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Life cycle and techno-economic assessment of bioresource production from wastewater

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Thermochemical conversion technologies present an opportunity to flip the paradigm of wastewater biosolids management operations from energy-intense and expensive waste management processes into energy-positive and economical resource extraction centers. Herein, we present a uniform "grading framework" to consistently evaluate the environmental and commercial benefits of established and emerging wastewater biosolids management processes from a life cycle and techno-economic perspective. Application of this approach reveals that established wastewater biosolids management practices such as landfilling, land application, incineration, and anaerobic digestion, while commercially viable, offer little environmental benefit. On the other hand, emerging thermochemical bioresource recovery technologies such as hydrothermal liquefaction, gasification, pyrolysis, and torrefaction show potential to provide substantial economic and environmental benefit through the recovery of carbon and nutrients from wastewater biosolids in the form of biofuels, fertilizers, and other high-value products. Some emerging thermochemical technologies have developed beyond pilot scale although their commercial viability remains to be seen.

In the United States, 12.56 million dry metric tons of municipal wastewater biosolids (or sludge) are produced and managed annually from 15,014 publicly owned treatment works (POTW)[1]. For much of recorded history, wastewater biosolids and human feces have existed within a circular economy, perceived as valuable fertilizer for agricultural applications. 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[2]. However, 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 as regulations have been established to protect the public from exposure to wastewater-borne pathogens[3,4].

Wastewater treatment accounts for about 3% of the entire US electrical consumption and about 3% of the total US greenhouse gas (GHG) emissions[5–8]. Much effort has been invested to improve the sustainability of wastewater treatment operations through the recovery of energy, nutrients, and other valuable resources[9–15]. Past research has focused on the fractionation of fats, oils and greases (FOG) from influent wastewater to yield energetic products[10], direct thermal energy recovery from influent wastewater if adequate temperature gradients exist[12,16], and nutrient recovery in-situ or from side stream unit operations to yield liquid and solid fertilizers[3,11,13,17].

Wastewater biosolids management accounts for up to 30% of the total energy demand, 40–50% of the total operating costs, and 40% of the lifecycle GHG emissions of conventional wastewater treatment plants[4,8,18]. Therefore, the recovery of energy and renewable substitutes for fossil-based products from biosolids may have a significant impact on the energy demand, carbon footprint and economic performance of municipal wastewater treatment facilities[4,8,19]. 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[1,20]. Although much effort has been invested to recover energy and nutrients from wastewater and biosolids[3,4,18,21–33], established practices 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[3].

Recently, several alternative bioresource recovery technologies including gasification (Gs)[34–40], pyrolysis (Py)[34,36,39,41–52], torrefaction (Torr)[53,54],

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hydrothermal liquefaction (HTL)[29,55–67], hydrothermal carbonization (HTC)[39,68–70], transesterification (TE)[71–74] and alternative fermentation[22] have emerged, which rely on biochemical and thermochemical processes to convert organic waste into value-added end-products such as biofuels, fertilizers, and bioplastics[4,22]. These emerging bioresource recovery technologies may improve the economic and environmental performance of wastewater biosolids management operations by closing the loop of nutrient emissions, GHG emissions and energy expenditure associated with established practices.

Established and emerging biosolids management processes may be implemented individually or in combination to recover energy and value-added products (Fig. 1). However, the economic and environmental benefits derived from upcycling wastewater biosolids must be balanced with the respective impacts of processing and final disposal[75]. Techno-economic assessment (TEA) and life cycle assessment (LCA) are two complementary frameworks that can be used to assess the economic performance and environmental implications of technologies and to compare alternatives in a more holistic sense. TEA is a method of evaluating economic feasibility in terms of both technology and economics. 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[54]. LCA is an assessment of the environmental impacts of a specific product or process, which accounts for its entire life cycle[76]. The first LCAs were conducted in the 1960s primarily to assess the energy requirements for chemical production and packaging industries and varied widely in their methodologies[77,78]. LCA has since developed into a framework used to determine the global warming potential (GWP), in net CO_2-equivalent (CO_2e) emissions, of a product or process over its entire life cycle. Today, LCA often extends past determination of GWP to include more comprehensive analysis of environmental and social impacts such as damage to human health, ecosystems, and resource availability[78,79].

TEAs and LCAs have been published assessing several established and emerging biosolids management practices[11,25,26,29,34,38,42,48,51,54,57,58,63–67,70,72,74,80–88]. 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 a harmonized TEA and LCA framework with uniform system boundaries to avoid varied results when assessing the sustainability of a technology, product or process[29,89,90]. Effort has been made to evaluate biochemical and thermochemical resource recovery processes using harmonized LCA and TEA system boundaries[25,29]. However, these assessments should be extended to include more emerging technologies in the context of wastewater biosolids.

To address this knowledge gap, findings from 10 peer-reviewed LCAs and TEAs were synthesized into harmonized system boundaries presented in Fig. 1 to assess the environmental and commercial benefit of 35 bioresource recovery process options for wastewater biosolids management. A reference case was established to compare the lifecycle net present value (NPV) and GWP of each process. Additionally, this study compares each process using a uniform grading framework that accounts for environmental (residual disposal, energy balance, and CO_2e emissions) and economic (CAPEX, net operating profit, and technology readiness level) factors. Results align with past harmonized biosolids management LCAs and TEAs that emerging thermochemical processes such as hydrothermal liquefaction, pyrolysis, and gasification may provide more economic and environmental benefit to wastewater utilities in comparison to conventional management options[25,29,38,42,44,54,58,64,74].

Results and discussion

Global warming potential and net present value of biosolids management

Governmental regulations, subsidies, and carbon credit markets play a substantial role in the economic feasibility of several biosolids management

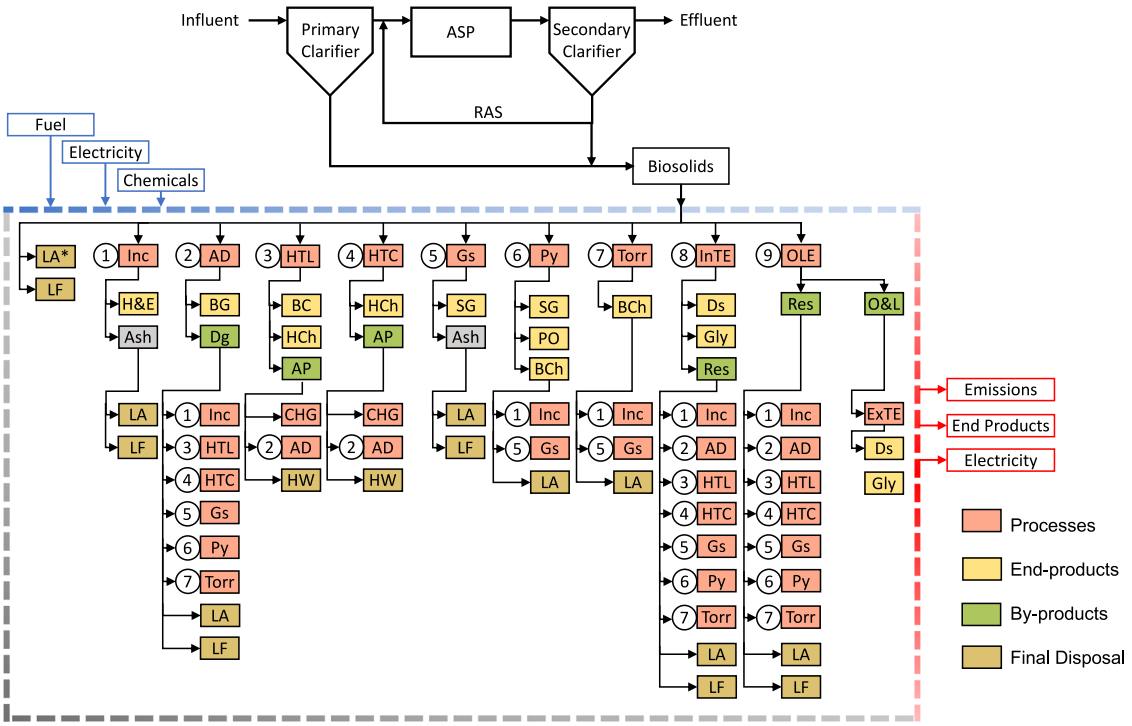

Fig. 1 | System boundaries for lifecycle and techno-economic synthesis. System boundaries and components for the different scenarios considered in this techno-economic and lifecycle analysis. The reactors, product separation, and product distribution for each process are different. Activated Sludge Process (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), In situ-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).

Table 1 | NPV analysis excluding the sale of carbon credits and implementation of carbon taxation

Process	CAPEX (USD)	Net Operating Profit (USD·t TS^{-1})	Annual Net Operating Profit (USD·yr^{-1})	Reference Case NPV (million USD)
LF[a]	3,580,500	−311	−10,249,885	−91
LF_LFG[a]	3,580,500	−311	−10,249,885	−91
TD-LF[a]	26,086,500	−288	−9,508,146	−107
TD-LF_LFG[a]	26,086,500	−288	−9,508,146	−107
LA[a]	3,580,500	−311	−10,249,885	−91
TD-LA[a]	26,086,500	−288	−9,508,146	−107
TD-INC-LF[a]	56,265,000	−266	−8,777,274	−131
AD-CHP-LF[a]	46,546,500	−232	−7,649,285	−112
AD-CHP-LF_LFG[a]	46,546,500	−232	−7,649,285	−112
AD-CHP-LA[a]	46,546,500	−232	−7,649,285	−112
AD-CHP-TD-LF[a]	63,937,500	−249	−8,226,541	−134
AD-CHP-TD-LF_LFG[a]	63,937,500	−249	−8,226,541	−134
AD-CHP-TD-LA[a]	63,937,500	−249	−8,226,541	−134
AD-CHP-TD-INC-LF[a]	87,978,000	−289	−9,522,592	−169
TH-AD-CHP-LF[a]	64,449,000	−309	−10,190,965	−151
TH-AD-CHP-LF_LFG[a]	64,449,000	−309	−10,190,965	−151
TH-AD-CHP-LA[a]	64,449,000	−309	−10,190,965	−151
TH-AD-CHP-TD-INC-LF[a]	92,070,000	−347	−11,461,509	−190
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

[a]Established biosolids management process.

process options[26]. 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. Although carbon emissions and sequestration are valued differently by different policies and industries, the price of carbon credits and taxes should be of equal value to society[91]. Therefore, the NPV of each process configuration was evaluated as the cost of carbon increased from 0 to 200 USD·t CO_2e^{-1}. This aligns with the United States Interagency Working Group estimation that the social cost of carbon could increase to more than 200 USD·t CO_2e^{-1} by the year 2035 and the California Air Resources Board (CARB) Low Carbon Fuel Standard (LCFS) credit sale price, which has fluctuated between 60 and 200 USD in the last five years[92,93].

A reference case was established to provide an objective comparison of each bioresource recovery process and the impact of carbon credits and carbon taxation on the net present value (NPV) of each process configuration. The reference case considered a biosolids management operation with a solids loading rate of 100 tonnes of dry solids per day (t TS·day^{-1}), 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 1–2. Detailed calculations of net CO_2e emissions, CAPEX, and net operating profit (NOP) are presented in Supplementary Tables 1–36. A comparison of the net CO_2e emissions and NPV of each technology and the economic impacts of carbon credits and taxes is presented in Fig. 2.

All established and emerging biosolids management processes attained negative NPVs for the provided reference case without carbon credits or taxes. Established processes attain NPVs ranging from −170 to −91 million USD without carbon credits or taxes. Emerging processes evaluated in this study focus on resource recovery and valorization of biosolids and most attain favorable NPVs without carbon credits or taxes. Most notably, HTL-CAS_FP, HTL-CAS_BC, and TE-PBR-TD-MWPy attain favorable NPVs ranging from −32 to −6 million USD, which can be attributed to modest CAPEX and improved net operating profits (NOP). However, some

Table 2 | Results of NPV analysis, accounting for the social cost of carbon priced at 200 USD·t CO_2e^{-1}

Process	CO_2e emissions (t CO_2·t TS^{-1})	Revenue from carbon credits (USD·t TS^{-1})	Cost imposed by carbon tax (USD·t TS^{-1})	Annual Net Operating Profit with credits & tax (USD·yr^{-1})	NPV with credits & tax (million USD)
LF[a]	5.3	0	−1066	−45,442,578	−390
LF_LFG[a]	0.8	0	−165	−15,700,565	−137
TD-LF[a]	6.2	0	−1247	−50,644,566	−457
TD-LF_LFG[a]	1.7	0	−345	−20,902,553	−204
LA[a]	0.4	0	−85	−13,068,107	−115
TD-LA[a]	1.3	0	−266	−18,270,095	−182
TD-INC-LF[a]	7.4	0	−1472	−57,366,534	−545
AD-CHP-LF[a]	2.2	0	−440	−22,155,047	−235
AD-CHP-LF_LFG[a]	0.4	0	−72	−10,020,305	−132
AD-CHP-LA[a]	0.2	0	−36	−8,841,847	−122
AD-CHP-TD-LF[a]	3.1	0	−628	−28,948,117	−310
AD-CHP-TD-LF_LFG[a]	1.3	0	−260	−16,813,375	−207
AD-CHP-TD-LA[a]	1.1	0	−224	−15,634,916	−197
AD-CHP-TD-INC-LF[a]	5.3	0	−1055	−44,337,253	−465
TH-AD-CHP-LF[a]	2.0	0	−402	−23,447,853	−264
TH-AD-CHP-LF_LFG[a]	0.2	0	−34	−11,313,112	−161
TH-AD-CHP-LA[a]	0.2	0	−38	−11,449,456	−162
TH-AD-CHP-TD-INC-LF[a]	5.4	0	−1073	−46,872,055	−491
HTL-CAS_BC	−0.6	130	0	2,865,445	5
HTL-CAS_FP	−0.9	189	0	8,718,046	47
HTL-NH3-CAS_BC	−0.6	117	0	2,455,680	−3
HTL-NH3-CAS_FP	−0.8	162	0	4,698,938	9
SupCrit HTL-CAS_BHO	−0.5	94	0	−3,368,067	−73
SubCrit HTL-CAS_BHO	−0.5	105	0	−2,582,145	−64
HTL-AD-CHP_BC	−1.4	280	0	5,761,561	−40
HTL-AD-Boiler_BC	−1.5	298	0	6,557,789	−30
HTL-CHG-CHP_BC	−1.3	267	0	−5,361,793	−208
HTL-CHG-Boiler_BC	−1.5	302	0	−3,937,943	−191
TD-AirGs-CHP	−0.2	49	0	−2,825,585	−68
TD-StmGs-CHP	−0.2	38	0	−3,525,030	−74
FD-Torr-Comb_BSF	−1.6	325	0	−382,604	−32
FD-Torr_BSF	−3.6	722	0	8,616,607	46
TE-PBR-TD-MWPy	−0.7	149	0	4,724,185	26
TD-Py	−1.9	383	0	−12,946,698	−117
HTC-AD-CHP-LA	−1.1	217	0	−11,956,042	−244

[a]Established biosolids management process.

emerging processes suffer high CAPEX or operating expenses OPEX that result in low NPV. Most notably, HTL-CHG-CHP_BC, HTL-CHG-Boiler_BC, TD-Py, and HTC-AD-CHP-LA suffer from high CAPEX or OPEX, resulting in low NPVs ranging from −305 to −225 million USD.

Carbon credits and taxes have a large impact on processes that are more net CO_2e negative or positive, respectively, and have a lesser impact on processes that are near carbon neutral. LA, TH-AD-CHP-LA, AD-CHP-LF_LFG and AD-CHP-LA were near carbon neutral and provided the highest NPV of all established processes with the implementation of the social cost of carbon (−112 and −102 million USD, respectively), yet still pose a significant cost burden. Processes that dispose of final residues in landfills without landfill gas collection and processes that have high net energy inputs (LF, TD-LF, TD-INC-LF, AD-CHP-TD-LF, AD-CHP-TD-INC-LF, and TH-AD-CHP-TD-INC-LF) have the highest net CO_2e emissions (3.1–7.4 t CO_2e·t TS^{-1}) and are most detrimentally impacted by the social cost of carbon. The NPV of these processes range from −545 to −298 million USD when the social cost carbon is priced at 200 USD per tonne of CO_2e.

Emerging thermochemical technologies attain lower net CO_2e emissions (−0.2 to −3.6 t CO_2e·t TS^{-1}), making them eligible for additional revenue from carbon credits. The NPV of emerging processes increased by as little as 11 million USD for TD-StmGs-CHP, and as much as 203 million

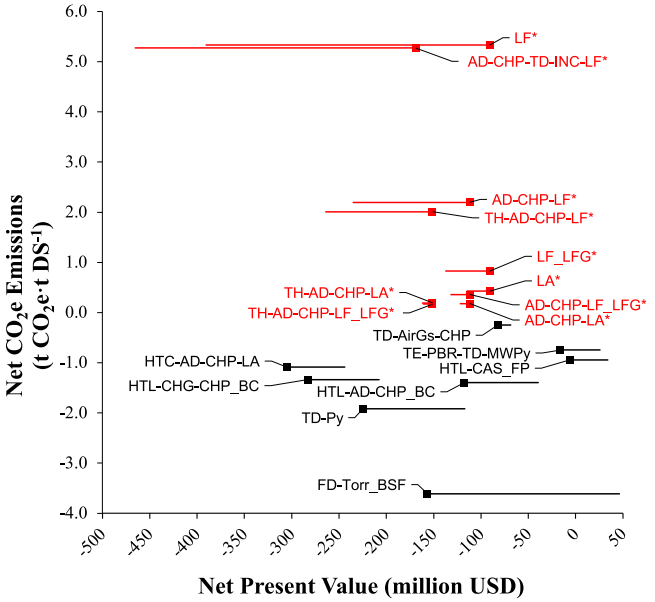

Fig. 2 | Comparison of net CO2e emissions vs. net present value of established and emerging wastewater biosolids management processes and the impact of carbon credits and carbon taxation. Net CO_2e emissions vs. NPV of established and emerging wastewater biosolids management processes and the impacts of carbon credits and carbon taxes on NPV. Position of square resembles base-case NPV without the implementation of carbon credits or carbon taxes (Table 1). Horizontal lines indicate the increase or decrease in NPV due to implementation of carbon credits and carbon taxes (Table 2), which match the social cost of carbon (up to 200 USD·t CO_2e^{-1}). Environmental and commercial benefits are summarized in Tables 3, 4. Established processes are highlighted red and are denoted with an asterisk. Emerging processes are labeled with black text. Detailed calculations are presented in Supplementary Tables 1–36. A summary of process-specific details is presented in Table 5. A list of acronyms and their definitions is presented in Table 6.

USD for FD-Torr_BSF from the revenue of carbon credits. However, only HTL-CAS_BC, HTL-CAS_FP, HTL-NH3-CAS_FP, FD-Torr_BSF, and TE-PBR-TD-MWPy attain a positive NPV (5–47 million USD) when revenues from carbon credit sales are considered. HTL-CAS_FP and FD-Torr_BSF attain an NPV of 47 and 46 million USD, respectively, when carbon credits are applied due to the high yield of bio-derived fuel products, which displace the consumption of carbon-intense fossil fuels. It is worth noting that the large improvement in NPV for FD-Torr_BSF is attributed to the displacement of fossil-based coal, which has a life-cycle emission factor of 1023 g CO_2e·kWh^{-1} [94]. Although TE-PBR-TD-MWPy provides a favorable NPV, it lacks the commercial maturity for immediate adoption in industry at its current technology readiness level (TRL) of 3. Gasification technologies did not attain positive NPVs in this scenario, but they attained NPVs that were 15–18 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 established processes that produce high CO_2e emissions such as LF, AD-CHP-LF, and TH-AD-CHP-LF. Paired with the sale of carbon credits, emerging thermochemical processes that attain net negative CO_2e emissions may become economically desirable, especially if carbon taxation is implemented.

It should be noted that in addition to variability in performance across different technologies, there is uncertainty associated with the TEA and LCA estimates for any given technology. Variability in TRL, scale, energy mix, input costs (e.g., energy, materials, interest rates), output prices, distance to final disposal, useful life etc. Each render both the economic and environmental performance of each pathway uncertain. In general, for any given technology, an increase in TRL leads to the greatest reduction in uncertainty in economic and environmental performance.

Environmental implications of bioresource recovery technologies

Table 3 presents the inputs and outputs of the environmental benefits grading framework. Commercially established biosolids management practices (denoted with an asterisk) are typically associated with the transportation of large amounts of waste residues to final disposal, modest net energy benefit, and high net CO_2e emissions relative to state-of-the-art bioresource production processes. Established practices yield between 2 and 5 metric tons of wet residuals per metric ton of total dry solids (TS) processed and have a lifecycle energy benefit ranging between −3,036 and 597 kWh·t TS^{-1}. Lifecycle CO_2e emissions from established processes range between 170 and 7362 kg CO_2e·t TS^{-1} with AD-CHP-LF_LFG, TH-AD-CHP-LA and TH-AD-CHP-LF_LFG being the most favorable while also attaining a modest net lifecycle energy export of 67 and 597 kWh·t TS^{-1}, respectively.

Emerging 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[4]. Emerging processes tend to yield less waste residues that must be transported to final disposal (0–2 wet t·t TS^{-1}) while producing improved net energy exports (491–5006 kWh·t TS^{-1}) and lifecycle CO_2e emissions (−191 to −3610 kg CO_2e·t TS^{-1}). Process options that include HTL attain the most favorable net energy benefit (up to 5006 kWh·t TS^{-1}) and improved lifecycle CO_2e emissions (as low as −1512 kg CO_2e·t TS^{-1}). Furthermore, HTL paired with catalytic hydrothermal gasification (HTL-CHG) produces the most favorable net energy benefit (4591–5006 kWh·t TS^{-1}) and net CO_2e emissions (−1335 to −1512 t CO_2e·t TS^{-1}) largely attributed to improved energy recovery from CHG while also limiting the waste residuals sent to disposal (0.13 wet t·t TS^{-1})[57,58,63]. Processes that utilize torrefaction and pyrolysis attain the lowest lifecycle CO_2e emissions (as low as −3610 kg CO_2e·t TS^{-1}) due to the displacement of fossil-sourced coal with biochar. Hydrothermal carbonization and gasification also effectively reduce the yield of waste residues (0–0.05 wet t·t TS^{-1}) and attain net negative lifecycle CO_2e emissions (−1087 to −246 kg CO_2e·t TS^{-1}) but have lower net energy benefit (491–978 kWh·t TS^{-1}) in comparison to hydrothermal liquefaction, pyrolysis, and torrefaction, due to limited end-product recovery[38].

Techno-economic implications of bioresource recovery technologies

Table 4 presents the inputs and outputs of the commercial benefits grading framework. Established biosolids management practices are typically associated with low CAPEX (36–921 thousand USD·t TS^{-1}·d^{-1}), but poor NOP (−347 to −232 USD·t TS^{-1}). Established biosolids management practices that implement anaerobic digestion have improved NOP from biogas recovery and reduced transportation and disposal costs but have higher CAPEX, which results in a lower NPV.

Emerging thermochemical processes have shown potential to improve NOP 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, emerging technologies often suffer from high CAPEX (up to 1.6 million USD·t TS^{-1}·d^{-1}) and lack commercial maturity (TRL 3–7). While in some cases the CAPEX of emerging technologies may be economically justified by the improved NPV, resource-limited municipalities may have difficulty fronting such a large expenditure[4]. 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^{-1}·d^{-1}) while also producing improved net operating profits (−196 to 76 USD·t TS^{-1}) without government subsidies or carbon credits[57]. Gasification, pyrolysis and torrefaction processes also benefit

Table 3 | Results of environmental benefit grading framework

Process	Final wet weight of residuals (Wet t·t TS^{-1})	Grade (0–3)	Net energy benefit (kWh·t TS^{-1})	Grade (0–3)	Net CO_2e emissions (t CO_2·t TS^{-1})	Grade (0–3)	Total Grade (0–9)
LF[a]	5.00	0.00	−876	0.81	5.33	0.00	0.81
LF_LFG[a]	5.00	0.00	423	1.29	0.83	0.65	1.94
TD-LF[a]	2.00	0.60	−3036	0.00	6.23	0.00	0.60
TD-LF_LFG[a]	2.00	0.60	−1736	0.48	1.73	0.18	1.26
LA[a]	5.00	0.00	−876	0.81	0.43	0.86	1.67
TD-LA[a]	2.00	0.60	−3036	0.00	1.33	0.39	0.99
TD-INC-LF[a]	0.11	2.87	−126	1.09	7.36	0.00	3.96
AD-CHP-LF[a]	3.40	0.00	−408	0.98	2.06	0.00	1.12
AD-CHP-LF_LFG[a]	3.40	0.00	122	1.18	0.22	0.97	2.29
AD-CHP-LA[a]	3.40	0.00	−408	0.98	0.04	1.07	2.19
AD-CHP-TD-LF[a]	1.36	1.37	−2680	0.13	3.00	0.00	1.64
AD-CHP-TD-LF_LFG[a]	1.36	1.37	−2150	0.33	1.16	0.47	2.31
AD-CHP-TD-LA[a]	1.36	1.37	−2680	0.13	0.98	0.57	2.21
AD-CHP-TD-INC-LF[a]	0.11	2.87	−721	0.86	5.14	0.00	3.88
TH-AD-CHP-LF[a]	3.40	0.00	67	1.16	1.78	0.15	1.53
TH-AD-CHP-LF_LFG[a]	3.40	0.00	597	1.36	−0.06	1.12	2.70
TH-AD-CHP-LA[a]	3.40	0.00	−419	0.98	−0.24	1.22	2.60
TH-AD-CHP-TD-INC-LF[a]	0.11	2.87	−952	0.78	5.14	0.00	3.88
HTL-CAS_BC	0.26	2.70	2542	2.08	−0.65	1.43	6.21
HTL-CAS_FP	0.26	2.70	2478	2.06	−0.94	1.59	6.34
HTL-NH3-CAS_BC	0.26	2.70	2391	2.02	−0.59	1.40	6.12
HTL-NH3-CAS_FP	0.26	2.70	2142	1.93	−0.81	1.52	6.15
SupCrit HTL-CAS_BHO	0.35	2.58	2181	1.95	−0.47	1.34	5.86
SubCrit HTL-CAS_BHO	0.35	2.58	2379	2.02	−0.52	1.37	5.97
HTL-AD-CHP_BC	0.13	2.85	4733	2.90	−1.40	1.83	7.58
HTL-AD-Boiler_BC	0.13	2.85	4957	2.98	−1.49	1.88	7.71
HTL-CHG-CHP_BC	0.13	2.85	4591	2.85	−1.34	1.80	7.49
HTL-CHG-Boiler_BC	0.13	2.85	5006	3.00	−1.51	1.89	7.74
TD-AirGs-CHP	0.05	2.94	630	1.37	−0.25	1.22	5.53
TD-StmGs-CHP	0.08	2.91	491	1.32	−0.19	1.19	5.41
FD-Torr-Comb_BSF	0.01	3.00	1424	1.66	−1.62	1.95	6.61
FD-Torr_BSF	0.01	3.00	1264	1.60	−3.61	3.00	7.60
TE-PBR-TD-MWPy	0.00	3.00	2302	1.99	−0.75	1.48	6.48
TD-Py	0.00	3.00	3602	2.48	−1.92	2.10	7.58
HTC-AD-CHP-LA	1.70	0.96	978	1.50	−1.09	1.67	4.12

[a]Established biosolids management process.

from modest CAPEX (69 to 444 thousand USD·t TS^{-1}·d^{-1}) but suffer from negative net operating profits (−776 to −135 USD·t TS^{-1}) due to increased costs associated with drying influent feedstock[38].

Comparison of established and emerging bioresource recovery pathways

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 Fig. 3a a comparison of the environmental benefit and TRL is presented in Fig. 3b. The ideal process configuration offers both environmental and commercial benefit (upper right quadrant). The proposed environmental benefit grading framework moderately correlates inversely (correlation factor −0.65) with the findings of the previously discussed net CO_2e emissions and the proposed commercial benefit grading framework strongly correlates with the previously discussed NPV analysis (correlation factor 0.90).

Several process configurations that utilize emerging 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 both environmental and commercial benefits over established methods (Fig. 3a) but lack commercial maturity for immediate adoption (Fig. 3b). Other process configurations that utilize emerging thermochemical technologies such as HTL-CHG, FD-Torr, and SupCrit HTL provide significant environmental benefits, but provide nominal to no commercial benefits (upper left corner) due to high CAPEX and/or low NOP. While some technologies currently offer poor commercial benefit,

Table 4 | Results of commercial benefit grading framework

Process	CAPEX (USD·t TS^{-1}·d^{-1})	Grade (0–3)	Net operating profit (USD·t TS^{-1})	Grade (0–3)	TRL (1–9)	Grade (0–3)	Total Grade (0–9)
LF[a]	$35,805	2.89	−$311	0.56	9	3.00	6.46
LF_LFG[a]	$35,805	2.89	−$311	0.56	9	3.00	6.46
TD-LF[a]	$260,865	2.22	−$288	0.71	9	3.00	5.92
TD-LF_LFG[a]	$260,865	2.22	−$288	0.71	9	3.00	5.92
LA[a]	$35,805	2.89	−$311	0.56	9	3.00	6.46
TD-LA[a]	$260,865	2.22	−$288	0.71	9	3.00	5.92
TD-INC-LF[a]	$562,650	1.31	−$266	0.85	9	3.00	5.16
AD-CHP-LF[a]	$465,465	1.60	−$232	1.06	9	3.00	5.66
AD-CHP-LF_LFG[a]	$465,465	1.60	−$232	1.06	9	3.00	5.66
AD-CHP-LA[a]	$465,465	1.60	−$232	1.06	9	3.00	5.66
AD-CHP-TD-LF[a]	$639,375	1.08	−$249	0.95	9	3.00	5.03
AD-CHP-TD-LF_LFG[a]	$639,375	1.08	−$249	0.95	9	3.00	5.03
AD-CHP-TD-LA[a]	$639,375	1.08	−$249	0.95	9	3.00	5.03
AD-CHP-TD-INC-LF[a]	$879,780	0.36	−$289	0.70	9	3.00	4.06
TH-AD-CHP-LF[a]	$644,490	1.07	−$309	0.58	9	3.00	4.64
TH-AD-CHP-LF_LFG[a]	$644,490	1.07	−$309	0.58	9	3.00	4.64
TH-AD-CHP-LA[a]	$644,490	1.07	−$309	0.58	9	3.00	4.64
TH-AD-CHP-TD-INC-LF[a]	$920,700	0.24	−$347	0.33	9	3.00	3.57
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

[a]Established biosolids management process.

future innovations and implementation experience could dramatically decrease CAPEX and/or OPEX thereby improving NOP and NPV. Established biosolids management practices tend to fall in or near the bottom right quadrant (commercially viable, but nominal environmental benefits) with TH-AD-CHP-LA offering the greatest commercial and environmental benefits. All established biosolids management processes have a high commercial maturity (TRL 9).

Limitations and future suggestions

In conclusion, a uniform grading framework was developed and applied to identify bioresource recovery technologies that provide both greater commercial and environmental benefits in wastewater biosolids management operations. Findings from 10 techno-economic and lifecycle assessments were synthesized into harmonized system boundaries and 35 process configurations with combinations of both established and emerging technologies were evaluated. While established 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. Emerging thermochemical bioresource recovery technologies such as hydrothermal liquefaction, gasification, pyrolysis, and torrefaction show potential to provide substantial economic and environmental benefit through the recovery of carbon and nutrients from wastewater biosolids in the form of biofuels, fertilizers, and other high-value products. Emerging technologies may 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. Readers should note that we propose this uniform grading framework to provoke critical

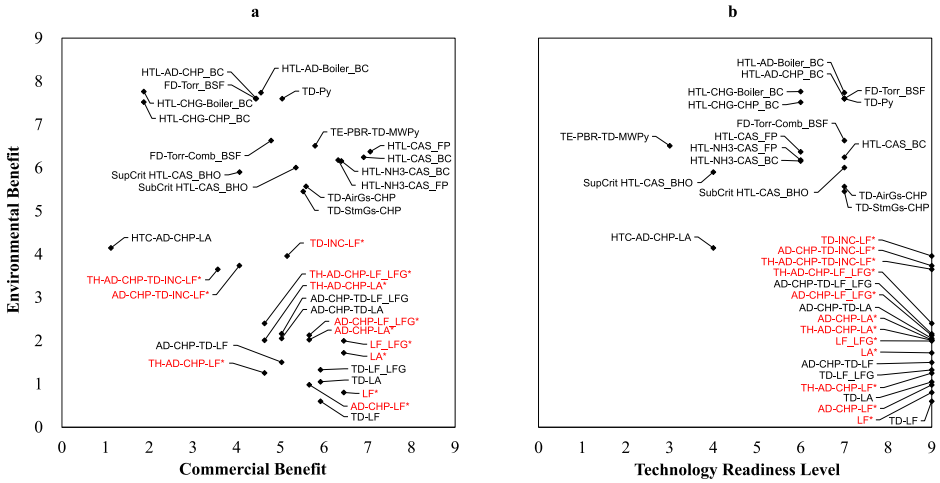

Fig. 3 | Environmental benefit vs. commercial benefit and TRL. Environmental benefit vs. commercial benefit (**a**) and environmental benefit vs. technology readiness level (**b**). Established processes are highlighted in red and denoted with an asterisk. Scoring data is referenced from Tables 3–4. Detailed calculations are presented in Supplementary Tables 1–36. A summary of process-specific details is presented in Table 5. A list of acronyms and their definitions is presented in Table 6.

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 potential to reduce the economic and environmental burdens posed by biosolids management to varying degrees, but each technology must be developed, implemented (at scale) and optimized to achieve commercial maturity. While detailed sensitivity assessments are presented in the referenced literature for each process, a simple sensitivity assessment is presented in Fig. 4, which evaluates the impact that a ±50% change in OPEX and end-product market value has on the NOP of each process. Aside from processes that include HTL, which are heavily reliant on the sale price of biocrude or derived fuel products, the NOP of most other processes are dominated by operating expenses. Comparisons of HTL-integrated processes remain robust because the value of biocrude derived from HTL processes is well understood at its current TRL. Although the reported market value of end products such as biochar, hydrochar, or biosolid fuel may vary in literature, NOP of processes that render these end products are dominated by operating expenses. Therefore, this analysis remains robust.

We caution that this work represents a snapshot in time, and all technologies assessed (and other emerging technologies not assessed) will continue to emerge, develop, and mature over time. Further, we encourage future evaluations of bioresource recovery technologies to utilize harmonized system boundaries to achieve holistic life cycle and techno-economic comparisons.

Methods

This study establishes a uniform grading framework to compare the environmental and commercial benefits provided by established and emerging biosolids management processes (Fig. 5). Analyses from ten techno-economic and lifecycle assessments were synthesized into the uniform boundaries presented in Fig. 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 subcategories. Data synthesized for each grading sub-category were linearly scaled between 0 and 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, NOP, and TRL.

Wet weight of final residues per mass of total dry solids processed ($WS_f TS_i^{-1}$) was calculated based on Eq. (1):

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

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 moisture content of the final residual solids. Process scenarios that did not incorporate drying steps were assumed to dewater final residues to a moisture content of 80%, a typical moisture content achieved via mechanical dewatering, before transporting to final disposal[95,96]. Processes that do not incorporate biochemical or thermochemical conversion steps yield large quantities of final residuals due to low total solids reduction and high moisture content. To avoid over-optimistic scoring, processes that produce more wet residuals relative to anaerobic digestion (≥2.5 $WS_f TS_i^{-1}$) receive a grade of 0. Processes that produce fewer wet residuals relative to anaerobic digestion (<2.5 $WS_f TS_i^{-1}$) receive grades ranging from 0 to 3, which are scaled linearly between the following upper and lower limits: 2.5 $WS_f TS_i^{-1} = 0$ and 0 $WS_f TS_i^{-1} = 3$.

The net energy balance was determined using a life-cycle approach as expressed by Eq. (2):

$$\begin{aligned} E_{NET} = {} & \left(E_{elec,out} + E_{elec,LFG} - E_{elec,in}\right) \times \left(1 + EROI_{elec}^{-1}\right) \\ & + E_{prod} \times \left(1 + EROI_{fossil}^{-1}\right) \\ & - E_{diesel} \times \left(1 + EROI_{diesel}^{-1}\right) \\ & - E_{NG,in} \times \left(1 + EROI_{NG}^{-1}\right) \end{aligned} \quad (2)$$

where E_{NET} is the net energy balance of a process scenario ($kWh{\cdot}t\ TS_i^{-1}$); $E_{elec,out}$ is the electric energy export of a process ($kWh{\cdot}t\ TS_i^{-1}$); $E_{elec,LFG}$ is the electric energy export from Landfill gas (LFG) combustion ($kWh{\cdot}t\ TS_i^{-1}$); $E_{elec,in}$ is the electric energy input required for a process ($kWh{\cdot}t\ TS_i^{-1}$); E_{prod} is the energy derived from a biofuel production as reported in literature normalized over the total solids managed for each process ($kWh{\cdot}t\ TS_i^{-1}$); E_{diesel} is the energy required for transportation of waste residues to final disposal ($kWh{\cdot}t\ TS_i^{-1}$); $E_{NG,in}$ is the energy import from natural gas ($kWh{\cdot}t\ TS_i^{-1}$). Electricity imports, exports, and natural gas imports were calculated on a paper-by-paper basis due to the nonuniformity in data reporting in literature. CHP operating units used to recover heat and electricity from biogas were assumed to have an electrical conversion efficiency of 35%, a useful heat conversion efficiency of 38%, and an overall heat loss of 27% per

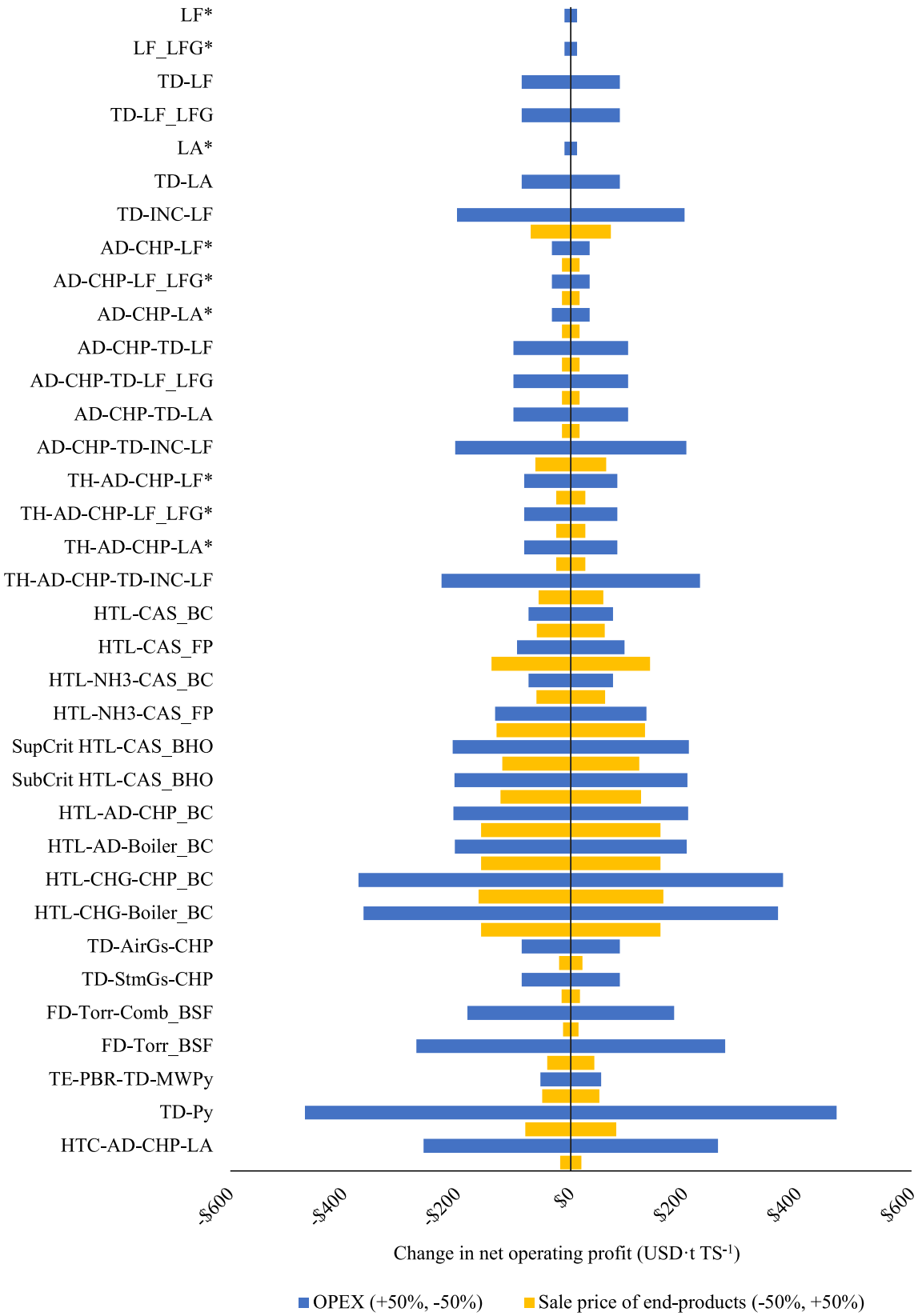

Fig. 4 | Sensitivity assessment evaluating the impact of OPEX and end-product market value on net operating profits. Sensitivity assessment evaluating the impact that a ±50% change in OPEX and end-product market value has on the net operating profits of each process.

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)

Fig. 5 | Grading criterion for environmental and commercial benefit of wastewater biosolids management options. Grading criterion for the environmental and commercial benefit of wastewater biosolids management options.

Hunt et al.[97]. Detailed calculations are included in Supplementary Tables 1–36.

To account for the life cycle primary energy consumed or displaced, energy return on investment (EROI) values were applied to electricity imports and exports, biofuel exports, transportation fuel consumption, and natural gas consumption. Like financial return on investment, which is a measure of the efficiency or profitability of an investment, EROI is simply the ratio of the energy delivered by a particular fuel to society and the energy invested in the capture and delivery of this energy[98]. EROI is an indicator of the economic value addition rather than thermodynamic efficiency of a resource. Therefore, only purchased energy inputs are accounted for under energy invested while the energy consumed in creating the resource such as solar radiation or atomic energy embodied in the resources, is typically excluded. Depending on at which point in the life cycle of an energy resource one calculates this ratio, say well-head or mine mouth for a fossil fuel, production of finished fuel (e.g., refinery gate or power plant) or final use (e.g., vehicle use or space heating or cooling) different estimates will result. For instance, EROI value of natural gas will be greater when estimated at the well-head compared to at the refinery gate, which will be greater than at the power plant due to increasing energy needs for cleaning and transportation and losses in conversion to an economically more useful (i.e., lower entropy) form as one goes up the value chain[98]. EROI for the direct use of fossil fuels to do useful work are higher than those for the generation of electricity. EROI comparisons are, therefore, more straightforward for a given resource, say comparing the EROI of oil from different countries and across time as opposed to comparing different resources, say comparing oil to coal or gas or solar.

$EROI_{fossil}$ values for the direct use of fossil fuels were reported to be 5 for petroleum diesel, 24 for crude and heating oil, 20 for Naphtha, 17 for natural gas, and 42 for coal, respectively[98–100]. Biofuel yields are process-specific. For bio-derived alternatives, $EROI_{fossil}$ was used to determine the avoided primary energy consumption. Detailed calculations are included in Supplementary Tables 1–36. $EROI_{diesel}$ and $EROI_{NG}$ are the EROI values for diesel imports for transportation and natural gas consumption for heating, respectively. Values for $EROI_{diesel}$ and $EROI_{NG}$ were reported to be 5 and 17, respectively[99,100]. $EROI_{elec}$ was determined by weighting the EROI of each source of electricity generation according to its percent contribution to the US electricity grid as expressed by Eq. (3):

$$\begin{aligned} EROI_{elec} = {} & \%NG \times EROI_{NG} + \%coal \times EROI_{coal} + \%nuclear \times EROI_{nuclear} \\ & + \%wind \times EROI_{wind} + \%hydro \times EROI_{hydro} + \%solar \\ & \times EROI_{solar} + \%diesel \times EROI_{diesel} + \%geothermal \\ & \times EROI_{geothermal} \end{aligned} \tag{3}$$

where %NG, %coal, %nuclear, %wind, %hydro, %solar, %diesel, and %geothermal are the percent contributions of natural gas, coal, nuclear, wind, hydroelectric, solar, liquid petroleum, and geothermal to the US electrical grid, respectively. In 2021 the US generated 32% of its electricity from natural gas, 26% from coal, 22% from nuclear, 8.5% from wind, 6.1% from hydroelectric, 3.8% from solar, 1% from liquid petroleum sources, and 0.6% from geothermal[101]. $EROI_{NG}$, $EROI_{coal}$, $EROI_{nuclear}$, $EROI_{wind}$, $EROI_{hydro}$, $EROI_{solar}$, $EROI_{diesel}$, and $EROI_{geothermal}$ are the EROIs for electricity generated from natural gas, coal, nuclear, wind, hydroelectric, solar, liquid petrol, and geothermal, respectively. The EROI values for electricity generation were reported to be 7 for $EROI_{NG}$, 14 for $EROI_{coal}$, 9 for $EROI_{nuclear}$, 22 for $EROI_{wind}$, 94 for $EROI_{hydro}$, 9 for $EROI_{solar}$, 20 for $EROI_{diesel}$ and 9 for $EROI_{geothermal}$[100]. It should be noted that EROI values are dependent on many factors, including but not limited to geographic location, time of year, and quality of the primary energy resource[100]. Therefore, average EROI values for each primary energy resource were used as reported in the literature[98–100].

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. (4):

$$E_{diesel} = \frac{\dot{m}_d \times e_d \times \frac{WS_f}{TS_i} \times d_t \times 2.2046}{\rho_d \times 3,412} \tag{4}$$

where E_{diesel} is the energy demand for transportation to final disposal (kWh·t TS_i^{-1}); $\dot{m}_d$ is the consumption rate of diesel for transportation provided by Suh and Rousseaux[102] (0.0635 kg·km^{-1}·t WS_f^{-1}); e_d is the energy density of diesel fuel provided by the U.S. Energy Information Administration (EIA) (137,381 Btu·gal^{-1}); 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^{-1}); 3,412 is the conversion of BTU to kWh. It was assumed that final waste residues were transported 160 km (~100 mi) to final disposal sites, since wastewater biosolids are typically hauled by truck one-way distances of up to 160 km for landfill disposal and land application[1,103]. Boston, Massachusetts, and New York City, for example, transport their biosolids long distances out of state[103]. For process scenarios that utilize landfill disposal for final residuals, it was assumed that landfill gas was captured and combusted to minimize methane gas emissions. Electricity generation from combusted landfill gas was determined for lifecycle and economic comparison. The landfill gas production rate was determined using methods established by Zhao et al.[80] and was calculated using Eq. (5):

$$P_{LFG} = \frac{TS_f}{TS_i} \times VS_{LF} \times DOC_F \times \frac{16}{12} \times MCF \times (1 - OX) \times F_{CH_4} \tag{5}$$

where P_{LFG} is the amount of CH_4 produced per metric ton of total solids managed (kg CH_4·t TS_i^{-1}); 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[80]. The effective electricity generation was calculated using Eq. (6):

$$E_{elec,LFG} = P_{LFG} \times R_{LFG} \times H_{LFG} \times \eta_{comb} \tag{6}$$

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^{-1}); R_{LFG} is the landfill gas recovery efficiency (%). The landfill gas recovery efficiency was assumed to be 80% according to Zhao et al.[80]. H_{CH4} is the lower heating value of methane, which was reported to be 55.048 MJ kg^{-1} by McAllister et al. 2011[104]. η_{comb} is the conversion efficiency for electricity generation from landfill gas, which was assumed to be 55% according to Storm 2020[105]. A positive E_{NET} value corresponds with a net energy export from the system boundaries. Each process receives a grade ranging from 0 to 3 scaled linearly between the lowest and highest E_{NET} values as follows: −3036 kWh·t TS_i^{-1} = 0 and 5006 kWh·t TS_i^{-1} = 3.

Net CO_2e emissions were calculated using a life cycle approach for 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. (7):

$$\begin{aligned} CO_2e_{NET} = {} & \left(E_{elec,out} + E_{elec,LFG} - E_{elec,in}\right) \times EF_{elec} + E_{NG,in} \times EF_{NG,in} + E_{diesel} \\ & \times EF_{diesel} + CO_2e_{LFG,rel} + CO_2e_{N_2O,LA} + CO_2e_{N_2O,Inc} \\ & - CO_2e_{disp,fuels} - CO_2e_{disp,fertilizers} \end{aligned} \tag{7}$$

where $CO_2e_{LFG,rel}$ 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; $CO_2e_{disp,fuels}$ 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, which was estimated to be 130 kg $CO_2e{\cdot}t\ TS_i^{-1}$ based on Zhao et al. 2019[80]. Detailed calculations for $CO_2e_{disp,fertilizers}$ is included in Supplementary Table 36. All values were normalized to the CO_2e emissions per metric ton of solids managed (kg $CO_2e{\cdot}t\ TS_i^{-1}$). To account for the lifecycle CO_2e emissions of primary energy consumption and displacement, emission factors were applied to electricity, natural gas, and diesel imports and exports reported as g $CO_2e{\cdot}kWh^{-1}$. EF_{elec}, $EF_{NG,in}$, and EF_{diesel}, are the emission factors for electricity, natural gas, and diesel, respectively. $EF_{NG,in}$ and EF_{diesel} were reported in literature to be 434 and 454 g $CO_2e{\cdot}kWh^{-1}$, respectively[99,106]. EF_{elec} was determined by weighting the emission factors of each source of electricity generation according to its percent contribution to the US electricity grid as expressed by Eq. (8):

$$\begin{aligned} EF_{elec} = {} & \%NG \times EF_{NG} + \%coal \times EF_{coal} + \%nuclear \times EF_{nuclear} + \%wind \\ & \times EF_{wind} + \%hydro \times EF_{hydro} + \%solar \times EF_{solar} + \%petrol \\ & \times EF_{petrol} + \%geothermal \times EF_{geothermal} \end{aligned} \tag{8}$$

where %NG, %coal, %nuclear, %wind, %hydro, %solar, and %petrol are the percent contributions of natural gas, coal, nuclear, wind, hydroelectric, solar, and liquid petroleum to the US electrical grid, respectively, used in Eq. (3). EF_{NG}, EF_{coal}, $EF_{nuclear}$, EF_{wind}, EF_{hydro}, EF_{solar}, EF_{petrol}, and $EF_{geothermal}$ are the emission factors for electricity generation source from natural gas, coal, nuclear, wind, hydroelectric, solar, and liquid petroleum, respectively. Emission factors were reported in literature to be 434 g $CO_2e{\cdot}kWh^{-1}$ for EF_{NG}, 1023 g $CO_2e{\cdot}kWh^{-1}$ for EF_{coal}, 5.13 g $CO_2e{\cdot}kWh^{-1}$ for $EF_{nuclear}$, 12.4 g $CO_2e{\cdot}kWh^{-1}$ for EF_{wind}, 10.7 g $CO_2e{\cdot}kWh^{-1}$ for EF_{hydro}, 36.7 g $CO_2e{\cdot}kWh^{-1}$ for EF_{solar}, 454 g $CO_2e{\cdot}kWh^{-1}$ for EF_{petrol} 47 g $CO_2e{\cdot}kWh^{-1}$ for $EF_{geothermal}$[94,99,106,107]. Fugitive CH_4 and N_2O emissions from final disposal practices were determined using methodologies established by Zhao et al[80]. CO_2e of fugitive CH_4 emissions from landfilled waste residues were calculated using Eq. (9):

$$CO_2e_{LFG,rel} = P_{LFG}\left(1 - R_{LFG}\right) \times 25 \tag{9}$$

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[80]. CO_2e of fugitive N_2O emissions from land-applied waste residues were calculated using Eq. (10):

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

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[80]. CO_2e of fugitive N_2O emissions from incinerated waste residues were calculated using Eq. (11):

$$CO_2e_{N_2O,INC} = \frac{TS_{INC}}{TS_i} \times TN_{INC} \times EF_{N_2O,INC} \times \frac{44}{28} \times 298 \tag{11}$$

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.[80]. Life cycle greenhouse gas emissions avoided from the displacement of fossil-derived fertilizers with biosolid soil amendment was estimated to be 130 kg $CO_2e{\cdot}t\ TS_i^{-1}$ based on Zhao et al.[80]. 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 Supplementary Tables 1–36. The life cycle CO_2e emissions displaced from the sale of biofuels was calculated from the total thermal energy of a derived biofuel per tonne of solids managed multiplied by the life cycle emission factor (EF) of the displaced fossil fuel according to Eq. (12):

$$CO_2e_{disp,fuels} = E_{prod} \times EF_{fossil} \tag{12}$$

where E_{prod} is the energy derived from a biofuel production as reported in literature normalized over the total solids managed for each process (kWh·t TS_i^{-1}); EF_{fossil} is the well-to-wheel emission factor for the displaced fossil fuel (g $CO_2e{\cdot}kWh^{-1}$); Displaced fossil fuels included diesel, crude oil, naphtha, natural gas, and coal. Well-to-wheel emission factors for each fossil fuel were 454, 319, 460, 434, and 1,023 g $CO_2e{\cdot}kWh^{-1}$ for diesel, crude oil, naphtha, natural gas, and coal, respectively, per values reported in literature[94,106,108]. The sale of biocrude oil displaces greenhouse gas emissions related to extraction of crude oil and the combustion of derived fuels from crude oil. However, greenhouse gas emissions related to the refining of crude oil are not avoided through the sale of biocrude oil. Therefore, $EF_{disp,fuels}$ for crude oil ($EF_{disp,crude}$) was calculated from values provided Rahman et al. according to Eq. (13):

$$\begin{aligned} EF_{disp,cude} = {} & Y_{gasoline}\left(EF_{gasoline} - EF_{refining,gasoline}\right) \\ & + Y_{diesel}\left(EF_{diesel} - EF_{refining,diesel}\right) \\ & + Y_{jet\ fuel}\left(EF_{jet\ fuel} - EF_{refining,jet\ fuel}\right) \end{aligned} \tag{13}$$

Where $Y_{gasoline}$, Y_{diesel}, and $Y_{jet\ fuel}$ are the volumetric yields of gasoline, diesel, and jet fuel, respectively, from California's Kern County heavy oil; $EF_{gasoline}$, EF_{diesel}, and $EF_{jet\ fuel}$ are the well-to-wheel emission factors for gasoline, diesel, and jet fuel, respectively; $EF_{refining,gasoline}$, $EF_{refining,diesel}$, and $EF_{refining,jet\ fuel}$ are the emission factors associated with the refining of gasoline, diesel, and jet fuel, respectively. The volumetric yields of gasoline, diesel, and jet fuel were reported to be 0.46, 0.28, and 0.07 barrel-per-barrel, respectively, from California's Kern County heavy oil. Well-to-wheel emission factors for gasoline, diesel, and jet fuel were reported to be 127.74, 126.02, and 118.17 g $CO_2e{\cdot}MJ^{-1}$, respectively. The emission factors associated with refining crude oil into saleable fuel products were 18.70, 15.33, and 9.92 g $CO_2e{\cdot}MJ^{-1}$ for gasoline, diesel, and jet fuel, respectively[106]. To avoid over-optimistic scoring, processes that produce higher net CO_2e emissions relative to anaerobic digestion followed by landfill application (≥2.06 t $CO_2e{\cdot}t\ TS_i^{-1}$) receive a grade of 0. Processes that produce less net CO_2e emissions than anaerobic digestion followed by landfill application (<2.06 t $CO_2e{\cdot}t\ TS_i^{-1}$) receive grades ranging from 0 to 3, which are scaled

Table 5 | Summary of TEA of physical, thermochemical, and biological pathways

Source	Process	Plant capacity	Operating conditions	End-product(s)
[80,96]	LF	80 MT·day^{-1}	Dewatered via belt press to 80% MC and disposed in landfill without landfill gas capture.	Biosolids
[80,96]	LF_LFG	80 MT·day^{-1}	Dewatered via belt press to 80% MC, and disposed in landfill, 80% CH_4 emissions captured from landfill gas and combusted.	Biosolids, Electricity
[80,96]	TD-LF	80 MT·day^{-1}	Dewatered via belt press to 80% MC, Thermal dried to 50% MC, disposed in landfill without landfill gas capture.	Biosolids
[80,96]	TD-LF_LFG	80 MT·day^{-1}	Dewatered via belt press to 80% MC, Thermal dried to 50% MC, and disposed in landfill, 80% CH_4 emissions captured from landfill gas and combusted for electricity generation.	Biosolids, Electricity
[80,96]	LA	80 MT·day^{-1}	Dewatered via belt press to 80% MC, Land applied in agricultural setting.	Land applied biosolids
[80,96]	TD-LA	80 MT·day^{-1}	Dewatered via belt press to 80% MC, Thermal dried to 50% MC, Land applied in agricultural setting.	Land applied biosolids
[80,96]	TD-INC-LF	80 MT·day^{-1}	Dewatered via belt press to 80% MC, Thermal dried to 57.7% MC, incinerated at 800–900 °C, disposed in landfill.	Electricity, Ash
[80,96]	AD-CHP-LF	80 MT·day^{-1}	Thicken to 97% MC, Mesophilic anaerobic digester with heat and electricity production from biogas, dewatered via belt press to 80% MC, disposed in landfill without landfill gas capture.	Electricity, Biosolids
[80,96]	AD-CHP-LF_LFG	80 MT·day^{-1}	Thicken to 97% MC, Mesophilic anaerobic digester with heat and electricity production from biogas, Belt press to 80% MC, 80% CH_4 emissions from landfill captured and combusted for electricity generation.	Electricity, Biosolids
[80,96]	AD-CHP-LA	80 MT·day^{-1}	Thicken to 97% MC, Mesophilic anaerobic digester with heat and electricity production from biogas, Belt press to 80% MC, Land applied in agricultural setting.	Electricity, Land applied biosolids
[80,96]	AD-CHP-TD-LF	80 MT·day^{-1}	Thicken to 97% MC, Mesophilic anaerobic digester with heat and electricity production from biogas, Belt press to 80% MC, Thermal dry to 41.3% MC.	Electricity, Biosolids
[80,96]	AD-CHP-TD-LF_LFG	80 MT·day^{-1}	Thicken to 97% MC, Mesophilic anaerobic digester with heat and electricity production from biogas, Belt press to 80% MC, Thermal dry to 41.3% MC, 80% CH_4 emissions from landfill captured and combusted for electricity generation.	Electricity, Biosolids
[80,96]	AD-CHP-TD-LA	80 MT·day^{-1}	Thicken to 97% MC, Mesophilic anaerobic digester with heat and electricity production from biogas, Belt press to 80% MC, Land applied in agricultural setting.	Biogas, Land applied biosolids
[80,96]	AD-CHP-TD-INC-LF	80 MT·day^{-1}	Thicken to 97% MC, Mesophilic anaerobic digester with heat and electricity production from biogas, Belt press to 80% MC, Incineration at 800–900 °C.	Biogas, Electricity, Ash
[80,96]	TH-AD-CHP-LF	80 MT·day^{-1}	Belt press to 80% MC, Thermal hydrolysis, mesophilic, Mesophilic anaerobic digester with heat and electricity production from biogas, belt press to 80%	Biogas, Biosolids
[80,96]	TH-AD-CHP-LF_LFG	80 MT·day^{-1}	Belt press to 80% MC, Thermal hydrolysis, mesophilic, Mesophilic anaerobic digester with heat and electricity production from biogas, belt press to 80%, 80% CH_4 emissions from landfill captured and combusted for electricity generation.	Biogas, Biosolids
[80,96]	TH-AD-CHP-LA	80 MT·day^{-1}	Belt press to 80% MC, Thermal hydrolysis, mesophilic, Mesophilic anaerobic digester with heat and electricity production from biogas, belt press to 80%, Land applied in agricultural setting.	Biogas, Land applied biosolids
[80,96]	TH-AD-CHP-TD-INC-LF	80 MT·day^{-1}	Belt press to 80% MC, Thermal hydrolysis, mesophilic, Mesophilic anaerobic digester with heat and electricity production from biogas, belt press to 80%, Thermal dry to 41.3% MC, Incineration at 800–900 °C	Biogas, Electricity, Ash
[57]	HTL-CAS_BC	99.8 MT·day^{-1}	Belt press to 80% MC, HTL (Residence time: 17 min, Pressure: 205 bar, Temp: 347 °C), aqueous coproducts returned to headworks.	Biocrude
[57]	HTL-CAS_FP	99.8 MT·day^{-1}	Belt press to 80% MC, HTL (Residence time: 17 min, Pressure: 205 bar, Temp: 347 °C), aqueous coproducts returned to headworks.	Diesel, Naphtha, Gasoline
[67]	HTL-NH3-CAS_BC	99.8 MT·day^{-1}	Belt press to 80% MC, HTL (Residence time: 17 min, Pressure: 205 bar, Temp: 347 °C), ammonia stripping, aqueous coproducts returned to headworks.	Biocrude
[67]	HTL-NH3-CAS_FP	99.8 MT·day^{-1}	Belt press to 80% MC, HTL (Residence time: 17 min, Pressure: 205 bar, Temp: 347 °C), ammonia stripping, aqueous coproducts returned to headworks.	Diesel, Naphtha, Gasoline
[64]	SupCrit HTL-CAS_BHO	20 MT·day^{-1}	Belt press to 80% MC, HTL (Pressure: 230 bar, Temp: 375 °C), aqueous coproducts returned to headworks.	Bioheavy Oil
[64]	SubCrit HTL-CAS_BHO	20 MT·day^{-1}	Belt press to 80% MC, HTL (Pressure: 120 bar, Temp: 325 °C), aqueous coproducts returned to headworks.	Bioheavy Oil
[63]	HTL-AD-CHP_BC	4.8 MT·day^{-1}	Belt press to 80% MC, HTL (Pressure: 200 bar, Temp: 350 °C), aqueous coproducts treated with mesophilic anaerobic digester with heat and electricity production from biogas	Biocrude
[63]	HTL-AD-Boiler_BC	4.8 MT·day^{-1}	Belt press to 80% MC, HTL (Pressure: 200 bar, Temp: 350 °C), aqueous coproducts treated with mesophilic anaerobic digester with heat and production from biogas	Biocrude
[63]	HTL-CHG-CHP_BC	4.8 MT·day^{-1}	Belt press to 80% MC, HTL (Pressure: 200 bar, Temp: 350 °C), CHG to produce gas combusted to produce heat and electricity.	Biocrude, Electricity
[63]	HTL-CHG-Boiler_BC	4.8 MT·day^{-1}	Belt press to 80% MC, HTL (Pressure: 200 bar, Temp: 350 °C), CHG to produce gas combusted to produce heat.	Biocrude

Table 5 (continued) | Summary of TEA of physical, thermochemical, and biological pathways

Source	Process	Plant capacity	Operating conditions	End-product(s)
[38]	TD-AirGs-CHP	5 MT·day^{-1}	Dewatered via belt press to 80% MC, Thermal drying, Air-blown gasification (Pressure: atmospheric, Temp: 850 °C) syngas combusted to produce heat and electricity.	Electricity
[38]	TD-StmGs-CHP	5 MT·day^{-1}	Dewatered via belt press to 80% MC, Thermal drying, steam gasification (Pressure: atmospheric, Temp: 850 °C) syngas combusted to produce heat and electricity.	Electricity
[54]	FD-Torr-CHP_BSF	9 MT·day^{-1}	Dewatered via belt press to 80% MC, Fry-drying (Oil Temp: 370 °C), Torrefaction, biochar combusted to produce heat and electricity for operation.	Biochar, Electricity
[54]	FD-Torr_BSF	9 MT·day^{-1}	Dewatered via belt press to 80% MC, Fry-drying (Oil Temp: 370 °C), Torrefaction	Biochar
[74]	TE-PBR-TD-MWPy	265 MT·day^{-1}	FOG fractionated from influent, Transesterification to produce diesel, glycerol recycled to PBR to produce algae, algae and biosolids dried, microwave pyrolysis (Temp: 500 °C)	Biodiesel, Bio-oil, syngas, Phosphorus Fertilizer
[51]	TD-Py	1.2 MT·day^{-1}	Dewatered via belt press to 80% MC, Thermal drying, pyrolysis (Pressure: atmospheric, Temp: 200–1000 °C)	Biochar, Biogas, Bio-oil
[70]	HTC-AD-CHP-LA	20.6 MT·day^{-1}	Belt press to 80% MC, HTC (Pressure: 20 bar, Temp: 208 °C, Residence time: 1 h), aqueous coproducts treated with mesophilic anaerobic digester w/ heat and electricity production from biogas, digestate land applied in agricultural setting	Hydrochar, Biogas, Land-applied Biosolids

Table 6 | Definition of process-specific acronyms

Abbreviation	Definition
AD	mesophilic anaerobic digestion
AirGs	air-blown gasification
BC	biocrude
BHO	bio-heavy oil
Boiler	boiler
BSF	bio-solid fuel
CAS	conventional activated sludge
CHG	catalytic hydrothermal gasification
CHP	combined heat and power
FD	fry dry
FP	fuel products
HTC	hydrothermal carbonization
HTL	hydrothermal liquefaction
INC	incineration
LA	land application
LF	landfill
LFG	landfill gas collection
MWPy	microwave pyrolysis
NH_3	ammonia stripping
PBR	photobioreactor
Py	pyrolysis
StmGs	steam gasification
SubCrit HTL	subcritical hydrothermal liquefaction
SupCrit HTL	supercritical hydrothermal liquefaction
TD	thermal drying
TE	transesterification
TH	thermal hydrolysis
Torr	torrefaction

linearly between the following upper and lower limits: 2.06 t CO_2e·t TS_i^{-1} = 0 and −3.61 t CO_2e·t TS_i^{-1} = 3.

CAPEX includes the total installed cost of equipment as reported for each process scenario in literature and excludes other direct costs such as site civil development, and indirect costs such as project contingency, startup permits, legal, working capital, and land requirements. The cost of land and equipment associated with landfill infrastructure is also not included as part of CAPEX. All CAPEX values reported in literature are adjusted to the 2019 economic year and normalized to the respective plant capacity (USD·t TS_i^{-1}·d^{-1}). Emerging 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^{-1} receive a grade of 0. Processes that have a CAPEX less than 1-million USD·t TS_i^{-1} receive grades ranging from 0 to 3, which are scaled linearly according to the following upper and lower limits: 1-million USD·t TS_i^{-1} = 0 and 0 USD·t TS_i^{-1} = 3.

Net operating profit included the deduction of all operating expenses from the revenues produced by each process and was calculated using Eq. (14):

$$\mathrm{NOP} = R - \mathrm{OPEX} - \mathrm{TDC} \tag{14}$$

Where NOP is net operating profit normalized to the initial dry mass of solids managed (USD·t TS_i^{-1}); 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 this analysis are included in Supplementary Tables 1–35. Although the NPV of a process configuration may be calculated as a function of CAPEX and NOP, 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[4]. OPEX is operating expenses normalized to the initial dry mass of solids managed (USD·t TS_i^{-1}). 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^{-1}). TDC is transportation and disposal costs normalized to the initial dry mass of solids managed (USD·t TS_i^{-1}). Transportation and disposal costs were often not reported for each respective process scenario and were therefore calculated using Eq. (15) derived from Marufuzzaman et al. 2015[95]:

$$\mathrm{TDC} = \frac{\mathrm{TS_f}}{\mathrm{TS_i}} \times \frac{\left(\mathrm{TF} + \mathrm{FC} + \frac{\mathrm{VC}}{1.61} \times d_\mathrm{T}\right)}{\rho_s} \times 1,000 \times 1.08 \tag{15}$$

Where TDC is transportation and disposal cost normalized to the initial dry mass of solids managed (USD·t TS_i^{-1}); 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[109]. 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^{-1} as reported by

Marufuzzaman et al.[95]. The standard conversion from miles to kilometers is 1.61. d_T is the distance to final disposal and was assumed to be 160 km as described above. 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 NOP calculated for thermal drying followed by pyrolysis is significantly lower than all other process scenarios. To avoid skewed scoring of other processes, NOP values lower than −400 USD·t TS_i^{-1} receive a grade of 0. All other processes receive grades ranging from 0 to 3, which are scaled linearly between the following upper and lower limits: −400 USD·t $TS_i^{-1} = 0$ and 76 USD·t $TS_i^{-1} = 3$. 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.

TRLs were reported based on the commercial maturity of each respective technology according to methodologies established by NASA[110,111]. Each process receives a grade ranging from 0 to 3, which is scaled linearly between TRL scores of 0–9, respectively.

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. (16):

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{\mathrm{NOP}}{(1+i)^t} - \mathrm{CAPEX} \tag{16}$$

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·d^{-1}), 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[92]. 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[112].

Boundaries for analysis presented in Fig. 1 assumed combined primary and secondary wastewater biosolids entered the system at a moisture content of 97–99%[4]. CO_2 equivalence 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 were 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 Supplementary Tables 1–36.

The selection and analysis of scientific literature were 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 discuss 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 established and emerging biosolids management processes. The literature survey in Table 5 presents the operating conditions of the 35 process scenarios. In total, the relevant content of this paper includes 112 articles (in journals and conference proceedings), reports, books, and databases.

Data availability

The authors declare that the data supporting the findings of this study are available within the paper and its supplementary information files.

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Author contributions

E.H. and K.C. conceived of the presented analysis. K.C. wrote the manuscript with support from E.H. and D.R. D.R. provided guidance related to life cycle assessment, greenhouse gas emissions, and energy return on investment. All authors provided critical feedback and helped shape the research, analysis, and manuscript. E.H. supervised the project.

Competing interests

All authors declare no competing interests.

Additional information

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