

Rethinking sewage sludge valorisation options and pathways via thermochemical output upgrading: a product-oriented analysis

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ABSTRACT

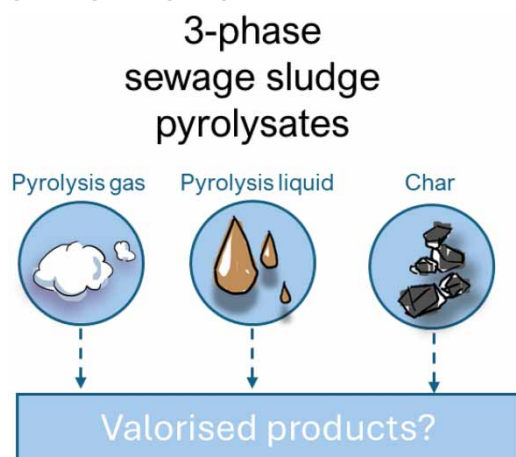
The recycling of digested sewage sludge (biosolids) to land is common, offering soil and nutrient benefits. However, regulatory uncertainty, emerging contaminants, and limited land availability call for alternative strategies. Thermochemical options, including pyrolysis and gasification, enable resource and energy recovery from sludge, producing outputs like biochar, syngas, and bio-oil. This study evaluates the potential of sludge pyrolysis alongside gasification by reviewing conceptual plant designs and assessing economic and technical feasibility. Pyrolysis gas, or syngas, upgrading is capital intensive but can yield high-value outputs. Alternatively, direct combustion of pyrolysis gas and syngas for heat or power offers lower post-treatment needs and economic viability, especially on large scales if quality standards are met. The research also examines sustainability and operational feasibility, noting key challenges such as sludge drying energy demands, feedstock variability, and regulatory uncertainty around land application of biochar. The findings support sustainable sludge management by identifying promising valorisation pathways and informing circular economy approaches in wastewater treatment. Further research is needed to optimise processes, improve output upgrading, and develop supportive regulatory frameworks.

Key words: conceptual plant, data synthesis, pyrolysis, resource recovery, sewage sludge, techno-economic analysis

HIGHLIGHTS

- Potential products from sewage sludge derived via pyrolysis are gas, liquid, and char.
- Output options identified and appraised.
- Techno-economic data were reviewed for comparison in terms of yield, capital cost, environmental impact, and efficiency.
- Char and syngas are potentially the most beneficial options.
- Environmental compliance and end-of-waste remain a challenge.

GRAPHICAL ABSTRACT



- What are the options
- How do their processes perform
- Which is the most desirable
- Regulative and technical challenges

INTRODUCTION

In the UK, treated sewage sludge (biosolids) is commonly applied to agricultural land under controlled conditions. This practice, however, faces growing uncertainty due to evolving regulations and environmental concerns (Water UK 2023). Currently, around 3.6 million tonnes of biosolids are land-applied annually following anaerobic digestion (frequently with thermal hydrolysis pre-treatment) and dewatering (Water UK 2025). The future of this disposal route is threatened by diminishing land bank availability and increasing scrutiny over pollutants such as organic contaminants, microplastics, and emerging substances. As a result, the wastewater sector is exploring alternative sludge management strategies that are both sustainable and scalable. Thermochemical conversion technologies, particularly pyrolysis, offer promising options by transforming sewage sludge into value-added outputs. These include biochar potentially for soil amendment (restoring nutrients where biosolids are restricted), syngas for hydrogen production, and pyrolysis liquid that may be converted to transportation fuels (Basri *et al.* 2025).

During the course of pyrolysis reaction, thermally dried sewage sludge solid releases its remaining free and bond moisture content as water vapour when it is first exposed to the heat, and as the solid feedstock continues to be heated up, the organic content (protein, lipids, carbohydrates, and fibre) start to break down under high temperature to form the pyrolysis vapour, which main components are H_2O , H_2 , CO , CO_2 , CH_4 , other hydrocarbon molecules, and condensable organic compounds (Hu *et al.* 2021). After condensation and at ambient temperature, the condensable fraction of the vapour is the pyrolysis liquid, and the non-condensable fraction is the pyrolysis gas. The solid residue left after devolatilisation is the char, which is rich in carbon and inorganics. Together, the pyrolysis gas, pyrolysis liquid, and char form the three phases of pyrolysate. Different thermochemical conversion technologies allow for the maximised production of each phase, e.g., gasification for the gas phase, fast pyrolysis or hydrothermal liquefaction for the liquid phase, and slow pyrolysis for the char. Valorised outputs can be obtained from upgrading any of the three phases, and it is up to the decision maker to decide which product to recover, depending on the process viability, the type of project, and the long-term benefits. Techno-economic analysis (TEA) on the potential recovery plant is used to assess the process, economic, environmental, and efficiency performance of the designed process, with these four performance assessments being important pillars of TEA.

However, a gap in knowledge still exists in knowing a comprehensive list of potential products, understanding how their corresponding plants' potential performance compares, and selecting the most desirable option. Decision-making regarding the selection of the optimal method for sewage sludge management can be found in a number of studies, involving the competency of pyrolysis compared to other thermal sludge management methods such as gasification and incineration (Samolada

& Zabaniotou 2014; Turunen *et al.* 2018; Zhou *et al.* 2020; Hosseinian *et al.* 2024). These decision-making processes were developed for specific cases and used different selection frameworks, mostly with options being numerically compared after a weighted calculation. For the product options derived from the pyrolysates from sewage sludge, the literature review by Hu *et al.* discussed the valorisation of each of the three phases of sewage sludge pyrolysate, regarding the general upgrading processes, and the possible end-products were appraised (2022). To provide new insights about the process of sewage sludge pyrolysis, Chang *et al.* reviewed the datasets from 37 studies on the three-phase pyrolysate yield on sewage sludge pyrolysis. They concluded that the energy output from these pyrolysis datasets was difficult to estimate (2022).

Thus, a shortage remains in the literature for an analysis that includes a list of output options that considers sewage sludge as the primary feedstock, and the critical analysis of the comparisons of these options. Thus, this study aims to appraise the techno-economic potential of various options for upgrading sewage sludge pyrolysis outputs. This comprises a comprehensive list of the potential options, comparing the four important pillars of the TEA, and suggesting the most desirable option based on a gross benefit metric. Reviewing TEA information from existing studies based on the four pillars was previously unexplored, to the best of our knowledge. The term 'product' in this paper is used interchangeably with the term 'output' in the sense that a thermochemical reaction results in a product, as well as being a potential product on the market.

METHODS

The output-oriented analysis started with identifying a list of potential products, followed by reviewing the performance of the integrated conversion and upgrading plants, and the selection of the most desirable product. This is demonstrated in Figure 1. To compile the list of potential products, each was verified to originate from either pyrolytic gas, liquid, or char. The search on technoeconomic information was conducted on the online database Google Scholar for journal articles, and on the search engine Google for project reports. The search keywords include 'product name' + 'techno-economic assessment', and the search results were manually selected. Sewage sludge was the preferred feedstock; however, due to limited studies, other feedstocks, such as biomass, municipal solid waste, and digestate, were also included. The plants are thermochemical conversion plants integrated with the necessary output upgrading. In total, 123 datasets were extracted (82 on gas, 33 on liquid, 8 on char). Plants using thermochemical conversion technologies other than pyrolysis were also appraised (48 datasets on pyrolysis, 74 on gasification, 1 on hydrothermal liquefaction). Key performance parameters, including process configuration, economic metrics, and energy/exergy efficiencies, were extracted and tabulated and can be found in the supplementary material. Data were recorded in their original form to account for variations in parameter definitions, particularly capital cost. Table 1 presents an overview of the referenced pilot and conceptual plants.

Process and economic performance of the potential plants for the different outputs were analysed quantitatively by using specific yield and unit capital cost, respectively. Specific yield is defined as the mass of product per mass of dry feedstock, excluding impurities and contributions from external feedstocks unless they significantly alter the synthesis reaction regime (e.g., hydrogen injection). Unit capital cost is defined as the capital cost per annual throughput (in tpa, tonnes per annum) of dry feedstock, with all costs converted to British pounds. Both the literature search and the currency conversion were completed in 2022. Process performance and economic performance were analysed qualitatively. Specific revenue was used to select the most valuable product option. It is defined as the product's potential selling price (per kg), divided by its specific yield, representing gross revenue per kg of dry sludge. Pyrolysis outputs, including gaseous, liquid, and solids, will require upgrading; however, the cost of upgrading has not been accounted for in this analysis. When necessary, prices were derived or adjusted using proxies; for example, syngas prices were inferred from natural gas prices based on energy

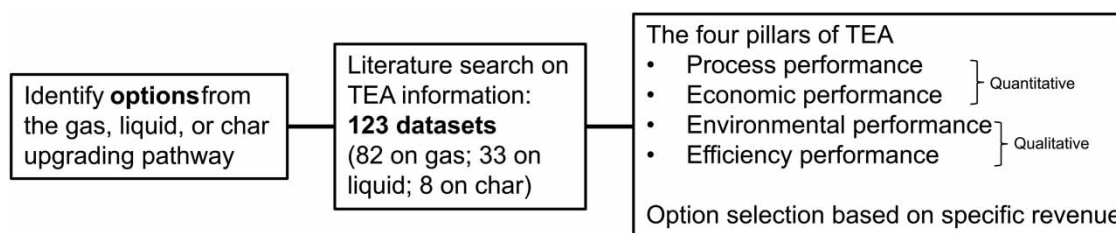


Figure 1 | The stages of the output-oriented analysis.

Table 1 | Overview of the reviewed studies on pilot or conceptual plants of thermochemical conversion and output upgrading.

Target output	Number of plants reviewed	Thermochemical technology	Feedstock and Throughput ranges (dry basis)	
			Sewage sludge	Non-sewage sludge
Gas	82 plants • Pilot plant (1) • Conceptual (81)	Pyrolysis (8)	7 plants (279 kg/h–17.4 t/h)	1 plant (100 t/h)
		Gasification (74)	15 plants (226 kg/h–30 t/h)	59 plants (20 kg/h–192 t/h)
Liquid	33 plants • Pilot plants (2) • Conceptual plants (31)	Pyrolysis (32)	6 plants (2 kg/h–11 t/h)	26 plants (50 kg/h–76 t/h)
		Hydrothermal liquefaction (1)	1 plant (833 kg/h)	0 plant
Char	8 conceptual plants	Pyrolysis (8)	3 plants (75–919 kg/h)	5 plants (1.25–83 t/h)

The three-phase thermochemical output is gas, liquid, and char, each of which can serve as a starting point to be upgraded to end-products.

Notes:

- Plant data: 3 entries out of 123 entries were from actual plant operation. 120 entries were conceptual plants, where data were based on process simulation. Some of the process simulations were completely based on simulated data, whereas others incorporated empirical data in part of the plant.
- In the reviewed studies, feedstock enters the plant with various moisture contents and is dried prior to thermochemical conversion if drying is required.

content (under the understanding that syngas is not inherently a natural gas substitute). Specific yield, unit capital cost, and the estimated selling prices are also included in the supplementary data.

RESULTS AND DISCUSSION

The output options and their pathways

The output options were identified by exploring the upgrading of the three phases, namely, the products obtained from the upgrade of gas, liquid, or char. The sludge-to-gas products are based upon the syngas-derived bulk chemicals, where their synthesis step utilises the same technology as the processes with syngas produced from natural gas reforming or coal gasification. The gas tailoring step of sludge-based processes requires specific designs to improve the syngas quality, because sewage sludge-derived fuels contain more impurities compared to coal or natural gas (Freda *et al.* 2019). The sludge-to-liquid products were identified as upgrading the pyrolysis liquid to a desired application, such as for co-refining in petroleum refineries (Talmadge *et al.* 2014), and for biochemicals production via extraction (Fonts *et al.* 2017). Wood constituents (cellulose, hemicellulose, and lignin) are found in sewage sludge due to toilet paper material (Djandja *et al.* 2020). Although conventional pyrolysis of sewage sludge destroys some wood-macromolecule-based biochemicals such as sugars (Fonts *et al.* 2017), to maximise the recovery of those chemicals, the optimum technique may be to pyrolyse the cellulosic material (toilet paper) recovered from the first stage of sewage treatment, where this feedstock could be obtained by retrofitting fine screens at the head of the sewage treatment work if not already in place (Khan *et al.* 2021). Thus, wood-macromolecule-based biochemicals, including sugars, furan derivatives, phenols, and acetates, are considered potential products from upgrading sewage sludge pyrolysates. Pyrolytic char derived from sewage sludge may be upgraded to an activated carbon substitute, a high-value product. The comprehensive product options are shown in Table 2. This list only includes products that have reached the conceptual plant study stage, with their study identifiable in the literature. This prerequisite ultimately reduces a long list

Table 2 | The potential products from upgrading the three phases

Sludge-to-gas	Sludge-to-liquid	Sludge-to-char
- Crude syngas	Bio-oil by application:	- Char (for soil amendment or applications as a fuel)
- Hydrogen	- Insertion into crude refineries	- Activated carbon
- Synthetic natural gas	- Transport fuels or stationary engine fuels	
- Methanol	- Aromatics or olefins	
- Dimethyl Ether (DME)	- Syngas via steam reforming, gasification, or fermentation	
- Methanol or DME-derived hydrocarbons	Biochemicals:	
- Other methanol and DME derivatives	- Sugars (levoglucosan, levoglucosenone)	
- Ethanol and other higher alcohols	- Furan derivatives (furfural, 5-Hydroxymethylfurfural)	
- Ammonia	- Phenols	
- Fischer-Tropsch (FT) products	- Acetic acid or acetate salts, glycolaldehyde, and acetol	

of biochemicals from sewage sludge-derived pyrolysis liquids, which are nitrogen-containing compounds, including nitriles, acetamide, and nitrogen-heterocyclic compounds (Fonts *et al.* 2017). Some applications of the sewage sludge char are not included in Table 2 due to not reaching the stage of conceptual plant study; such possible applications include anode material and capacitors (Hedayati Marzbali *et al.* 2024). This work identifies the sewage sludge pyrolysate valorisation options by presenting the different options from the upgrading of the three-phase products, whereas in the research by Hu *et al.* (2022), the three-phase discussion is less focused (Hu *et al.* 2022). The desired pyrolysate phase could be either gas, liquid, char, or a combination of the three, and optimised pyrolysis technology may be selected based on this. The optimised thermochemical conversion technologies can be vastly different from one another, from the large-scale oxy-steam gasification for the sludge-to-gas platform to the small-scale rotary kiln for the sludge-to-char platform. For optimising pyrolysis processes to produce high-quality syngas, liquid, and char, it is beneficial to operate at moderate (intermediate) conditions, including temperature, heating rate, and vapour phase residence time, where the three phases of pyrolysate can be produced at sufficient quality for further valorisation (Wang *et al.* 2022). This is demonstrated in a recent project (TO-SYN-FUEL 2022), producing high-quality outputs under intermediate conditions using the hot char for catalytic reforming. The focus of this study is pyrolysis; however, gasification, another syngas-producing process, is also included in the assessment.

Figure 2 provides an overview of the pathways of the product options, highlighting that some products can be synthesised via more than one pathway (see also Table 2). To be noted firstly, vapour upgrading is an additional pathway to the sludge-to-gas, sludge-to-liquid, and sludge-to-char platforms. Via either *in situ* or *ex situ* catalytic upgrading of the sewage sludge pyrolysis vapour phase, the recoverable product options are ammonia, aromatic hydrocarbons, and olefins (Liu *et al.* 2016; Wang *et al.* 2017), where those three products can already be produced via other pathways. For ammonia, the three routes are the Haber-Bosch process via syngas (Gilbert *et al.* 2014), the catalytic vapour upgrading route (Wang *et al.* 2017), and heat-integrating pyrolysis with ammonia stripping of sludge liquor (Salman *et al.* 2019). For olefins, the three pathways are synthesis via methanol or dimethyl ether (DME) (Jiang *et al.* 2019), the catalytic vapour upgrading route, and the cracking of the pyrolysis liquid (Brown *et al.* 2012). For aromatic hydrocarbons, benzene, toluene, and xylene (BTX), the two pathways are the catalytic vapour upgrading route, and the cracking of the pyrolysis liquid route. Also, as indicated by Figure 2, the two hydrogen production pathways are the syngas upgrading pathway (Wang *et al.* 2022) and the bio-oil pathway via either gasification or reforming (Zhang *et al.* 2013). Methanol and DME can act as intermediates for producing hydrocarbons – olefins, gasoline, and poly(oxymethylene) ethers (OMEn), where gasoline can also be synthesised from olefins separately (Haro *et al.* 2013; Zhang *et al.* 2014). DME can be synthesised directly from syngas or via methanol (Im-orb & Arpornwichanop 2022). This leads to four different pathways of synthesising gasoline and three pathways of synthesising jet fuel, as indicating on the figure: methanol- or DME-to-gasoline, olefins-to-gasoline, Fischer-Tropsch synthesis (FTS), and pyrolysis liquid upgrading for gasoline production (Hamelinck *et al.* 2004; Shemfe *et al.* 2015); FT synthesis, alcohol-to-jet, and pyrolysis liquid upgrading for jet fuel (Atsonios *et al.* 2015; Bashir *et al.* 2022). Acetic acid can also be produced from either the gas platform via methanol (Guevara-Fernandez & Proano-Aviles 2022) or the liquid platform via extraction (Vitasari *et al.* 2015). As for

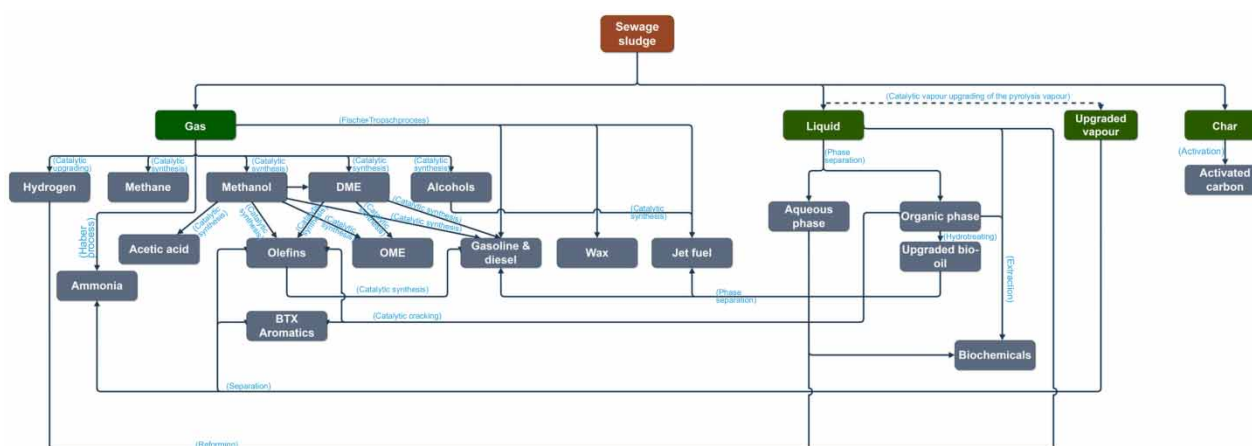


Figure 2 | The pathways of pyrolysate upgrading. The indicative process is labelled on the pathways.

biochemicals extraction, either the organic phase, the aqueous phase, or the whole pyrolysis liquid can be used (Fonts *et al.* 2017). Comparative techno-economic studies are commonly used to show how different pathways compare, and the comparative plant performance is discussed in the following section. It is especially important to start from this pathway network when envisioning a resource recovery factory, for example, currently there is a high interest in recovering ammonia from digested sludge liquor stripping, then this ammonia recovery can be boosted by considering thermochemical conversion pathways.

Special considerations of the pathways when sewage sludge is the feedstock

There are three distinct gas utilisation scenarios and the gas cleaning requirement for each should be considered separately. The first case is the combustion of the whole vapour phase, comprising the condensable and non-condensable gases formed, with no requirement for gas cleaning, but flue gas cleaning is required. The second case is the utilisation of syngas in gas engines (designed for syngas), for this application, only particulate removal may be required, and the particulate limit should be reduced according to the specific equipment, including the engine and the compressors (Thapa *et al.* 2017). The third case is the tailoring and upgrading of syngas for downstream synthesis, where the gas cleanliness requirement is defined by the synthesis catalyst. It is typical that a heat exchanger is employed after the reactor for immediate heat recovery. Water scrubbing is a suitable way to clean syngas if the syngas undergoes the water-gas shift process, as the water vapour content will be utilised during that stage. For the almost complete removal of sulphur gases for sensitive catalysts, a ZnO bed is used for the polishing of syngas. As for the comparison of the treatment intensity of the three cases, in general, gas cleaning is the most intense for the third case and the least intense for the second case. For the first case, the gas cleaning unit on the designed sludge combustion plant is calculated to cost around 47% of that of the sludge thermal converter (Bagheri *et al.* 2022). For the second case, the equipment cost of gas cleaning is expected to be around 40% of that of a sludge gasifier (Sanaye *et al.* 2022). For the third case, the equipment cost of the gas cleaning section can be as high as 67% of that of a gasifier for a sludge-to-methanol plant (Shi *et al.* 2022). Crude syngas is cleaned but not refined syngas, and once produced, crude syngas is used in engines for power generation or used in downstream synthesis. Sanaye and co-researchers (2022) calculated that the production cost of syngas on a sewage sludge gasification plant is 57 £/GJ (Sanaye *et al.* 2022).

For disposing of the aqueous phase of the pyrolysis oil when not being considered for aqueous phase valorisation, the liquid must not be recycled to the primary or secondary treatment of the wastewater treatment work without assessing the impact on the organic load to the plant and characterising the liquid in terms of inhibition potential, toxicity, and biodegradability. High levels of ammonia and phosphate, leading to insufficient treatment, could cause discharge to the environment and non-compliance (Snowden-Swan *et al.* 2017). The treatment options for ammonia removal are not discussed in detail but include biological treatment, ammonia stripping, and membranes (Snowden-Swan *et al.* 2017). Wang *et al.* (2015) proposed pre-treating the pyrolysis aqueous phase before returning to the works by ammonia and hydrogen cyanide removal in a specific treatment process (Wang *et al.* 2015). As for aqueous phase valorisation, the high potential for non-biodegradability (recalcitrant soluble and/or particulate content in terms of chemical oxygen demand) must be carefully evaluated before considering returning to anaerobic digesters. By returning the aqueous phase to anaerobic digesters, it may be possible to recover methane as compounds present in the aqueous phase are substrates for the bacteria. Batch experiments have shown increased methane yield, but loading above a certain threshold may decrease the methane yield due to the inhibition of the toxic compounds present in the aqueous phase (Raya 2021); more research, including continuous anaerobic digestion (AD) to understand long-term impact, is required for this route (Liu *et al.* 2020). Ammonia recovery, recovery of other chemicals, and steam reforming or hydrogen production may be considered for aqueous phase valorisation.

Performance of the conceptual plants

Of the 123 datasets collected, 3 are based on existing plants, while the rest are based on conceptual plants. The studies determined the performance of the conceptual plants using process simulation. Data from these published studies were compiled and normalised to enable a detailed comparison. The overall dataset is available in the supplementary materials. All data points included process details; 76% provided economic data, 45% included CO₂ emissions, 58% reported energy efficiency, and 17% indicated exergy efficiency. The thermochemical conversion process included pyrolysis (48 datasets), gasification (74 datasets), and hydrothermal liquefaction (1 dataset), where the inclusion of gasification and hydrothermal liquefaction is to support the discussion on the pyrolysates. This section presents a quantitative comparison of the process and economic

performance, while the environmental and efficiency performance were qualitatively reviewed. The quantitative results are indicative because the data were taken from selected literature and cannot represent absolute accuracy and sensitivity.

Process performance

The calculated specific yield comparison between the product options is presented in Figure 3. The data are grouped into the gas, liquid, and char platforms and the products. If the data are obtained from a conceptual plant study using sewage sludge as a feedstock, the bar is shown in the lighter colour, and if using non-sludge-based feedstock, the bar is shown in the darker colour.

As discussed, there are three established pathways for ammonia production and three pathways of jet fuel production via pyrolysis. Ammonia produced via the heat-integrated stripping-pyrolysis pathway has a specific yield of 0.012 (1.2%), which is much lower than that via the Haber-Bosch route at 0.170–0.800. The third pathway, the catalytic vapour upgrading route for ammonia production from sewage sludge, does not have a published study; however, it was reported that 32% of the total nitrogen content in sludge is converted to ammonia during catalytic pyrolysis (Wang *et al.* 2017), thus this route potentially has a yield comparable to the other two pathways. As for two of the routes of jet fuel production, the sewage sludge pyrolysis oil upgrading route yields much less fuel compared to the Fischer–Tropsch route, with a specific yield of 0.015 compared

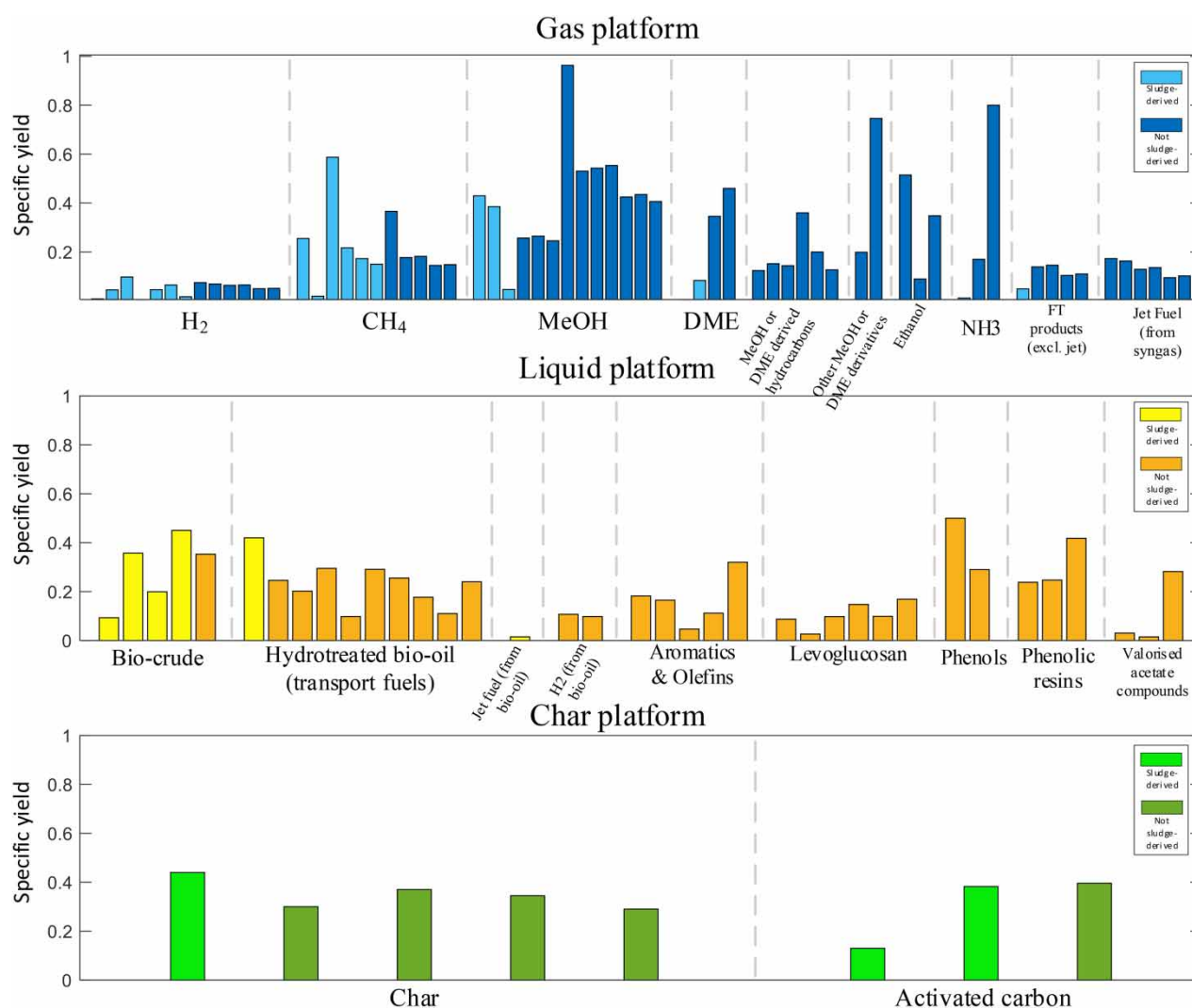


Figure 3 | Specific yield (kg product/kg dry feedstock) of the selected product options reported in the conceptual plant studies. The bars refer to a single entry of data from a single conceptual plant study.

to 0.095–0.173 (Bashir *et al.* 2022). This suggests that the sludge-to-liquid platform has limitations in mass transfer from the feedstock into jet fuel.

Economics

The relationship between unit capital cost and plant scale was analysed to compare the estimated economic performance of sludge-to-gas, sludge-to-liquid, and sludge-to-char platforms. As shown in Figure 4, plant scales are categorised into demonstration scale, single-WWTP or multi-WWTP scale (centralised pyrolysis plant), and large scale, reflecting increasing throughput. Trend lines illustrate the degree of economies of scale. Most reported capital cost data represent total capital investment, though some studies that use slightly different definitions of their capital expenditure are included in Figure 4, nevertheless.

Figure 4 reveals two key observations: first, capital cost generally follows the order gas platform > liquid platform > char platform; second, sensitivity to economies of scale also follows the same trend. This indicates that gas upgrading plants are more capital intensive than liquid and char upgrading plants. Given the increasing complexity of processing, gas > liquid > char, gas platforms are typically suited to large-scale deployment, liquid platforms to medium scale, and char platforms to small scale.

Almost all reviewed conceptual plant studies are based on the *n*th plant assumption, meaning the design reflects a mature, commercial-scale facility rather than a first-of-a-kind installation (Kazi *et al.* 2010). This assumption, also referred to as the learning effect (Vimmerstedt *et al.* 2015; Michailos *et al.* 2017), accounts for cost reductions through experience and technological refinement. For example, Michailos *et al.* (2017) modelled capital costs for pyrolysis plants decreasing exponentially with deployment, halving by the 12th plant. Indicators of maturity include improved yields, increased capacity, reduced capital cost escalation, and lower investor risk (Vimmerstedt *et al.* 2015). This suggests that total capital costs for pyrolysis-upgrading plants are likely to decline as the technology matures.

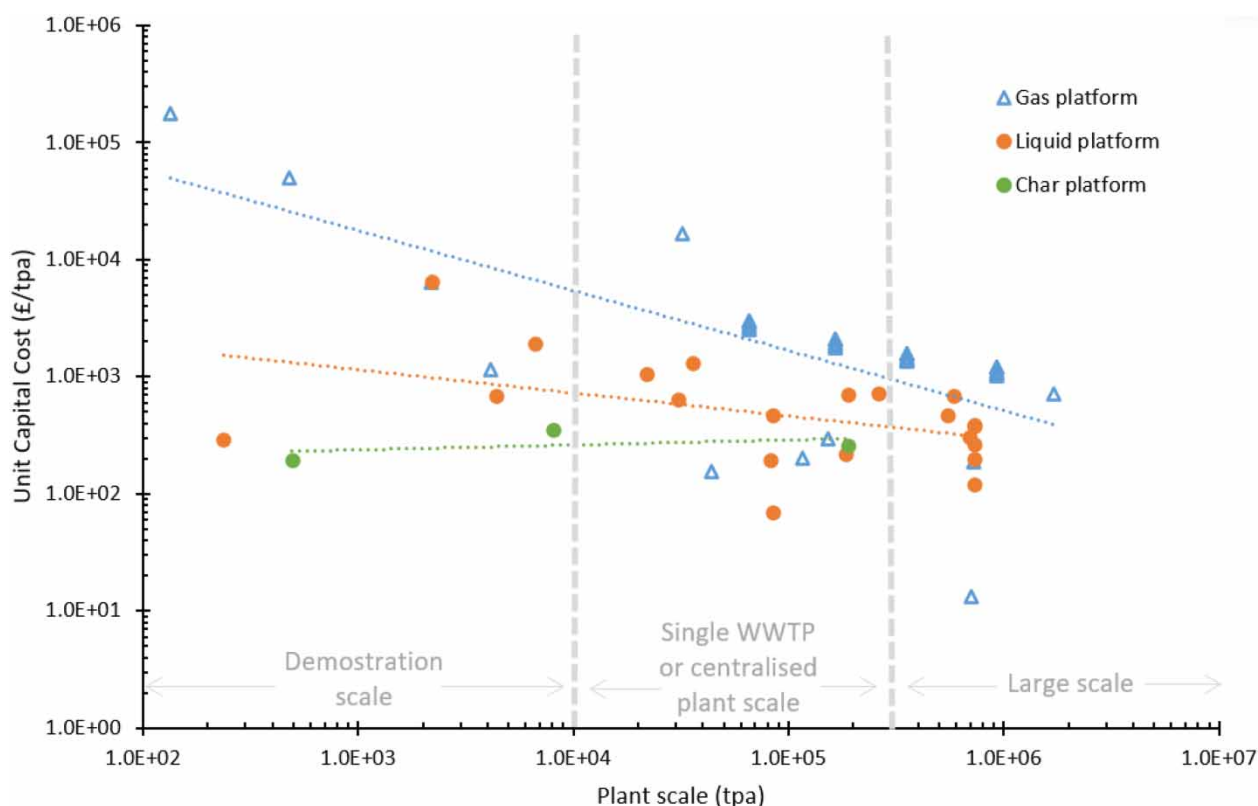


Figure 4 | The relationship between plant scale and unit capital cost. Tpa stands for tonnes per annum, and this is regarding the feedstock on a dry basis. WWTP stands for wastewater treatment plant.

Environmental impact and efficiency

Drawing firm conclusions about the environmental impact of the reviewed conceptual plant studies is challenging due to limited and inconsistent reporting. Additionally, variations in life cycle assessment methodologies can lead to significantly different CO₂ emission estimates. Therefore, insights from broader comparative studies are more reliable. For instance, BEIS (2021) ranks CO₂ emissions from gasification-based upgrading options, including Fischer-Tropsch (FT), as follows: methanol < FT diesel < FT aviation fuel < CH₄ < H₂, with emissions ranging from 57.3 to 93.9 ktpa CO₂ for a 100 ktpa (kilo tonne per annum) waste gasification plant (BEIS 2021). Reported energy efficiencies among reviewed studies range from 40 to 65%. Exergy efficiencies, which account for efficiency of converting one form of energy to another considering the loss of reversibility, vary by product: 22–74% for hydrogen, 34–57% for methane, and 38–56% for methanol.

Selection of options

Specific revenue comparison is used for comparing the gross benefit of the products considering only the unit revenue that can be generated from 1 kg of sewage sludge, not including any operational and capital costs. For simplicity, the cost of the sewage sludge treatment is not included. The cost of the thermochemical conversion and upgrading processes is not included, either. Figure 5 shows the bubble diagram summarising the specific revenues against the specific yield of some selected products. The selected products are based on the availability of data from sludge-based conceptual plant studies, and the selected products have potential markets subject to the regulatory classifications of the outputs (e.g., end of waste status). Figure 5 is based on a low and a high estimate of the selling price, and a low and a high estimate of the specific yield.

This specific revenue analysis can be validated by comparing it to other similar analyses identified in the literature. Balakshin *et al.* (2021) compared the specific revenues of potential valorised products from lignin and reported that the lignin pyrolysis oil-derived biofuel has a specific revenue of 0.186–0.559 £/kg lignin (Balakshin *et al.* 2021), which is within the 0.0057–0.95 £/kg sludge range estimated by this study for untreated and treated bio-oil.

There is greater confidence in the estimated yield ranges than in the revenue estimates, as product prices vary significantly depending on factors, such as purity, target market, and potential incentives or niche demand. As a result, potential specific

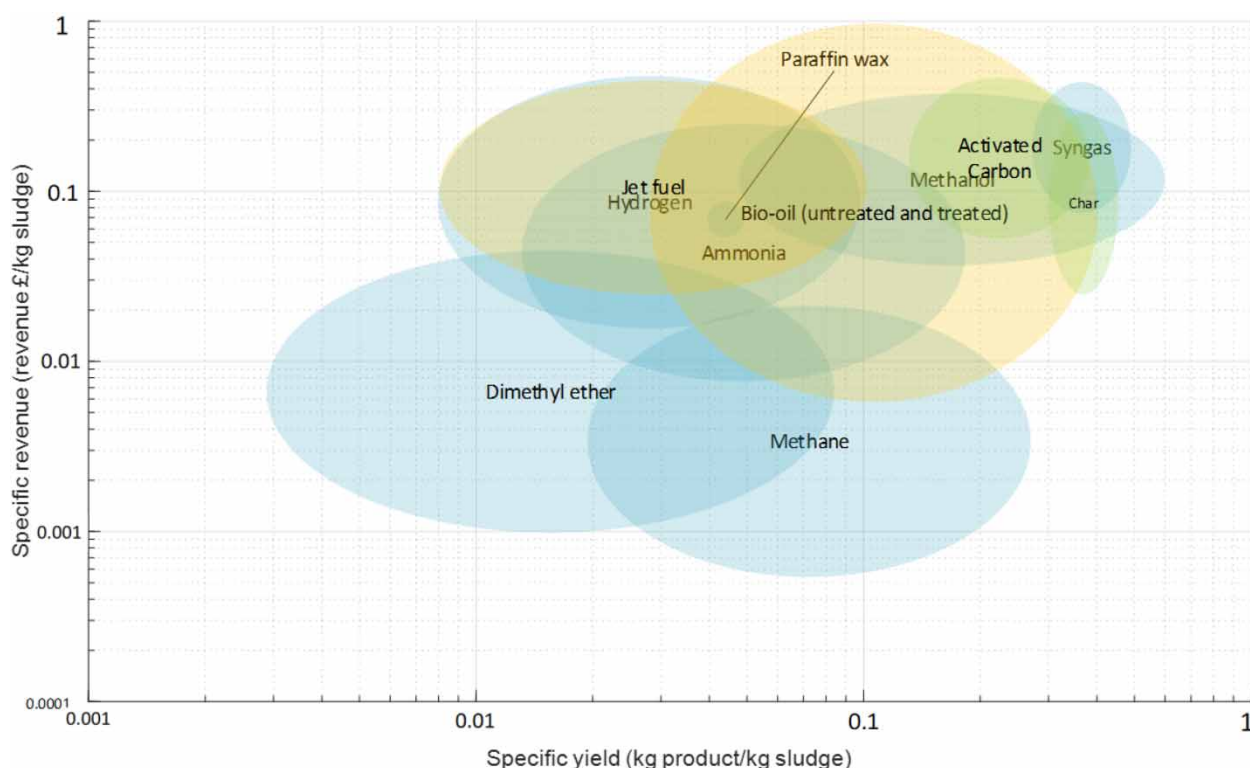


Figure 5 | Bubble diagram showing the range of specific revenue and the range of specific yield for the product options. Blue, yellow, and green suggest gas, liquid, and char upgrading platforms, respectively.

revenues can differ by orders of magnitude for the same product, as shown in [Figure 5](#). A sensitivity analysis is therefore essential in later-stage decision-making.

To maximise the economic benefit and to compensate cost of treatment, the product with high specific revenue may be preferred, and this is the aim of this preliminary selection criteria, however it is understood that aiming for the highest price end product may not necessarily be an appropriate strategy without taking into account the capital and operational cost of each of the specific thermochemical conversion technology. [Figure 5](#) shows that treated bio-oil, hydrogen, jet fuel, activated carbon, syngas, methanol, and char all have potential for significant specific revenues (listed in descending order). Syngas, char, and activated carbon are found on the top right corner of the graph because they have both high specific revenue and specific yield, the latter partly driven by the former. Since specific revenue excludes capital and operating costs, when gross benefits are similar, products requiring less upgrading may be favoured to maximise net benefit, thus making syngas and char the most promising options. For a comprehensive selection, other criteria such as consistency, competition, and outlets will need consideration.

Regulative and technological challenges, and future prospects

Sludge management in the UK is influenced by evolving environmental pressures and a complex regulatory landscape. Decision-making around resource recovery must align with current and future regulations to ensure viable and compliant solutions. While the sludge-to-land route remains a favourable option, it is increasingly challenged by declining landbank availability, environmental concerns (e.g., Per- and polyfluoroalkyl substances or PFAS, and microplastics), and tightening regulations. In the UK, the potential move from Sludge Use in Agriculture Regulation to Environmental Permitting Regulation aims to close data gaps and support confidence in land application, while also introducing flexible oversight for emerging technologies like pyrolysis ([Environment Agency 2023](#)). According to the latest biosolids management strategy for England ([Water UK 2023](#)), both land-spreading and thermal conversion with resource recovery are likely to play a role in future sludge strategies. Demand for fertiliser, uncertainties in environmental impact, and regulatory developments will influence the balance between these routes.

Beyond resource recovery, pyrolysis outputs (gas, liquid, and char) can also provide on-site energy. This is especially important for drying sludge, a process that is both energy-intensive and critical to pyrolysis efficiency. While some moisture aids syngas production via the water–gas shift reaction, excess water increases thermal load significantly; the latent heat of water (2.3 MJ/kg) competes with the calorific value of dry sludge (15–22 MJ/kg). Conventional dewatering methods (e.g., filter presses or centrifuges) reduce moisture to about 70%, with further drying achieved via thermal methods, such as low-temperature belt drying, hot air paddles drying, or steam drying ([Clausen *et al.* 2019](#)). Energy for drying and pyrolysis may be recovered from several sources, including combustion of pyrolysis gas (condensed or uncondensed) or char, solar energy, or biogas engine waste heat. Successful examples abroad, such as in Finland ([HSY – Sludge char project – Process description n.d.](#)), have demonstrated energy self-sufficient operations using combustion of the uncondensed pyrolysis vapour.

Despite its potential, pyrolysis faces significant technical and operational hurdles. These include limited industry experience, Health and Safety considerations, feedstock variability, tar deposition, and scale-up challenges. Diversifying outputs, rather than focusing on a single product, can reduce commercial risks. Hydrogen, in particular, is potentially a valuable targeted output due to its role in the green economy.

Regulatory barriers are a key constraint. Under the EU Waste Framework Directive, pyrolysis products remain classified as waste unless an end-of-waste status is obtained ([Štrubelj 2022](#)). Gas products like hydrogen and methanol are closer to certification, benefiting from established markets and production pathways, but may have restricted applications. In contrast, the complex and variable composition of pyrolysis liquids limits their applications, with lower demand and stricter quality requirements. Char shows promise as a soil amendment, serving as a potential substitute for biosolids in land applications in terms of nutrients, but cannot replace the benefits from organic matter addition, which comes with biosolids application. However, heavy metal content remains a concern ([EBC 2023](#)), and regulatory acceptance is still pending. Additionally, one study suggested that applying biochar does not offer economic benefit to the farmers ([Berdini 2024](#)). Although the EU has updated fertiliser regulations (Regulation 2019/1009) to include pyrolysis-derived chars, sewage sludge char has only recently been added to the positive feedstock list as EBC-Basic Material, and its use may require country-specific exceptions, with only a few EU countries allowing sewage sludge-derived biochar for land application. Within the UK, to move forward with unlocking biochar's future potential, it has been suggested either to improve pragmatically within legacy regulation or to develop a comprehensive biochar framework ([Štrubelj & Ghaleigh 2025](#)).

Successful adoption of pyrolysis will depend on overcoming interlinked technical, financial, and regulatory challenges (Cooper *et al.* 2019). Past experiences with biomass gasification underline the importance of stepwise scale-up, transparent communication, and supportive regulation (Howard 2024). The UK water sector, supported by its innovation funding mechanisms and culture of collaboration, is making progress through pilot pyrolysis and gasification projects (Ofwat 2024). These efforts, if sustained, can lay the foundation for broader deployment of thermal conversion technologies in biosolids management.

CONCLUSIONS

Sewage sludge pyrolysate valorisation can be broadly categorised into three main pathways: pyrolytic gas upgrading, pyrolytic liquid upgrading, and char upgrading. Additionally, the less mature catalytic vapour upgrading pathways were also discussed. This data synthesis on techno-economic data from conceptual plants expands the scope of resource recovery discussions beyond commonly examined products such as biochar, hydrogen, and liquid fuels, offering a broader view of potential value chains.

Some potentially high-value products, like ammonia and jet fuel, can be produced via multiple routes. However, gas upgrading generally achieves higher product mass yields compared to liquid upgrading. In terms of unit capital cost (per unit of dry feedstock), the trend is: gas platform > liquid platform > char platform, with a similar trend observed in sensitivity to economies of scale. Comparing plant performance of the conceptual plants across studies remains difficult due to inconsistent techno-economic methodologies.

Specific revenue analysis highlights syngas and char as potentially the most economically attractive outputs, given their high yields and minimal upgrading requirements, which could make sludge treatment more cost-effective and ultimately result in reduced customer bills. Hydrogen could also be a strategic target due to its relevance to the hydrogen economy albeit not commonly utilised in the water industry. Nonetheless, commercial-scale implementation faces major barriers, including managing the high energy demand for sludge drying and pyrolysis, and the regulatory uncertainty for land application of sewage-derived char.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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Rethinking sewage sludge valorisation options and pathways via thermochemical output upgrading: a product-oriented analysis

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