Thermochemical conversion of sewage sludge for energy and resource recovery: technical challenges and prospects

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**ABSTRACT**
Thermochemical processes are considered as a promising technology for sewage sludge management, which could achieve volume reduction, energy and resource recovery, and effective destruction of pathogens. However, there are still many technology limitations and challenges of the thermochemical processes toward industrialization and commercialization. This review first briefly discusses the impact of sewage sludge on environmental sustainability and its current treatment and disposal methods. Typical thermochemical conversion technologies i.e., incineration/combustion, pyrolysis, gasification, and hydrothermal liquefaction for energy and resource recovery from sewage sludge are then comprehensively summarized. Subsequently, the technical challenges of thermochemical conversion of sewage sludge and the solutions that have been and/or are being developed to address the challenges are in-depth analyzed. Meanwhile, the prospects and future directions of the thermochemical technologies are outlined. In addition, the economic analysis and life cycle assessment of thermochemical conversion technologies are evaluated. Finally, the conclusions are put forward.

**KEYWORDS**
Thermochemical conversion; sewage sludge; energy and resource recovery; technical challenges; solutions

1. Introduction

Industrial civilization relies on the energy consumption and much of the socioeconomic wealth is based on petroleum-based economy. Petroleum is not only used as principal energy source for transportation fuels but is also the feedstock for the production of many chemicals and materials. However, rapid depletion of petroleum reserve and the environmental emissions including greenhouse gas from petroleum use are the two most serious issues of fossil fuels [1]. Hence, development and utilization of alternative energy sources can greatly alleviate the depletion of fossil resources, and decrease the greenhouse gas emissions [2,3]. Energy crisis and environmental pollution are considered the most critical challenges for sustainable development of the global society.

Sewage sludge, an inevitable by-product of wastewater treatment plants, is regarded as a biomass feedstock for energy (biogas, fuel gas, syngas, biodiesel, bio-oil, etc.) and resource (nutrients, hydrolytic enzymes, biofertilizers, biochar, heavy metals, ash for construction materials production, etc.) recovery due to its high organic and valuable inorganic content [4-6]. About 32–52 million tonnes (~80 wt% water content) of sewage sludge are produced annually in China, and this number may increase by ~10% per year [7]. Usually, sewage sludge obtained from the section of biological treatment in wastewater treatment plants (WWTPs) is used for energy and resource recovery, while its typical components include 59–88% (w/v) of organic matter, composed of 50–55% C, 25–30% O, 10–15% N, 6–10% H with little amount of P and S [8]. Meanwhile, some minerals (e.g. Fe, Ca, K, and Mg) and heavy metals (e.g. Cr, Ni, Cu, Zn, Pb) can also be detected in the sewage sludge [8].

Biochemical conversion (e.g. anaerobic digestion (AD), fermentation) and thermochemical conversion (e.g. incineration/combustion, pyrolysis, gasification, and liquefaction) technologies are traditional methods to recover energy and resources from sewage sludge [9]. In contrast to biochemical conversion, thermochemical conversion can potentially convert the entire organic fraction of the feedstock. Moreover, it is more efficient, taking only a few seconds up to a few hours rather than days for biochemical conversion. More importantly, thermochemical conversion can produce a broad range of products that can be separated for various utilisations. Hence, thermochemical conversion has been considered as an attractive and promising technology for the management/treatment/volume reduction of sewage sludge [10,11]. Although thermochemical conversion of sewage sludge is advantageous over bioconversion, its conversion processes are multi-phase and generally at elevated temperatures, bringing with them many challenges in large-scale operations. For instance, emission of...
various pollutants, agglomeration and sintering, de-fluidization and high operating cost are major technical challenges in fluidized bed incineration of sewage sludge [12]. Pyrolysis/gasification of sewage sludge is limited by the need of feedstock de-watering and drying, which are energy intensive [13,14]. For gasification, tar formation reduce energy recovery efficiency and increase the cost of investment in gas cleaning system. Although hydrothermal liquefaction can be directly utilized feedstock with high-moisture contents [15], it still has potential challenges such as continuous feeding at high pressures and temperature, recover and reuse of catalyst, and separate of products, etc.

Several review articles have been published on employed thermochemical technologies to recover energy and resources from sewage sludge, focusing on the reaction mechanism, reactor types, reaction parameters, products characteristics and fine processing, etc., while few reports comprehensively summarized and analyzed the main problems existing in thermochemical technologies [16–20]. Although, the previous studies already analyzed the technical limitations in a piecemeal manner and many efforts have been devoted to overcome the challenges towards the industrialization and commercialization of thermochemical technologies, there is still lack of a comprehensive review involving the technical challenges of thermochemical conversion of sewage sludge for energy and resource recovery and limited literatures specifically focused on the effective measures that have been and/or are being developed to overcome the challenges. Therefore, this review aims to discuss the main challenges and analyze the solutions to overcome the challenges in thermochemical conversion of sewage sludge for energy and resource recovery. The economic analysis and life cycle assessment of thermochemical conversion technologies are evaluated. Through this review, it is expected that recovery of energy and resource from sewage sludge by thermochemical technology can be systematically and compendiously understood from fundamentals to implementations.

2. Impact of sewage sludge on environmental sustainability and its current treatment and disposal methods

Sewage sludge is considered as a bioresource since it contains a large amount of non-toxic organic matters and nutrients [21]. However, it also contains heavy metals, toxic organic matters and a large number of pathogenic microorganisms, parasites, etc., and if mishandled, may cause serious secondary pollution to waterbodies, land and atmosphere, and hence impacts on environmental sustainability, as illustrated in Figure 1. As shown in Figure 1, the organic and inorganic nitrogen in sewage sludge would form NO_{2} (a part of which would be nitrified to form NO_{3}^{-}) through a series of physical, chemical and biological interactions with soil colloid, and eventually lead to photochemical smog, destroy the ozone layer and form acid rain. In addition, nitrogen and phosphorus carried by rainwater would enter waterbodies, resulting in eutrophication, one of the most popular environmental pollations. Proteins in the dead animals and plants are decomposed into NH_{4}^{+} by microorganisms, and subsequently forms N_{2} by nitrification and denitrification. Heavy metals can cause serious health problems if they

![Figure 1. Potential impact of sewage sludge on environmental sustainability.](image-url)
enrich by bioaccumulation and enter into the human body through the food chain. Moreover, pathogens in sewage sludge could spread in various ways, polluting the atmosphere and waterbodies. Therefore, there is an urgent need to find effective management ways towards safe treatment and disposal of sewage sludge.

Currently, as shown in Figure 2, major ways for sewage sludge disposal or utilization can be divided into three categories: landfill, incineration and land-farming [22]. Landfill has been widely used for sewage sludge disposal in China [23]. The landfill approach has become unpopular and even is prohibited due to the limited landfill sites and the prevalent environmental risks associated with public health. Although incineration can reduce sewage sludge mass by 70% while thermally decomposing toxic and harmful substances [24], the exhaust gases released into the environment can cause multiple environmental issues such as formation of acid rain, contribution to the global climate change and emission of heavy metals to the environment through leaching of the ashes [25,26]. Moreover, incineration is currently considered as a high-cost approach for sewage sludge disposal due to the need of dewatering/drying of the feed [27]. Utilization of sewage sludge for land-farming is increasingly regarded as an insecure disposal route due to the presence of heavy metals and pathogens in sewage sludge, which may eventually deteriorate the quality of soil and cause a potential safety risk [23]. Apart from the above mentioned three major ways for disposal, other alternative ways have been proposed for sewage sludge utilization, as also summarized in Figure 2, which include (i) land reclamation; (ii) horticulture and landscaping; (iii) forestry; (iv) industrial processes; (v) resource recovery; and (vi) energy recovery [23]. From the perspective of economic feasibility and environmental sustainability, recovering energy and resources from sewage sludge through thermochemical conversion is more promising.

### 3. Technologies for thermochemical conversion of sewage sludge

Thermochemical technologies are advantageous approaches for managing sewage sludge owing to their promise in recovery of energy and resources, significant volume reduction, effective destruction of pathogens, etc. [28,29]. Main thermochemical technologies include incineration/combustion, pyrolysis, gasification, and hydrothermal liquefaction [30]. In general, the choice of thermochemical technologies depends mainly on the type and quality of feedstock, the desired form of the target products, local emission standards, economic aspects, etc. Comparative analyses of different thermochemical technologies with respect to typical operating conditions, target products and pros and cons, are outlined in Table 1. The following section briefly outlines the working principles of the main thermochemical technologies.

#### 3.1 Incineration/combustion

Incineration can be defined as a unit operation that employs thermal decomposition via oxidation to
convert carbonaceous matter and recover heat [31]. The principal products of incineration are CO$_2$, water, ash, and heat. The heat generated can be further used as energy source for power generation, feedstock drying, steam generation via heat exchange, etc. Ash can be used as the raw material for value-added functional materials production, such as ceramics, bricks, foamed concrete, etc. [32,33]. Whereas, other by-products from combustion such as sulfur and nitrogen compounds, halogens, heavy metals, etc. pose notable environment pollution concerns. Incineration is a high-temperature process in which a part of heat is stored in the flue gas and the remaining is lost to the incinerator walls. Ideally, the feed attains a complete combustion in the following reactions:

\[ 2H_2 + O_2 \rightarrow H_2O + 39.5 \text{ kWh/kg} \cdot H_2 \]  
\[ C + O_2 \rightarrow CO_2 + 9.11 \text{ kWh/kg} \cdot C \]  

However, complete combustion is not usually achievable in an incinerator, as the C may be incompletely combusted to form CO rather than CO$_2$. To ensure that there is sufficient oxygen in the incineration process, excess air with more than a stoichiometric amount of oxygen must be provided.

The fundamental behaviors of sewage sludge in an incinerator/combustor are illustrated in Figure 3(a) [34]. The whole incineration process can be briefly described as follows: when sewage sludge particles are heated, dehydration and devolatilization occur simultaneously from the sewage sludge surface to the interior of the particle, resulting in release of steam and volatiles that pass through and react with the hot layers of char produced from devolatilization; then, the volatiles and light gases burn on the feedstock surface in the presence of oxygen, resulting in an increase of the temperature of the feedstock surface, where the ash layer would melt at a high temperature forming a covering layer of molten ash droplets on the

### Table 1. Comparative analyses of various thermochemical techniques applied for sewage sludge utilization.

| Technologies | Description | Target products | By-product | Pros | Cons | Refs |
|--------------|-------------|-----------------|------------|------|------|------|
| Incineration/combustion | Operating temperature: 800–900°C; O$_2$/air atmosphere; Atmospheric pressure; Suitable for dry sewage sludge. | Heat and power | Ash | -High volume reduction; -Nearly complete elimination of the organics and pathogens. | Air emissions (GHG, NO$_x$, SO$_x$, PMs); Dewatering/drying of sewage to 41–65 wt% solids content required; Low energy efficiency; Far from zero waste; High cost due to feed drying, gas cleaning and ash disposal; Corrosion due to high inorganics content in sewage sludge; Dewatering/drying required. | [10,34,48] |
| Pyrolysis | Operating temperature: 500–600°C; Inert atmosphere; Atmospheric pressure; Suitable for dry sewage sludge. | Bio-oil | Gas | Char | Volume reduction potential; Lower GHG air emissions than incineration; Deactivation of antibiotic resistant genes; Removal of bioactive compounds; Biochar and syngas with potential added values. | More complex when compared with incineration; Air emissions (NO$_x$, SO$_x$) and heavy metals remained in biochar; High capital/investment costs. | [30,36] |
| Gasification | Operating temperature: >700°C; Gasifying agent (steam/CO$_2$, etc.) needed; Atmospheric pressure; Suitable for dry to semidy sewage sludge. | Syngas | Tar | Char | High thermal efficiency and carbon balance; Syngas useful for both fuel and chemical synthesis; Biochar and tars with potential added values; Avoiding SO$_x$, NO$_x$ emissions. | Dewatering/drying to >50 wt% solids content required; Heavy organic pollutant compounds present in tar; Extensive syngas cleaning required; High investment/operaion costs. | [3,4] |
| Hydrothermal | Liquefaction | Operating | | | | |
| | | | | | | |
| Gaseous phase | Direct use of wet sewage sludge; Much lower operating temperature; Deactivation of antibiotic resistant genes; Removal of bioactive compounds. | Mostly at bench-scale; High | | | Bio-crude oil (or bio-oil) | Aqueous phase | [45,71] |


surface. Finally, combustion of the remaining char would facilitate agglomeration of the ash droplets [35].

### 3.2 Pyrolysis

Figure 3(b) describes the stages of a sewage sludge pyrolysis process in thermal environment [36,37]. Heat is firstly transferred to the surface of the sewage sludge particle through radiation and/or convection, and then gradually to the interior of the particle. During transient heating of the sewage sludge particle, temperature increases locally, leading first to the evaporation of moisture (dry in stage) and then to the progressive release of pyrolytic volatiles (primary pyrolysis stage).

The primary volatiles (denoted by ‘Volatiles-P’ in Figure 3(b)) are mainly generated from the thermal scission of chemical bonds of the organics in the sewage sludge, such as proteins, carbohydrates and lipids. The composition of pyrolytic volatiles mainly includes H₂O, CO₂, CO, H₂, CH₄, other non-condensable hydrocarbons and condensable organic compounds (i.e. tar) [38].

The residual carbon-rich solids become biochar (denoted as ‘Char-P’ in Figure 3(b)), containing a significant portion of mineral matters originally present in the sewage sludge. The condensable volatile species at ambient conditions are denoted as ‘Bio-oil-P’. As the temperature further increases, some of the
primary pyrolysis products can participate in a variety of secondary reactions to form secondary products ‘S’, e.g. ‘Volatiles-S’ (as energy recovery), ‘Char-S’ (as resource recovery) and ‘Tar-S’ (as energy recovery) (Figure 3(b)).

A complex series of reactions such as cracking, reforming, dehydration, condensation, polymerization, oxidation and gasification reactions can occur simultaneously [39]. The distinction between primary pyrolysis and secondary pyrolysis is not apparent as the secondary reactions of volatiles can occur both in the pores of the particles and/or in the bulk gas. Thus, the primary and secondary reactions can occur simultaneously in different parts of the feedstock particles. The char obtained from the primary pyrolysis stage can act as adsorbent and catalyst in the secondary reactions (cracking reactions and polymerization reactions) to convert the organic vapors into light gases and secondary char. In addition, in the presence of H₂O and CO₂, char can be gasified into gases through steam gasification and Boudouard reactions [40]. However, the gasification reaction rates of char with H₂O and CO₂ are generally orders of magnitude lower than those of the primary pyrolysis, the gasification of char is limited. In comparison, the secondary conversion of the primary volatiles is a rapid process, depending on the operational conditions, which has a great influence on the final composition and yield of the volatiles.

### 3.3 Gasification

Gasification mainly aims to obtain syngas products that can be used directly for heating or further processing into methanol, dimethyl ether or other chemicals by Fischer-Tropsch process [41]. Gasification may be viewed as extension of pyrolysis, in which the feedstock heated firstly undergoes drying and pyrolysis, releasing volatiles and leaving solid residues as char, followed by gas-solid and gas–gas reactions in the presence of a gasifying agent. Figure 3(c) illustrates the four steps of gasification for a single particle of sewage sludge [42]. At about 70–200°C, drying as the first step takes place to remove the moisture. The rate of drying depends on the surface area of the feedstock particle, the recirculation velocity, the relative humidity of the drying gas, the internal diffusivity of moisture within the sewage sludge particle, and the temperature differences between the particle and hot gases. In the secondary or pyrolysis step at about 350–500°C, thermal decomposition of the organics takes place when approx. 60–70 wt% of the feedstock can be converted to a complex liquid fraction, gases and char. The chemical compositions of the sewage sludge, the heating rate, the gasification agent and the reactor temperature have important effects on the products distribution. However, the total yield of pyrolysis products and the amount of char can be roughly estimated from the proximate analysis of sewage sludge (i.e. volatile and fixed carbon content, respectively). The third step is gas-solid reactions that convert the solid carbon (char) into gases, e.g. H₂, CO, CO₂ and CH₄. The carbon oxidation and/or partial oxidation reactions are strongly exothermic, providing significant energy for feedstock drying, pyrolysis, and other endothermic solid-gas reactions. Moreover, hydrogenation reactions might also occur and contribute to the energy requirements of the gasifier. Homogeneous gas–gas reactions take place in the fourth step of gasification, affecting the compositions of the final gaseous products.

### 3.4 Hydrothermal liquefaction

Hydrothermal liquefaction (HTL) is a thermochemical process operating in water or another suitable solvent at elevated temperatures (generally 250–375°C) and high-pressure (5–20 MPa) during which the organic feedstock is broken down into four products, i.e. biocrude oil or bio-oil (the target product), aqueous phase, gas and solid residue [43,44]. The basic reaction pathways for the hydrothermal liquefaction of sewage sludge may be illustrated in Figure 3(d) comprising three major steps [45]: (1) depolymerisation of various biomolecules (e.g. lipids, proteins, and carbohydrates) into monomer or oligomer units; (2) decomposition of the monomers or oligomers by cleavage, dehydration, decarboxylation and deamination, forming fragments of small molecules that are unstable and active; (3) rearrangement of light fragments through condensation, cyclization and polymerization, leading to new compounds: bio-oil, aqueous phase and solid residue.

The depolymerisation of organic feedstock involves a series of dissolution reactions occurring to dissolve the macromolecules (protein, carbohydrates, lipid, etc.) into monomer/oligomer units in water or organic solvent by hydrolytic or solvolytic reactions, facilitated by elevated temperature and pressure. Then, the decomposition step occurs, which involves loss of water, CO₂ and removal of amino acid content by dehydration, decarboxylation and deamination reaction, respectively. It is worth noting that the dehydration and decarboxylation reactions reduce the content of oxygen in the bio-oil by forming H₂O and CO₂, which improves the stability and energy density of the bio-oil product. In the third step, opposite to the initial steps, condensation, cyclization and polymerization reactions of some unstable and reactive decomposition products (free radicals), forming high molecular weight char or bio-oil. If a stabilization agent such as hydrogen is freely available in the process, the free radicals will be capped yielding stable bio-oil products with lower molecular weights.
4. Technical challenges in thermochemical conversion of sewage sludge

4.1 The main technical challenges of sewage sludge incineration

4.1.1 Pollutants emission
Because incineration is carried out in oxidizing atmosphere, the nitrogen- and sulfur-containing compounds in sewage sludge would convert to air pollutants NOx and SOx, causing major environmental problems such as acid rain and photochemical fog [46,47]. HCl and Cl2 can also be detected in the flue gas while incinerating sewage sludge due to the presence of chlorine in the feedstock [48], which leads to corrosion of incinerator [49]. Furthermore, Cl2 would serve as the major chlorinating agent in the formation of toxic polychlorinated dioxins and furans (PCDD/Fs) [50]. PCDD/Fs are not directly derived from sewage sludge, but generated in the post-incineration stage via oxy-chlorination process that can be promoted by the catalytic effects of the metallic species contained in the fly ash [50,51]. Besides, CO and polycyclic aromatic hydrocarbons (PAHs) are also generated from incomplete incineration of organics [52,53]. In addition to the above gas pollutants, fly ash poses existential health risks, e.g. respiratory threats due to its carriage of toxic heavy metals such as mercury and lead, along with other pollutants such as PCDD/Fs [54]. Therefore, controlling/reducing the formation/emission of these pollutants is one of the major technical challenges for the incineration technology.

4.1.2 Operating problems
Fluidized bed incinerators are widely applied for waste disposal, where some operational problems exist, among which bed materials agglomeration is one of the main problems encountered in fluidized bed incineration of sewage sludge. The agglomeration often results from the in-bed formation of low-melting point eutectic mixtures through the reaction of mostly alkali compounds of the sewage sludge with the silica bed materials [55]. In addition, sintering of the bed materials can also occur at high temperatures [56]. Agglomeration and sintering promote the particle growth of the bed material, ultimately resulting in defluidization of the bed [53]. Therefore, tackling these operating problems is another challenge in the application of incineration technology for sewage sludge disposal.

4.2 The main technical challenges of sewage sludge pyrolysis/gasification

4.2.1 Tar issue
Tar is a thick, black, highly viscous liquid comprising aromatic compounds (1–5 ring) plus other oxygen-containing hydrocarbons and PAHs [57]. During the pyrolysis/gasification process, tar formation can cause several problems such as forming coke, plugging the filters and lines, etc., resulting in serious operational interruptions. It was reported that the tar content in the syngas from an air-blown circulating fluidized bed biomass gasifier was about 10 g/m³, while the tar content could reach 0.5 to 100 g/m³ in other types of gasifier [58]. However, most applications of syngas require a tar content level as low as 0.05 g/m³ or less [58]. Tar is also harmful to the health of human beings due to the containing teratogenic and carcinogenic compounds. In addition, tar contains significant amounts of energy that can be transferred to product gas. Hence, formation of tar in the pyrolysis/gasification process would not only lead to unacceptable levels of maintenance for downstream equipment, but also lower the energy efficiency of the process.

4.2.2 Catalysts deactivation
In the thermochemical processes, catalyst plays a vital role in improving the reaction efficiency and product quality. Ideally, a catalyst should have high activity, stability, and durability as these will substantially reduce the frequency of catalyst regeneration. In practices, many factors may cause catalyst deactivation, such as fouling, coke/carbon formation, poisoning, sintering, and phase change. For acid- or based-catalyst, the deactivation of catalyst is mainly due to coking, whereas in the case of supported metal catalysts, the deactivation could be due to the formation of coke or the synergy between coking and sintering of the metal. In some cases, the activity of catalysts may be decreased due to the chemical transformations or stream washing of the metals, leading to the loss of active species on the catalyst surfaces. Consequently, the deactivation mechanism between catalysts is different, while it also hinges on the reaction conditions. Catalyst deactivation is a common issue in catalytic processes, mainly due to poisoning of catalytically active sites by some of the contaminants present in the feed, or due to blockage of active sites and/or pores by the coked formed during the cracking or condensation of reactants and/or products. Sometimes the products formed can decompose on prolonging the reaction time and strongly adsorb on the catalyst surface [59]. Similarly, a catalyst during pyrolysis/gasification of sewage sludge may be deactivated by the fly ash generated in the processes that covers the surface or block the pores of the catalyst. In addition, in catalytic processes operating at high temperatures, thermal degradation of the catalyst might occur in the form of sintering leading to loss of active surface area via structural modification of the metal crystallites in the catalyst or loss of support surface area due to growth of its crystallite size. Metal catalysts may also react with various impurities, such as Cl, S, and O, leading to some changes in phase or formation.
of new phases, altering the catalyst’s activity [60]. Moreover, the generated CO₂ during thermochemical conversion was also identified as a deactivation agent especially for alkali metal carbonates catalysts [61]. In addition to the abovementioned chemical reasons, mechanical reasons such as attrition may also cause catalyst deactivation. In addition to the abovementioned chemical reasons, mechanical reasons such as attrition may also cause catalyst deactivation. It is well known that having well mechanical strength to tolerate high attrition is an essential feature of fluid catalytic cracking (FCC) catalysts, because the catalysts particles needed to be looped continuously in the reaction system. Similarly, attrition causes the catalyst to deactivate is also an important fact in Fischer-Tropsch synthesis while slurry bubble column reactors are employed.

The catalyst deactivation can be evidenced by the reduced reaction rates and declined products quality and quantity [62]. Moreover, from the perspective of industrial application, recycling, regenerate and reuse of the catalyst is very important, considering the green chemistry principles (to minimize waste generation and avoid hazardous reagents in the preparation of fresh catalysts) and the dwindling supply and high price of precious metals used in many catalysts. For organometallic complex catalysts, their recycling and reuse are even more desirable because of their high prices. As such, continued efforts are needed to develop robust catalysts and proper methods for recovery, reactivation and regeneration of the used/deactivated catalysts.

4.2.3 Formation of NO₃ and SO₄ precursors

Sewage sludge generally contains about 9 wt% nitrogen and 1 wt% sulfur by dry weight, which would release NO₃ and SO₄ precursors in the pyrolysis/gasification process, and may eventually cause secondary pollution of photochemical smog and acid rain [63,64]. For example, nitrogen and sulfur in sewage sludge can be converted to NH₃, HCN and H₂S gases under reductive conditions, or NO₃ and SO₄ under oxidation conditions. In order to reduce the formation of nitrogen/sulfur-containing compounds during the pyrolysis/gasification of sewage sludge, many research efforts have been made. For instance, it was found that nitrogen mainly existed as protein in sewage sludge [63,65], and HCN and NH₃ were found to be the major nitrogen-containing species derived in the sewage sludge pyrolysis, which can be further converted into NOₓ. In order to develop measures to minimize the NOₓ emissions, it is essential to better understand the sewage sludge-nitrogen nexus during pyrolysis/gasification. The nitrogen migration and transformation is a very complex process due to the heterogeneity of sewage sludge and different pyrolysis conditions. For example, Cao et al. [63] found that a high-concentration NH₃ was generated in the sewage sludge pyrolysis process, while high-concentration HCN was detected in the study by Tian et al. [66]. Organic sulfur in sewage sludge should not be neglected, including sulphonylic acid, sulphotrope, aromatic sulfur and aliphatic sulfur [67], and decomposition of aromatic sulfur and aliphatic sulfur formed sulfur-containing gases in pyrolysis/gasification of sewage sludge. It should also be noted that these sulfur-containing gases would corrode metal surfaces, and be oxidized to SOₓ.

4.2.4 High moisture content of the feedstock

Sewage sludge in particular secondary sludge contains a high moisture content (generally over 80–90 wt%) needs to be dewatered or dried prior to pyrolysis/gasification treatment, which compromises the energy recovery efficiency, although appropriate moisture content can promote tar decomposition and biochar gasification. In addition, sewage sludge with high moisture content is pasty, which brings great challenges to continuous feeding. For instance, it was reported that the allowable maximum moisture content in the feedstock was about 25 wt% in down-draft gasifier and 50 wt% in up-draft gasifier [68], and the gas yield decreased at the moisture content of over 30% in sewage sludge gasification. Therefore, it is necessary to reduce the moisture content of sewage sludge to an acceptable level prior to feeding it to the pyrolysis or gasification process.

4.3 The main challenges of sewage sludge hydrothermal liquefaction

4.3.1 Batch vs. continuous-flow reactor systems

Although hydrothermal liquefaction (HTL) is a promising technique for conversion of sewage sludge to liquid fuels, some technical challenges need to be addressed. High temperature and high pressure operational conditions require use of pressure reactors. Meanwhile, a corrosive environment formed by subcritical water during the HTL reaction requires resistant materials (e.g. stainless steel) for reactor construction, which leads to a high capital cost. Furthermore, the generated substances with low solubility in water (e.g. coke, tar, and solid residue) are easy to deposit in the reactor or downstream units, which could obstruct the functions of equipment. As such, most of the works on HTL of sewage sludge were carried out in batch reactor system. From the perspective of large-scale industrial applications, a continuous-flow hydrothermal liquefaction system with higher efficiency and economic feasibility should be developed, although continuous-flow HTL of sewage sludge was demonstrated by the Xu’s group at Western University at lab-scale (0.6 kg/h feeding capacity) [69]. However, HTL of sewage sludge is by far lack of commercial-scale installment and operating experience.
4.3.2 Catalysts recovery
The essence of HTL is pyrolysis in hot-compressed water, which theoretically does not require a catalyst [69]. However, in order to increase the efficiency of this process and reduce solid residue yield while increasing bio-oil yield, catalysts are usually employed [70]. Homogeneous catalysts, e.g. alkali catalysts (Na₂CO₃, NaOH, etc.) and acid catalysts (H₂SO₄, H₃PO₄, etc.) have been widely employed in HTL [71]. However, it is a challenge to recover these soluble catalysts from the end product, which requires costly and energy-intensive separation processes [70]. To tackle such challenges, some heterogeneous catalysts (supported metal or metal oxide catalysts) have been tested, which can be easily recovered and possibly reused for several times [72,73]. Whereas, other challenges are associated with the heterogeneous catalysts, such as deactivation due to the leaching loss of metals or poisoning by deposits of tars or inorganics [71].

4.3.3 Product separation
After hydrothermal liquefaction, the obtained products need to be separated. So far, most studies reported in the literatures used organic solvents to extract the biocrude oil from the aqueous phase and solid residues, but few attentions had been paid to the effects of organic solvent on the yield and quality of the biocrude oil products. Employing organic solvent increase the overall cost of HTL process as the solvent need to be recovered by evaporation or distillation, when small molecules of biocrude oil could be lost by evaporation along with the solvent, resulting in reduction in the bio-crude yield. Thus, efficient and cost-effective separation of biocrude oil from HTL remains a challenge.

5. Solutions to the technical challenges and future prospects of thermochemical conversion of sewage sludge
5.1 Reducing the pollutants emission and operating problems in incineration
The formation of pollutants during incineration process depends on operating conditions and fuel characteristics. For example, maintaining optimum excess air ratio and a high enough temperature is crucial to minimize CO in the incineration gases [74]. Both SOₓ and HCl are acid gases, which can be abated by measures such as in-furnace adding calcium-based compounds (limestone, CaO, or Ca(OH)₂), combined with a post-incinerator injection of CaO or NaHCO₃, etc., or co-incinerating with wastes of a high calcium content [75,76]. However, while increasing the SOₓ capture in the flue gases, the concentration of soluble sulfates in the fly ash or flue gas cleaning residue would increase, resulting in an increase in the concentration of sulfates in the leachate from these residual solids, limiting the calcium recycling. As for NOₓ, in order to control and/or reduce its emission, incinerator modification (air and/or fuel staging) and De-NOₓ techniques (selective catalytic reduction or selective non-catalytic reduction) are usually employed [77,78]. As the formation of PCDD/Fs and PAHs are favored in the presence of incomplete incineration products, measures to control these pollutants are the same as those for CO minimization, e.g. good control of the incineration process (excess air and temperature) to ensure complete burn-out, as well as using activated carbon or lignite powder particles in the flue gas for adsorptive removal of these compounds [53]. Before removing acid gas in flue gas, an electrostatic precipitator or baghouse filter are usually used to remove fly ash. On the other hand, there are measures to reduce the risk of defluidization, including off-line and on-line detection, control of operating parameters and addition of additives to reduce the risk of bed materials agglomeration and sintering.

As introduced above, although there are technologies developed to mitigate the challenges, integrating these technologies into the incineration system is undoubtedly of increased investment. Efforts should be made in developing green engineering approaches: prevention, e.g. to explore: (i) cost-effective higher-efficiency incineration processes with in-furnace pollutants control; (ii) pretreatment of feedstock to reduce the content of pollutants-precursors (e.g. by leaching removal of heavy metals from sewage sludge); (iii) high-efficiency co-incineration technology to reduce various pollutant emissions.

5.2 Strategies for tar minimization/removal
Several approaches are currently available for tar minimization/removal. These include physical treatment, thermal cracking, non-thermal plasmas and catalytic cracking/refforming [79,80]. Physical treatment (e.g. scrubbing and electrostatic precipitation) are operated effectively at lower temperature, thus additional condensation is needed since tar has a high temperature when coming out from the pyrolysis/gasification reactor. Recently, a rotating particle separator was tested for tar removal, but with low efficiency [58]. Thermal cracking of tar is accomplished at a high temperature from 1100°C to 1300°C, hence with poor economic feasibility [81]. While plasmas had also been applied for tar decomposition, this technology is too complex and expensive to be applied at a large scale. However, catalytic cracking/refforming can be an economically viable approach for tar removal and minimization owing to the reduced activation energy of tar decomposition employing catalysts [57]. Various kinds of catalysts such as nickel-based (on Al₂O₃ or SiO₂), noble metal based (Pt, Pd), other transition metals (Fe, Cu,
Co), alkali metals (K₂CO₃), natural minerals (dolomite, olivine), zeolites and carbon-supported (e.g. biochar) catalysts have been investigated on tar minimization/removal in pyrolysis/gasification processes [57]. Nickel-based catalysts were found to be very effective for tar removal and usually were used for syngas or H₂ production [82]. Nevertheless, these catalysts are relatively easy to be deactivated by self-sintering and carbon deposition and, especially by sulfur poisoning. Noble metal-based catalysts have high catalytic activity with high sulfur resistance and long-term stability, but they are very expensive. Some other transition metal-based catalysts such as Fe, Cu and Co have also demonstrated moderately active for cracking of biomass tar. To improve the performance of catalysts for tar reforming/cracking, bimetallic or trimetallic catalysts are also studied [83,84]. Alkali metal-based catalysts in-furnace added to the reactor also showed good catalytic ability for reducing tar formation, whereas they could evaporate quickly during the pyrolysis/gasification process, and hence are hard to recover. Natural mineral catalysts (dolomite, olivine) have been widely used for in-furnace cracking/reforming of tar, owing to their abundance and inexpensiveness. However, the natural mineral catalysts are inferior to other catalysts with respect to their catalytic activities and mechanical strengths. Zeolite was identified as a good catalyst owing to its better thermal stability, relatively high tolerance to sulfur and nitrogen compounds and easy regeneration. However, the main drawback of zeolite is the rapid deactivation caused by coke deposition [85]. Carbon-supported catalysts are inexpensive and have a fair performance in the minimization/removal of tar, which can be attributed to the large pore size, high surface area, and the presence of various ash or mineral (serving as catalysts too) contents in the carbons. However, the carbon-supported catalyst has both advantages and disadvantages. On the one hand, it can recover energy through simple gasification or combustion when char is deactivated; On the other hand, it is easy to be gasified in the catalytic reaction process, thus reducing the catalytic activity. Actually, if the coke deposits rate on the surface of carbon-supported catalyst is higher than the coke consumption rate which gasification by steam/CO₂, coke deposition will occur. On the contrary, if the coke consumption rate is higher than the coke deposition rate, the refresh of the active site on the surface of carbon-supported could be occurred, promoting the catalytic cracking reaction continues. Thus, seeking the balance between coke consumption rate and coke deposition rate is the key to ensure the effective operation of carbon based catalyst. According to the above analysis, a highly active and durable catalyst is urgently needed for more cost-effective tar minimization/removal and some suggestions are also presented in Table 2.

### 5.3 Controlling of NOₓ and SOₓ precursors emission in sewage sludge pyrolysis/gasification

The NOₓ and SOₓ precursors emission control technologies can broadly be classified into: (i) pre-pyrolysis

| Catalyst | Advantages | Disadvantages | Future works and some suggestions | Refs |
|----------|------------|---------------|-----------------------------------|------|
| Nickel-based | High tar destruction activity; Reverses ammonia reaction; reduce NOₓ emission; Favorable for methane reforming and water-gas shift reaction; Low-cost; Easy regeneration. | Rapid deactivation caused by coke deposition and the sintering of metal particles; | (1) Steam reforming of heavy tar; coke on the catalyst is more easily occurred in the case of heavy tar, thus, it is necessary to understand the mechanism on the steam reforming of heavy tar on the catalyst; | [82] |
| Noble metal-based | High catalytic activity with high sulfur resistance and long-term stability | Very expensive | (2) Novel catalyst development; based on the coking mechanism, analyze and design the structure and composition of catalyst; develop composite catalysts with several compositions for the reforming of tar; develop catalysts with high activity at lower temperature; improve the strength by ‘skeleton enhancement’ method; | [57–59] |
| Other | transition metals | Moderately active for cracking of biomass tar; Some of them showed higher catalytic activity than Ni catalyst. | (3) Catalyst application in scale-up: in the lab scale, catalyst may show good performance, however, in the scale-up the reaction conditions are very complex. Thus, future works should be considered the practical process; | [61] |
| Alkali metals Natural catalytic activities and | Deactivated easily by carbon deposition in the case of high heavy tar content in tar; Very effective in steam reforming of tar and can improve the quality of gaseous product; minerals | easy to evaporate and hard to recover | (4) Catalyst regeneration technology: in a practical process, a chemical looping system design for continuous tar removal with simultaneous catalyst regeneration is always considered. Thus, how to regenerate the catalyst rapidly is very important. | [83,84] |
| Zeolites | Good thermal stability, relatively high tolerance to sulfur and nitrogen compounds and easy regeneration | Inexpensive and abundant; show considerable activity for the reforming of tar; | | [62] |
| Biochar-based | Inexpensive; natural production inside the gasifier; high tar conversion comparable to dolomite | Consumption because of gasification reactions | | [57] |
/gasification approaches that involve the use of low N/S biomass mixed with sewage sludge. The co-processing of sewage sludge and low N/S biomass could effectively reduce the emission of NOx and SOx precursors due to overall reduction in N/S contents in the feed [10,86,87]; (ii) catalytic pyrolysis/gasification, employing suitable catalysts or minerals (e.g. Fe, Ca, Al and other elements) to convert nitrogen compounds to N2 rather than NH3 and HCN. Currently, Fe and Ca salts have been extensively investigated as catalysts for nitrogen conversion in pyrolysis/gasification, although their catalytic mechanisms were found to be different. Fe could catalyze decomposition of NH3 and increase the yield of N2, while Ca could hydrogenate HCN first to form NH3 followed by decomposing NH3 into N2 [88–90]. During sewage sludge pyrolysis, a part of nitrogen is released as volatile-N and the remainder is retained as char-N. Volatile-N can subsequently decompose into N2 on the surface of Fe-based catalysts. Another route for nitrogen transformation is catalytic conversion of char-N to form N2 via the following reactions:

\[
\alpha - \text{Fe} + \text{char} - N \rightarrow \text{Fe}_\alpha \text{N} (\text{Fe}_\alpha \text{C}_\gamma \text{N}) \tag{3}
\]

\[
\text{Fe}_\alpha \text{N} (\text{Fe}_\alpha \text{C}_\gamma \text{N}) \rightarrow \alpha - \text{Fe} + \text{N}_2 \tag{4}
\]

With Ca-based minerals, such as CaO, it can react with pyrrolic-N/pyridinic-N in char to form the non-stoichiometric calcium carbides, i.e. CaC\_y\_N\_x, which can easily decompose into N\_2:

\[
\text{CaO} + \text{pyrrolic} - \text{N}/\text{pyridinic} - \text{N} \rightarrow \text{CaC}_y\_\text{N}_x + \text{CO} \tag{5}
\]

\[
(\text{CaC}_y\_\text{N}_x) \rightarrow +\text{CaC}_2 + \text{N}_2 \tag{6}
\]

Sulfur-containing gases are mainly derived from decomposition of organic sulfur in sewage sludge, e.g. aromatic sulfur and aliphatic sulfur, via C-S bond cleavage at low temperatures [91]. H\_2\_S was the dominant sulfur-containing gas produced from thermal treatment of sewage sludge [67]. Alkali catalysts/additives have proved effective for reducing the emission of sulfur-containing gases from low-temperature pyrolysis of sewage sludge [92] owing to the alkali-catalyzed C-S bond cleavage at a high temperature or fixation of sulfur in the solid products by the alkali additives [93,94]; (iii) post-pyrolysis/gasification approaches – cold/hot cleaning of the producer gas. Cold gas cleaning includes dry gas cleaning and wet gas cleaning, and hot gas cleaning involves thermal treatment and catalytic treatment, as reviewed extensively by Asadullah [95], and Woolcock and Brown [81].

Although considerable progresses have been made in controlling of NO\_x and SO\_x precursors emission in sewage sludge pyrolysis/gasification, the following issues still need to be tackled in the future: (i) the intermediates formed between nitrogen/sulfur and other components especially inorganic species of sewage sludge should be investigated; (ii) functional materials or novel catalysts should be developed for in-situ/ex-situ capture of NO\_x and SO\_x precursors or selective enrichment of nitrogen/sulfur species in the char/tar products; (iii) cost-effective new processes such as Ca-looping-based technologies should be developed to suppress emission of NO\_x and SO\_x precursors from pyrolysis/gasification of sewage sludge.

### 5.4 Reduction of moisture content of sewage sludge

Reducing the moisture content of sewage sludge has been commonly achieved by mechanical dewatering (e.g. centrifuging, vacuum filtrating, and belt filter pressing), drying (e.g. tradition thermal drying using hot air, solar drying, fry-drying using hot oil and bio-drying), and mixing with other solid fuels of lower moisture contents, e.g. biomass, coal, etc. [29]. The major advantage of mechanical dewatering is that it is low cost and much easier performed than the thermal methods [96]. However, mechanically dewatered sewage sludge still has a high moisture content, ranging from 80% to 85% [97], which is still not suitable for most of the thermochemical conversion processes except for HTL. A thermal drying step is thus necessary to further reduce the moisture content, whereas it is an energy-intensive process. Recently, various pretreatments (e.g. physical, chemical, and biological conditioning) have been investigated to enhance sewage sludge dewatering [98–100]. Physical conditioning refers to physical methods to change the physicochemical properties of sewage sludge, e.g. by adding skeleton builders (e.g. gypsum, lignite, slag and construction waste, etc. [101,102], or applying thermal [103], microwave [104], ultrasonic pretreatment [105], or their combinations [106,107]. Chemical conditioning is made by adding acids or alkalis [108], surfactants [109], bio-chemical agents [110], coagulant/flocculants [111], or using electrochemical methods, etc., [112]) to change the intrinsic nature of sewage sludge and improve the dewatering performance. Biological conditioning method mainly includes bioleaching, an environmentally friendly and economically sustainable method with a great application promise [99,113].

However, practical operation indicates that the current sewage sludge dewatering is less efficient and of a high cost. Therefore, cost-effective, user-friendly sewage sludge dewatering technologies are still needed. Combination of various synergistic technologies may be used for improving the sewage sludge dewatering efficiency.

### 5.5 Chemical looping processes towards CO\_2 capture

Although the use of sewage sludge for energy production is considered to be approximately carbon neutral,
negative CO₂ emission can be achieved if combined with CO₂ capture technology. CO₂ capture and storage (CCS) have been recognized as an effective technology for reduction in greenhouse gas emission, but it is still limited by the high operating cost [54,114]. Among other CO₂ abating techniques (pre-combustion, oxygen combustion, and post-combustion, etc.), chemical looping processes (CLPs) have emerged as a competitive option because it is capable of minimizing energy loss and intrinsically capturing CO₂ [115,116]. CLPs can be classified based on the looping material, i.e., oxygen carrier or CO₂ carrier, and the corresponding typical CLPs can be termed as chemical looping combustion (CLC) (Figure 4a) and Ca-looping combustion (CaLC) (Figure 4b), respectively.

In a CLC process, an oxygen carrier, most commonly a metal oxide (MeOₓ), reacts with fuel to produce CO₂ and H₂O and MeOₓ⁻¹ (Eq. 7), whereas in the air reactor, MeₓOₓ⁻¹ is oxidized, as illustrated in Eq. 8. The net chemical reaction is shown in Eq. 9. However, as the air is not mixed with the fuel during the CLC process, a highly concentrated stream of CO₂ formed can be efficiently captured after water condensation. Similarly, in a CaLC where a CO₂ carrier (usually CaO) is used as a looping material, CO₂ could be captured in-situ in the combustor where the CO₂ carrier (CaO) is frequently recycled for the capture through the carbonation reaction (Eq. 10). Whereas in the regenerator, CaO is regenerated and CO₂-rich gas can be captured by the calcination reaction (Eq. 11). Thus, when sewage sludge/biomass is used as the fuel for CLPs, negative CO₂ emissions can be realized.

Although CLPs have many advantages over traditional CCS techniques, they also encounter some big challenges such as the looping materials deactivation and unstable cycle performance, as well as the requirement for separation of the looping materials from ash. Solid fuels, e.g. coal and lignocellulosic biomass are commonly used in CLPs, while use of sewage sludge in CLP is rare due to the high contents of ash, nitrogen and sulfur. In order to increase use of sewage sludge in CLP, future work should be devoted to the following aspects: (i) develop of sewage sludge chemical looping gasification processes for syngas/H₂ generation, especially focusing on the process intensification to allow produce syngas/H₂ in a single step with in-situ capture of CO₂; (ii) research of appropriate looping materials with multifunctional nature and superior oxidation-reduction/carbonation-calcination performance, as well as a low cost, better availability and environmental and safety performance; (iii) systematically analyze the synergistic effect of CO₂ capture and nitrogen/sulfur catalytic decomposition in CLPs;

5.6 HTL of sewage sludge coupled with algae cultivation

The ultimate goal of sewage sludge HTL is to convert it into biocrude oil or bio-oil as a substitute for fossil fuels [117]. However, from the perspective of economic
feasibility, the HTL process needs to address its technical challenges mainly related to the high operation pressure. On the other hand, in order to further improve the economic performance of the HTL processes, the solid/aqueous/gaseous byproducts from the process should be fully utilized. Figure 5 depicts an integrated process to maximize the economic/environmental benefits and energy sustainability of HTL process by combining sewage sludge HTL and algae cultivation. Four products/byproducts, e.g. solid residue, biocrude oil, aqueous phase with high concentrations of organics and nutrients, and gaseous phase rich in CO$_2$, obtained after sewage sludge HTL could be fully utilized [118]. The solid residues can be used for soil conditioners or as activated carbon-based material for environmental and energy applications [71], while biocrude oil can be used as transportation fuels after upgrading. The handling of the aqueous phase is critical as it accumulates most of the sewage sludge-containing nutrients and some organics, which provides a significant opportunity for nutrients and carbon sources, e.g. for algae cultivation. Typical limitations of algae cultivation and biofuel production are the consumption of water, nutrients, energy and environmental pollution [45]. Therefore, it is a promising solution to direct use of the nutrients and carbon in the aqueous phase from sewage sludge HTL for algae cultivation. After that, the wet algae are harvested for the used as co-feed for the HTL process to recover energy, while recovering nutrients and carbon resources for the next cycle. This suggest that the integrated process not only has the potential to produce energy but also yield great environmental benefits. In addition to direct reuse of the aqueous phase for algae cultivation, catalytic hydrothermal gasification and anaerobic digestion are also interesting alternatives for generation of H$_2$-rich fuel gas and CH$_4$-rich fuel gas, respectively [119,120]. On the other hand, gaseous phase rich in CO$_2$ from sewage sludge HTL can be recovered and reused in algae cultivation.

Although it is a promising technology, HTL is still in the early stage for bio-oil production from sewage sludge [121]. More research is needed to address the above-mentioned technical challenges, in particular to reduce the operating costs, while maximizing the energy and resources recycling. Thus, future research should strive to achieve the following: (1) a breakthrough in the development of inexpensive new reactor materials with increased corrosion and fouling resistance under high temperature and pressure conditions; (2) an economically stable continuous feed system for industrial application of HTL; (3) development of catalysts towards target products, while having excellent engineering operability and reduced energy consumption; (4) new separation and upgrading techniques in order to maximize the recovery of valuable products from HTL; (5) increase the growth rate of algae when aqueous phase is used as the growth medium which some inhibitors are in it limit the algae growth.

6. Economic analysis and life cycle assessment

Although incineration is a relatively mature technology for solid waste management, it has been criticized for its high costs and harmful emissions. The costs associated with incineration mainly include capital investment (equipment and devices, infrastructure, and land use, etc.) and operational costs (raw materials, staff salaries, energy consumption and depreciation, etc.). Meanwhile, the costs are also closely related to selection of incineration technology and its scale. For example, for an incineration plant of 1000 t/d, the equipment cost could account for 48.2% of the total investment cost, plus 21.5% and 26.0% of the cost for the construction and installation, respectively [122]. The capital cost of mechanical-grate incineration technology (MGIT) appears to be higher than that of circulating fluidized bed incineration technology (CFBIT). In the estimation of the capital cost, the land cost is an
uncertain factor, largely depending on the local economic situation and governmental policy. On the contrary, the operation cost is mainly determined by the type of incineration technology adopted. For example, the operation cost of MGIT ranges from 16.3 US$/t to 32.6 US$/t, compared with from 9.78 US$/t to 19.56 US$/t for CBFBT [122]. The benefits of incineration may come from government subsidies, electric energy recovery, tax incentives, heat generation, etc.

Recently, pyrolysis has been considered as a promising technology for energy and resource recovery from sewage sludge. However, the properties of the pyrolysis products differ substantially. In addition, the environmental sustainability and economic viability of pyrolysis of sewage sludge are largely determined by the process scale, technology selected, sludge collection, transportation costs, etc. For possible profit generation, the cost-associated with the feedstock should not exceed 83 US$/t dry mass for slow pyrolysis and 64 US$/t dry mass for fast pyrolysis [123].

The capital and operational costs of sewage sludge gasification plants largely depend on the plant capacity, type of gasifier and potential reusing of the end products. The capital cost mainly includes costs for collection, transportation and storage of sewage sludge, and the equipment and land costs, etc. Depending on the scale of the gasification plant, the operation cost usually falls into the range of US$15/t to US$230/t [124], in which the auxiliary materials (i.e. chemicals, bed materials, catalysts, etc.) may account for about 3.5–5.7% of the total operation cost [124]. For large-scale sewage sludge gasification plants, the revenue can be derived from the government subsidies and the sale of the end products. In general, government subsidies to sewage sludge gasification range from US$42–166/t [125]. Biocrude produced from HTL of sewage sludge can be used as a substitute for fossil fuels. Different from pyrolysis, HTL does not require drying of sewage sludge, as wet feedstock such as sewage sludge can be directly liquefied without de-watering/drying, which greatly reduces the operation cost of HTL when compared with pyrolysis. In addition, HTL biocrude oils have a lower water content and higher heating value and hence higher quality than pyrolysis bio-oils. Therefore, HTL offers an economically feasible engineering solution to sewage sludge management.

To assess the environmental implication of thermochemical technologies, life cycle assessment (LCA) has generally employed as a tool to judge the potential of upscaling the thermochemical technologies towards energy and resource recovery. Akyüz et al. [126], employed LCA to compare and analyze an existing incineration plant for heat and power generation with digested sewage sludge in a fluidized bed combustor (FBC) and a hypothetical cement kiln (CK) facility. The results indicated that incineration of sewage sludge in an FBC had a better environment performance than CK in most impact categories (such as global warming, aquatic and terrestrial ecotoxicity, etc.) except the human health category. The main reason could be attributed to the residues of incineration in the CK are immobilized with the generated clinkers whereas the residues from FBC can be recovered and landfilled. Liu et al. [127] carried out an LCA analysis on energy recovery from incineration of dried sludge and used oil. The global warming potential (GWP) decreased from 639.2 to 609.2 tonnes CO₂-eq if increasing the substitute proportion of coal by sewage sludge from 10 wt% to 14 wt%. However, if the content of sewage sludge increased further from 14% to 92% in the mixture, the GWP showed an opposite trend and finally reached 3131.8 tonnes CO₂-eq, which indicated that co-incineration of sewage sludge and reused oil with coal should be controlled at an optimal substitute proportion so as to minimize the GWP. Superior to incineration processes, gasification of sewage sludge can recover both energy and resources such as syngas, bio-chars as soil conditioners, liquid fuels and valuable chemicals. Previous studies have indicated that the net electrical efficiency of sewage waste gasification (more than 27%) is generally higher than that of incineration process [128,129]. Meanwhile, the GWP of gasification process is less than incineration process too due to the oxygen-deficient atmosphere in the gasifier and production of biochar followed by its storage in soils (carbon sequestration). Ramachandran et al. [130], compared LCA of two processes for electricity generation: a proposed decentralized sewage sludge and woody biomass co-gasification system and an existing system (sewage sludge/biomass incineration + steam turbine). The results indicated the proposed co-gasification system provides a net annual emission reduction of 137.0–164.1 kilotones of CO₂-eq and an increase in the net electricity generation by 3–24%. Similarly, Houillon and Jolliet [131] performed LCA of pyrolysis of wastewater urban sludge, focusing on energy generation and global warming analysis. It was found that the sludge drying process by electricity and natural gas consumption demands 6.8 GJ/tDM of energy demand and produces 997 kg CO₂/tDM. However, reuse of pyrolysis gas enables reduction of 835 kg CO₂/tDM. In addition, Li and Feng [132] evaluated the environmental impacts and energy efficiency of an integration of sludge anaerobic digestion (AD) and pyrolysis by LCA. The results indicated that the AD-pyrolysis integrated process had better environmental performance and energy efficiency than pyrolysis only due to the enhanced conversion of sludge to energy by prepositive AD. There are a few LCA studies assessed the generation of bio-crude oil
through hydrothermal liquefaction (HTL) process while they are mainly focused on biomass and algae (rarely on sewage sludge), suggesting that HTL has significantly less emissions than incineration [133]. Moreover, Chan et al. [134] verified that HTL has a relatively lower average GWP compared with pyrolysis, whereas compared with gasification, HTL has a relatively higher average GWP due to the subsequent bio-crude upgrading processes for green diesel and/or jet fuel production.

7. Conclusions
The amount of sewage sludge has been continuously increasing with the expansion of global population and urbanization. Traditional treatment methods for sewage sludge, such as landfill and land-farming, are no longer acceptable for future sewage sludge management, and indeed have been banned in more and more countries and regions. As such, environmentally friendly and economically viable technologies are urgently needed for proper handling of sewage sludge. Currently, thermochemical technology is considered as a promising approach for sewage sludge management owing to the multiple advantages such as concurrent volume reduction, pathogens destruction and energy recovery. Despite the promise of the thermochemical platform, the end products usually have unsatisfactory quality due to the complex nature of sewage sludge, and various thermochemical technologies are associated with some technical challenges in operation, as overviewed in this work. Various solutions to addressing these challenges have been and/or are being developed. They include: strategies/technologies for preventing pollutants emission and operating problems in incinerations, tar minimization/removal, control of NOx and SOx precursors emission in pyrolysis/gasification, reducing sewage sludge moisture content, chemical looping process towards CO2 capture, and hydrothermal liquefaction coupled with algae culture, etc. It is expects that this review could shed light on possible industrialization of thermochemical conversion technologies for environmentally sustainable and economically viable management of sewage sludge.

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