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A perspective on hydrothermal processing of sewage sludge
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Abstract
The US annually produces 79 million dry tons of liquid organic waste including sewage sludge. Anaerobic digestion can only reduce the sludge volume by 50% in mass, leaving the other half as a growing waste management and hygienic problem. Hydrothermal processing (HTP), a set of several chemical digestion processes, could be used to convert sewage sludge into valuable products and minimize potential environmental pollution risks. Specifically, hydrothermal carbonization and hydrothermal liquefaction have been extensively studied to sustainably manage sewage sludge. Two of the main reasons for this are the high upscalability of HTP for public waste management and that it is estimated that HTP can recover eleven times more energy from waste products than landfills. An integration of HTP with anaerobic digestion or recycling the soluble organics (in the HTP aqueous products) into the HTP process could lead to a higher overall rate of energy recovery for municipal sewage sludge.

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Introduction
Sewage sludge is a byproduct of wastewater treatment which may contain metals, pharmaceuticals, and organic compounds such as phthalates, pesticides, phenols, polychlorinated biphenyls, personal care products, and pathogens [1]. Owing to low capacity of current wastewater processing systems, the escalating amount of sewage sludge from wastewater treatment facilities has become a notable concern [2]. In the US, 79 million dry tons of liquid organic waste including sewage sludge was produced every year [2]. Furthermore, the Organization for Economic Cooperation and Development predicts a cost of 2% of global GDP (gross domestic product) to treat all of the human waste currently generated [3,4].

Hydrothermal processing (HTP), in which water serves as an important solvent and reactant, uses subcritical and supercritical water (and sometimes organic cosolvents) to convert sewage sludge into valuable end products in the absence of free oxygen (i.e. a thermochemical deoxygenating process) [2]. Because HTP can directly use water as a reaction medium, there is no need for moisture removal before processing, thus significantly reducing the energy usage of HTP compared with other waste conversion mechanisms (e.g. oil extraction and pyrolysis) [2].

HTP is a promising method to manage sewage sludge as it can concurrently convert sewage sludge into useful products while also reducing the environmental and health risks posed by excess sewage sludge in the environment. Products from HTP are normally biocrude oil, aqueous products (containing fertilizer precursors), and hydrochar [5,6]. Yields from the process depend on the reaction temperature [6], reaction time [6], feedstock characteristics (e.g. biochemical compositions, physicochemical properties, ash contents [2,6,7]), initial pressure [8,9], total solid content [7], cosolvents [9,10], and catalyst composition [6,9].

HTP of sewage sludge
HTP can be classified into hydrothermal carbonization (HTC) [11], hydrothermal liquefaction (HTL) [6], and hydrothermal gasification [12,13] based on reaction parameters including temperature, pressure, and time. This perspective focuses on recent publications (within the last two years) about HTC and liquefaction of sewage sludge. The literature regarding the use of hydrothermal gasification to treat sewage sludge in the past two years is limited and thus was not included. Table 1 also identifies the key literature on HTP of biowaste within the last two years.

Hydrothermal carbonization
HTC decomposes organic matter under high temperatures and in the presence of water to produce solid
| Category                              | Crude fat (wt.%) | Crude protein (wt.%) | Carbohydrates (wt.%) | Ash (wt. %) | C (wt. %) | H (wt. %) | N (wt. %) | Optimum conditions for bioproduct production | Optimum bioproduct yields (wt.%) | Optimum HHV of biocrude oil (MJ/kg) | References |
|--------------------------------------|------------------|----------------------|----------------------|-------------|-----------|-----------|-----------|---------------------------------------------|---------------------------------|-----------------------------------|------------|
| Sewage sludge                        | N/A              | N/A                  | N/A                  | 31%         | 29.0      | N/A       | N/A       | HTL, sewage sludge and 0.10 Carbohydrates, 0.16 Human Tissue, 24.4 Anaerobic sludge and 15.0 Anaerobic sludge, 34.5 Carbohydrates, 41.6 Carbohydrates, 32.0 Carbohydrates | N/A                             | 33 – 35                            | [8]         |
| Activated sludge                     | N/A              | N/A                  | N/A                  | N/A         | N/A       | N/A       | N/A       | Activated sludge and 34.5 Carbohydrates, 32.0 Carbohydrates, 26.3 Carbohydrates | N/A                             | 34 – 41                            | [14]        |
| Anaerobically digested sludge        | N/A              | N/A                  | N/A                  | N/A         | N/A       | N/A       | N/A       | Anaerobic sludge and 34.5 Carbohydrates, 32.0 Carbohydrates, 18.0 Carbohydrates | N/A                             | 225 – 280                          | [14]        |
| Sewage sludge from cheese processing waste | N/A              | N/A                  | N/A                  | N/A         | N/A       | N/A       | N/A       | Sewage sludge from cheese processing waste | N/A                             | 225 – 280                          | [14]        |
| Human feces                          | 24.4             | 34.5                 | 25.0                 | 16.0        | 45.5      | 6.5       | 5.7       | Biocrude oil, 45.5 Carbohydrates, 38.0 Carbohydrates, 26.3 Carbohydrates | 47.2 N/A                         | 340 – 300                          | [6]         |
| Anaerobic sludge                     | <1               | 15.0                 | 54.0                 | N/A         | N/A       | N/A       | N/A       | Biocrude oil, 45.5 Carbohydrates, 38.0 Carbohydrates, 26.3 Carbohydrates | 47.2 N/A                         | 340 – 300                          | [15]        |
| Activated sludge and sawdust         | N/A              | N/A                  | 23.6                 | N/A         | 38.0      | 5.2       | 7.2       | Biocrude oil, 45.5 Carbohydrates, 38.0 Carbohydrates, 26.3 Carbohydrates | 47.2 N/A                         | 310 – 340                          | [16]        |
| Sewage sludge from cheeseprocessing waste | N/A              | N/A                  | N/A                  | N/A         | 41.7      | 6.0       | 5.8       | Biocrude oil, 45.5 Carbohydrates, 38.0 Carbohydrates, 26.3 Carbohydrates | 47.2 N/A                         | 380 – 400                          | [17]        |
| Sewage sludge from salad dressing processing waste | N/A              | N/A                  | N/A                  | N/A         | 41.7      | 6.0       | 5.8       | Biocrude oil, 45.5 Carbohydrates, 38.0 Carbohydrates, 26.3 Carbohydrates | 47.2 N/A                         | 380 – 400                          | [17]        |

HHV, higher heating value; HTC, hydrothermal carbonization; HTL, hydrothermal liquefaction; N/A, not available.

* Calculated by difference (i.e., carbohydrate [wt.%] = 100 – crude fat – protein – ash).

b Phosphorus.
products (225–320 °C, Table 1). Products resulting from HTC are primarily hydrochar (a solid phase enriched in carbon content), some liquid products containing phenolic compounds, and a small quantity of gas (mostly CO2) [18]. HTC shares similar working temperatures with HTL [14]. However, HTC mainly generates solid products, whereas the major product from HTL is a viscous liquid: biocrude oil.

HTC is mainly governed by dehydration, decarboxylation, and decarbonylation mechanisms [19]. In the last five years, HTC has been extensively used for phosphorus recovery. Thus, this perspective focuses on recent publications about recovering phosphorus from sewage sludge via HTC.

In the context of HTC, the phosphorus speciation is important, so it is critical to understand the mechanism of phosphorus transformation during HTC. Selective transfer and conversion of phosphorus in sewage sludge has been investigated in two ways. Standard measurements and testing methods were used to understand the speciation and bioavailability of phosphorus. NMR and X-ray absorption near edge structure analysis were also used to characterize the transformation of phosphorus [11,14]. The addition of hydrogen chloride was used to achieve a high-efficiency transfer of phosphorus into the aqueous phase [14]. Precipitation of phosphorus using struvite, was carried out to recover the phosphorus, originated from sewage sludge [11].

Hydrothermal liquefaction

HTL requires elevated temperatures (260–450 °C) and pressures (7–25 MPa), at which water is present in the subcritical or supercritical state [6,13,17]. Ionic and free-radical reactions are believed to be the major reactions in HTL. The kinetics of these reaction pathways have been studied to investigate the relationship between temperature and pressure on reaction yield, with temperature showing a large effect on the output of the process [13]. Subcritical water exhibits limited interaction with sewage sludge owing to low diffusivity and, therefore, acts mainly as a reaction medium [13]. In contrast, supercritical water exhibits higher diffusivity and increases the rate of interaction between the solvent and sewage sludge. This conclusion is based on growing evidence that the rate constants of HTL reactions are heavily dependent on pressure in the critical pressure point, wherein water reaches supercritical conditions (i.e. the near-critical region of water) [20,21]. The conversion efficiency is highly enhanced when water reaches the supercritical point [12].

When water changes from the normal conditions (20 °C/0.1 MPa) to its critical point (374 °C/22 MPa), the density, viscosity, and dielectric constants of the liquid change significantly [22]. In fact, the density of water can be changed by adjusting temperature and pressure in the subcritical and supercritical states. In the near-critical water region, hydrogen bonding in water is weaker, and thus, water can serve as a hydrogen donor for sewage sludge conversion. In the supercritical region, however, free-radical reactions are dominant because the possibility of generation of radicals from a series of elemental reaction steps increases at high temperatures [13,20,21]. In short, the effect of pressure is different on subcritical and supercritical water. For subcritical water, temperature is the dominant factor affecting the reaction efficiency, whereas for supercritical water, both temperature and pressure play a key role in promoting the conversion efficiency.

HTL converts various types of sewage sludge into biocrude oil [2,7,22]. In addition, HTL has also been used to achieve dechlorination [23], denitrogenation [24], and the removal of chemicals of emerging concerns (CECs) [25,26]. This perspective focuses on using HTL for environmental health promotion.

Dechlorination

Dechlorination is necessary for treating chlorinated waste (e.g. sewage sludge containing polyvinyl chloride) [23]. Currently established chlorine (Cl) removal technologies mainly focus on inorganic Cl removal. Alkaline bases or ammonia are usually added to promote Cl transformation from the organic to the inorganic state [27]. Hydrochloric acid produced in HTL can be neutralized by alkaline bases (e.g. KOH), resulting in inorganic salts (e.g. KCl), which can be removed easily from the solid phase by washing. The results show that up to 96% of inorganic Cl can be removed by HTL and one-time washing with a water:product ratio of 1:1 [28].

Denitrogenation

Sewage sludge usually contains around 3% of nitrogen, with the majority as organic nitrogen in complex molecules such as proteins and nucleic acids, and low nitrate (NO3-) content [24]. Burning of sewage sludge can release nitrogen oxides (NOx). These NOx molecules have highly disruptive potential in the environment and can contribute to environmental issues including the greenhouse effect, photochemical smog, acid rain, acidification of the aquatic system, and visibility degradation. Thus, denitrogenation of sewage sludge is necessary.

Analysis of the significant factors in denitrogenation yield gives three main steps in the reaction. First, denitrogenation process yields typically increase with temperature and reaction time in HTL. These conditions likely increase the opportunity for dissolution and hydrolysis of proteins and thus release more nitrogen. Second, nitrogen yield also varies markedly with changes in pH in the reaction medium, indicating that
denitrogenation occurs readily under acidic or basic conditions during HTL [29]. Finally, more nitrogen can be removed by increasing the basicity of alkaline metals used to separate nitrogen from the mixture through ionic reaction pathways. Identification of these factors leads to a theory that denitrogenation happens via an ionic reaction path catalyzed by OH⁻ ions in aqueous alkaline solutions [29].

However, denitrogenation is still a key challenge of HTL biocrude oil converted from high-protein sewage sludge because traditional petroleum-upgrading techniques mostly focus on deoxygenation, desulfurization, or cracking reactions, which fails to deal with problems related to high nitrogen content [6,17,21]. HTL biocrude oil converted from high-protein feedstocks typically has a nitrogen content of 3–7%, which is inappropriate for fuel application [8]. To date, denitrogenation of HTL biocrude oil has been investigated with hydrotreating [30,31], cracking [31,32], chemical extraction/separation from HTL biocrude oil [33,34], and supercritical fluid treatment [35–37]. However, the high nitrogen content of biocrude oil generated by HTL would result in fouling of conventional catalysts (e.g., zeolites) because of the high basicity caused by the nitrogen heterocyclic compounds [15,34,38]. Developing catalysts suitable for denitrogenation represents a knowledge gap in this area.

However, upgraded HTL biocrude oil can be used as a 5–10% drop-in fuel (e.g., blending 10% upgraded HTL biocrude with 90% petroleum fuel) such that the nitrogen content would be highly diluted and therefore be less of a concern. In addition, identifying which nitrogen-containing compounds negatively affect combustion processes is also essential (e.g., nitrogen heterocyclic compounds versus nitrogen-containing alkyl compounds). Further combustion tests are needed to examine the effect of nitrogen-containing compounds on combustion performance and emissions of HTL biocrude oil.

**Removal/degradation of CECs**

A large variety of pathogens from human waste streams reside in sewage sludge. The presence of viruses is particularly challenging as their wide genotypic variety creates different shapes, sizes, infection potential, and transport phenomena in the environment and human body. In 90% of sewage sludge investigated, DNA viruses, adenovirus, herpesvirus, and papillomavirus, were found, whereas RNA viruses, coronavirus, klassevirus, and rotavirus, were detected in concentrations higher than 80% [39]. Consolidation and concentration of pharmaceuticals, personal care products, and other wastewater solids are also significant causes of concern. Antibiotics, for example, are particularly scrutinized as they increase the risk of antibiotic resistance through genetic mutation of bacterial strains present in wastewater treatment facilities. Antibiotics and their metabolites can enter sewage through feces, urine, or direct medication disposal and will enter the environment if not removed during sewage treatment. Removal of bioactive compounds (by tracking radiolabeled 14C) can be done by HTL [25], in which biocrude oil can be produced simultaneously. With the addition of granular activated carbon in a mixed algal—bacterial bioreactor, HTL can also be used to remove estrogenic hormones [26].

**Continuous/pilot development for HTL**

In the last two decades, HTL has attracted a large amount of interest in the area of converting sewage sludge and high water content biomass into valuable products. Because of the operational simplicity, the publications mainly focused on batch-scale tests. Publicly available information about continuous/pilot HTL process is still limited. This indicates a knowledge gap between laboratory research and commercialization of HTL technology.

Recent publications (primarily for the past two years) about continuous HTL are summarized in Table 2. The listed continuous reactions were performed at temperatures from 300°C to 400°C. The reaction time mostly ranged from 15 to 60 min, except that some fast HTL processes were conducted in less than 5 min [10,30]. The biocrude oil yield varied from 12.1 to 62.6 wt.% in the sewage sludge (which led to a higher heating value of 25.8–26.0 MJ/kg) [41].

In the past five years, different feedstocks were tested under continuous HTL, but the majority were algae (Table 2). The feedstock biochemical composition played an important role in dictating the oil yield. A comparison of different feedstocks shows that the highest oil yield was reached using a high-lipid feedstock. The higher heating value of the biocrude oil produced via continuous HTL typically ranged from 33.2 to 39.3 MJ/kg for most of the feedstocks, but not the sewage sludge (which led to a higher heating value of 26.8 MJ/kg) [41].

Data in Table 2 show that most of the continuous HTL reactors used, were operated in the plug flow reactor mode. The reactor size varied from the laboratory (0.05 L) to pilot scale (35 L). The largest flow rate available in the literature was 90 L/h from the University of Sydney [10]. A continuous-flow pilot plant reactor was operated at temperatures of 300–350 °C. The process was a fast HTL process (residence time = 3–5 min), so the reactor size was not big (estimated to be 4.5–7.5 L). In comparison, the largest flow rate
Table 2
Parameter comparison of different continuous HTL reactors.

| Approximated scale (L/h) | Temperature (°C) | Pressure (bar) | Oil yield (wt.%) | Time (min) | Oil HHV (MJ/kg) | Highest solid content (wt.%) | Feedstock | Reactor size (L) | Reactor type | Reference |
|--------------------------|------------------|----------------|------------------|------------|----------------|-----------------------------|-----------|------------------|-------------|-----------|
| 0.18–0.42                | 300–340          | 165            | 12.1–21.9        | 7–17       | 34.9           | 5.0                         | Wastewater algae | 0.05             | Vertical double tube | [46]        |
| 0.6                      | 350              | 200            | 42.6–54.8        | 15         | 35.8–37.3      | 18.2                        | Microalgae     | 0.19             | CSTR        | [47]       |
| 1.44                     | 350              | 250            | 38.90            | 15         | 35.3           | 20.0                        | Dried distillers grain | 0.68             | PFR         | [46]       |
| 1.5                      | 350              | 200            | 58.8             | 40         | NA             | 21.7                        | Macroalgae     | 1                | PFR         | [49]       |
| 1.5–2.2                  | 350              | 200            | 38–62.6          | 27–60      | NA             | 35.0                        | Algae         | 1                | PFR         | [44]       |
| 2.1                      | 350              | 200            | 50–56            | 29         | 38.8–39.3      | 17.0                        | Grapes pomace  | 1                | PFR         | [41]       |
| 2.5                      | 350              | 185            | 39.7, 36.8       | 1.4, 5.8   | 32.9, 36.1     | 10.0                        | Microalgae     | 0.098            | PFR         | [30]       |
| 3–7.5                    | 300–400          | 270            | 48.2–60.9        | 12–30      | 35.8–37.2      | 4.0                         | Fungi         | 1.5              | PFR         | [50]       |
| 4.5                      | 325–350          | 180            | NA               | 3–9        | NA             | 5                           | Wastewater algae | 0.5              | PFR         | [51]       |
| 9&14 kg/h                | 400              | 300            | 20–33            | 50         | 34.3           | 16.9                        | Aspen wood     | 10               | PFR         | [52]       |
| 45                       | 260–280          | 110–124        | NA               | 30–120     | 34.1–40.4      | 10–15                       | Swine manure, food | 35               | PFR         | [2,22]     |
| 60                       | 350              | 220            | 25–33            | 20         | 26.8–33.2      | 16.0                        | Energy grass, sewage sludge | 20               | PFR         | [42]       |
| 90                       | 300–350          | 120–200        | 25               | 3–5        | NA             | 5.0                         | Macroalgae     | 4.5–7.5          | PFR         | [10]       |
| NA                       | 350              | 240            | 30–40            | 15         | 34–37          | 5                           | Microalgae     | NA               | CSTR        | [53]       |
| 0.9–2.1                  | 300–350          | 200            | 30–50            | 20–47a     | 21–23          | 3                           | Lignin         | 0.7              | CSTR        | [54]       |

HHV, higher heating value; HTL, hydrothermal liquefaction; NA, not available; PFR, plug flow reactor; CSTR, continuous stirred-tank reactor.

*a Space time instead of residence time.
documented in the literature was 60 L/h from Aarhus University (Denmark) [42]. The residence time was 20 min, which led to a reactor volume of 20 L. Recently, the University of Illinois at Urbana-Champaign also developed a 35-L continuous plug flow reactor using swine manure and food processing waste as the feedstock [2,22]. The biocrude oil products were proven to be suitable for powering transportation machinery after modest refinement (lower than 100 °C) [2,22].

Summarizing from the available literature, it is generally agreed that possible peripheral bottlenecks to the scale-up (continuous- or pilot-scale) of HTL include (1) continuous feeding/pumping mechanism, (2) high-pressure pumping, (3) reactor corrosion caused by salts, (4) fouling/clogging of the continuous reactor, (5) product collection system, and (6) technology suitable for abating strong odors [6,22,40,42–44]. Detailed discussion of each possible bottleneck is described in the following list:

1) Continuous feeding/pumping mechanism: The continuous feeding mechanism is identified as one possible peripheral bottleneck because of two reasons. First, phase separation may occur in sewage sludge. This would be a serious issue especially in the winter, given that sewage sludge may contain high amounts of water. (Water would freeze in the winter, and thus, an external heating source is needed for the feeding tank.) Second, the viscosity of the sewage sludge could be very high and thus slow down its flow rate. Preferably, 20–25 wt.% of solid content is favored to achieve a net positive energy gain [7,44]. However, increasing the solid content may decrease the flowability of sewage sludge. The viscosity of the sewage sludge slurry dictates if the pumping system can be stably operated with a constant feedstock flow rate to the reactor. Possible solutions include the development of efficient pumping methods and pretreatments to reduce the viscosity of sewage sludge [40,45].

2) High-pressure pumping: Sewage sludge can be very viscous and may contain solid particles (e.g. gravel) and other compositions (e.g. plastic waste) that cannot be well homogenized before entering the upscaled HTL system. In this case, specialized high-end pumps such as a metering pump (i.e. a valveless rotary piston pump) are required to avoid possible blockage and undesired backflow (caused by flaky particles) in the sewage sludge feedstock [43].

3) Corrosion caused by salts: Sewage sludge feedstock may contain corrosive contents. For instance, dechlorination and debromination would be necessary for treating chlorinated and brominated waste (e.g. sewage sludge may contain polyvinyl chloride or brominated flame retardants that may exist in electronics) [27,28].

4) Fouling/clogging of the continuous reactor: Unwanted restriction of flow in continuous-flow reactors can result in serious clogging. In particular, the sewage sludge feedstock may contain highly volatile content (e.g. food waste), semivolatile content (e.g. paper or plastic), and nonvolatile content (e.g. metals and minerals) [22]. Because of a huge difference of their volatility (which indicates their convertibility under HTL), possible clogging may occur. How to mitigate or prevent the clogging when running a continuous pilot-scale HTL reactor is especially important because even a small clogging would build up the pressure and lead to safety problems. To resolve this issue, a recent study from Aarhus University (Denmark) has used a hydraulic oscillator to enhance the mixing of sewage sludge by increasing the turbulence in the reactor system [42].

5) Product collection system: The products from HTL may be flowable at relatively high temperatures (e.g. >100 °C) but not at ambient conditions (i.e. 20–25 °C). Without a proper collection system, the HTL products may also lead to clogging of full-scale continuous-flow reactors. Furthermore, how to safely reduce the pressure from the reactor system to the product collection end is another issue. Last but not least, optimization of the heat exchanger represents an important aspect of the product collection system and a significant factor in the overall energy efficiency of a continuous HTL system [40].

6) Technology suitable for abating strong odors: Sewage sludge typically contains certain amounts of proteins, which would be converted into odorous compounds such as nitrogen-containing (e.g. ammonia and pyridines) and sulfur-containing (e.g. H2S) compounds by HTL. Removal of these odorous compounds would be critical for a large-scale HTL operation to meet industrial hygiene and safety standards.

In addition, catalysis has also been recently used in continuous HTL reactors to increase the oil yield and oil quality [42]. These improvements of the continuous HTL reactor design are the foundation for the future commercial implementation of HTL with economically feasible business scenarios.

Energy analysis of HTP and integration with existing technologies

An energy analysis of HTP is critical because innovations in wastewater treatment technologies and clean energy are interdependent. The Electric Power Research Institute estimated that about 4% of the nation’s electricity use goes to moving and treating water and wastewater [55]. A recent report to the
US Congress expected that the demand for electricity at drinking water and wastewater treatment facilities (WWTFs) will increase by 20% as populations grow and environmental requirements become more severe [55]. For instance, in Massachusetts alone, 20 million MWh energy (0.5% of the nation’s electricity consumption) is used by WWTFs and 54% of this energy is related to aeration operation for sludge treatment (Figure 1a) [55,56].

Biochemical and thermochemical processes are two main technologies for management of sewage sludge. Traditionally, incineration was used to dispose of sewage sludge. Conventional incineration systems generally consume more energy than they produce because of the high moisture content in sewage sludge. Alternatively, anaerobic digestion (AD), an oxygen-free microbial fermentation of organics for biomethane generation, could be considered to cope with the increasing quantity of sewage sludge. AD is generally more effective than incineration for energy recovery. AD is also the most common method for sewage sludge stabilization, resulting in the reduction of volatile solids. However, AD usually suffers from poor conversion efficiencies (<50%), slow reaction rates (several weeks), and high capital costs. Moreover, a large volume (>50%) of the wet residual digestate (or AD sludge) would be generated after AD [57].

Figure 1

Energy analysis for WWTFs and possible alternatives. (a) Energy consumed by different sectors in WWTFs (the data are from a prior publication; see more details in the studies by Copeland and Carter [55] and Crawford [56]); and (b) comparison of (a) process energy input, (b) energy output/energy input, and (c) greenhouse gas (GHG) emissions of HTL and the current solutions, as well as competitive technologies. (Notably, we only compared the energy demand and GHG emissions during the production process. Energy demand and GHG emissions for implementing the entire system are excluded.) (The data are from previous publications; see more details in the studies by Chen et al [2] and Si et al [3] and Supplementary data.) WWTF, wastewater treatment facility; HTL, hydrothermal liquefaction.
HTP is an emerging technology for AD sludge conversions with considerably faster reaction times (minutes) and high conversion efficiencies (>50%). Herein, we have provided an estimated energy process input, energy output/input for processes, and the greenhouse gas emissions of different sewage sludge treatment methods (Figure 1b; more details are included in Table S1 in Supplementary Data). As Figure 1b shows, HTP can recover at least four-fold the amount of energy put into in a laboratory-scale reactor, primarily because HTL can directly treat wet feedstock without drying (but not other methods). Compared with similar technologies for AD sludge management (e.g. landfilling), HTP not only sterilizes the sludge but also converts it into valuable end products, with 11-fold higher energy recovery and emissions in greenhouse gas decreased by 78–85% [2]. Multiple published studies also suggest that an integration of AD and HTP could benefit a resilient water-energy nexus [2,5].

**Challenge and outlook**

**Basic cost analysis**

The literature showed that using algal feedstock to produce biocrude oil via HTP was costly, with more than 70% of total cost attributed to algae harvesting (Figure 2) [58,59]. Consequently, researchers have recently switched the feedstock from algae to sewage sludge, which are much cheaper than algae [58]. However, there is room to further study the potential of sewage sludge. For instance, as most wastewater treatment plants produce approximately equal amounts of primary and secondary sludge, testing of appropriate ratios of these feeds will help to shape planning of biocrude production plants. In addition, increasing the feed solid contents for continuous HTP will improve the economics through decreased capital costs and increased energy efficiency. Sensitivity analysis indicates significant economic benefits are available if the HTP aqueous product can be recycled back to the headworks of WWTFs. For example, about 30% cost is attributed to HTP aqueous product treatment (Figure 2). If combined improvements in the analyses are considered, cost of HTP fuel could be significantly reduced. Moreover, it should also be pointed out that by recycling the soluble organics into the HTP process, the main energy vector (i.e. biocrude oil) would be increased, instead of being distributed out of the system.

**Environmental impact of using HTP technology to treat sewage sludge**

More research on low-temperature sewage sludge treatment is required to reduce the environmental impact of HTP. For instance, cosolvent HTP has been shown as an effective way in increasing the biocrude oil yield and enhancing the process efficiency of HTP [10]. Various organic solvents with different solvent:water ratios may lead to an effective cosolvent mixture for HTP to maximize reaction yields at lower temperatures. The kinetic study of HTP will also give a better understanding of generic reaction pathways and the formation of HTP products.

**Commercialization potential of HTP technology**

Before commercializing HTP, techno-economic analysis of the process along with energy calculations should be examined. Further research should be conducted with continuous-flow reactors using different types of sewage sludge and cosolvents. Particularly, increasing the sewage sludge concentration to around 20–25% without losing the fluidability of the slurry for continuous HTL is critical in terms of process development to the industrial scale [40]. A higher solid content of sewage sludge (with a maximum content of 35% from a batch-scale study) typically can lead to a higher biocrude oil yield. As a result, the energy balance of continuous HTL systems would be improved because energy lost to a volume of water would decrease with a reduction in water content, and therefore, the production costs can be reduced [9]. One possible method to increase the sewage sludge concentration is pretreatment of sewage sludge. For instance, several pretreatment methods using acid hydrolysis, alkaline treatment, liquid hot water, ammonia, and steam explosion were applied to the slurries for enabling their pumpability for continuous HTL systems [40,45,60]. It was also found that an alkaline environment was preferable for preparing pumpable woody biomass for continuous HTL reactions [45,60]. Of course, further pretreatment also would further increase overall process costs.
Conclusion

The primary objective of sewage sludge management is to develop more environmentally friendly processes to reduce environmental pollution risks of sewage sludge to humans. HTP, including HTC and HTL, is a promising method to sustainably manage sewage sludge because it can convert sewage sludge into useful products while mitigating the environmental risks of sewage sludge simultaneously. HTC has been extensively used for phosphorus recovery, while HTL can effectively remove CECs. Energy analysis of HTP indicated that HTP has a 11-fold higher energy recovery than land-filling. Further research on techno-economic analysis, environmental impact, and commercialization potential of HTP technology is recommended.

Author contributions

WTC designed and supervised the overall project and contributed to literature analysis, preparation, and writing of the manuscript. MAH designed the scope of this perspective article; analyzed data and results from the literature; and wrote the manuscript. AA assisted the design of the scope of this perspective article and contributed to literature analysis and preparation of the manuscript regarding continuous hydrothermal liquefaction. GR assisted the preparation and writing of the manuscript.

Conflict of interest statement

Nothing declared.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.coesh.2020.02.008.

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• of special interest
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