Hydrothermal carbonization (HTC) for recovery of organic fractions in municipal solid waste (OFMSW)

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Abstract

Organic waste, such as food waste, yard waste, natural biomass as well as agro-industrial waste, accounts for almost half of municipal solid waste in developing countries. The unique property containing high content of moisture makes it difficult to treat organic fractions in municipal solid waste (OFMSW) with traditional methods. Used to be applied in preparation of carbon-enriched material, hydrothermal carbonization (HTC) method has been expanded into organic waste treatment recently. During HTC process, energy is maintained within solid product known as 'hydrochar' to maximize the added value of recovery products. This review compares properties of hydrochar generated from different types of OFMSW to highlight biorefinery potential of HTC conversion. The results show that energy density of hydrochar benefit mainly from increasing initial carbon content of feedstock. Reaction conditions also have significant effects on hydrochar properties including solid yield, ash/carbon content as well as energy densification where temperature is the most notable one. Extensive information of recent industrial use of HTC treatment is also summarized. An integrated HTC treatment can be developed with improvement of heat transfer system and utilization of process water to benefit the further application of HTC method on organic waste utilization.

Keywords

Hydrothermal carbonization, Organic fractions in municipal solid waste, Hydrochar, Biorefinery

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1. Introduction

With population growth and economic prosperity, the amount of municipal solid waste (MSW) is increasing rapidly. The organic fractions in MSW (OFMSW), such as food waste, yard waste, natural biomass as well as process residues from agro-industrial production [1, 2], is the main component accounting for 47%-62% of MSW in developing countries (Figure 1). These kinds of waste usually mainly consist of organic matter along with high content of moisture since generation. The unique characteristic of OFMSW has been identified as a disadvantage since it lowers average heating value (HV) of MSW and might cause unexpected interactions during waste collection, transportation, and disposal in conventional treatments[3, 4], which makes centralized incineration and landfill the least desirable option[5].

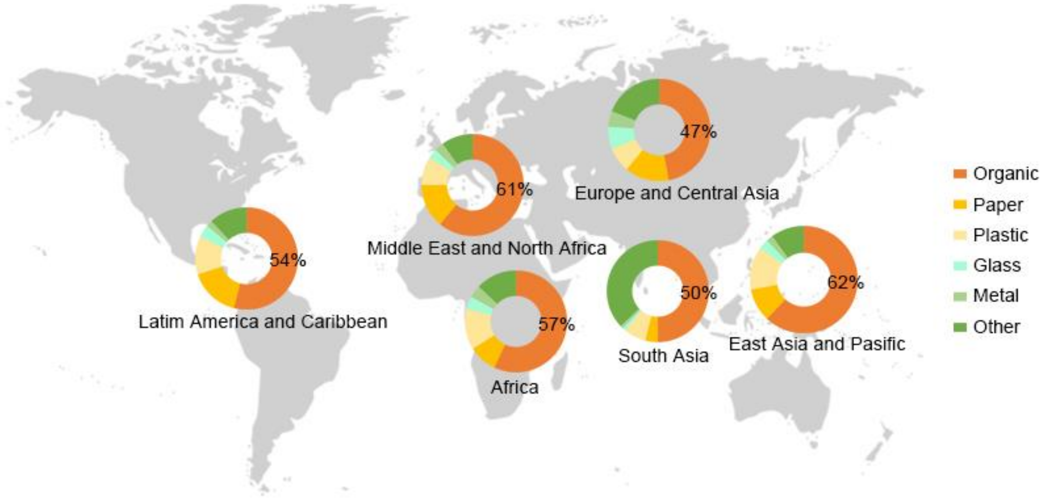

Figure 1. Composition of MSW in developing countries by region[2]

To meet the urgent demand of environmental protection and resource utilization, environmental friendly and efficient treatments are in great need to combine recovery of bio-based chemicals and energy along with reduction of waste amount. A new biorefinery concept of waste treatment can be developed based on the use of organic waste as feedstock for new sustainable chemicals and fuels using a variety of technologies[6, 7]. However, bioconversion methods are generally time consuming and have strict requirements for precursors. Furthermore, the high content of moisture, lipid, salts and pathogens in the garbage are unfavorable for biochemical treatment or as feedstuff directly[8].

Modern industry in Europe has turned to a series of thermochemical approaches that treating organic waste as a precious bioresource including gasification, pyrolysis and hydrothermal carbonization (HTC) method[9]. Hydrothermal carbonization (HTC), one of hydrothermal (HT) treatment, is a novel thermal conversion processes under the condition of relatively low temperature (180-350℃) and autogenous pressure. This novel thermal conversion process with relatively low temperature is gaining significant attention as a sustainable and environmentally beneficial approach for conversion of waste streams to value-added products[10]. This review aims to give extensive information in the view of product, reaction condition, and industrial use to highlight biorefinery potential of HTC conversion of OFMSW thus benefits the further use of HTC method on organic waste treatments.

2. HTC comparing with other HT treatment and different char-deriving methods

2.1 Comparison between different HT treatment

HT treatment has been applied in solubilization and extraction to recover valuable organic compounds such as glucose and organic acids from organic waste treatment for a long period[11] and only few researchers have focused on recovering solid fuel from municipal solid waste[12]. Previous HT treatment has succeeded in fixation of carbon and recovery of different chemicals with subcritical water[12]. The physical and chemical properties of water, which is the key ingredient of HT process, can demonstrate significant changes when observed with gradually rising temperature[13]. The moisture content in this operation system can be used as a heating medium, stream, to decompose structure-firmed solid waste[12]. In which case, those properties share similar characters with that of organic solvents and beneficial for dissolution of macromolecular organics.

Specifically, HT treatment can be divided into four main types as hydrothermal liquefaction (HTL), hydrothermal carbonization (HTC), hydrothermal gasification (HTG) and aqueous phase reforming (APR)[14] based on different products and relevant conditions, which are listed in Table 1. Products of solid, liquid and gas phase are generated under each method while dominant patterns differ distinctly. Though H2 is regarded as an ideal target chemical with wide applications[15], HTG and APR turn to be less promising for large-scale treatment because of the strict reaction condition and the expensive catalyst. On the contrary, both HTL and HTC occur under relatively mild condition where adding catalyst is not necessarily, making them more practical for industrial treatment. The high conversion rate from feedstocks to hydrochars and the mildest reaction conditions comparing to the other HT treatment has gained renewed interest for HTC treatment[14].

Table 1. Comparison of four types of different hydrothermal method

Method	Temperature, pressure & reaction time	Catalyst	Target patterns & types of products	Research status	Reference
HTL	280-370℃, 10-25 MPa, t=5-30 min	Not necessary: (Common acid & alkali or special ion)	Liquid: Bio-oil (mostly organic acids and sugars)	Long research history and very promising in commercialization	[14] [16] [17] [18]
HTC	180-350℃, <2 MPa, t=1-12 hr	Not necessary: (Common acid & or special ion)	Solid： Energetically favorable hydrochar	Very promising in both research activities & commercialization	[14] [13]
HTG	300-700℃, 13.5-25 Mpa, t=60s-120min	Necessary: (Alkali with H_2O_2 & Trona catalyst with red mud etc.)	Gas: H_2-rich syngas	Under further development & optimization on pilot plant	[14]

APR	220-250℃, 1.5-5MPa, t=4-6 hr	Necessary: (Ni, Pt and their supported on Al_2O_3, Si_2O_3 etc.)	Gas: H_2, CH_4	Under challenge of catalyst design	[14] [19]

2.2 Comparison of gasification, pyrolysis and hydrothermal carbonization

Table 2 compared process conditions and products between gasification, pyrolysis and hydrothermal carbonization. During these methods, energy is maintained within solid product known as ‘biochar’ or ‘hydrochar’[20] to obtain higher HV and maximize the added value of recovery products after treatment[6]. Unlike gasification and pyrolysis, feedstocks went through HTC under incomplete oxidation and relatively lower temperature supposed to reduce CO2 emissions[20, 21] and energy consumption, which is also perceived more sustainable and environmental friendly. The products properties of hydrochar shows less stable structure (dominated by alkyl moieties) than biochars (dominated by aromatics) but higher nutrient retention capacity as a result. Further use of the carbon enriched end products as energy carriers[22], natural soil-organic matter [23, 24], anionic surfactants[25] and other bio-based chemicals[26] has been widely discussed on a biorefinery perspective.

HTC has been recognized as wet process[3] that operates with moisture as heating medium[13] on the country to pyrolysis and gasification. Less requirement of feedstock drying process suggested HTC favorable for treating wet MSW like FW [10, 27]. Comparing to combustion, gasification and pyrolysis process, HTC can generally save operation energy because phase change from water to steam is largely avoided. Thus the energy required to heat water (in a closed system to saturation conditions) is smaller in comparison to the traditional thermochemical conversion processes that requires water evaporation[13].

Table 2. Comparison of gasification, pyrolysis and hydrothermal carbonization(HTC)

Method	Gasification	Pyrolysis	Hydrothermal Carbonization (HTC)
Typical Temperature	850-900℃	400-700℃	180-350℃
Typical Residence Time	Short	Long	Long
Reaction Medium	Dry	Dry	Wet
Product	Biochar		Hydrochar
Char Yield	10-35%		>50%
pH	>7		<7
H/C (atomic ratio)	<0.6		1.0-1.6
O/C (atomic ratio)	<0.4		0.3-0.6
Dominate Organic Composition	Aromatics		Alkyl moieties

*Summarized from references [9, 13, 28]

3. HTC for recovery of OFMSW

3.1 Properties of initial feedstock

Most OFMSW consisting of organic matters, such as agricultural residuals, food waste and yard waste, contain large amounts of water and high content of carbon. The bromatological analysis of OFMSW shows various recyclable compounds, where carbohydrates as the most abundant components[14] account for more than 40% in terms of dry basis (Figure 2). HTC process on pure carbohydrates compounds like cellulose[29], starch[17] and glucose[30], has been proved to generally follow hydrolysis and carbonization stages[27], during which optimal reaction conditions and reaction kinetics[31] has been studied to receive ideal char properties. Extensive researches are completed using mixed organic waste samples on both batch and scale-up equipment[12] experiment under different conditions to produce hydrochar[5]. The composition of the OFMSW produced hydrochar suggests both dehydration and decarboxylation occur during carbonization[13], though an agreement on formation mechanisms has not been reached since observed variation in samples could be unrepresentative in different tests.

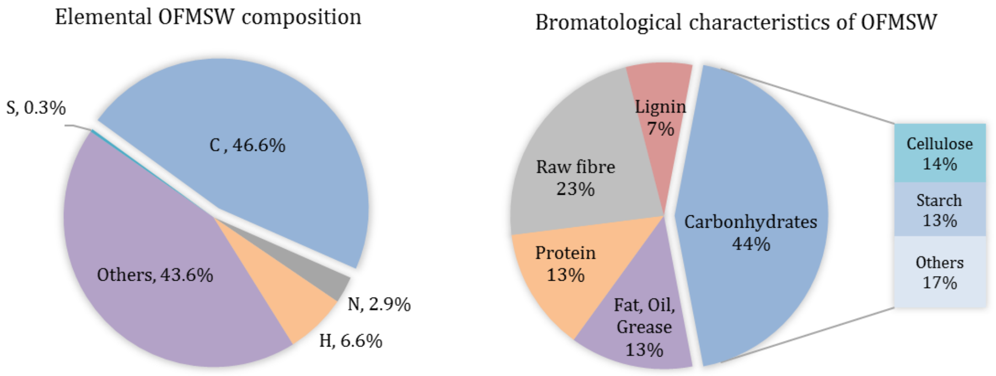

Figure 2. Elemental composition and bromatological analysis of OFMSW[2]

The initial feedstock of HTC usually is a mixture of solid particles and deionized water at particular solid/liquid ratio (w/v%). Previous study suggests that adding initial liquid volume may influence the carbon distribution of products by increasing the potential of compound solubilizing[32]. Lu et. al considered using alternative liquid waste streams to replace deionized water, such as landfill leaches and activated sludge which are plentiful and require extensive treatment prior to their discharge to the environment[33]. The results are not obvious comparing to the initial carbon content of the feedstock, which is considered more influential than any other characteristics of the initial liquid source[34]. The recovered solids energy contents can be predicted by chemical composition of feedstocks while functional groups in generated hydrochars have more complex relationship with known structural complexity[35].

Table 2 listed several typical kinds of organic waste as feedstock with its observed difference in generated hydrochar properties. These experiments result in the agreement that carbon content and energy density of hydrochar benefit mainly from increasing C% of initial feedstock[32]. Ash content tended to be a significant factor when the feedstocks possess in quantity like paper mill sludge residue, which indicates a higher concentration of carbon as fixed carbon are thought to improve the HHV of solid char[12]. Among all types of organic waste listed above, food waste (FW) with relatively high initial carbon retention and mostly underutilized fraction may be the most ideal material for energy-related use whereas carbonization of stabilized solids may have little impacts on carbon fate[13]. The highest potential HHV of FW can reach 25 MJ/kg^{-1} accordingly[12, 32, 34].

For most countries that collecting OFMSW together with other waste, it is also critical to realize that plastic was proved to be non-degradable under HTC condition by In-Hee Hwang[12] considering its abundant use as packing materials. Other materials including paper and cardboard, were also shown to skew the energy content of recovered solids while under HTC condition mixed with food waste[32]. Xiaowei Lu[20] et. considered glass and aluminum as unfavorable factors in MSW treatment. The increasing complexity of composition in MSW may lead to lower energy content of generated char thus efficient waste sorting is demanded for industrial HTC treatment on biorefinery purpose.

Table 3. Comparison of hydrochar generated from different organic feedstock

Feedstock		Initial composition				Hydrochar properties			Reference
		C (%)	H (%)	N (%)	Ash content (%)	Carbon content (%)	HHV_{char} (MJ/kg^{-1})	HHV_{FC} (MJ/kg^{-1})	
Paper mill sludge residue		20.9	1.7	0.2	46.8	19-30	9.6-11	20-31	[36]
Faecal sludge		38.1	-	-	-	39	18-21	-	[27]
Off-specification compost (Byproduct of organic MSW treatment)		37.7	4.8	2.8	18.56	44.1-53.8	>19	-	[37]
Paper		36.3-38	5.1-6	0.05	5	49-63	16-23.7	32.1-32.3	[12, 34]
Wood		47	6	-	0	61-69	23.5-26.8	33.4-34.1	[12]
Plastic		86	13	6	0	84-85	-	-	[12]
[1]Yard waste	Grass clipping	66.95	6.55	1.22	-	68-72	30	-	[34]
	Shredded shrub	45.97	6.08	1.56	-				
Grape marc		49.7	6.2	2.4	6	56.2-68.1	19.8-24.1	-	[3]
Dog food		45	6	4	8	56-58	25.9-26.1	29.3-31.7	[12]
Food waste (Restaurant)		52.3-52.4	8.3-8.6	2.7-2.8	-	52.4-70	22-25	-	[32, 34]
Food waste (Campus)		-	-	-	-	43.7-65.4	17.4-26.9	-	[38]
[2]Packaging waste	Paper	40.6	6.4	0.08	-	47.7	17.9	-	[32]
	Cardboard	40.0	6.0	0.13	-				
	Plastic	62	4.8	0.10	-				
Food+Packaging waste		P : F = 7/30 – 20/27				49.7-51.5	19.6-21.2		[32]

NA = Not available；HHV = High heating value；FC = Fixed carbon in initial feedstock.

[1] Yard waste has the following composition (%, dry wt.) 50% grass clippings and 50% shredded shrubs.

[2] Packaging waste has the following composition (%, wet wt.): 27% plastic, 24% paper, and 49% cardboard.

3.2 Effects of HTC conditions on hydrochar production

The rate and extent of HTC process likely depend on process conditions[20](Figure 3). Previous researches[13, 32, 39-41] were conducted at different conditions, spanning a range of reaction temperatures (180–350 °C) and times (0.5–120 h), with additional chemicals to change process water quality (i.e pH, inorganic ion and other catalyst). Results also indicate that the carbonization product composition and yields are largely influenced by system reaction conditions, both physically and chemically. Therefore process analysis is restricted to influence of experiment condition on modeled hydrochar properties and uncertainty associated with the fate of elements (e.g., metals, nutrients) are still of significant amount during carbonization[10].

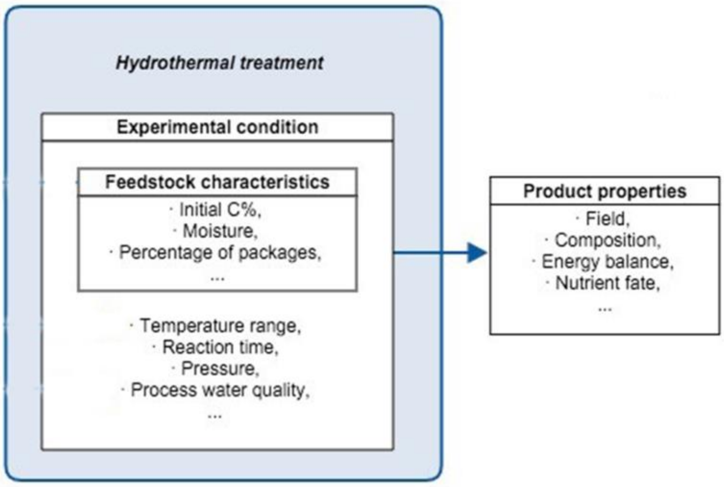

Figure 3. Effects of process condition on hydrothermal products properties

3.2.1 Temperature

It is commonly assumed that temperature is the most notable variable, which gives significant effects on the result of HTC reaction. Accordingly, a typical range of 15–60% dry-weight biomass is suggested to decrease in the solid residue with an increasing production temperature [42]. Higher temperature has promoted some reactions [43] and accelerates not only dissolution of feedstock but also decomposition of products. The organic N compounds of OFMSW were reported to hydrolysis and dissolution in water especially at high HTC reaction temperature [44], representing decomposing of the majority of nitrogenous organic fractions rely on temperature rise. Thereby, the increased temperature may not lead to high yield while some specific structures in hydrochar like aromatic rings are suggested to be formed or recombined [45].

The properties of hydrochar generated from OFMSW tended to restrain more thermal stable compounds within solid residues owing to the decrease in the amount of volatile compounds and thermo-sensitive molecules when the temperature rises up[3]. Lin[46] et al. investigated paper sludge generated hydrochar fuel characteristics and thermal behavior under different HTC temperature (180-300℃). When the temperature increased up to 300℃, more volatile matter of hydrochar is converted into fixed carbon and a small portion of other substances as liquid or gaseous, based on the comparative results and mass balance. As it was also found by Lu and Berge using office paper, pine wood, and sweet corn as feedstocks, larger fractions of carbon are measured within the liquid and more gases are produced at higher temperatures. Lower H/C and O/C atomic ratios of waste derived hydrochars are also observed with temperature increasing[3, 46] indicating enhanced decarboxylation and dehydration reactions. improved coal ranks of hydrochar since less smoke and reduced loss in water and energy are expected during combustion[47].

However, the optimal temperature for HTC is always balanced from energy densification ($HHV_{char}/HHV_{feedstock}$) multiply hydrochar yield as energy recovery efficiency[48, 49]. Hence relatively mild reaction condition is preferred considering more energy supply under higher temperature. For organic waste containing large amount of biomass fractions, higher temperature condition is required though energy contents of the produced hydrochar could be further increased with the addition of biomass[50-53]. Since cellulose and hemicellulose are reported to be completely decomposed when HTC temperature exceeded 250℃ while lignin still showed certain thermal stability[39].

3.2.2 Residence time

Residence time have showed less significant impacts on HTC products generated from loblolly pine[54], paper mill sludge[36], argo-industrial waste[3] and compost[37] in accordance with temperature-related change. Though reported residence time varies from hours to days, carbonized loblolly pine solid-product mass yield seemed to decrease rapidly during the first few minutes[31] indicating most reactions take place in the first hour[37]. Unlike pyrolysis, there is no obvious evidence that solids yields increase with increases in residence time[55]. But assumption exists that a longer reaction time may correlate to greater energy, which can be recovered from the gas-phase thus maximize the production of energy-favorable hydrochar[20, 32].

3.2.3 Existing ions in process water (PW)

Effect of existing ions including acid, basic and salt ion in PW on carbonization product yields and composition has not been understood very well. During HTC, cellulose dissolution appears to be accelerated in the presence of initially acidic process water and it is correlated with acid concentration[33]. However, NaOH concentration increase leads to decreasing dissolution of cellulose. Results also indicate that another potential way to promote dissolution is to disrupt hydrogen bonding of cellulose by addition of Cl^-. Lu and Flora[33] tested impacts of $CaCl_2$ that high concentrations negatively influence recovered products because solid surfaces become passivated.

Another HTC result using food waste as feedstocks[8] shows that adding ferric salts results in higher char yield and lower ash content than ferrous salt due to the acidic system developed by the strong hydrolysis of ferric ions. In the meantime, the anions turn to increase the char yield with the order of nitrates>sulphates>chlorides in ferric salts. Zhang[8] et.al also presented that the presence of ferric ions also shows impacts on morphologies of generated spheres ranging from nano to micro while ferrous ions promoted the formation of hollow nano-spheres from soluble organics. However, Berge[13] prepared mixed MSW waste with aluminum added and was not observed to influence solid yield. Thus impacts of trace metal ion in HTC process are insignificant.

3.3 Feasible use of recovered hydrochar from HTC

3.3.1 Carbon enriched char for co-combustion as energy supplement

According to Lu et.al[56], the combustion behaviors of hydrochar are controlled both by the substances in majority of OFMSW feedstock. Both food waste[32] and lignin waste[47] has succeeded in generating hydrochar with high energy density under high-temperature HTC (over 250℃) that is comparable to lignite. Not only considerable enrichment of carbon content, the HTC from lignin waste also shows improved hydrophobicity and reduction in alkali and alkaline earth metal content comparing to raw agro-waste[57] as well as torrefied pellets[40, 47]. Lu[20] et.al calculated the energy derived from food waste and the result shows it is higher than those from landfill biogas, anaerobic digestion and even direct incineration. Since most hydrochars presented good dewatering and drying properties[51], the liquid phase can be separated considerably efficiently after HTC. Thus the net calorific value of hydrochar is often higher than that first has to be dewatered or dried[58].

Liu[59] et.al investigated co-combustion of lignite and hydrochar generated from coconut fibers and eucalyptus leaves at varying amounts. It proved that both two kinds of hydrochar addition improved energy conversion by increasing the burnout, tensile strengths[60] and shortened the combustion range of the blends. The HTC process showed high removal rates of chlorine, sodium and potassium according to Lin[46] et.al which can be favorable for pollutant emission control of co-combustion process. However, it is inconsistent with the result detected by Hwang et.al[12] that most Cl compounds which mainly originates from salt of food waste remained in char. Therefore, char washing procedure may be required to avoid ash-related problems when hydrochar acts as fuel.

3.3.2 Highly functional carbon material as soil amendment for carbon storage

Small clusters of microspheres are found in pure carbohydrates-generated hydrochars in previous research with core and shell structures [29]. The morphologies of the hybrid carbon materials derived from KW presented similar structure with those made by pure saccharides[8]. Interesting products such as peat or humus can be gained for soil improvement[58]. The supposed ring aromatics structure with reduction of O-alkyl groups in hydrochar which is highly bioresistant may contribute to the long-term stability of carbon in the char [13]

Approximately less than 10% of the carbon is released as gas (mainly carbon dioxide) after HTC Of OFMSW according to [58] and [13]. Therefore, if the hydrochar is used as a soil amendment for carbon storage, the total gas produced during HTC results in fewer g CO_2-equivalent emissions comparing to other treatment methods because of limited expose to oxygen[20]

4. Industrial application of HTC treatment

4.1 In-used industrial HTC plants

A rapid commercialization of HTC is undergoing in recent years since the first demonstrative industrial scale HTC plant (HTC-0) was introduced into operation in 2010 by AVA-CO2 Company[14] in Germany. With promising research progress, HTC has been listed as a feasible approach in several conducted European projects aiming at the converting of waste substrates into biofuel production for renewable energy supply, i.e. BIOBOOST project (2015) and NEWAPP project (2015). Combustion of HTC-generated hydrochar as alternative fuel is the main application of in-used industrial HTC plants[14], which has been listed in Table 3.

4.2 Pending problems during industrial application of HTC

4.2.1 Uncertainty of aqueous phase utilization

As known, the aqueous phase from HTC is one of the main drawbacks of hydrothermal process if it is not appropriately treated [40]. The liquid intermediates represent 20-37% of initial catrbon remains in the liquid[13]. For example, the resulting process water from agro-waste by Oliveira[51] et.al has a high TOC(13-26g/l) that can be further utilized by biogas generation plants. Riedel[61] et.al performed wet oxidation (WO) treatment on the process water directly from HTC of pure carbohydrates and beer processing waste to reduce the dissolved organic carbon (DOC) content and chemical oxygen demand (COD). The reaction condition is mild (120℃) to avoid significant degradation of hydrochars. After appropriate treatment, the resulting process water could either be used to heat up the reactor or introduced in the process for reaction optimization[62].

On the other hand, valuable sugar and lignin are derived compounds in aqueous phase after HTC experiment on lignocellulosic waste according to Xiao[39] et.al. Thus, the extraction of valuable chemicals and recirculation in the aqueous phase [61] has been suggested as another favorable option for industrial HTC devices to increase carbon yield in hydrochar and system heat recovery[63, 64]. Martin Hitzl[7] et al. evaluated the suitability of HTC process as a decentral biorefinery for wet biomass at a pilot plant scale. A local biorefinery concept was brought up for more attention on inorganic parts of the HTC carbon and inorganic and organic matter present in process water. It involves local valorization of the solid HTC carbon product, using the ash as fertilizer, irrigation with the process water and a closed cycle which is guaranteed for carbon dioxide as well as for plant nutrients[7]. However, industrial HTC productions provide more possibilities as well as practical problems. The complexity of PW composition made it challenging to identify each individual organic component[61] thus caution is needed when PW is reused or discharged during industrial HTC application.

4.2.2 Significant energy consumption during heating process

In order to make the hydrothermal process of biomass carbonization more efficient technologically and environmentally friendly, the significant energy consumption during heating process need more efficiency and less environmental impacts. The local biorefinery concept proposed by Hitzl[7] et.al exploited solar energy into combustion energy employing wet lignocellulosic waste as energy carrier. Another improvement is the application of microwave irradiation. Having replaced conventional heating methods in the processing of materials such as synthesis and carbohydrate hydrolysis[65], microwave irradiation has also been applied during HTC process known as microwave-assisted hydrothermal carbonization (MAHC) method. Guiotoku[65] et.al used MAHC of lignocellulosic waste in shorter time and milder conditions. Comparision between MAHC and conventional HTC results show that MAHC could shorten the reaction time to some extent thus have the potential for use in thelarge-scale production of hydrochars. However, the effect of microwave on hydrochar properties is not clear.

Table 4. In-used industrial HTC plant

Company (Location)	Type of process (batch/ continuous)	Feedstock	Scale	HTC condition	Product & use	Reference
AVA-CO2 (Karlsruhe, Germany)	Batch	Organic waste	8,000 t/year	Approximately 220℃	HTC-coal and high-performance carbons such as powdered activated carbon or carbon black for use in the rubber industry	[66, 67]
AVA-CO2 (Relzow, Germany)	Batch	Biomass	40,000-50,000 t/year	-	Biochar with more than 90% carbon efficiency used as biocoal	[67]
Carbon Solutions (Berlin, Germany)	Continuous	Dry biomass	10,000 t/year	-	-	[67]
Sun Coal (Ludwigsfelde, Germany)	Continuous	Biomass	1752t/year (200 kg/h)	-	-	[67]
Shiraoi-Cho (Hokkaido, Japan)	Continuous	Combustible wastes including food waste collected from residential and commercial areas	13,505t/year (37 t/d)	234℃, 3 MPa, 4–6 h operation time including the time for waste input and product discharge (1–1.5 h).	Obtained solid char pelletized with shredded wooden and plastic wastes and used as alternative fuel for the boiler of a paper-manufacturing plant	[12]
Ingelia (Valencia, Span)	Continuous	Wet biomass waste including agricultural waste, garden waste and organic fraction of MSW	438-876t/year (1,200-2,400 kg/d)	Bottom temperature >200℃, 8 - 16 h operation time	(Potential application) Solid products obtained from garden waste as solid fuel; aqueous effluents as crop irrigation and biogas production; ash as soil conditioner	[7]

4. Conclusion

This review summarized recent research progress of HTC using OFMSW as feedstocks and concludes as below:

(1) The high content of carbohydrates in OFMSW is quite promising for carbon enrichment during HTC treatment. The carbon content of recovered solid products (hydrochar) can be predicted with chemical properties of feedstock. Thus, OFMSW with high initial carbon content, such as food waste, is commonly favorable for energy-rich hydrochar generation.

(2) Besides initial properties of OFMSW, reaction conditions also have significant effects on hydrochar properties including solid yield, ash/carbon content as well as energy densification. To properly increase the reaction temperature and extent reaction time are both desirable for carbon recovery where temperature is the most notable one for carbon enrichment. Ferric salts show most obvious impacts of additional ions in process water on both char yield increasing and sphere morphology.

(3) Feasible use of hydrochar generated from OFMSW includes energy supplement and soil amendment. Co-combustion of lignite and hydrochar shows promising result with increasing of the burnout, tensile strengths and combustion range. The application of hydrochars as soil amendment turns to has least environmental impact with limited gas emissions.

(4) Combustion of HTC-generated hydrochar as alternative fuel is the main industrial application for OFMSW treatment. Two main obstacles for HTC industrial application are the uncertainty of aqueous phase utilization and significant energy consumption during heating process. Thus, an integrated HTC treatment for OFMSW can be developed with improvement of heating system and utilization of process water for future industrial application.

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