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Review

Wet wastes to bioenergy and biochar: A critical review with future perspectives

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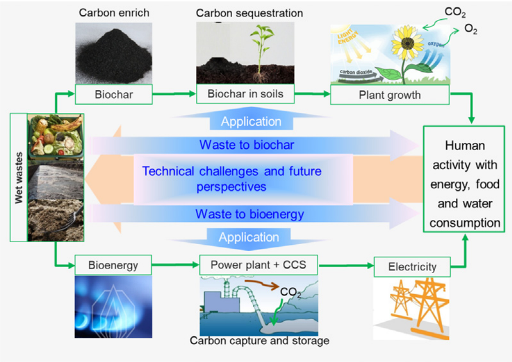
HIGHLIGHTS

- Emerging technologies for wet wastes to bioenergy and biochar are reviewed.
- Six conversions are discussed for technical challenges and potential improvement.
- Integration conversion systems have potential to improve waste valorization.
- Holistic approaches should be developed for waste conversion design and evaluation.

GRAPHICAL ABSTRACT



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ABSTRACT

The ever-increasing rise in the global population coupled with rapid urbanization demands considerable consumption of fossil fuel, food, and water. This in turn leads to energy depletion, greenhouse gas emissions and wet wastes generation (including food waste, animal manure, and sewage sludge). Conversion of the wet wastes to bioenergy and biochar is a promising approach to mitigate wastes, emissions and energy depletion, and simultaneously promotes sustainability and circular economy. In this study, various conversion technologies for transformation of wet wastes to bioenergy and biochar, including anaerobic digestion, gasification, incineration, hydrothermal carbonization, hydrothermal liquefaction, slow and fast pyrolysis, are comprehensively reviewed. The technological challenges impeding the widespread adoption of these wet waste conversion technologies are critically examined. Eventually, the study presents insightful recommendations for the technological advancements and wider acceptance of these processes by establishing a hierarchy of factors dictating their performance. These include: i) life-cycle assessment of these conversion technologies with the consideration of reactor design and catalyst utilization from lab to plant level; ii) process intensification by integrating one or more of the wet waste conversion technologies for improved performance and sustainability; and iii) emerging machine learning modeling is a promising strategy to aid the product characterization and optimization of system design for the specific to the bioenergy or biochar application.

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1. Introduction

The current global population is estimated at 7 billion, and this number is anticipated to reach 9.3 billion by 2050 (Scarlat et al., 2015). With the majority of the global population residing in urban areas, the consumption of large amounts of energy and resource, e.g., fossil fuel, food, and water, followed by the associated pollution issues, would be inherent. Based on the report, over 14,000 Mtoe of energy was consumed in 2018 (Tian et al., 2019), and the total energy requirement is projected to be approximately 6 times higher than the current demand by the end of this century (Awasthi et al., 2019). Currently, fossil fuels continue to be the dominant energy source for electricity generation (Asongu et al., 2020). The resulting greenhouse gas (GHG) and pollutants (e.g., NO_x, SO_x, and PM2.5, etc) which are eventually released into the atmosphere have led to serious environmental concerns (Chen et al., 2022; Zhou et al., 2020), such as global temperature rise, erratic weather patterns, and ozone depletion, etc. (Tao et al., 2022). In the preview of these issues, it is of paramount importance to minimize the dependencies on conventional sources of energy and hunt for green and renewable sources of energy.

The steady increase in urbanization and improvements in living standards worldwide have resulted in a considerable generation of organic wet wastes. Particularly, sewage sludge (Ding et al., 2021), food waste (Liu et al., 2022), and animal manure (Wang et al., 2021) are three main wet streams arising from the production and consumption of water and food. The above three wastes are identified as wet wastes given their high moisture contents. Based on the reported studies, more than 150 million tons of sewage sludge is generated annually from wastewater treatment plants in China, Europe, and the United States combined (Gao et al., 2019; Wang et al., 2019). Approximately 1.3 billion tons of food waste is generated from food production and consumption globally every year (Girotto et al., 2015). In China, nearly 4.2 billion tons of animal manure was generated in 2016 due to the rapidly growing economy and intensive demand for meat (Zheng et al., 2019). These wet wastes have led to various environmental issues, such as antibiotics with resistance genes and heavy metals pollution (Liu et al., 2021; Swain et al., 2021), as well as unpleasant odor and CO_2 emission (Godlewska et al., 2017). Food waste from food production was estimated to be 2.2 Gt CO_2 equivalent (CO_2-eq) in 2011 (Mondello et al., 2017). It is estimated that 15% of the human-made GHG is caused by livestock production, with 5% CH_4 emission from animal manure storage process (Awasthi et al., 2019; Gerber et al., 2013).

Compared to dry biomass wastes, wet wastes are more difficult to be treated and utilized due to their complex compositions in nature, including high water content and various contaminants which could lead to serious environmental issues. On the other hand, these wet wastes are rich in organic matter such as fixed and volatile matters, as well as nutrient elements, e.g., N, P, and K (Li et al., 2021f; Vanden Nest et al., 2021). To overcome these challenges of wet waste utilization to protect the environment and recovery renewable energy, we focused on the review of emerging technologies for wet waste conversion in this work. Substantial efforts have been made to realize this goal in recent years (Hafid et al., 2021). Biological and thermal conversions, including anaerobic digestion (AD) (Hunter et al., 2021), incineration (Kasina et al., 2021), gasification (Yan et al., 2020), hydrothermal liquefaction (HTL) (Li et al., 2021d), hydrothermal carbonization (HTC) (Li et al., 2021f), fast (FP) and slow pyrolysis (SP) (Raj et al., 2021), are prevalent approaches for high value-added product generation from wet wastes. Depending on the application, two categories can be formulated from the above-mentioned conversion technologies for wet waste treatment. One is the wet-wastes-to-energy (WWtE) strategy which can produce bioenergy for power plant incineration with a subsequent carbon capture and storage (CCS) to avoid the carbon emission effectively. Biogas, syngas, and bio-oil, which are biofuels with high calorific values, are produced via AD, gasification, HTL and FP. Such combustible gases and liquid fuel can not only supply energy for waste treatment but also replace fossil fuels to alleviate the current global energy crisis and reduce GHG emissions. The second strategy is wet-wastes-to-biochar (WWtB). Biochar, a stable and carbon-rich material produced from HTC and pyrolysis, can not only be as solid fuel but also can be readily used as a conditioner or fertilizer for soil remediation and improvement (You et al., 2020). Biochar production is a form of carbon sink, and biochar applied in soils results in a negative carbon emission process, which further fosters carbon sequestration and improvement of plant productivity and the overall CCS (Dissanayake et al., 2020). However, despite the numerous benefits, the widespread application and adoption of the WWtE and WWtB are limited by challenges such as higher processing costs, energy consumption, and lower efficiencies than the thermochemical conversion of conventional dry biomass (such as agriculture and forest wastes). This fact encouraged us to conduct a comprehensive review on this topic to find insights for the acceleration of these conversion technologies.

Given the significance of this topic, a few review papers have been published in recent years. Gao et al. discussed the thermochemical conversions of sludge, including the pyrolysis, gasification, and combustion (Gao et al., 2020). Hunter et al. reviewed the AD of food waste, while Wang et al. presented a review about the HTC of sludge (Hunter et al., 2021; Wang et al., 2019). Yet, there is a dearth of comprehensive reviews in the existing literature, which accounts for the conversion of various wet wastes as a whole, inclusive of all the relevant conversion technologies. Thus, in this work, we address this paucity and present a comprehensive review about WWtE and WWtB processes of food waste, sludge, and manure, focusing on their respective technical implication and product application to evaluate their potential for sustainability from energy and environmental perspectives, which has not been published previously and is the main essence and novelty of this work. In detail, the conversion technologies, including incineration, AD, gasification, HTC, HTL, FP, and SP, are reviewed and critically discussed with respect to their bottlenecks and limitations of development, as well as the product applications, including the bioenergy for heat and electricity generation and biochar in soils for carbon sequestration. Moreover, a critical analysis of these technologies is addressed with respect to the technical shortcomings along with potential solutions and their future perspectives.

2. Wet wastes to bioenergy for heat/electricity generation

Bioenergy, e.g., CH_4 and H_2, can be produced from wet wastes via various WWtE technologies. The merits associated with WWtE strategies include: (1) significant reduction of the volume of wet wastes, which eases the burden on the urban environment, (2) bioenergy production as alternatives for conventional energy-saving and negative carbon emission, and (3) elimination of most organic contaminants in wet wastes, immobilization of inorganic pollutants, particularly in thermal conversion process (Li et al., 2021a; Li et al., 2020c). In this part, AD, gasification, HTL, FP, and incineration as WWtE technologies are reviewed in the case of sewage sludge, food waste, and animal manure treatment. According to the literature survey, sludge is the most commonly used feedstock for bioenergy generation (Fig. 1a), although its fuel properties are not as favorable as food waste and animal manure. A potential reason could arise from the fact that serious environmental issues are caused by sludge generation, which calls for its urgent handling. For food waste and animal manure as feedstock for bioenergy generation, the number of publications was relatively the same. In terms of WWtE technologies, AD is the most popular choice to treat the three types of wet wastes, followed by incineration, gasification, HTL, and FP. This observation may be explained by the fact that AD not only utilizes these wet wastes directly without prior dewatering, but also consume less energy compared with other thermal conversions.

2.1. Anaerobic digestion for biogas production

Anaerobic digestion (AD) involves the degradation of organic matters by microbial organisms under anaerobic conditions with the formation of methane (Kelleher et al., 2002; Zhang et al., 2020). The three main reactions of this process are hydrolysis, acidification (acidogenesis and acetogenesis), and methanation (Fig. 1b) (Zhang et al., 2016b). First, extracellular enzymes from hydrolytic bacteria aid in generating simple organic monomers such as sugars, amino acids, and fatty acids from the organic matter during the hydrolysis process. Subsequently, acids, e.g., propionic acid, butyric acid, and acetic acid, are produced through acidogenesis, and yield acetic acid, H_2, and CO_2 as the main products of the acidification process by acid-forming bacteria. Lastly, in the methanation step, the acetate, H_2, or CO_2 will be further consumed by methane-forming archaea such as acetoclastic and hydrogenotrophic methanogens to produce methane.

Currently, AD is one of the most prevalent WWtE technologies, due to its environmental benefits. Clean energy can be obtained through AD with reduced CO_2, CH_4, and NO_X emissions compared to landfills (Sommer et al., 2013). Moreover, the water in digestate residue can be separated for further application in much simpler ways as compared to raw wastes. In this part, a comprehensive literature review about AD for sewage sludge, food waste, and animal manure, including feedstock species, pretreatment methods, reactor types, operational parameters for maximum biogas or CH_4 yield, is performed and main results are summarized in Table 1. The operating conditions have significant impacts on the products of AD; hence, a statistical analysis of process conditions and products formed through AD is performed and discussed. The median values of pH, total solid (TS) concentration, time, and temperature of AD for various wet wastes are depicted in Fig. 2a. The pH values in most AD reactors were close to 7.65, with an initial TS concentration of 10.25 $g\cdot L^{-1}$. The values of other essential parameters, such as time and temperature, were found to be 20.5 d and 30.5 °C, respectively. In terms of product composition, the main component of biogas was CH_4, and the median of CH_4 yield of AD from wet wastes was 15.04 $mol\cdot kg^{-1}$ VS (volatile solid). In detail, the CH_4 yield from the AD of food waste was the highest at 20.91 $mol\cdot kg^{-1}$ VS followed by sludge and animal manure, with the CH_4 yield of 15.37 and 11.99 $mol\cdot kg^{-1}$ VS, respectively.

Based on the literature review, it was found that much effort has been put into overcoming the limitations of wet wastes AD, e.g., long start-up time, low biogas quality, and unstable production. Sewage sludge mainly contains organic (e.g., antibiotics) and inorganic (e.g., heavy metals) contaminants, microbial aggregates, and extracellular polymeric substances (EPS) (Zhen et al., 2017). The presence of EPS transforms the sludge into a gel-like and negatively charged biopolymer. This particular structure prevents the cell rupture and lysis, which potentially weakens the dewaterability and biodegradability of sludge. Food wastes, due to their high organic content, serve as a suitable source for AD to produce biogas; while some of its characteristics such as high nitrogen and salt concentrations, especially the high contents of sodium, potassium, calcium, and magnesium cations, could inhibit the anaerobes growth in AD (Chen et al., 2008). Animal manure as the feedstock of AD also has limitations. These include solid impurities like sand and gravel, low organic matter content, low carbon to nitrogen (C/N) ratio, and low biodegradability of lignocellulosic and structured manure fibers. Moreover, AD involving wet wastes is negatively impacted by containments. Wang et al. found that cationic polyacrylamide suppressed the rate of AD and reduced methane yield (Wang et al., 2018a). Another study showed that the antibiotics could inhibit the CH_4 production rate, and antibiotics synergized with ZnO could further enhance the inhibition of CH_4 production (Zhao et al., 2019).

Pretreatment of wet wastes and co-digestion with other biomass have been proven to be two effective ways to improve AD performance. Many researchers have conducted comprehensive studies on wet waste pretreatment technologies (especially in the case of sludge) for AD in recent years (Carrere et al., 2016; Pilli et al., 2015; Zhen et al., 2017). Physical (e.g., mechanical and high pressuring machines), chemical (dilute-acid, alkaline pretreatment), thermal (steam explosion, microwave heating, hydrothermal treatment), and biological (enzymatic hydrolysis) technologies are the most common methods employed for pretreatment of these wastes (Pham et al., 2015). As presented in Table S1, enzymatic, thermal (including microwave, hot air oven, thermo-alkaline), ultrasound, fungal-based solid-state, and aqueous ammonia soaking pretreatments have been well investigated by researchers. Pretreatment approaches can enhance biogas production and speed up the digestion of microbes in different ways. For example, the organic micropollutants can be eliminated through thermal hydrolysis (170 °C for 20 min) (Taboada-Santos et al., 2019); the soluble chemical oxygen demand, free amino nitrogen, and glucose can be significantly increased after enzymatic pretreatment (Li and Jin, 2015); while the hot alkali pretreatment can decompose the hemicellulose and lignin contents in animal manure. In the co-digestion, the composition of wet wastes can be adjusted by adding other forms of biomass to establish a preferable environment (preferable C/N ratio, pH, and concentration of volatile fatty acids) for the anaerobes to survive (Neshat et al., 2017). Co-digestion of food waste with low nitrogen waste decreased the concentration of nitrogen in the AD system, which in return reduced the accumulation of NH_3 and intermediate volatile compounds (Castillo et al., 2006). Many different biomasses, such as aged refuse, seaweed, microalgae, water hyacinth, crude glycerol, corn silage, and spent poppy straw, are reported as suitable additives for co-digestion with wet wastes, as seen in Table 1. The co-digestion of sewage sludge and animal manure, sewage sludge and food waste, or food waste and animal manure also benefits biogas production. The co-digestion of banana peels (63%), cow dung (21%), and water hyacinth (16%) yielded a maximum CH_4 yield of 296 mL CH_4/g VS due to the synergism between the balance of nutrients and the adaptable and dynamic microbial community (Barua et al., 2019).

2.2. Gasification for syngas production

Gasification is a thermochemical decomposition process in which the organic wastes are converted into combustible gases in an oxygen-starved

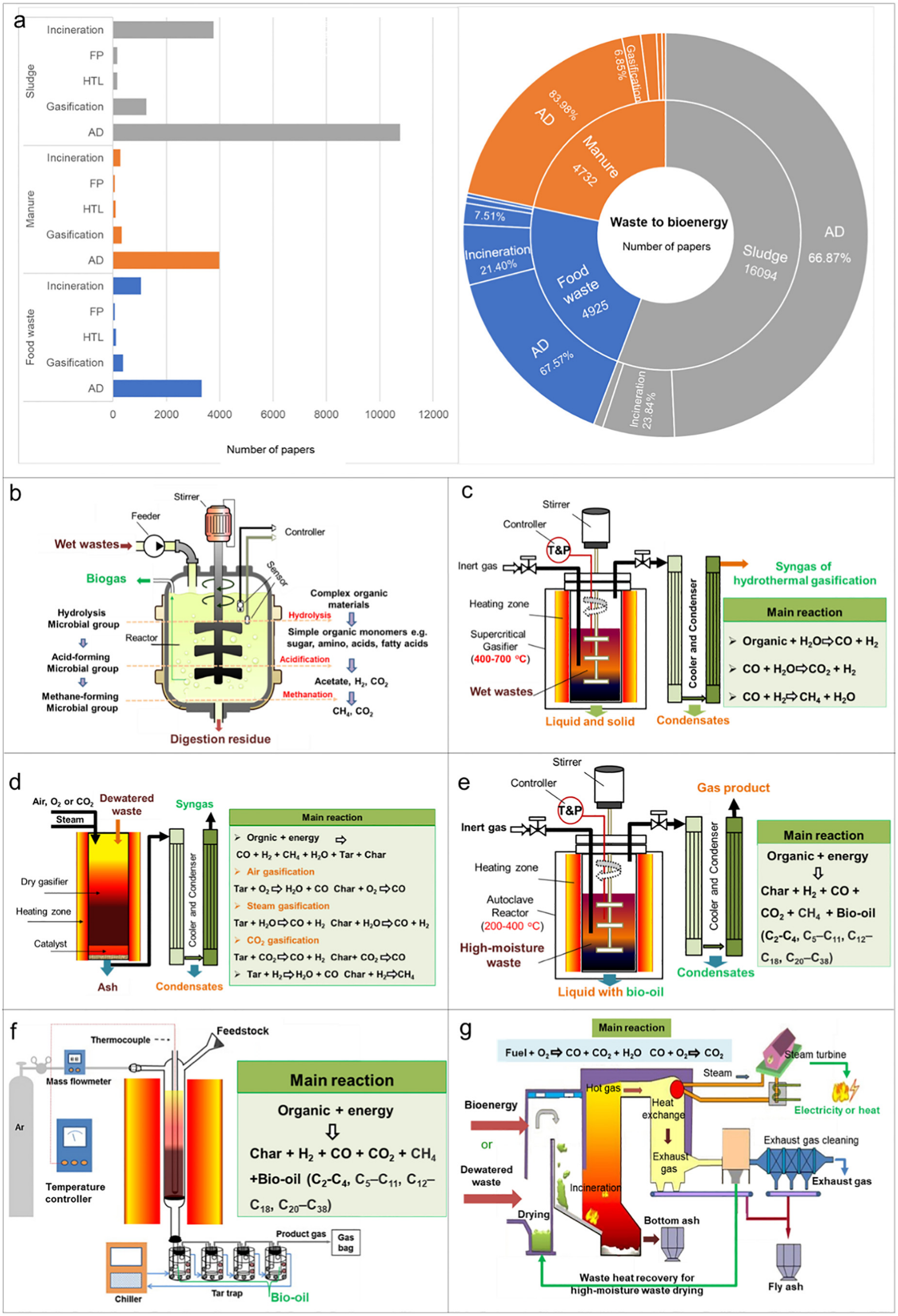

Fig. 1. Results of (a) literature survey in Scopus on sewage sludge, animal manure, or food waste with gasification, anaerobic digestion, or incineration since 2010, schematic presentation and main reactions of (b) anaerobic digestion, (c) supercritical water gasification, and (d) dry gasification, (e) hydrothermal liquefaction, (f) fast pyrolysis, and (g) incineration.

Table 1
Summary of the literature about anaerobic digestion (AD) of wet wastes for biogas production.

Feedstock (Ratio)	Pretreatment (Conditions)	Reactor (Volume)	Optimal conditions	Maximum production	Main results	Reference
Activated Sludge	Enzymatic pretreatment (60 °C / 24 h)	Serum bottles (0.16 L)	35 °C / 10 g TS $\cdot L^{-1}$ /7 d	366.8 mL CH_4 $\cdot g^{-1}$ VS	The CH_4 yield increased by 34.6% by enzymatic pretreatment with shorter time.	(Yin et al., 2016)
Secondary sewage sludge	Thermal treatment (165 °C / 6 bar)	Continuously stirred-tank reactors (1.0 L)	43 °C/ 8–9% TS / 20 d	9.52 L CH_4/ total	CH_4 yields improved by 54% while NH_3 reduced to 92 mg$\cdot L^{-1}$ by continuous removal of ammonia.	(Tao et al., 2017)
Sewage sludge	–	Semi-continuous reactors	35 °C / 10% TS / 30 d	0.383 L CH_4 $\cdot g^{-1}$ VS	The hydrogenotrophic and methylotrophic methanogens increased with the increasing TS.	(Liu et al., 2016a)
Activated sludge + Aged refuse (400 mg/g)	–	Batch reactors (1.0 L)	35 °C/ 10.25 g TS $\cdot L^{-1}$ /15 d	0.2134 L CH_4 $\cdot g^{-1}$ VS	Aged refuse accelerated sludge solubilization, hydrolysis, and acidogenesis.	(Zhao et al., 2017)
Sewage sludge + Seaweed (1: 3)	–	Serum bottles (0.28 L)	35 °C/ pH = 7.8–8.0 /10 g VS $\cdot L^{-1}$ /12 d	0.308 L $CH_4 \cdot g^{-1}$ VS	The yield of CH_4 increased with the increasing ratio of seaweed by providing biodegradable organics.	(Shin et al., 2018)
Activated sludge + microalgae (3:1)	–	Batch reactors	35 °C/ pH = 7.5 / 20.0 g TS $\cdot L^{-1}$ /25–30 d	0.442 L CH_4 $\cdot g^{-1}$ VS	Co-digestion of waste activated sludge and microalgae enhanced the yield of CH_4 significantly.	(Beltrán et al., 2016)
Sewage sludge + Food waste (3:2)	Microwave pretreatment	Serum bottles (1.8 L)	37 °C /Substances to inoculums ratio = 5:1 /35 d	0.338 L CH_4 $\cdot g^{-1}$ VS	Methane production was enhanced by both co-digestion and microwave pretreatment.	(Zhang et al., 2016a)
Sewage sludge + Food waste	Enzymatic pretreatment (60 °C / 24 h)	Serum bottles (0.16 L)	35 °C / 10 g TS $\cdot L^{-1}$ /10 d	0.601 L CH_4 $\cdot g^{-1}$ VS	The CH_4 yield increased by 31.3% with enzymatic pretreatment and to 38.9% in digestion of sludge with food waste.	(Yin et al., 2016)
Food waste + Seaweed (1: 3)	–	Serum bottles (0.28 L)	35 °C/ pH = 7.8–8.0 /10 g VS$\cdot L^{-1}$ /12 d	0.35 L CH_4 $\cdot g^{-1}$ VS	The highest CH_4 yield was achieved at 10 g VS$\cdot L^{-1}$ with 75% seaweed addition in food waste.	(Shin et al., 2018)
Food waste + Brown water (7:3)	–	Continuously stirred tank reactor	37 °C / pH = 6.5–7/ 5.67% TS /20 d	0.728 L CH_4 $\cdot g^{-1}$ VS/0.0998 L $H_2 \cdot g^{-1}$ VS	A high yield of CH_4 and H_2 can be obtained with different optimum HRT and organic loading rate.	(Paudel et al., 2017)
Food waste	–	Two-stage laboratory-scale continuously stirred tank reactor	Stage 1: 2 L/ 55 °C/ 8–9% TS/ 5 d Stage 2: 4.5 L/ 35 °C/ 8–9% TS /9 d	Stage 1: 0.135 L H_2 $\cdot g^{-1}$ VS Stage 2: 0.51 L CH_4 $\cdot g^{-1}$ VS	Two-stage AD process yielded a positive impact on food waste digestion.	(Algapani et al., 2019)
Food waste (50%–66%) + Animal manure	Thermal treatment (70 °C / 1 h)	Continuous digester	48 °C/ 944 kg VS$\cdot d^{-1}$ /10.7 d	0.477–0.499 L CH_4 $\cdot g^{-1}$ VS	Food waste has a higher CH_4 potential than solid and liquid manure (0.243 and 0.91 L CH_4 $\cdot g^{-1}$ VS).	(Lansing et al., 2019)
Banana peels (63%) + Cow dung (21%) + Water hyacinth (16%)	Hot air oven at 90 °C / 1 h	Batch reactor (1.0 L)	50 g inoculum / 50 d	0.296 L CH_4 $\cdot g^{-1}$ VS	Pretreatment shortened the digestion time from 16 to 11 days. a mixing ratio of 1.5 achieved the highest biogas.	(Barua et al., 2019)
Food waste	Enzymatic pretreatment (60 °C / 24 h)	Serum bottles (0.16 L)	35 °C / 10 g TS$\cdot L^{-1}$ /20 d	0.817 L CH_4 $\cdot g^{-1}$ VS	The CH_4 yield increased by 33.8% with the enzymatic pretreatment.	(Yin et al., 2016)
Kitchen waste	Thermal pretreatment (120 °C / 50 min)	Airtight reactors (5.5 L)	35 °C / 21 d	0.899 L CH_4 $\cdot g^{-1}$ VS	Thermal pretreatment promoted the anaerobic degradability and reduced the time	(Li and Jin, 2015)
Swine Manure + Rice straw (1.7:1)	–	Semi-batch reactors (20 L)	55 °C/ 27% TS /40 d	0.30 L CH_4 $\cdot g^{-1}$ VS	The addition of rice straw adjusted the C/N of swine manure and prevented the ammonia inhibition	(Riya et al., 2016)
Cattle manure (87%) + Food waste (10) + Raw glycerine (3)	Ultrasound pretreatment	Continuous digester	55 °C/ 3.8 g VS$\cdot L^{-1}$ /20 d	0.52 L CH_4 $\cdot g^{-1}$ VS	The CH_4 production increased by 79% with ultrasound pretreatment.	(Ormaechea et al., 2017)
Swine manure (99%) + crude glycerol (1%)	–	Batch digester	37 °C/ Inoculum-to-substrate ratios = 4:1/ 23.34 g TS$\cdot L^{-1}$ / pH = 7.5 /30 d	0.605 L CH_4 $\cdot g^{-1}$ VS	1% addition of crude glycerol was more efficient for CH_4 production.	(Lymperatou et al., 2018)
Swine manure (97%) + crude glycerol (3%)	–	Continuous stirred tank reactor (3 L)	37 °C/ Inoculum-to-substrate ratios = 4:1/ 23.34 g TS$\cdot L^{-1}$ / pH = 7.5 /17 d	0.48 L CH_4 $\cdot g^{-1}$ VS	3% crude glycerol did not exhibit any inhibition and resulted in 222% increase of biogas productivity.	(Lymperatou et al., 2018)
Dairy cow manure	–	Batch reactor (80 L)	28 °C/ 15–19%TS /28–30 d	0.229–0.286 L CH_4 $\cdot g^{-1}$ VS	The yield of CH_4 obtained at 28 °C was 50% higher than at 20 °C, and 90–100% pathogens were eliminated.	(Rajagopal et al., 2019)
Cattle Manure (80%) + *Dalbergia sissoo* leaves (or *Malus domestica*)	–	Glass bottles (0.542 L)	28 °C/ 23.6% TS/ pH = 8/36 d	0.229 or 0.251 L CH_4 $\cdot g^{-1}$ VS	The biodegradability of feedstock was increased by adjusting the C/N ratio, improving the yield of methane.	(Awais et al., 2018)
Cow manure + Corn silage	Fungal-based solid-state pretreatment	Semi-continuous pilot-scale bioreactor	37 °C/ 8–9%TS /21 d	0.236 L CH_4 $\cdot g^{-1}$ VS	The pretreatment had a positive effect on pH stability and increased biogas productivity.	(Tišma et al., 2018)
Dairy manure	Thermal-alkaline (8% NaOH/180 °C/30 min)	Sterile glass bottle (0.50 L)	37 °C /34 d	0.285 L CH_4 $\cdot g^{-1}$ VS	Hot alkali pretreatment improved the methane production of dairy manure by 50%.	(Yang et al., 2017)

(continued on next page)

Table 1 (*continued*)

Feedstock (Ratio)	Pretreatment (Conditions)	Reactor (Volume)	Optimal conditions	Maximum production	Main results	Reference
Swine manure + Manure fibers	Aqueous ammonia soaking	Continuous stirred tank reactors (3 L)	38 °C / At a TS ratio of 0.52 manure per 0.48 fibers /25 d	0.25 L CH_4 $\cdot g^{-1}$ TS	The pretreatment accelerated the disintegration and hydrolysis, resulting in a 98% increase in the CH_4 yield.	(Jurado et al., 2016)
Chicken manure + Spent poppy straw (4.3:1)	–	Continuously stirred anaerobic digester (16 L)	36 °C/ 5.7–14.9% TS /240 d	0.36 L CH_4 $\cdot g^{-1}$ VS	Total ammonium nitrogen and free ammonia nitrogen had a significant impact on methane yield.	(Bayrakdar et al., 2017)

Note: TS: total solid; VS: Volatile solid.

medium (air, steam, or CO_2) or a water medium at a specific temperature and pressure (Sanlisoy and Carpinlioglu, 2017). Almost any organic waste, including forest and agricultural biomass, municipal solid waste, sewage sludge, food waste, and animal manure, can be used as the feedstock for gasification. The organic components of waste are mainly converted to syngas with rich flammable gases comprising H_2 and CH_4 that can be used as an energy source for heat and electricity generation (You et al., 2018). Primarily, the H_2-rich syngas can be generated from both hydrothermal gasification (HTG) and steam gasification with a specific catalyst. Moreover, most organic pollutants can be decomposed in the thermal-chemical process, while N and S elements could be recovered, which can reduce the NH_3 and H_2S in the syngas products. In addition, the gasification process stops the heavy metals in wastes from moving into syngas, without dioxins, chlorinated dibenzodioxins, and dibenzofurans generation in syngas utilization, which is more environmentally friendly than incineration (Samolada and Zabaniotou, 2014). Gasification is classified into many categories based on the reactive atmosphere and heating methods such as HTG, air gasification, steam gasification, and plasma gasification. Among these gasification technologies, hydrothermal gasification serves as an economical and efficient approach to handle wet wastes without prior drying (Yukananto et al., 2017). The other above-mentioned dry gasification methods are most suitable when the solids content is over 60% (Spinosa et al., 2011). Thus, wet waste needs to be subjected to pre-dewatering before being used in dry gasification, e.g., air, steam, and CO_2 gasification.

HTG, also called wet gasification, is a thermochemical process that transforms biomass to syngas in hot compressed water and steam under near-critical temperatures up to about 500 °C (Peterson et al., 2008). When the temperature and pressure exceed the critical point (374.3 °C and 22.1 MPa) of water, the hydrothermal gasification is called supercritical water gasification (SCWG) (Peterson et al., 2008). Recent years have seen a surged interest in the SCWG research for energy production by utilizing wet wastes (Okolie et al., 2019). HTG offers greater energy efficiency and economic viability than dry gasification, as it eludes the pre-drying requirement (Amrullah and Matsumura, 2018). Conventionally, complete gasification occurs at temperatures greater than 550 °C, whereas the presence of catalyst can promote complete gasification at lower temperatures (374–550 °C) (Louw et al., 2016). A schematic of the HTG system and its main reactions are presented in Fig. 1c (Louw et al., 2016).

Some operating parameters e.g., feedstock categories, catalyst species, and adding ratio, reaction time, and pressure, are important to determine the carbon conversion efficiency, energy recovery, and syngas production of HTG. An overview of recent literature on HTG of wet wastes has been summarized and analyzed according to different feedstocks, the optimal operating parameters, and optimal syngas yield in Table 2 and Fig. 2b. Various types of catalysts can be used in the HTG to promote the water-gas shift reaction, including transition metals catalysts, e.g., Ru and Ni modified, alkalis catalysts (e.g., Na_2CO_3, K_2CO_3, and KOH), and others, e.g., organic solvent formic acid and activated carbon (Table 2). Based on the boxplot analysis depicted in Fig. 2b, the median of catalysts concentration was found to be 5.5 wt% of the dry-based feedstock. The commonly used temperature of SCWG was 500 °C with a residence time of 45 min and a pressure of 24 MPa. H_2 was the predominant gaseous constituent in the product stream, with its median of 10.16 mol·kg^{-1}. However, the H_2 yield from various types of wet waste varied significantly, with the H_2 yield of 4.2, 14.21, and 10.16 mol·kg^{-1} for sewage sludge, animal manure, and food waste, respectively. To maximize the gas yield of the HTG process, it is essential to optimize the operating conditions and catalyst selection. For example, after the optimization of gasification temperature (400–550 °C), the catalysts types and concentrations (KOH and dolomite) and the reaction time (0–60 min), a high syngas yield (38 mol syngas·kg^{-1}) with a calorific value of 24.3 MJ·(Nm^3)$^{-1}$ was obtained from sludge under optimal conditions (550 °C/ 30 MPa/ 30 min/ 10 wt% KOH) (Yildirir and Ballice, 2019).

Dry gasification, e.g., air gasification, steam gasification, CO_2 gasification, is another potential technology to convert the organic wastes into energy. One difference between dry and hydrothermal gasification arises from their operating parameters, including higher temperature, use of various gasification agents (e.g., steam, air, and CO_2), and lower pressure in the former. A schematic representation of the dry gasification system and the main reactions with different gasification agents is presented in Fig. 1d (Abdoulmoumine et al., 2015; Han et al., 2017a). Another difference is that the wet wastes need to be dewatered and dried before dry gasification. The feedstock, pretreatment methods, reactor types, catalysts, maximum of syngas yield, and corresponding optimal process conditions in the literature are reviewed in Table 3. It was observed that hydrothermal treatment and air drying was commonly used as pretreatment methods to prepare dried feedstock, and steam gasification was the popular mode for post gasification.

Moreover, co-gasification of wet wastes with other low-moisture biomass has received significant attention in recent years due to the improved quality of syngas, operational stability, environmental benefits, and energy-saving in terms of reduced pre-dewatered requirement (Chiang et al., 2016; Hu et al., 2016), as seen in Table 3. Besides, the summary table shows that Ni, Ca, Fe modified catalysts were commonly employed, while the catalyst concentrations varied as per different gasification reactors, including fixed bed reactor, fluidized bed reactor, continuous fixed gasifier, and fluidized bed gasifier. In this review, the data related to equivalence ratio (ER), steam-to-feedstock ratio (SF), temperature, and residence time are statistically analyzed, as seen in Fig. 2c. The median value of ER was 0.29 in the air gasification system, and the SF ratio was 1.00, with the steam introduced as gasification agents. Temperature, which is another critical parameter in the dry gasification, had a median close to 850 °C. However, the impact of gasification residence time was relatively less significant, with a median value of 60 min. In terms of the products, the main combustible

Fig. 2. Process conditions and the main products of (a) anaerobic digestion, (b) hydrothermal gasification, (c) dry gasification, (d) hydrothermal liquefaction, and (e) fast pyrolysis from wet wastes (AD: anaerobic digestion, HTG: hydrothermal gasification, DG: dry gasification, HTL: hydrothermal liquefaction, FP: fast pyrolysis, TS: total solid, VS: volatile solid, ER: equivalence ratio, S-F: steam-to-feedstock ratio).

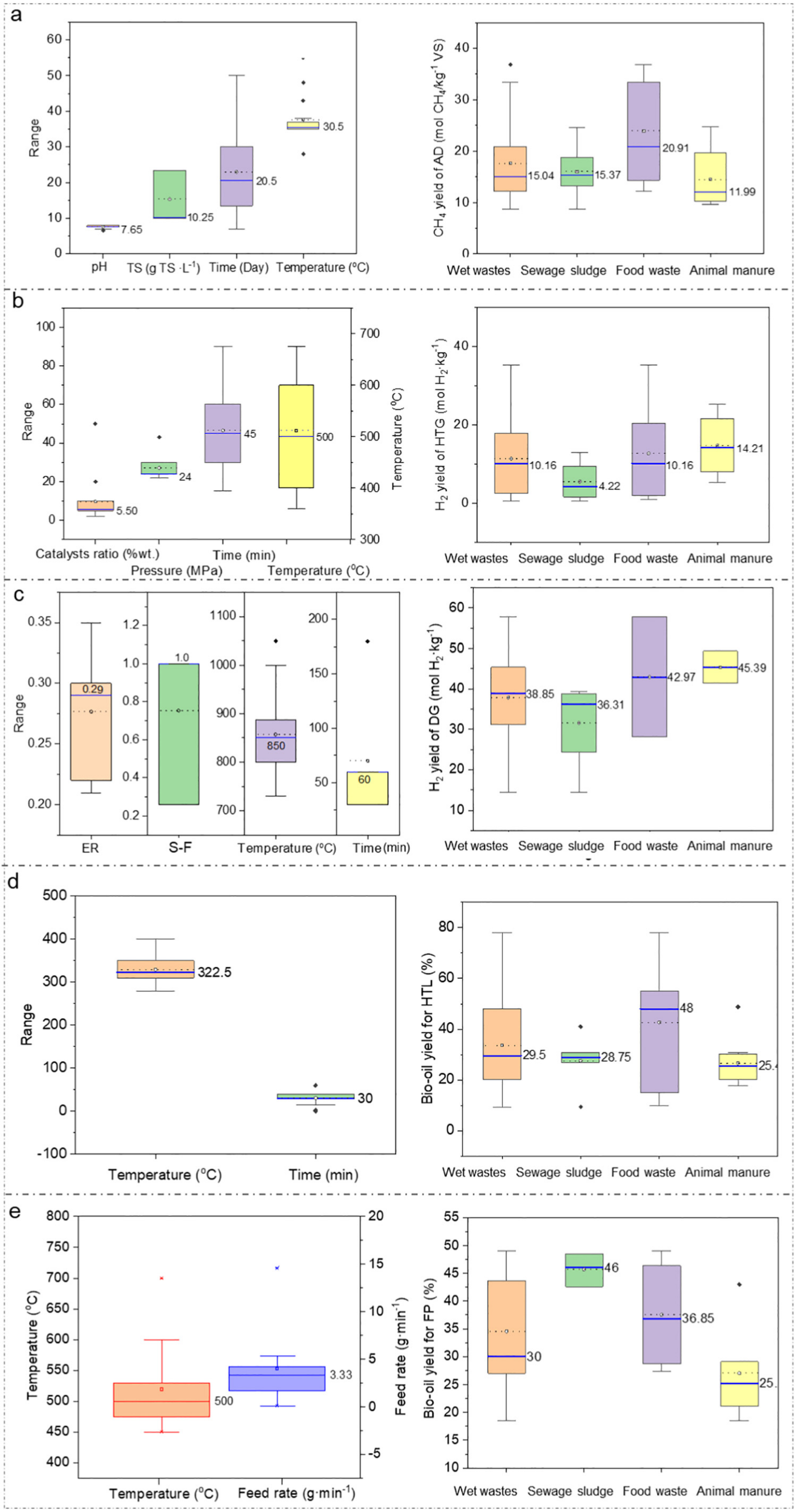
a
Range
7.65
10.25
20.5
30.5
pH
TS (g TS ·L⁻¹)
Time (Day)
Temperature (°C)
CH₄ yield of AD (mol CH₄/kg⁻¹ VS)
15.04
15.37
20.91
11.99
Wet wastes
Sewage sludge
Food waste
Animal manure
b
Range
5.50
24
45
500
Temperature (°C)
Catalysts ratio (%wt.)
Pressure (MPa)
Time (min)
Temperature (°C)
H₂ yield of HTG (mol H₂·kg⁻¹)
10.16
4.22
10.16
14.21
Wet wastes
Sewage sludge
Food waste
Animal manure
c
Range
0.29
1.0
850
60
ER
S-F
Temperature (°C)
Time (min)
H₂ yield of DG (mol H₂·kg⁻¹)
38.85
36.31
42.97
45.39
Wet wastes
Sewage sludge
Food waste
Animal manure
d
Range
322.5
30
Temperature (°C)
Time (min)
Bio-oil yield for HTL (%)
29.5
28.75
48
25.4
Wet wastes
Sewage sludge
Food waste
Animal manure
e
Temperature (°C)
Feed rate (g·min⁻¹)
500
3.33
Temperature (°C)
Feed rate (g·min⁻¹)
Bio-oil yield for FP (%)
30
46
36.85
25.
Wet wastes
Sewage sludge
Food waste
Animal manure

Table 2
Summary of the literature about hydrothermal gasification of wet wastes for syngas production.

Feedstock (Moisture)	Reactor (Volume)	Catalyst	Optimal conditions	Syngas yield	Main results	Reference
Paper waste sludge (90 wt%)	Batch reactor	Ni/Al_2O_3–SiO_2 (50%)	450 °C / 29.2 MPa/ 60 min	5.8 mol H_2·kg^{-1} + 14.9 mol CH_4 ·kg^{-1}	90% carbon was converted to the gas with 83% energy recovered.	(Louw et al., 2016)
Sewage sludge (83.2 wt%)	Batch reactor (316 L)	2 wt% H_2O_2 + 5 wt % Ni catalysts	400 °C / 60 min / 22.1 MPa	0.58 mol H_2·kg^{-1}	The Ni and H_2O_2 additives enhanced H_2 production and inhibited PAH generation significantly.	(Wang et al., 2017)
Activated sludge (70 wt%)	Batch reactor (0.050L)	10 wt% KOH	500 °C / 30 MPa / 30 min	13 mol H_2·kg^{-1} + 6 mol CH_4 ·kg^{-1}	Syngas from sludge had a calorific value of 22 MJ·Nm^{-3}, and the addition of KOH promoted the water-gas shift reaction.	(Yildirir and Ballice, 2019)
Sewage sludge (73.87 wt%)	Batch reactor (316 L)	6 wt% organic solvent formic acid	400 °C / 24 MPa / 30 min	2.64 mol H_2·kg^{-1}	Formic acid served as an effective agent to promote the acid hydrolysis of carbohydrates.	(Fan et al., 2016)
Chicken manure (81.33 wt%)	Continuous fluidized bed reactor	6 wt% activated carbon	600 °C / 24 MPa	25.2 mol H_2·kg^{-1}	Activated carbon was an effective catalyst, and the metal cations in manure were removed effectively.	(Cao et al., 2016)
Human feces	Batch gasification reactors	6 wt% Ni-Ru/AC catalysts	400 °C / 30 MPa / 30 min	10.61 mol H_2·kg^{-1}	Potential catalyst synergy existed between the two catalysts investigated, which further enhanced H_2 production.	(Watson et al., 2017)
Cattle manure (97.5 wt%)	Pipe reactor (0.045 L)	Ni/activated carbon + Hydrochar catalysts	440 °C / 20 min	44 mol syngas ·kg^{-1} (17.8 mol H_2·kg^{-1})	The addition of porous catalyst enhanced activity, and increasing its blend increased the H_2 and total gas yields.	(Tavasoli et al., 2018)
Horse manure (91 wt%)	Tubular batch reactor	2 wt% Na_2CO_3	600 °C / 23–25 MPa / 45 min	20.8 mol syngas ·kg^{-1} (5.31 mol H_2 ·kg^{-1})	The H_2 yield maximized at 2 wt% catalyst loading in the order of preference as NaOH < K_2CO_3 < Na_2CO_3.	(Nanda et al., 2016a)
Olive-pomace	Batch autoclave (0.10 L)	10 wt% KOH	600 °C / 43Mpa	16.80 mol H_2 ·kg^{-1}	H_2 formation increased with temperatures from 300 to 600 °C and catalyst addition, while decreased at elevated pressure.	(Sert et al., 2018)
Waste cooking oil (75 wt%)	Tubular fixed bed reactor	5 wt% Ru/Al_2O_3	675 °C / 60 min / 23–25 MPa	10.16 mol H_2·kg^{-1} 2.17 mol CO·kg^{-1} 3.5 mol CH_4·kg^{-1}	The order of catalysts for promoting H_2 yields was Ru/Al_2O_3 > Ni/Si-Al_2O_3 > K_2CO_3 > Na_2CO_3.	(Nanda et al., 2019)
Food waste (90 wt%)	Hastelloy batch reactor	5 wt% KOH	360 °C / 90 min	1.88 mol H_2·kg^{-1}	The catalysts' activity was ranked as: KOH > NaOH > Ni/γ-Al_2O_3 > Ni/ZrO_2 > $FeCl_3$.	(Su et al., 2019)
Sugarcane bagasse (94 wt%)	Batch reactor (0.01 L)	20 wt% Na_2CO_3	650 °C / 23–25 MPa / 15 min	35.3 mol H_2·kg^{-1}	A higher temperature, a lower bagasse concentration, and a longer time led to a higher hydrogen yield.	(Cao et al., 2018)
Food waste (98 wt%)	Hastelloy batch reactor (0.20 L)	5 wt% KOH	500 °C / 60 min	38.36 mol syngas·kg^{-1} (20.37 mol H_2·kg^{-1})	The activity of the catalysts was ranked: KOH > activated carbon > $FeCl_3$ > K_2CO_3.	(Yan et al., 2019)
Orange peel (91 wt%)	Tubular batch reactor	2 wt% K_2CO_3	600 °C / 45 min / 23–25 MPa	5.5 mol syngas·kg^{-1} (0.91 mol H_2·kg^{-1})	The elevated temperature, longer reaction time, and lower feed concentration favored higher H_2 yield and total gas yield.	(Nanda et al., 2016b)
Food waste (88.6 wt%)	Autoclave (0.45 L)	5% K_2CO_3	450 °C / 1 h	3.64 mol H_2·kg^{-1} 3.2 mol CH_4·kg^{-1}	K_2CO_3 was the best catalyst for hydrogen production compared to trona and seaweed ash.	(Duman et al., 2018)

gas was H_2, with a median value of 38.85 mol·kg^{-1} dry-based feedstock. For various wet wastes, the H_2 yield was different, with animal manure leading the lot (45.39 mol·kg^{-1}), closely followed by food waste (42.97 mol·kg^{-1}) and finally sludge (36.31 mol·kg^{-1}) (Fig. 2c).

2.3. Hydrothermal liquefaction and fast pyrolysis for bio-oil production

In addition to energy of rich gaseous products from AD and gasification, liquid energy, e.g., bio-oil, can also be produced from wet wastes. Hydrothermal liquefaction (HTL) and fast pyrolysis (FP) are the two main conversion technologies which can convert the waste into bio-oil as a desired product. Fig. 1d presents the basic batch reactor of HTL which is similar to the HTG. The main difference between them is the reaction temperature. The HTL temperature ranges commonly between 200 and 400 °C to generate hot and compressed water as solvent (Prestigiacomo et al., 2019). Such solvent can cleavage the wet waste to generate simple organic molecules which mix to form the bio-oil. FP is another widely used technology which converts the waste biomass into bio-oil as the mainly product along with low yields of solid and gas by-products under relatively low temperature, rapid heating rate, and short reaction time in an oxygen-free atmosphere (Huang et al., 2014). The basics diagram of the equipment with main reaction presented is shown in Fig. 1f (Huang et al., 2014; Ly et al., 2021).

According to the review of the HTL of sludge, food waste, and manure (Table 4), batch reactors with various capacities were the commonly used and the important process parameters of HTL were reaction temperature and time. In detail, the wide exploration range of HTL temperature was between 250 °C and 400 °C with a median of 322.5 °C, and the reaction time ranged from 0 to 60 min with 30 min as the median (Fig. 2d). It has been proven that proper increase in temperature improves the bio-oil yield (Saengsuriwong et al., 2021). In the case of bio-oil produced from various wet wastes based on their optimal conditions of each research, the median of bio-oil yield from food waste was 48%, which was higher than those derived from manure and sludge. However, the yield of bio-oil from food waste had a large variation ranging from 10 to 80%, revealing that the diverse feedstock input of food waste could have a significant impact on bio-oil production (Aierzhati et al., 2019).

In terms of the bio-oil produced from FP, the bubbling fluidized-bed reactor was the most widely used type of reactor. Sand and quartz were commonly used as bed material to transfer heat with waste for a rapid rising of temperature under a fluidizing velocity (Ly et al., 2021). In addition to the reaction temperature, the feed rate of the feedstock into the reactor was another critical process parameter since the fast pyrolysis of waste in bubbling fluidized-bed reactor is a continuous reaction process (Huang et al., 2014). Table 5 presents the summary of literature review on the FP of wet waste. Furthermore, the optimal reaction temperature of FP was mainly in the range of 450–600 °C based on the statistical analysis Fig. 2e, while the feed rate varied from 0.1 to 6.0 g·min^{-1} due to the variation of reactor size. With respect to the bio-oil yield from FP, it was found that the yield from sludge FP was the highest (46%), followed by food waste and manure.

Table 3
Summary of the literature about dry gasification of wet wastes for syngas production.

Feedstock (Moisture)	Pretreatment	Reactor	Catalyst	Gasification agent	Optimal conditions	Syngas yield (g/kg)	Main results	Reference
Sewage sludge	HTC (220 °C / 1 h /1.9 MPa)	Fixed-bed reactor	–	S-F = 1.0	1050 °C	76.70 g $H_2 \cdot kg^{-1}$	Hydrochar with nickel, iron, alkali, and alkaline earth metallic species increased H_2 production.	(Gai et al., 2016)
Sewage sludge	Nickel-Doped HTC (200 °C /1 h)	Fixed-bed reaction system	Ni	S-F = 1.0	800 °C	78.7 g $H_2 \cdot kg^{-1}$	0.1 M Ni solution doped HTC showed the highest catalytic activity.	(Gai et al., 2017)
Sewage sludge (85 wt%)	Thermally dried	Fixed bed	CaO-3A molecular sieve (20%)	SF = 0.2 $g \cdot min^{-1}$	850 °C / 60 min	0.77 m^3 $H_2 \cdot kg^{-1}$	CaO-3A molecular sieve showed the best performance on H_2 production, and Ni and Fe were favorable to tar cracking.	(Chen et al., 2017)
Sewage sludge	HTC	Fixed-bed tube reactor	–	20% CO_2 + 80% N_2	900 °C / 60 min	0.57 L syngas (0.52 L CO + 0.05 L H_2)	HTC improved coalification, desulfurization, and deamination.	(Shen et al., 2018)
Food waste	Torrefaction (280 °C)	Vertical fixed bed reactor	–	H_2O / C molar ratio = 2	1000 °C	1300 mL $H_2 \cdot g^{-1}$ 520 mL $CO \cdot g^{-1}$	The torrefied sample shows better gasification performance.	(Huang et al., 2019)
Food waste (88.6 wt%)	HTC (200 °C / 1 h)	Two-stage fixed bed reactor	Iron – ceria catalyst and dolomite (1:1)	SF = 0.6 $mL \cdot min^{-1}$	850 °C / 60 min	28.08 mol $H_2 \cdot kg^{-1}$	H_2 yield from the steam gasification process was about 7.7 times that of SCWG.	(Duman et al., 2018)
Cow manure	HTC (260 °C / 30 min)	Thermogravimetric Analyzer	–	CO_2 oxidizing 0.3 of ER	850 °C	1.95 m^3 $gas \cdot kg^{-1}$	Syngas from hydrochar had LHV of 15 $MJ \cdot (Nm^3)^{-1}$, while H_2 decreased with temperature > 950 °C.	(Saha, 2019)
Cattle manure (85. wt%)	Thermally dried + pyrolysis (500 °C / 30 min)	Fixed bed reactor	–	SF = 1.66 $g \cdot min^{-1}$	850 °C / 30 min	1.61 m^3 $syngas \cdot kg^{-1}$ 0.93 m^3 $H_2 \cdot kg^{-1}$	Two-step gasification was an efficient waste-to-H_2 energy process.	(Xin et al., 2017)
Beef cattle manure	Thermally dried	Fluidized bed reactor	–	ER = 0.35	730 °C	1.87 Nm^3 $syngas \cdot kg^{-1}$	The H_2 was significantly affected by the type of biomass.	(Maglinao et al., 2015)
Cattle manure (85.12 wt%)	Carbonization (450 °C)	Tubular reactor	–	SF = 1.66 $g \cdot min^{-1}$	850 °C / 30 min	1.87 m^3 $syngas \cdot kg^{-1}$ 1.11 m^3 $H_2 \cdot kg^{-1}$	Char for gasification reduced tar in the gas and increased H_2 yields by 2.27 times.	(Xin et al., 2018)
Poultry litter (22.10 wt%)	Thermally dried	Continuous fluidized bed gasifier (0.61 $kg \cdot h^{-1}$)	Limestone (8 wt %)	S-F = 0.26 / ER = 0.28	750 °C	1.25 Nm^3 $syngas \cdot kg^{-1}$	Limestone overcame the fluidization problems. High temperature and steam injection promoted CO and H_2 production.	(Pandey et al., 2016)
Sewage sludge (77.32 wt%) + sawdust (4: 6)	–	Continuously fed gasifier (5–10 $g \cdot min^{-1}$)	NiO / modified dolomite (MD) catalyst 1 kg / 800 °C)	–	900 °C	14.44 mol $H_2 \cdot kg^{-1}$ 1.23 syngas $Nm^3 \cdot kg^{-1}$	NiO/MD as catalysts, the carbon conversion efficiency achieved was 84.56 wt%.	(Hu et al., 2016)
50% sewage sludge (8.51%wt %) + hydrolysis residues (3.82 wt%)	–	Downdraft fixed-bed reactor	CaO (CaO/C molar ratio = 1.0)	ER = 0.22	800 °C	1.20 syngas $Nm^3 \cdot kg^{-1}$	The fuel gas with LHV of 6.83 MJ $\cdot (Nm^3)^{-1}$; a higher ER favored the decrease in tar formation.	(Chen et al., 2018)
Sewage sludge + Paper-mill sludge (Mixed moisture 43.9%)	Dry with the heat of steam from heat exchanger	Continuously fluidized-bed gasifier (12.5 $kg \cdot min^{-1}$)	–	ER = 0.3	858 °C	29.4 syngas $Nm^3 \cdot min^{-1}$ (4.13 vol% H_2)	Approximately 2.2 tons of syngas and 4.46 tons of steam were produced from 2 tons sludge.	(Chiang et al., 2016)
30% food waste and 70% wood chips	Thermally dried (68 °C / 24 h)	10 kW fixed-bed downdraft gasifier (10 $kg \cdot h^{-1}$)	–	AF =4 $L \cdot s^{-1}$	850–900 °C / 3 h	20 vol% CO 18 vol% H_2	The co-gasification produced syngas with higher quality than pure wood waste.	(Ng et al., 2017)
Chicken manure	Mobile belt	Fixed bed gasifier	–	ER = 0.21	800 °C	27 vol% CO	The concentration of chicken manure	(Tańczuk

(continued on next page)

But it is also worth noting that food waste with proper composition may also have potential to produce high bio-oil yield, given the wide range of yield from different types of food waste.

According to the bio-oil yield from HTL and FP of wet waste, the median yield was 29.5% and 30%, respectively, which were lower than the average values (33% and 35%). This indicated that the yield from most of the wet waste was relatively low, while it could be improved by fast co-pyrolysis with other biomass waste based on optimal conditions. Alvarez et al. found the bio-oil yield from fast co-pyrolysis of sludge and biomass was much higher than the single sludge as feedstock (Alvarez et al., 2015). Moreover, the bio-oil produced from HTL and FP, especially without the presence of catalyst in the reaction, is quite viscous at room temperature and it is a complex mixture with high contents of oxygen, nitrogen, and sulfur. The oxygen content in bio-oil could impact its quality and combustion performance (Ly et al., 2021). The nitrogen and sulfur in bio-oil could also lead to serious issues, such as corrosion and mission of gaseous pollutants during combustion (Prestigiacomo et al., 2019). Therefore, additional upgrading processes in the presence of suitable catalysts (Haider et al., 2018), such as hydrodeoxygenation, hydrodeazotation (Prestigiacomo et al., 2019), and hydrodesulfurization, are usually needed to improve the

Table 4

Summary of the literature about hydrothermal liquefaction (HTL) of wet wastes for bio-oil production.

Feedstock (Moisture)	Reactor (Volume)	Catalyst	Optimal conditions	Highest Bio-oil yield	Main results	Reference
Municipal secondary sludge	Batch reactor (1.0 L)	Different acids	300 °C / 30 min	26.75 wt%	HCl pretreatment showed the best performance	(Liu et al., 2018)
Primary sewage sludge (97.8 wt%)	Batch reactor (0.0041 L)	–	350 °C / 2 min	30.9 wt%	32%-d 63% N transferred to oil, Dehydration and decarboxylation were important	(Qian et al., 2020)
Primary sewage sludge (97.8 wt%)	pilot reactor (19 L)	–	325 °C / 20 min	41 wt%	Micropollutants were successfully destroyed at 325 °C	(Silva Thomsen et al., 2020)
Sewage sludge	Batch reactor (0.041 L)	K_2CO_3	350 °C / 30 min	28.5 wt%	K_2CO_3 as catalyst can promote the hydrolysis of carbohydrate to improve the oil yield	(Shah et al., 2020)
Sewage sludge (75.8 wt%)	Batch reactor (0.016 L)	NiMo, CoMo, activated carbon	375 °C / 0 min	29 wt%	NiMo and CoMo decreased the S content in bio-oil.	(Prestigiacomo et al., 2019)
Digested anaerobic sludge (74 wt%)	Batch reactor (2.0 L)	–	300 °C / 11Mpa / 30 min	9.4 wt%	Feedstock composition was important for biocrude	(Vardon et al., 2011)
Swine manure (73 wt%)				30.2 wt%		
Cattle manure (76.37 wt%)	Batch reactor (1.8 L)	NaOH	310 °C / 15 min	48.78 wt%	Bio-oil yield highly depended on temperatures and process gases in which CO was the best.	(Yin et al., 2010)
Swine manure	Batch reactor (0.10 L)	–	340 °C / 30 min	25.58 wt%	Organic pollutant and heavy metal risk were decreased in HTL.	(Lu et al., 2018)
Swine manure	Batch reactor (0.10 L)			30.85 wt%	Swine manure showed the highest potential for bio-oil production	(Li et al., 2018b)
Sheep manure				25.47 wt%		
Cow manure			310 °C / 30 min	19.40 wt%		
Beef manures				20.20 wt%		
laying hen manure				21.01 wt%		
Broiler manure				17.77 wt%		
Mixed food waste (70.13 wt%)	Batch reactor (0.030 L)	–	360 °C / 40 min	50 wt%	Biochemical composition of food waste and HTL conditions have significant impacts on bio-oil yield	(Aierzhati et al., 2019)
Salad dressing (59.07 wt%)			320 °C / 40 min	78 wt%		
Cream cheese (55.38 wt%)			320 °C / 40 min	75 wt%		
Beef (67.53 wt%)			300 °C / 40 min	55 wt%		
Chicken (76.49 wt%)			360 °C / 40 min	40 wt%		
Hamburger bun (36.67 wt%)			360 °C / 40 min	10 wt%		
Vegetable (93.86)			280 °C / 40 min	15 wt%		
Fruit peels (91.97)			360 °C / 40 min	14 wt%		
Mixed food waste (60–65 wt%)	Batch reactor (0.40 L)	–	300 °C / 60 min	48 wt%	The bio-oil produced from food waste could substitute the bio-binder in asphalt pavement.	(Mahssin et al., 2021)
Mixed food waste (71.3 wt%)	Batch reactor (0.0041 L)	–	400 °C / 30 min / 35.3 MPa	30 wt%	The temperature, pressure, biomass loadings and time were examined.	(Motavaf and Savage, 2021)
Blended food waste (71.3 wt%)	Batch reactor (0.20 L)		340 °C / 30 min	55 wt%	The bio-oil yield increased with the increase of temperature and mixture ratio.	(Saengsuriwong et al., 2021)

bio-oil properties. Catalyst-aided HTL and PF could also be an effective way to improve the bio-oil quality (Park et al., 2010; Prestigiacomo et al., 2019). Besides, the yield and quantity of bio-oil could be improved by symmetrical optimization of process conditions and feedstock composition. Our recent work successfully employed data-driven approaches to design the feedstock composition and operating conditions of HTL to obtain a high yield of bio-oil with low O and N content (Li et al., 2021d; Zhang et al., 2021a).

2.4. Incineration for heat and electricity generation

The bioenergy obtained through AD and gasification can be further converted into heat and electricity through incineration, as well as the raw wet wastes after dewatering and drying. A basic schematic representation of the incineration process is shown in Fig. 1g. Incineration is a thermal conversion process that decomposes organic materials in the presence of oxygen at a high temperature of 800–1000 °C with the generation of slags (bottom ash) and hot exhaust gas (Zhao et al., 2016). It mainly includes five steps: incineration of feedstock in a furnace, energy recovery from hot gas through a heat exchanger, waste heat recovery, exhaust gas cleaning to avoid air pollution, and the bottom ash and fly ash collection. Hot steam at a certain temperature and pressure is produced by a heat exchanger from hot flue gas, which could be used for electricity generation or to provide auxiliary heat (Lombardi et al., 2015). After heat exchange, some waste heat can be further recovered to dry or preheat the feedstock in the waste incineration system.

Currently, incineration is one of the main technologies to convert organic wastes into heat or electricity. It has been widely used in developing and developed countries to treat sewage sludge, food waste, and animal manure. The typical amounts of sludge treated with incineration have reached more than 24%, 20%, 14%, 25%, and 55% in Denmark, France, Germany, the United States, and Japan, respectively (Samolada and Zabaniotou, 2014). It was reported that the sludge with 41–65 wt% of dry material can be incinerated in fluid bed combustion reactors (Fytili and Zabaniotou, 2008), and the calorific value of the dry sludge is 12–20 MJ· kg $^{-1}$ which is equivalent to that of lignite (11.7–15.8 MJ· kg $^{-1}$) (Samolada and Zabaniotou, 2012). However, most dewatered sludge has 30–40 wt% water content which exceeds the acceptable limits (15 wt%) as a fuel in combustion reactors. Co-firing with other fuels e.g., coal and biomass, is employed to improve power generation efficiency and minimize the energy consumption of drying (Liu et al., 2017). Compared to sludge and food wastes, animal manure's moisture content is inherently lower (Li et al., 2021f). Beef cattle manure with a moisture content of 14–18% was used as a combustion fuel in fluidized bed combustion directly, and 12.4–14.9 MJ· kg $^{-1}$ heat was recovered from its combustion (Sweeten et al., 1986). Interestingly, it has been reported that horse manure with 40% moisture could be used as a potential fuel for heat production, although its NO_x emission was higher than that of wood-chips (Lundgren and Pettersson, 2009).

Many bottlenecks persist in the incineration of wet wastes, including the immaturity of technologies for dewatering of these wastes effectively and economically, to satisfy the combustion requirements along with the low calorific value of dewatered waste due to incomplete dehydration and high content of inorganic components, and finally, the generation of exhaust gas and ash during incineration. The composition of the exhaust gas produced during the incineration process is quite complex, consisting of CO_2 and other harmful gases, e.g., SO_2, NO_x, and dioxins. It is worth mentioning that some of the ash derived from the wastes (especially sludge) contains inorganic containments like heavy metals and dioxins and must

Table 5
Summary of the literature about fast pyrolysis (FP) of wet wastes for bio-oil production.

Feedstock (Moisture)	Reactor (Volume)	Catalyst	Optimal conditions	Highest bio-oil yield	Main results	Reference
Sewage sludge	Drop tube quartz reactor	–	500 °C / 0.1 g·min^{-1}	45.3 wt%	Chemical composition of bi-oil highly related to temperature	(Huang et al., 2014)
Sewage sludge	Conical spouted bed reactor	–	500 °C / 1.0 g·min^{-1}	48.5 wt%	The heating value of bio-oil needed to be improved and nitrogen content should be further reduced.	(Alvarez et al., 2016)
Sewage sludge	Fluidized bed reactor and a catalyst bed reactor	CaO, La2O3	450 °C / 2.5 g·min^{-1}	42.6 wt%	CaO and La_2O_3 slightly decreased the bio-oil but effectively removed the chlorine from the bio-oil.	(Park et al., 2010)
Sewage sludge	Drop tube quartz reactor	–	500 °C / 0.1 g·min^{-1}	46.0 wt%	NH_3 was a predominant nitrogenous gas during fast pyrolysis	(Cao et al., 2013)
Food waste	Downdraft tube reactor	–	700 °C / 2 min	30 wt%	Food waste pyrolysis in H_2 significantly increased the content of H_2 and CH_4.	(Xu et al., 2020a)
Food waste	Fluidized-bed reactor	Dolomite, red mud, and HZSM-5	475 °C / 1.67 g·min^{-1}	49.05 wt%	The upgraded bio-oil contained $C_5 - C_{18}$ was suitable for green fuel.	(Ly et al., 2021)
Pomegranate Grape marcs	Fixed bed tubular reactor	Aluminum-MCM-41	500 °C / 700 °C min^{-1} 600 °C / 700 °C min^{-1}	43.7 wt% 27.4 wt%	The catalyst decreased the yield of bio-oil while promote the aromatic hydrocarbons.	(Ateş et al., 2019)
Poultry litter	Fluidized-bed reactor	–	530 °C / 14.6 g·min^{-1}	27 wt%	The high ash content resulted in low bio-oil yield, and the N content in oil was high.	(Pandey et al., 2019)
Swine manure	Fluidized-bed reactor	–	600 °C / 4.17 g·min^{-1}	18.48 wt%	Swine manure was suggested to mixed with other biomass to increase the yield and quality of oil.	(Jeong et al., 2015)
Poultry litter	Fluidized-bed reactor	–	450 °C / 5.33 g·min^{-1}	43 wt%	Bio-oil from 50% wood +50% manure was the most stable.	(Mante and Agblevor, 2012)
Poultry litter	Microwave heated fixed bed	ZSM-5/MCM-41	500 °C / 45 min	21.1 wt%	ZSM-5/MCM-41 promotes hydrocarbon production in oil.	(Zhang et al., 2018a)
Chicken litter Turkey litter	Fluidized bed reactor	–	500 °C / 3.33 g·min^{-1} 450 °C / 3.33 g·min^{-1}	23.39 wt% 29.08 wt%	Bio-oil yield of manure was lower than that from wood, highest heating value was 29 MJ·kg^{-1}	(Kim et al., 2009)

be treated appropriately to avoid secondary pollution of any kind (Li et al., 2017a). Therefore, converting the wet wastes into clean bioenergy (biogas, syngas, and bio-oil) for heat and electricity generation is an alternative approach to avoid the above-mentioned shortcomings. For example, methane production from a full-scale AD with food waste as feedstock was investigated by Lansing et al., who reported that 882 m^3 CH_4 could be produced per day with electric power and heat generation of 3519 ± 4 and 1768 ± 6 kW·d^{-1} from the CHP system, respectively (Lansing et al., 2019). Galvagno et al. integrated a gasification and CHP system within a citrus juice factory wherein 7875 MWh electricity was generated from the available citrus peels, with savings of 27,905 MWh of non-renewable energy and reductions of 5032 t CO_2-eq emission annually (Galvagno et al., 2019).

3. Wet wastes to biochar for carbon sequestration

Bioenergy from wet wastes is primarily used to generate heat and electricity, which offers its benefit as alternatives to fossil fuels, and thereby reduces dependency on non-renewable resources and avoids carbon emission. Another strategy to realize the negative carbon emission is the WWtB. Biochar is derived from the thermal decomposition of organic feedstock under inert or oxygen-deficient conditions (Libra et al., 2011). It is a carbonaceous material with various functional groups, which can be applied to soils for improving soil properties and carbon sequestration (Palansooriya et al., 2019). When biochar is applied in soils, the impact of carbon durability/stability is related to the O/C and H/C ratio of the biochar (Han et al., 2017b). It is reported that biochar with an O/C ratio < 0.4 and H/C ratio < 0.6 serves as an effective carbon sequestration agent when applied to soils (Tag et al., 2016), and biochar with O/C < 0.2 and H/C ratio < 0.4 have the potential for carbon sequestration with the half-life of about 1000 years (Brassard et al., 2018; Spokas, 2010).

HTC and slow pyrolysis are two main technologies for biochar production to convert organic carbon from wet wastes to a stable form of fixed carbon. In detail, the biochar obtained from HTC and pyrolysis are called hydrochar and pyrochar, respectively (Gai et al., 2016; Libra et al., 2011). It should be noted that biochar is also a by-product of fast pyrolysis and gasification which were reviewed in the previous section. Nevertheless, the biochar yield from such processes is quite low compared to the yield of biochar obtained from HTC and slow pyrolysis. Huang. et al. found that the yield of biochar from fast pyrolysis was between 15% and 30% when the pyrolysis temperature ranged from 400 to 700 °C. The carbon content in such biochar was less than 30% (Huang et al., 2014). Jeong et al. revealed that less than 20% of biochar was produced from the fast pyrolysis of swine manure under temperature of 500–650 °C (Jeong et al., 2015). The details about the gasification biochar have been reviewed in our previous work, where we also found that most of the gasification biochar yield was below 20% with a low carbon content (You et al., 2017). Hence, the primary focus was on the biochar produced from the HTC and pyrolysis processes in this work. The production of biochar from wet wastes has several advantages: (1) almost any organic solid wastes can be used as feedstock for biochar production; (2) the volume of organic wastes can be reduced significantly, especially for wet wastes after HTC treatment, and the remaining solid residue can be further reduced via pyrolysis; (3) most organic contaminants, e.g., antibiotics, pathogens in wet wastes, can be eliminated in the thermal conversion process (Libra et al., 2011), and finally, (4) various valuable products such as biochar, biogas, and bio-oil can be obtained by adjusting the pyrolysis process parameters.

As depicted in Fig. 3a, many papers have been published on biochar preparation from sewage sludge, animal manure, and food waste. The number of publications specifically dealing with pyrolysis of sludge was found to be the highest, followed by animal manure and food waste. A plausible explanation for the same could account for the fact that heavy metals in sludge can be immobilized to some extent through pyrolysis, which is beneficial to solve the pollution of heavy metals (Li et al., 2018a). It should be noted that the biochar with high heavy metal concentration, exceeding the defined threshold is not permitted for use in soil (Li et al., 2018c; Li et al., 2019). In terms of HTC, the number of published papers is far less than that of pyrolysis for the three wet wastes, because it is challenging to prepare a hydrochar with desired physical and chemical properties owing to its lower reaction temperature, which ultimately affects its performance. However, HTC should not be ignored for the wet wastes treatment since it avoids prior dewatering or drying process, which is quite economical and energy-saving. Therefore, it is usually used as a pretreatment for wet waste utilization.

3.1. Hydrothermal carbonization

HTC also referred to as hydrous pyrolysis, is a thermochemical decomposition of organic substances by hot compressed water and steam in a

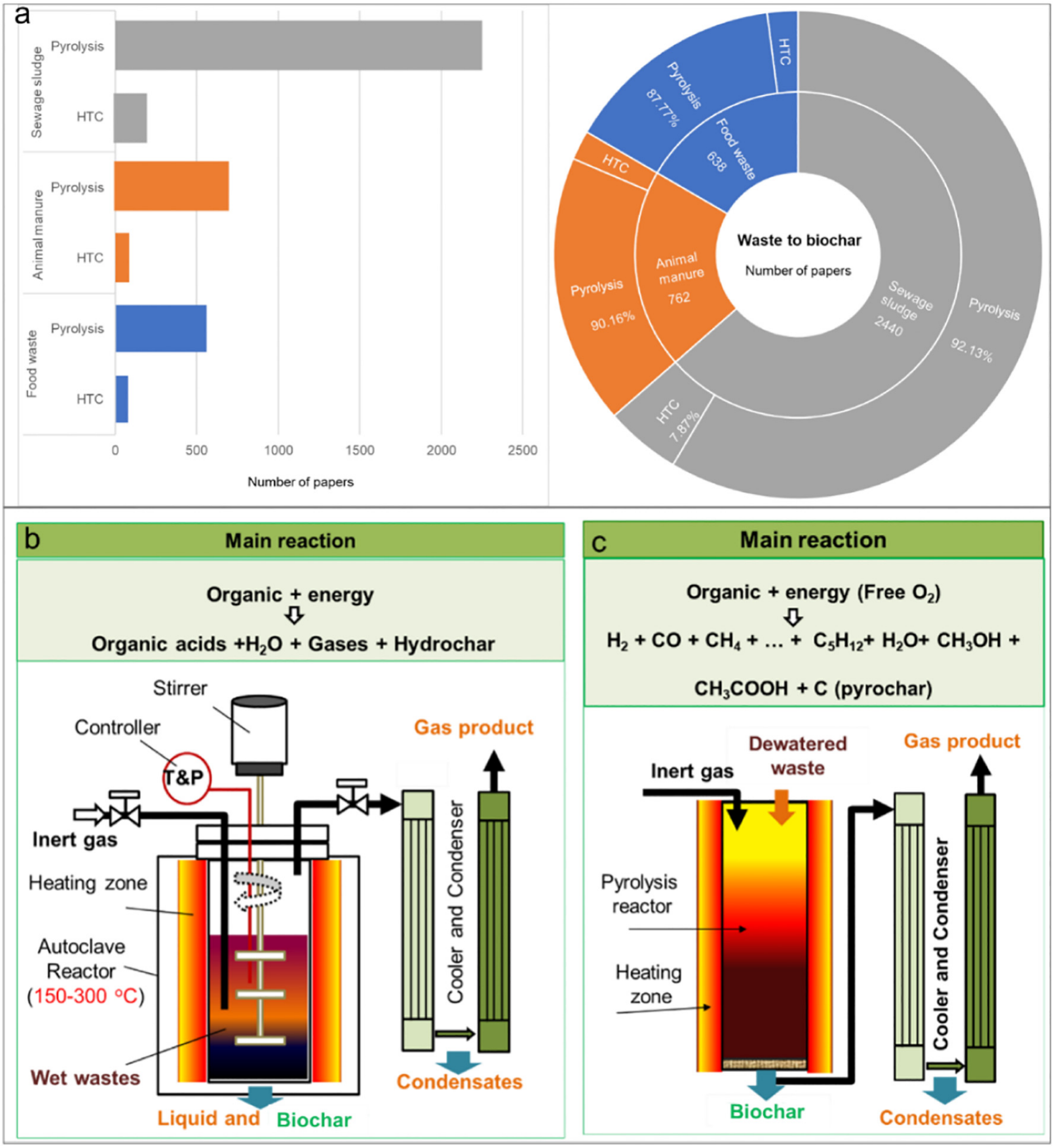

Fig. 3. (a) Results of the literature survey in Scopus on sewage sludge, animal manure, or food waste with hydrothermal carbonization or pyrolysis since 2010, and schematic presentation and main reactions of (b) hydrothermal carbonization and (c) pyrolysis.

sealed and high-pressure reactor (Kambo and Dutta, 2015; Libra et al., 2011). A pictorial representation of the HTC system and its main reactions are presented in Fig. 3b (Toufiq Reza et al., 2016). Many valuable products and chemicals, e.g., hydrochar and lactic acid (Xu et al., 2020b, 2021), could be produced via hydrothermal conversions due to its advantage of energy saving without dewatering. However, to evaluate the carbon sequestration potential, the hydrochar derived from HTC as the desired product is targeted in this review. According to the summary of the literature review shown in Table 6, the HTC temperature ranges from 150 to 300 °C. In hydrothermal processes, the product species are decided by the reaction temperature (and pressure) of the reactor. Most of the organic matters and components remain in the solid phase (hydrochar), and approximately 1–5% gases are generated when the temperature reaches around 220 °C (about 20 bar in the reactor) (Libra et al., 2011). Carbonaceous solids can be achieved from wet wastes via HTC without pre-drying. Hydrolysis of the organic matter first takes place with water as a reacting medium, reducing their degradation and depolymerization activation energy in HTC. HTC with low temperature (below 200 °C) is usually regarded as hydrothermal treatment which could be coupled with other waste to energy technologies for dewatering of wet waste as a pretreatment step. A combination of hydrothermal pretreatment and pyrolysis for sewage sludge utilization was investigated, where it was found that the water content decreased from 85 to 33 wt% after hydrothermal pretreatment (Li et al., 2018a). In this part, the HTC of wet wastes for hydrochar production is comprehensively reviewed with the main results summarized in Table 6.

3.2. Slow pyrolysis

In pyrolysis, the biowastes are thermally degraded under an inert atmosphere to produce three main types of products, including biochar, bio-oil, and gas. Slow pyrolysis (550–950 °C/ 0.1–1.0 $^{\circ}C{\cdot}s^{-1}$) favors the formation of char with small amounts of liquid and gaseous products (Tripathi et al., 2016; Demirbaş and Arin, 2002). Therefore, the literature specific to the

Table 6
Summary of the literature about hydrothermal carbonization (HTC) of wet wastes for biochar production.

Feedstock (moisture)	Reactor (volume)	Collected based on the maximum *CRS*					Main results	Reference
		HTC condition	yield/C content	H/C	O/C	*CR*		
Sewage sludge (93 wt%)	Autoclave reactor (0.50L)	180 °C / 60 min	84.01% / 26.39%	1.23	0.30	85.83%	After HTC, the solid yield decreased from 94.2% to 61.8%, while the HHV of hydrochar increased by 11.25%.	(Tańczuk et al., 2019)
Sewage sludge (83 wt%)	Stainless reactor (0.10 L)	240 °C / 600 min	59.85% / 30.65%	1.64	0.21	58.03%	The dewaterability of sludge was improved by HTC with 30% of drying energy saved.	(Liu et al., 2019b)
Sewage sludge (93.75 wt%)	Autoclave reactor (0.25 L)	210 °C / 30 min	76.00% / 20.32%	1.36	0.70	68.18%	The maximum HHV was 9.76 $MJ \cdot kg^{-1}$ with an energetic recovery of 90.12%. Hydrochar had lower N, S, Cl, Na, and K contents while higher fuel ratio.	(Lin et al., 2015)
Sewage sludge (90 wt%)	Glass tube (500 mL)	240 °C /45 min	50.21% / 67.96%	1.00	0.00	66.64%	HTC temperature played the most important role in solid fuel properties. About 40% of net energy was recovered in the hydrochar.	(Zhao et al., 2014)
Sewage sludge (83 wt%)	Stainless steel batch reactor (0.25 L)	160 °C /60 min	81.13% / 37.69%	1.83	0.38	83.48%	High temperatures and sho rter times were beneficial for the hydrochar carbon and energy properties.	(Danso-Boateng et al., 2015)
Food waste (90.25 wt%)	Parr 4575 reactor (0.50 L)	230 °C /30 min	74.5% / 68.5%	0.50	0.00	94.75%	Fixed carbon and HHV increased from 18.8 to 22.4% and 25.1 to 33.1 $MJ \cdot kg^{-1}$ with increasing HTC temperature.	(McGaughy and Toufiq Reza, 2018)
Food waste (80 wt%)	Stainless steel reactor (0.50 L)	180 °C / 60 min	53.82% / 65.51%	1.35	0.17	84.03%	The N content in liquid increased with the temperature rising, The N in hydrochar was stable prepared above 220 °C.	(Wang et al., 2018b)
Food waste (89 wt%)	Autoclave (0.50 L)	200 °C / 60 min	56.15% / 66.11%	1.29	0.15	72.59%	The pellets from food waste hydrochar had excellent strength due to the solid bridge and agglomeration by molasses and lime.	(Zhai et al., 2018)
Slaughterhouse wastes (83 wt%)	Lab-scale reactor (0.50L)	180 °C / 30 min	77.50% / 61.93%	1.35	0.13	77.49%	The dewaterability was improved, and the heating value was increased because the H/C and O/C ratios decreased.	(Kim et al., 2018)
Brewer's spent grain (87.5 wt%)	Stainless steel vessel (0.40 L)	215 °C / 720 min	56.10% / 67.30%	1.32	0.17	72.75%	Hydrochar yield decreased from 73% to 45% with the temperature from 180 to 250 °C; the LHV of hydrochar rose from 20.6 to 30.3 $MJ \cdot kg^{-1}$.	(Velebil et al., 2016)
Poultry litter (65 wt%)	Stainless steel autoclave (0.50 L)	225 °C / 120 min	42.21% / 57.57%	0.97	0.36	68.06%	The fuel properties of hydrochar were similar to that of biochar prepared from torrefaction at 300 °C.	(Toptas Tag et al., 2018)
Pig manure	Hastelloy autoclave	200 °C /120 °C	58.76% / 33.77%	1.50	0.34	57.92%	Hydrochar prepared at 220, and 240 °C possessed the highest field capacity; hydrochar was potential as green roof materials and soil growing media.	(Gascó et al., 2018)
Swine manure (80 wt%)	Stainless autoclave (0.050 L)	220 °C /600 min	55.54% / 50.64%	1.29	0.26	71.08%	The CaO addition increased the pH and yield of hydrochar and almost 100% of phosphorus remained.	(Lang et al., 2019)
Dairy manure (95 wt%)	Alloys reactor (1.0 L)	220 °C / 240 min	51.55% / 41.60%	1.20	0.70	59.22%	Hydrochar yield reduced from 58.34% to 43.48% with temperature rose from 200 °C to 280 °C, while its HHV increased with temperature.	(Wu et al., 2017)
Cow manure (83 wt%)	Parr reactor (0.10 L)	260 °C / 30 min	50.8% / 54%	1.16	0.18	61.23%	The P and other minerals were recovered effectively in the hydrochar, while about 50% of the N and most of the K are dissolved in the liquid.	(Toufiq Reza et al., 2016)

Note: CRS: Carbon recovery and stability; CR: Carbon recovery.

slow pyrolysis for biochar production were reviewed to evaluate its maximum potential of carbon sequestration in this work. The typical pyrolysis flow diagram and the thermochemical reaction are shown in Fig. 3c (Zaker et al., 2019). In recent years, considerable research has been published on converting wet organic wastes to energy and resource through pyrolysis (Table 7).

It should be pointed that some gas products, such as CO_2, CH_4, NO_x or other gases could be produced during pyrolysis. However, such gases usually mix with bio-oil vapor under the high pyrolysis temperature, which could be transported to pyrolysis furnace for energy self-supply. The final combustion flue gases could be cleaned by exhaust gas cleaning system. Such centralized gas cleaning can efficiently avoid the emission of air pollution, which is much cleaner than the landfilling treatment that could generate not only greenhouse gas and leachates, but also occupy land (Liu et al., 2016b; Muangrat, 2013). Although pyrolysis of wet wastes involves additional energy requirement for prior dewatering and drying in the form of pretreatment, the multi-products, including biochar, bio-oil, and pyrolysis gas, could be produced during pyrolysis. Apart from the bio-oil and pyrolysis gas for energy self-supply, biochar can also be used as alternatives to fossil fuels for electricity generation, the concepts of which are similar to the bioenergy mentioned in Section 2. Based on our previous study, the HHV of biochar mainly ranged from 15 to 30 MJ/kg with an average of around 22.5 MJ/kg which is similar with the HHV of sub-bituminous coal (24.6 MJ/kg) (Abdullahi et al., 2017; Li et al., 2020b). So, it could be estimated that one ton of sub-bituminous coal can be substituted by biochar prepared from HTC of 1.78 ton dried-waste (biochar yield = 56% from Fig. 4) and from pyrolysis of 2.22 ton dried-waste (biochar yield = 45% from Fig. 5). Moreover, co-pyrolysis of mixed wastes is a useful way to adjust feedstock properties, improve the quality of pyrolysis products, and decrease energy consumption (Li et al., 2020d). Optimization of the pyrolysis conditions is another approach to improve the biochar properties (He et al., 2021). More details are tabulated in Table 7.

3.3. Carbon recovery and stability in biochar

In this sub-section, the carbon recovery (*CR*) and carbon stability (*CS*) of biochar are reviewed and analyzed to evaluate the carbon capture and sequestration potential when applied for soil remediation. The *CR* is defined as the percentage of carbon content remaining in the biochar in comparison with the original carbon in wastes; *CS* can be estimated according to the atomic ratios of H/C and O/C. To integrate both *CR* and *CS*, another index called the carbon recovery and stability (*CRS*), was identified based on the ratio factor of half-to-half for the *CR* and *CS* (Li et al., 2021f). The calculation of CRS and CR are as follows (Eqs. (1) and (2)):

$$CRS = 0.5\,CR - 0.5\left(\frac{H}{C} + \frac{O}{C}\right) \tag{1}$$

Table 7
Summary of the literature about pyrolysis of wet wastes for biochar production.

Feedstock (Moisture)	Pretreatment (Conditions)	Reactor/ Volume	Collected based on the maximum *CRS*					Main results	Reference
			Conditions	Yield / C content	H/C	O/C	*CR*		
Sewage sludge	Naturally dried (20 °C)	Homemade pyrolysis furnace	550 °C	58.76% / 20.66%	0.59	0.17	45.78	With temperature increase, the pH, ash content and specific surface area increased. The bioavailability of heavy metals was reduced.	(Jin et al., 2016)
Sewage sludge (10 wt% after dried)	Thermally dried	Bench-scale intermediate pyrolysis reactor (15 kg·h^{-1})	500 °C / 10 min	53% / 23.80%	0.55	0.03	41.77	The metals (except mercury) and other minerals were retained in biochar, while some N and S migrated to oil and gas.	(Tomasi Morgano et al., 2018)
Sewage sludge Animal manure Sewage sludge + Animal manure (1:1)	Thermally dried (105 °C)	Bench-scale stirred batch reactor	525 °C / 8 °C·min^{-1} / 30 min	52% / 20% 49% / 42% 50% / 30%	0.56 0.43 0.47	0.10 0.23 0.11	37.28 64.92 50.34	Carbon content increased, compared to sludge biochar, indicating that co-pyrolysis could be a feasible alternative in locations where both wastes were generated.	(Ruiz-Gómez et al., 2017)
Sewage sludge + Bamboo sawdust (1:1)	Air-dried (20 °C)	Pyrolysis and carbonization furnace	500 °C	44.5% / 30.4%	0.64	0.19	51.05	The biochar yield from co-pyrolysis was lower, while its C content was higher. The toxicity of toxic metals was decreased.	(Jin et al., 2017)
Sewage sludge Sewage sludge +Sawdust (1:1) Sewage sludge + Rice straw (1:1)	Oven-dried (105 °C/ 24 h)	Crucible with a lid in a muffle furnace	600 °C / 20 °C·min^{-1} / 60 min 700 °C	61% / 16.7% 48% / 49.3% 47% / 26.3%	0.43 0.49 0.27	0.22 0.05 0.17	39.18 64.39 39.06	The thermal stability, surface area, and pore volume of biochar decreased after the adding sawdust. The total heavy metals were reduced.	(Huang et al., 2017)
Sewage sludge	Thermally dried	Spiral continuous reactor	700 °C / 6 min	70% / 26.33%	0.38	0.00	52.42	The yield and volatile content of char decreased with increase in temperature and residence time, while gas yield increased.	(Gao et al., 2017)
Sewage sludge (85 wt%)	Hydrothermal (180 °C / 30 min)	Rotary furnace (12 t /d)	600 °C / 45 min	64% / 10.6%	0.48	0.42	27.50	The water content decreased after pretreatment. The heavy metals were well immobilized in the sludge biochar pyrolyzed at 600 °C.	(Li et al., 2018a)
Food waste	Thermally dried (70 °C / 4 h)	Horizontal tube furnace	500 °C / 10 °C·min^{-1} / 4 h	43% / 71.3%	0.35	0.07	66.51	Only about 10.5% of energy extracted by AD. Over 50% energy was in bio-oils, and biochar with rich energy was produced at 500 °C.	(Opatokun et al., 2015)
Sugarcane	Oven-dried (65 °C / one week)	Horizontal tube furnace	550 °C / 10 °C·min^{-1} / 1 h	29.45% / 85%	0.05	0.07	55.63	The biochar pH increased significantly with increase in temperature which also affected the biochar's structural properties.	(Zhang et al., 2017)
Peanut shell			750 °C / 10 °C·min^{-1} / 1 h	30.23% / 80%	0.23	0.09	50.12		
Food waste Food waste digestate	Thermally dried (105 °C / 24 h)	Fixed-bed horizontal Tubular reactor	700 °C / 10 °C·min^{-1}	32% / 74.6% 39% / 36.7%	0.13 0.29	0.04 0.01	51.78 31.05	7.4 and 5.3 wt% of gas and 60.3 and 52.2 wt% of bio-oil were achieved from food waste and its digestate.	(Zhang et al., 2017)
Human manure (80.4 wt%)	Thermally dried (75 °C)	Electrically horizontal oven	400 °C / 15 °C·min^{-1} / 40 min	44.7% / 42%	1.00	0.35	44.28	Most P and K was recovered in biochar; biochar with porous structure and rich nutrients could potentially enhance soil fertility.	(Liu et al., 2014)
Swine manure	Thermally dried (105 °C / 12 h)	Vertically fixed-bed reactor	700 °C / 10 °C·min^{-1} / 40 min	23% / 43.9%	0.25	0.01	35.37	Pore structure, ash and pH values of manure biochar increased as the temperature increased, while the yield, N, O contents decreased.	(Tsai et al., 2012)
Poultry litter	Thermally dried (105 °C / 12 h)	Stainless steel 1 L vertical reactor	350 °C / 5 °C·min^{-1} / 30 min	43% / 57%	0.67	0.21	68.67	350 °C was suitable for biochar production used as fuel, while the biochar with stable carbon produced at 500 °C and 600 °C.	(Tag et al., 2016)
Swine manures	Air dried	Muffle furnace	700 °C / 25 °C·min^{-1} / 120 min	48.87% / 33.68%	0.27	0.11	47.31	The surface area, pH, and nutrients of biochar produced at 700 °C were higher than at 400 °C; the latter also had high adsorption capacity for Cu^{2+}.	(Meng et al., 2013)
Pig manure	Thermally dried (105 °C)	Fluidized bed reactor	600 °C / 1.5 h	36.4% / 52.1%	0.41	0.02	38.69	92%–97% of P remained in char, and 60%–75% of that was directly leached as ortho-phosphate.	(Azuara et al., 2013)
Swine solid (75 wt %)	Oven dried (100 °C)	Batch pyrolysis reactor	500 °C / 2 h	38.9% / 46.5%	0.46	0.06	41.97	10% plastic mulch film was co-pyrolyzed with swine solids to produce enough gas energy for pyrolysis.	(Ro et al., 2014)
Pig manure	Convection oven dried (60 °C / 72 h)	Muffle furnace	700 °C / 5 °C· min^{-1} / 1 h	35.5% / 41.5%	0.23	0.06	40.36	Char with higher cation exchange capacity, available nutrients, and lower salinity and alkalinity produced at low temperature.	(Zornoza et al., 2016)

Note: CRS: Carbon recovery and stability; CR: Carbon recovery; HHV: Higher heating value; PC: Principal component.

$$CR = \frac{C_w * m_w}{C_h * {}_m} \tag{2}$$

where H/C is the atomic ratio value of hydrogen to carbon, O/C is the atomic ratio value of oxygen to carbon, C_w is the carbon content in dry-based waste, m_w is the mass of dry-based waste, C_h represents the carbon content in dry-based biochar, and m_h is the mass of dry-based biochar.

For biochar from HTC of different wet wastes, the data on the elemental analysis (C, H, N, and O) were collected from the published papers. The *CRS*, *CR*, H/C, and O/C of biochar prepared under different conditions of HTC and feedstocks in the literature were calculated based on Eqs.(1) and (2). The higher *CRS* indicates a better effect on the carbon sequestration of biochar in soil. Hence, the maximum *CRS* was chosen in each published work to determine the optimal operation conditions, the yield, carbon

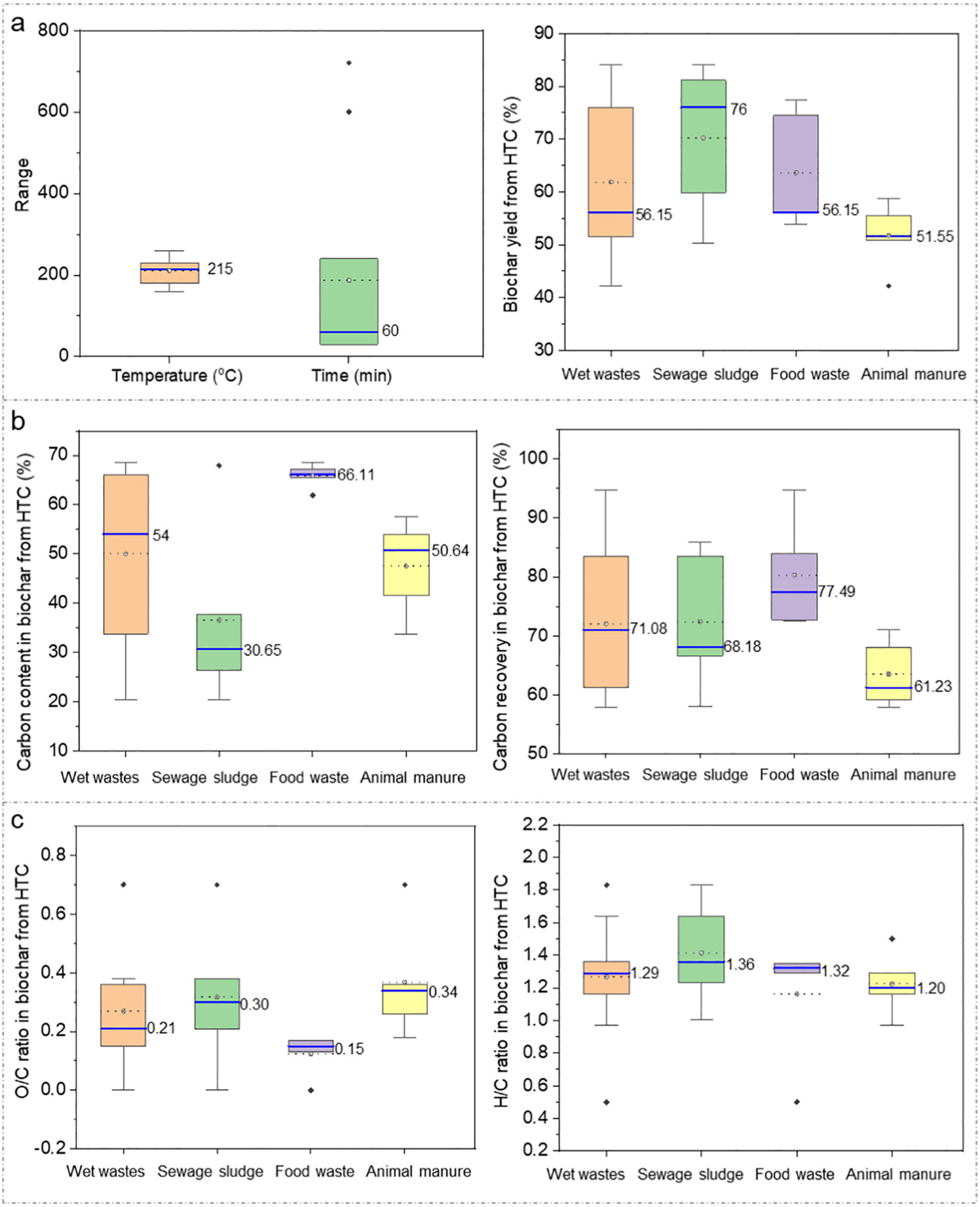

Fig. 4. Statistics of (a) process conditions of with biochar yield, (b) carbon capture performance, and (c) atomic ratios of biochar from hydrothermal carbonization (HTC) of wet wastes.

content, *CR,* and atomic ratios of H/C and O/C of biochar. The details of the above information from the literature review are listed in Table 6, and the data are statistically analyzed, which is presented in Fig. 4. Temperature and time were the two main operating parameters for HTC, and their median values were 215 °C and 60 min (Fig. 4a). Moreover, the properties of biochar derived from HTC of various wet wastes were different. The yield of biochar from sludge was 76%, which was the highest compared to food waste and animal manure. However, the carbon content (30.65%) of sludge-based biochar was lowest due to its high ash content (Fig. 4b). The carbon content of biochar from food waste was the highest (66.11%) owing to its highest carbon content (Li et al., 2021f), and *CR* (77.49%). The median value of *CR* in sludge-based biochar was 68.18%, and the lowest (61.27%) *CR* was from manure-based biochar. In terms of atomic ratios (Fig. 4c), the O/C of most biochar from wet wastes was 0.21, and the lowest one (0.15) was observed in food waste biochar. The H/C ratio of hydrochar from various feedstock was quite similar and centered around the average value of 1.29. It was suggested that the carbon in most biochar from HTC might not be stable when used in soil due to their higher atomic ratios (Brassard et al., 2018; Enders et al., 2012).

For biochar from pyrolysis of wet wastes, the maximum *CRS* with corresponding feedstock and operating conditions and biochar properties in

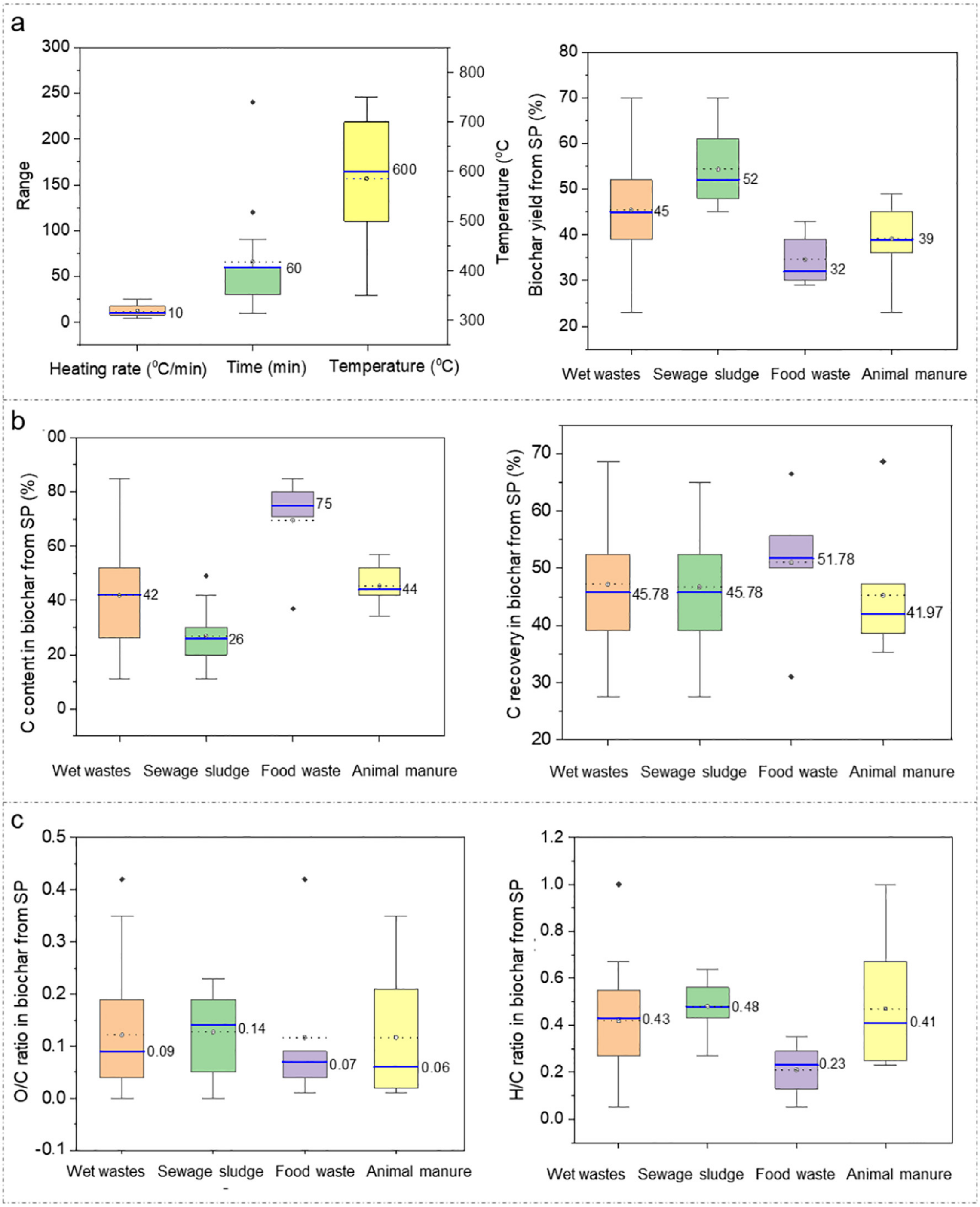

Fig. 5. Statistics of (a) process conditions with biochar yield, (b) carbon capture performance, and (c) atomic ratios of biochar from slow pyrolysis (SP) of wet wastes.

each literature are summarized in Table 7, and statistically analyzed in Fig. 5. The optimal pyrolysis conditions for the maximum *CRS* value of biochar from wet wastes were identified at 600 °C with the heating rate and time of 10 °C·min^{-1} and 60 min, respectively. The biochar yield in the case of maximum *CRS* was found to be 45%. On comparing the different types of wet waste, the biochar yield derived from sludge was the highest (52%), followed by animal manure (39%), and food waste was the lowest (32%). However, the carbon content in biochar from food waste was 75%, which was the highest among the three wet wastes with a *CR* of 51.78%. This result indicated that most of the carbon in food waste can be effectively captured in biochar. Compared to hydrochar, the yield and *CR* of biochar were significantly lower due to high-temperature conversion Moreover, the carbon content in biochar from sewage sludge and animal manure was lower compared to its hydrochar counterparts. Only the carbon content in biochar from food waste was higher, possibly due to the lower ash and high carbon content in food waste. For the atomic ratios, the median of O/C of biochar from all wet wastes was 0.09, and the respective O/C in biochar from sludge, food waste, and manure were 0.14, 0.07, and 0.06, respectively. Moreover, the median value of H/C ratio was as low as 0.43 in all biochar, with the lowest one (0.23) derived from food waste. Compared to hydrochar, both the O/C and H/C of biochar were significantly lower due to the high extent of decomposition and aromatization during the pyrolysis process.

3.4. Carbon sequestration of biochar

The above findings imply that the carbon in biochar from dewatered waste exhibited high stability, and could stay for a long time in soil to realize carbon sequestration (Brassard et al., 2018; Enders et al., 2012). Besides, the pyrolysis of food waste is a promising strategy to achieve carbon capture and sequestration in soil due to its high *CR* and carbon content in biochar (Igalavithana et al., 2017). Although the carbon content in biochar from sewage sludge and animal manure was not high, the carbon was stable enough. To increase the carbon content in the biochar, co-pyrolysis with other biomasses can be an alternative. Li et al. reported that the C content in sludge biochar increased from 15.55 to 22.7% after adding 20% bamboo pyrolysis at 700 °C (Li et al., 2020d). In general, biochar (especially the biochar produced from food waste) offers a desirable performance for carbon recovery and sequestration in soil, while co-pyrolysis can further improve the carbon content of biochar.

A carbon sink will be generated when biochar is used in soils, wherein the biomass is pyrolyzed to biochar, and subsequently applied to the soil for promoting biomass growth. The CO_2 in the air is taken up by plants and converted into carbohydrates, which form the chemical constituents of biomass and can finally be transferred into biochar as stable carbon. It will be carbon negative cycle if the preparation and utilization of biochar retain more carbon than they emit (DAS et al., 2014). The carbon sequestrated in biochar can improve physicochemical properties and fertility of the soil. Biochar can be stored in the soil for a long time with its unique properties and plays a vital role in stabilizing organic carbon pools, increasing carbon storage capacity due to its stable carbon and unique characteristics. It is well reported that about 50% of the feedstock carbon remains in the biochar, and biochar supplementation to soil enhances its carbon sequestration (Sohi et al., 2010). Méndez et al. stated that sludge biochar when applied to the soil, reduced the CO_2 emissions by 11%–32% compared to raw sludge when used for soil amendment (Méndez et al., 2013). Gascó et al. reported that biochar from pig manure mitigated the carbon mineralization in soil (Gascó et al., 2016). The unique aromatic structure and carbon-silicon complexes formed during pyrolysis make it structurally stable and prevent easy decomposition in the environment (Xiao et al., 2014). The reaction of soil minerals and the functional groups on the surface of biochar maintain the stability of biochar during its aging process as well (Chen et al., 2015; Li et al., 2014). Also, adsorption of soil organic matter on biochar and the interaction with soil microbes led to soil aggregate formation, which was stable macroaggregates (>250 mm) and helpful in soil carbon sequestration (Awad et al., 2013). In addition, biochar prepared from pig manure positively maintained microaggregate stability, enhanced the soil carbon sequestration, and even prevented the release of N_2O and CH_4 (Xu et al., 2012b; Zhu et al., 2017).

4. Critical analysis and future perspectives

The waste conversion processes, namely AD, gasification, HTC, HTL, FP, SP, and incineration along with their technical performance, product application, and carbon emission potential, were reviewed in the preceding sections of this review. In this section, we further analyze the advantages, disadvantages, and challenges of each of these technologies with proposed solutions and critically evaluate these conversion technologies in terms of the future perspectives.

The advantages, limitations, and proposed solutions for the AD, combustion, gasification, HTC, HTL, FP and SP processes, are summarized in Table 8. It is evident that various alternate strategies, including new reactor design and configurations, novel catalysts, and integrated technologies for process intensification, have been proposed to make up for the limitations faced by waste to energy and resource technologies. These strategies have aided in improved product quality, optimum utilization of wastes, and enhanced reaction process. Despite all this, it remains uncertain whether these approaches contribute to energy savings and environmental sustainability; as there are insufficient studies to uncover a holistic perspective of these new developments. Such life cycle inventories and impacts can vary significantly based on process configurations and material and energy inputs under optimal operating conditions. For example, the production of novel or reusable catalysts, including their regeneration and treatment, is energy- and resource-intensive, thus adding to the cost as well as the potential for secondary environmental pollution.

On the other hand, the wet wastes need to be dewatered before incineration, dry gasification, and pyrolysis. Hydrothermal treatment is one of the practical approaches to enhance the dewaterability of wet wastes. Hydrothermal treatment at a higher temperature is referred to as HTC, the products of which can be further converted into energy and resources of high-quality by integrating with other waste conversions (He, 2021). For instance, the hydrochar derived from HTC can be combusted for heat generation, or pyrolysis and gasification can be employed to convert hydrochar into syngas bio-oil, and biochar. The digestate from AD can be further converted into energy and resource by coupling HTC (He et al., 2022). Incineration systems with flue gas cleaning system can be further post-integrated with gasification or pyrolysis to burn the product for electricity and heat generation. While the liquid from the HTC can potentially be used for bioenergy generation via AD and gasification, due to the high concentration of COD, NH_4-N, and other organic matters (Danso-Boateng et al., 2015; Zhang et al., 2018b). Pilot-scale verifications of integration of hydrothermal treatment with AD and pyrolysis for the sludge and food waste digestate conversion have been reported, and biogas derived from AD, syngas, and oil from pyrolysis can be used to offset the energy consumption of these processes (Li et al., 2017b, 2018a, 2020a). However, a simple combination of different technologies without consideration of process optimization, product property, and energy/material consumption of entire integrated systems may not be the best approach for waste to energy and resource. Hao et al. claimed that the integration of thermal hydrolysis with AD or AD with incineration resulted in a higher overall energy deficit and a higher installation cost than the single processes (Hao et al., 2020).

Recently, some modeling approaches, including data-driven and mechanistic modeling, were published for aiding the process interpretation, design, and assessment to promote the development of waste valorization. For example, a sustainability assessment, including the environmental and economic performances, of biomethanol production from hydrothermal gasification was conducted by applying artificial neural network modeling and ASPEN simulation (Fózer et al., 2021). Our previous work also proved that machine leaning algorithm is a powerful tool to model the waste conversion processes, including hydrothermal carbonization (Li et al., 2021f), pyrolysis (Li et al., 2020b), hydrothermal liquefication (Li et al., 2021d; Zhang et al., 2021b), and gasification systems (Li et al., 2021b, 2021c), for process interpretation and operating condition optimization. Specifically, these kinds of modeling approaches could aid the product characterization for the estimation of the potential applications and the performance of the conversion technologies. Moreover, such machine leaning models could be applied to optimize the operational conditions of conversions and design the conversion systems to produce desired products. This can save extensive time by reducing the rounds of experiments for trial and error and accelerate the development of waste valorization. These models can also be integrated with life cycle assessment to evaluate the economy, energy profile, carbon emission, and environmental impacts. Therefore, simulated system design and optimization may offer a feasible way to conquer the limitations of traditional system design and evaluation.

To sum up, the waste conversion systems could be further improved by the following three aspects: a) further work on the holistic life cycle assessment with the consideration of conversion reactor design and configurations, catalyst utilization and regeneration, conversion process design and operation, and product application to evaluate the waste valorization system is demanded; b) new conversion systems with less energy consumption and emissions could be designed by the combination of different conversion technologies to recover more energy and resource from waste; c) emerging modeling approaches, especially data-driven machine learning modeling, could be applied in the waste conversion process to aid the

Table 8
Advantages, challenges and proposal solutions of various waste to energy and resource technologies.

Technology	Advantages	Disadvantages and challenges	Proposed solutions
Incineration	(1) Large reductions of waste volumes (Fytili and Zabaniotou, 2008; Samolada and Zabaniotou, 2014). (2) Elimination of all the organic containments and odor (Fytili and Zabaniotou, 2008; Samolada and Zabaniotou, 2014). (3) High energy recovery from waste (Samolada and Zabaniotou, 2014). (4) Low energy deficit, capital, and I & O costs (Vamvuka et al., 2009).	(1) Large energy consumption of dewatering and drying (Pham et al., 2015). (2) Poor flammability of wastes (Xie et al., 2018). (3) Emission of greenhouse gases and air adverse consequences (Muangrat, 2013). (4) Further treatment of ash required. (5) Slag, fouling, corrosion of equipment caused by mineral matter in waste (Hagman et al., 2013; Vamvuka et al., 2009).	(1) Developing high-efficiency dewatering approaches (Liu et al., 2016c). (2) Co-firing with other high calorific value biomass (Liu et al., 2017; Sun et al., 2019; Vamvuka and Sfakiotakis, 2019). (3) Developing advanced technologies for exhaust gas cleaning and CO_2 capture (Chen et al., 2019; Hagman et al., 2013; Svoboda et al., 2006). (4) Developing new approaches for ash utilization (Ma et al., 2019; Vamvuka and Sfakiotakis, 2019). (5) Removing mineral matter before use or developing special equipment for waste (Ma et al., 2019; Vamvuka et al., 2009).
Anaerobic digestion	(1) Clean energy generation (Sommer et al., 2013). (2) Reduction of waste volume. (3) Simple reactor configuration. (4) Low energy consumption and low cost.	(1) Long duration of the microbial reaction and operational instability. (2) Low bioenergy productivity and efficiency of organic matter utilization (Hao et al., 2020; Moon et al., 2015). (3) Remaining contaminants issues (Wang et al., 2018a; Zhao et al., 2019). (4) Low biogas purity and energy density. (5) Digestion residue generation.	(1) Pretreatment of feedstocks and co-digestion with other feedstocks (Solé-Bundó et al., 2019). (2) Adjusting the AD environment by removing generated inhibitors (Tao et al., 2017). (3) Acclimation of methanogens and addition of functional materials in AD (Fagbohungbe et al., 2017). (4) Developing low-cost and high-efficiency gas separation materials and processes. (5) Combination of other technologies for digestion residue utilization
Gasification	(1) Energy and resource production. (2) No limitation for organic wastes. (3) Production of desired gas with adjustment of operating conditions. (4) Organic containments elimination and inorganic containments trapping.	(1) Relatively high energy consumption and running cost. (2) High requirements of catalysts. (3) Safety concerns and plugging and corrosion problems of the system due to high temperatures and pressures (Xu et al., 2012a). (4) Low syngas productivity and impurity of syngas (Nanda et al., 2019). (5) Post-treatment of by-product.	(1) Developing new gasification reactors with lower energy consumption (Liu et al., 2019a; Xu et al., 2012a). (2) Developing recyclable/regenerable catalyst with low cost and low reaction temperature. (3) Developing material for manufacture reactor that can resist high pressure, temperature, and corrosion (Tańczuk et al., 2019; Xu et al., 2012a). (4) Optimizing operational parameters and developing low-cost and high-efficiency gas separation materials and processes. (5) Combination of other technologies for by-products utilization (Ng et al., 2017).
Hydrothermal liquefaction	(1) Energy and valuable chemicals production. (2) Organic containments elimination. (3) Low energy consumption for wet waste conversion.	(1) Low yield of bio-oil. (2) Low quality of bio-oil with high O, N, and S content (Ly et al., 2021) (Prestigiacomo et al., 2019). (3) Mixed composition in nature.	(1) Co-conversion of wet waste with other biomasses (Alvarez et al., 2015). (2) Development of catalyst to improve the quality. (3) Post upgrading of bio-oil (Prestigiacomo et al., 2019). (4) Conduction systematic optimization of conversion conditions and feedstock composition (Li et al., 2021d; Zhang et al., 2021a).
Fast pyrolysis	(1) Valuable energy and resource production. (2) Organic containments elimination.	(1) Requirement of prior dewatering of wet waste. (2) High requirement of pyrolysis vapors condensation and gas cleaning system. (3) Relatively complex reactor. (4) Low yield and quality of bio-oil (Ly et al., 2021) (Prestigiacomo et al., 2019).	(1) Coupling with high dewatering method or mixing with other dry biomass to decrease the water content (Jin et al., 2017). (2) Development of catalyst to improve the quality. (3) Post upgrading of bio-oil (Prestigiacomo et al., 2019). (4) Conduction systematic optimization of conversion conditions and feedstock composition.
Hydrothermal carbonization	(1) Low energy and resource consumption. (2) Improvement of dewaterability. (3) Production of high value-added products (4) Organic containments elimination	(1) High requirement of the HTC equipment. (2) The wastewater generation. (3) Further investigation of hydrochar utilization.	(1) Developing outstanding material for manufacture reactor that can resist high pressure, temperature. (2) Combination of other technologies for by-products treatment (Li et al., 2018a). (3) Combination of different technologies for hydrochar utilization (Duman et al., 2018; Gai et al., 2016).
Slow pyrolysis	(1) Production of various high value-added products. (2) Easy operation and control. (3) rganic containments elimination and inorganic containments trapping.	(1) Relatively high energy consumption. (2) High requirement of pyrolysis vapors separation and gas cleaning system. (3) Much loss of nutrient elements.	(1) Developing high-efficiency dewatering approaches and co-pyrolysis with other biomasses (Jin et al., 2017). (2) Developing excellent posttreatment systems for pyrolysis vapors. (3) Additive addition for nutrient elements trapping.

product characterization, operational condition optimization, and the system design for avoiding repeated experiments and thereby promoting the concepts of artificial intelligence (AI) in sustainability.

5. Conclusions

Faced with the rising global wet waste generation, global climate change, and the need for clean energy, conversion of wet wastes to valuable energy and resource is a promising strategy for environmental protection and energy/resource-saving. In this review, the conversion technologies for waste to bioenergy and biochar were comprehensively reviewed considering their technical challenges and future perspectives. From a technical perspective, co-treatment of wet waste with high organic-content biomass or pretreatment of feedstock would improve the process performance and the quality of products. The application of bioenergy for heat/electricity generation and biochar for soil amendment serve as potential routes for carbon mitigation. A systematic and critical analysis of all the wet wastes conversion systems, along with their pros and cons, and potential solutions were also presented. Given the potential of these conversion processes, substantial efforts on reactor configuration and catalyst design need to be made, to improve the quality of their products, and minimize the installation and operations cost. Besides, more research on the integration of various conversion technologies should be conducted to recover as much resource/energy as possible in an economic and environmental strategy. Moreover, a holistic evaluation approach should be considered and developed to assess the feasibility of the overall single or combined conversion systems by considering all relevant factors such as reactor design, catalyst suitability and re-usability, operating conditions, product properties, and post-process purification with a specific focus on sustainable process intensification. Simulation and optimization of a waste valorization system with the adid of computational tools may provide a more holistic perspective on waste management.

CRediT authorship contribution statement

Jie Li: Conceptualization, Data curation, Methodology, Formal analysis, Visualization, Writing – original draft. **Lanyu Li:** Data curation, Methodology, Formal analysis, Writing – original draft, Visualization. **Manu Suvarna:** Formal analysis, Writing – review & editing. **Lanjia Pan:** Writing – original draft, Writing – review & editing. **Meisam Tabatabaei:** Writing – review & editing. **Yong Sik Ok:** Conceptualization, Resources, Writing – review & editing. **Xiaonan Wang:** Supervision, Project administration, Conceptualization, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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