	1.33	9	3.00	**5.93**
AD-CHP-TD-LF	$639,375	1.08	-$207	1.22	9	3.00	**5.30**
AD-CHP-TD-LF_LFG	$639,375	1.08	-$207	1.22	9	3.00	**5.30**
AD-CHP-TD-LA	$639,375	1.08	-$207	1.22	9	3.00	**5.30**
AD-CHP-TD-INC-LF	$879,780	0.36	-$246	0.97	9	3.00	**4.33**
TH-AD-CHP-LF*	$644,490	1.07	-$238	1.02	9	3.00	**5.09**
TH-AD-CHP-LF_LFG*	$644,490	1.07	-$238	1.02	9	3.00	**5.09**
TH-AD-CHP-LA*	$644,490	1.07	-$238	1.02	9	3.00	**5.09**
TH-AD-CHP-TD-INC-LF	$920,700	0.24	-$277	0.78	9	3.00	**4.01**
HTL-CAS_BC	$196,407	2.41	-$43	2.25	7	2.25	**6.91**
HTL-CAS_FP	$271,195	2.19	$76	3.00	6	1.88	**7.06**
HTL-NH3-CAS_BC	$242,508	2.27	-$43	2.25	6	1.88	**6.40**
HTL-NH3-CAS_FP	$314,991	2.06	-$20	2.40	6	1.88	**6.33**
SupCrit HTL-CAS_BHO	$448,063	1.66	-$196	1.29	4	1.13	**4.07**
SubCrit HTL-CAS_BHO	$420,812	1.74	-$183	1.37	7	2.25	**5.36**
HTL-AD-CHP_BC	$886,317	0.34	-$105	1.86	7	2.25	**4.45**
HTL-AD-Boiler_BC	$861,393	0.42	-$100	1.89	7	2.25	**4.56**
HTL-CHG-CHP_BC	$1,620,709	0.00	-$430	0.00	6	1.88	**1.88**
HTL-CHG-Boiler_BC	$1,572,015	0.00	-$422	0.00	6	1.88	**1.88**
TD-AirGs-CHP	$443,691	1.67	-$135	1.67	7	2.25	**5.59**
TD-StmGs-CHP	$443,691	1.67	-$145	1.61	7	2.25	**5.53**
FD-Torr-Comb_BSF	$286,390	2.14	-$336	0.40	7	2.25	**4.79**
FD-Torr_BSF	$271,028	2.19	-$461	0.00	7	2.25	**4.44**
TE-PBR-TD-MWPy	$144,990	2.57	-$6	2.48	3	0.75	**5.80**
TD-Py	$68,694	2.79	-$776	0.00	7	2.25	**5.04**
HTC-AD-CHP-LA	$1,419,675	0.00	-$580	0.00	4	1.13	**1.13**

[*] Conventional biosolids management process

While each process option has its own merits and advantages in specific circumstances, a uniform comparison of the environmental and commercial benefits of each process is presented in Figure 4a and a comparison of the environmental benefit and TRL is presented in Figure 4b. The ideal process configuration offers both significant environmental and commercial benefit (upper right quadrant). Several process configurations that utilize state-of-the-art thermochemical bioresource recovery technologies including HTL-CAS, TE-PBR-TD-MWPy, TD-AirGs-CHP, TD-StmGs-CHP, HTL-AD, and TD-Py have the potential to offer significant environmental and commercial benefit as shown in Figure 4a but lack commercial maturity for immediate adoption in industry (Figure 4b). Other process configurations that utilize state-of-the-art thermochemical technologies such as HTL-CHG, FD-Torr, and SupCrit HTL provide significant environmental benefit but provide poor overall commercial benefit (upper left corner) due to high CAPEX and/or low net operating profits. It is important to note that while some technologies currently offer poor commercial benefit, future innovations may soon lead to decreased CAPEX and/or OPEX and improve net operating profits. Conventional biosolids management practices tend to fall in or near the bottom right quadrant (commercially viable, but nominal environmental benefit) with TH-AD-CHP-LA offering the greatest commercial and environmental benefit. All conventional biosolids management processes have a high commercial maturity (TRL 9).

Readers should note that we propose this uniform grading framework to provoke critical thought rather than as an endorsement or criticism of any specific biosolids management practice. We realize limitations are inherent to any such ranking system. The most obvious limitation is that our assessment represents a ‘snapshot in time’ of the bioresource recovery technology landscape, which is ever changing. While our intent is to provide an objective evaluation of the technologies included, we realize that our ranking may be somewhat subjective. Regardless of the current ranking, each process configuration described has the potential to reduces the economic and environmental burdens posed by biosolids management in varying degrees, but each technology must be developed, matched, and optimized to suit each specific circumstance.

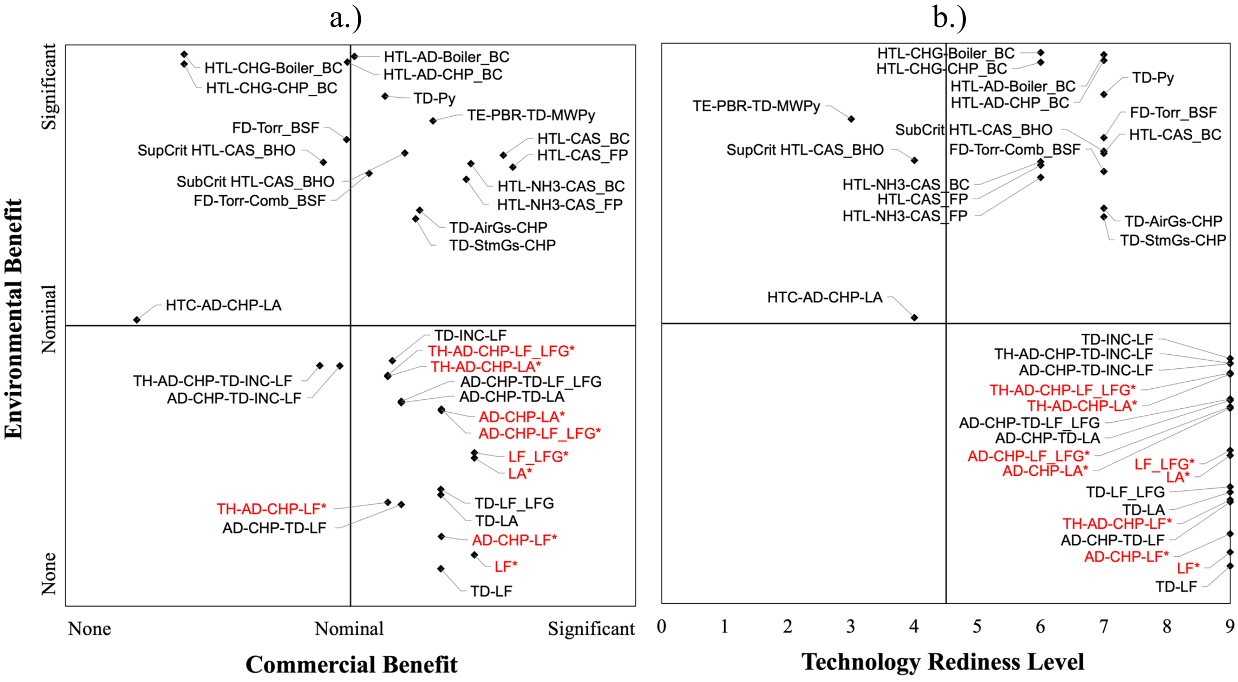

Figure 4: Environmental benefit vs. commercial benefit (a) and environmental benefit vs. technology readiness level (b). Air-blown gasification (AirGs), Ammonia Stripping (NH3), Anaerobic Digestion (AD), Biocrude Oil (BC), Bioheavy Oil (BHO), Biosolid Fuel (BSF), Combined Heat & Power (CHP), Conventional Activated Sludge (CAS), Fry-drying (FD), Fuel Products (FP), Hydrothermal Carbonization (HTC), Hydrothermal Liquefaction (HTL), Incineration (INC), Land Application (LA), Landfill (LF), Landfill gas collection and combustion (LFG), Microwave-assisted Pyrolysis (MWPy), Photobioreactor (PBR), Pyrolysis (Py), Subcritical (SubCrit), Supercritical (SupCrit), Thermal Drying (TD), Thermal Hydrolysis (TH), Transesterification (TE), Torrefaction (Torr), Steam Gasification (StmGs).

The net operating profits reported in Table 3 exclude the revenues from the sale of carbon credits (if applicable) and any costs that could be associated with future carbon taxes. Governmental regulations, subsidies, and carbon credit markets play a substantial role in the economic feasibility of several biosolids management process options.[113] Processes that attain net negative CO_2e emissions may benefit from the sale of carbon credits, and processes that produce net positive CO_2e emissions may be detrimentally impacted by the implementation of future carbon taxes. Therefore, a reference case was established to provide an objective comparison of the effects of carbon credits and carbon taxation on the NPV of each process configuration included in this study (Figure 5). Carbon credits were assumed to be valued at 200 USD/t CO_2e abated, which aligns with the California Air Resources Board (CARB) Low Carbon Fuel Standard (LCFS) credit sale price.[102] Carbon taxation was assumed to be valued at 80 USD/t CO_2e emitted, which aligns with the rates reported by the Center for Climate and Energy Solutions (C2ES).[114] The reference case considered a biosolids management operation with a solids loading rate of 100 tons of dry solids per day (t TS/day), 330 operating days per year, a discount rate of 10%, and a project life expectancy of 20 years. Results from the NPV analysis are summarized in Tables 4-5.

Figure 5 includes the comparison of the net CO_2e emissions and NPV of each technology and the economic impacts of carbon credits on net CO_2e negative processes and carbon taxes on net CO_2e emitting processes. AD-CHP-LF_LFG, AD-CHP-LA, TH-AD-CHP-LF_LFG, and TH-AD-CHP-LA were the only conventional biosolids management process that achieved negative net CO2e emissions and are therefore the only conventional processes eligible to attain revenue from carbon credits. AD-CHP-LA provides the highest NPV of all conventional processes with the implementation of both carbon credits and taxation (-88 million USD), yet still poses a significant cost burden. Process configurations with state-of-the-art thermochemical technologies provide lower net CO_2e emissions and improved NPV over the lifespan of the reference case. The NPV of several state-of-the-art processes increased by as little as 11 million USD for TD-StmGs-CHP, and as much as $66 million USD for HTL-CHG. However, none of the state-of-the-art processes attain a positive NPV without carbon credit sales, and only HTL-CAS_BC and TE-PBR-TD-MWPy attain a modest positive NPV accounting from revenues from carbon credit sales.

Although TE-PBR-TD-MWPy provides a favorable NPV, it lacks the commercial maturity for immediate adoption in industry at its current TRL 3. Gasification technologies did not attain positive NPVs in this scenario, but they attained NPVs that were 14-20 million USD greater than AD-CHP-LA. HTL-CAS and gasification technologies are currently at TRL 7, indicating they may be commercially mature enough for wide-scale market adoption soon. TD-Py attained net negative CO_2e emissions comparable to HTL-CAS and gasification processes but suffered from high OPEX, which could not be ameliorated from additional revenue sourced from carbon credits. The implementation of future carbon taxes will have a detrimental impact on the economic feasibility of conventional processes that produce high CO_2e emissions such as LF, AD-CHP-LF, TH-AD-CHP-LF, and LA. Paired with the sale of carbon credits, state-of-the-art thermochemical processes that attain net negative CO_2e emissions may become economically desirable, especially if carbon taxation is implemented.

Table 4: Results of NPV analysis, excluding the sale of carbon credits and implementation of carbon taxation.

Process	**CAPEX (USD)**	**Net Operating Profit (USD/t TS)**	**Annual Net Operating Profit (USD/yr)**	**Reference Case NPV (million USD)**
LF*	3,580,500	-311	-10,249,885	**-91**
LF_LFG*	3,580,500	-311	-10,249,885	**-91**
TD-LF	26,086,500	-288	-9,508,146	**-107**
TD-LF_LFG	26,086,500	-288	-9,508,146	**-107**
LA*	3,580,500	-311	-10,249,885	**-91**
TD-LA	26,086,500	-288	-9,508,146	**-107**
TD-INC-LF	56,265,000	-266	-8,777,274	**-131**
AD-CHP-LF*	46,546,500	-189	-6,248,359	**-100**
AD-CHP-LF_LFG*	46,546,500	-189	-6,248,359	**-100**
AD-CHP-LA*	46,546,500	-189	-6,248,359	**-100**
AD-CHP-TD-LF	63,937,500	-207	-6,825,615	**-122**
AD-CHP-TD-LF_LFG	63,937,500	-207	-6,825,615	**-122**
AD-CHP-TD-LA	63,937,500	-207	-6,825,615	**-122**
AD-CHP-TD-INC-LF	87,978,000	-246	-8,121,666	**-157**
TH-AD-CHP-LF*	64,449,000	-238	-7,866,998	**-131**
TH-AD-CHP-LF_LFG*	64,449,000	-238	-7,866,998	**-131**
TH-AD-CHP-LA*	64,449,000	-238	-7,866,998	**-131**
TH-AD-CHP-TD-INC-LF	92,070,000	-277	-9,137,543	**-170**
HTL-CAS_BC	19,640,739	-43	-1,423,502	**-32**
HTL-CAS_FP	27,119,530	76	2,496,889	**-6**
HTL-NH3-CAS_BC	24,250,820	-43	-1,420,694	**-36**
HTL-NH3-CAS_FP	31,499,114	-20	-655,537	**-37**
SupCrit HTL-CAS_BHO	44,806,275	-196	-6,458,876	**-100**
SubCrit HTL-CAS_BHO	42,081,215	-183	-6,035,181	**-93**
HTL-AD-CHP_BC	88,631,745	-105	-3,464,506	**-118**
HTL-AD-Boiler_BC	86,139,268	-100	-3,291,669	**-114**
HTL-CHG-CHP_BC	162,070,936	-430	-14,175,080	**-283**
HTL-CHG-Boiler_BC	157,201,499	-422	-13,916,214	**-276**
TD-AirGs-CHP	44,369,130	-135	-4,446,971	**-82**
TD-StmGs-CHP	44,369,130	-145	-4,788,469	**-85**
FD-Torr-Comb_BSF	28,639,016	-336	-11,096,555	**-123**
FD-Torr_BSF	27,102,817	-461	-15,212,038	**-157**
TE-PBR-TD-MWPy	14,498,978	-6	-203,934	**-16**
TD-Py	6,869,418	-776	-25,598,837	**-225**
HTC-AD-CHP-LA	141,967,461	-580	-19,131,990	**-305**

Table 5: Results of NPV analysis, accounting for the sale of carbon credits and implementation of carbon taxation.

Process	**CO_2e emissions (t CO2/t TS)**	**Revenue from Carbon Credits (USD/t TS)**	**Cost imposed by Carbon Tax (USD/t TS)**	**Annual Net Operating Profit w/ credits & tax (USD/yr)**	**NPV w/ credits & tax (million USD)**
LF*	5.17	0	-413	-23,893,901	**-207**
LF_LFG*	0.66	0	-53	-11,988,818	**-106**
TD-LF	5.53	0	-443	-24,116,824	**-231**
TD-LF_LFG	1.02	0	-82	-12,211,740	**-130**
LA*	0.26	0	-21	-10,944,113	**-97**
TD-LA	0.63	0	-50	-11,167,036	**-121**
TD-INC-LF	6.82	0	-545	-26,770,942	**-284**
AD-CHP-LF*	1.81	0	-145	-11,039,200	**-141**
AD-CHP-LF_LFG*	-0.03	5	0	-6,082,276	**-98**
AD-CHP-LA*	-0.20	40	0	-4,912,261	**-88**
AD-CHP-TD-LF	2.20	0	-176	-12,634,163	**-171**
AD-CHP-TD-LF_LFG	0.36	0	-29	-7,776,889	**-130**
AD-CHP-TD-LA	0.18	0	-15	-7,308,883	**-126**
AD-CHP-TD-INC-LF	4.44	0	-355	-19,848,838	**-257**
TH-AD-CHP-LF*	1.54	0	-123	-11,924,046	**-166**
TH-AD-CHP-LF_LFG*	-0.30	61	0	-5,866,433	**-114**
TH-AD-CHP-LA*	-0.48	96	0	-4,696,418	**-104**
TH-AD-CHP-TD-INC-LF	4.39	0	-351	-20,729,920	**-269**
HTL-CAS_BC	-0.64	128	0	2,799,218	**4**
HTL-CAS_FP	-0.64	128	0	6,719,610	**30**
HTL-NH3-CAS_BC	-0.56	112	0	2,284,145	**-5**
HTL-NH3-CAS_FP	-0.56	112	0	3,049,302	**-6**
SupCrit HTL-CAS_BHO	-0.77	155	0	-1,358,688	**-56**
SubCrit HTL-CAS_BHO	-0.84	169	0	-462,978	**-46**
HTL-AD-CHP_BC	-1.16	231	0	4,165,962	**-53**
HTL-AD-Boiler_BC	-1.17	233	0	4,400,465	**-49**
HTL-CHG-CHP_BC	-1.18	236	0	-6,389,536	**-216**
HTL-CHG-Boiler_BC	-1.18	236	0	-6,116,450	**-209**
TD-AirGs-CHP	-0.25	50	0	-2,804,583	**-68**
TD-StmGs-CHP	-0.20	39	0	-3,499,666	**-74**
FD-Torr-Comb_BSF	-0.47	93	0	-8,027,320	**-97**
FD-Torr_BSF	-1.02	205	0	-8,454,884	**-99**
TE-PBR-TD-MWPy	-0.99	198	0	6,334,155	**39**
TD-Py	-0.88	177	0	-19,764,755	**-175**
HTC-AD-CHP-LA	-0.31	63	0	-17,056,607	**-287**

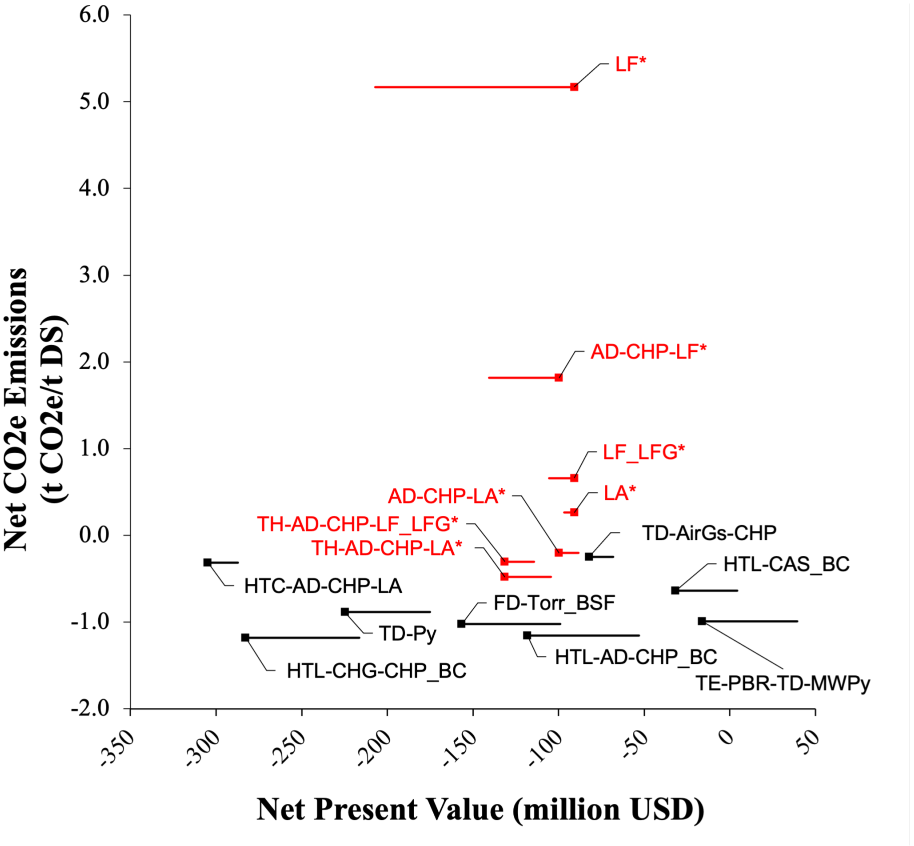

Figure 5: Net CO_2e emissions vs. net present value of wastewater sludge management processes and the impacts of carbon credits and carbon taxes on net present value.

There is a degree of uncertainty ingrained in the environmental and techno-economic analyses of the studies cited in this paper, which is not captured in this analysis. Some variables that may affect the overall economic and environmental benefit of each process are process scale, TRL, electricity and energy costs, sale prices of end-products, distance to final disposal, carbon credit prices, carbon tax rates, interest rates, and project life expectancies. Sensitivity studies have been conducted by many of the referenced authors for the technologies assessed in this study. However, a comprehensive sensitivity study is out of the scope of the analysis presented in this paper.

4.1 Multi-objective Optimizations

Choosing the most beneficial biosolids management process is innately circumstantial to many factors such as proximity and availability of solid waste disposal sites, agricultural land, and the prices of electricity, natural gas, crude oil, and bio-derived end-products. Furthermore, social factors including public perception of environmental protection, human health, and economic performance play an important role in choosing infrastructure improvements. Optimizing biosolids management processes for only one of the variables described above will rarely suffice for adequate decision-making.[115] Furthermore, choosing a biosolids management process is clouded by conflicting objectives (i.e. environmental benefit and economic performance).[116] Therefore, multi-objective optimization can improve these decisions by assigning degrees of importance to each objective of a desired solution in a system with the understanding that improving the result of one objective will result in the degradation of all other objectives. Pareto statistics can then be used to determine the best-case system that optimizes the desired objectives. Few multi-objective optimizations have been conducted for organic waste management[116–118], and fewer have been conducted for wastewater biosolids specifically.[115] Algae biomass has been shown to behave as a suitable analog for wastewater biosolids and other wet organic matter.[53] Thomassen et al[117] conducted a multi-objective optimization to determine which combination of energy and resource recovery processes for algal biomass had the greatest likelihood of producing a positive NPV while also reducing greenhouse gas emissions. Additionally, Chandra et al[119] developed a biorefinery complexity index (BCI), which is a function of the number of processing steps and the complexity of each component of a processing step to determine the effects of combining processing steps together in a biorefinery. Both Thomassen et al and Chandra et al concluded that the highest net present value (NPV) technology was also relatively simple. Thomassen et al determined that while the highest NPV process option was to pelletize the biomass into aquaculture feed, the optimal processing option for greenhouse gas mitigation was to gasify the biomass.[117] Castro-Amoedo et al[115] conducted a multi-objective optimization to evaluate the performance of HTL and gasification technologies for wastewater biosolids management operations and found that in almost all configurations, HTL was found to be favorable due to synergies with existing wastewater infrastructure and its ability to process HTL aqueous co-products. The findings of Castro-Amoedo et al support the findings of the techno-economic synthesis conducted in this study, that HTL paired with existing wastewater infrastructure provides substantial environmental and economic benefit.

5. Summary and Future Perspectives

In this study a uniform grading framework was proposed to identify bioresource recovery technologies that provide both commercial and environmental benefits in wastewater biosolids management operations. Findings from 10 techno-economic and lifecycle assessments were synthesized into uniform system boundaries and 35 process configurations with combinations of both conventional and state-of-the-art technologies were evaluated. While conventional wastewater biosolids management practices such as anaerobic digestion, landfilling, land application, and incineration are commercially mature, they produce significant greenhouse gas emissions and pose a large economic burden on municipalities. State-of-the-art thermochemical bioresource recovery technologies such as hydrothermal liquefaction, gasification, and pyrolysis show the potential to provide substantial economic and environmental benefit through the recovery of additional carbon and nutrients from wastewater biosolids in the form of biofuels, fertilizers, and other high-value products that could reduce demand for fossil-based resources and provide additional sources of revenue for wastewater utilities. At this time, hydrothermal liquefaction paired with existing wastewater infrastructure provides the greatest economic and environmental benefits for wastewater utilities. We caution that this work represents a snapshot in time, and all technologies assessed (and new technologies not assessed) will continue to emerge, develop and mature over time. Further, additional work should be done to harmonize system boundaries of techno-economic and lifecycle assessments of bioresource recovery technologies applied towards biosolids management applications. Finally, multi-objective optimizations could be conducted on several process configurations to improve our understanding of the impacts of different priorities on how various technologies compare.

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