Microwave-assisted Hydrothermal Carbonization for Solid Biofuel Application: A Brief Review

Muhammad Fikri Zulkornain [a], Abd Halim Shamsuddin [a,*], Saifuddin Normanbhay [a], Juniza Md Saad [b], Ye Shui Zhang [c], Shafirah Samsuri [d], Wan Azlina Wan Ab Karim Ghani [e]

[a] *Institute of Sustainable Energy (ISE), Universiti Tenaga Nasional Putrajaya Campus, Jalan Ikram-UNITEN, 43000, Kajang, Selangor, Malaysia*
[b] *Department of Science & Technology, Faculty of Humanities, Management & Science, Universiti Putra Malaysia Bintulu Sarawak Campus, 97008, Bintulu, Sarawak, Malaysia*
[c] *Electrochemical Innovation Lab (EIL), Department of Chemical Engineering, University College London, Torrington Place, London, WC1E 7JE, UK*
[d] *HICoE-Centre for Biofuel and Biochemical Research (CBBR), Universiti Teknologi, PETRONAS, 32610 Seri Iskandar, Perak, Malaysia*
[e] *Sustainable Process Engineering Research Centre (SPERC), Department of Chemical & Environmental Engineering, Universiti Putra Malaysia, 43000 UPM, Serdang, Selangor, Malaysia*

A B S T R A C T

Carbon dioxide and greenhouse gas emissions have been a known threat globally. One of the significant contributors to this issue is coal usage in the power generation industry. Hydro-thermal carbonization (HTC) is considered one of the alternative methods for producing hydrochar to replace coal. Moreover, the application of microwave heating in HTC process is in demand due to its advantageous characteristics such as rapid heating and selective heating. This paper reviews microwave-assisted HTC (MAHTC) as an alternative solid biofuel with an emphasis on lignocellulosic biomass as the feedstock as it is abundant in nature, the influence of process parameters on the hydrochar quality and the kinetic models of hydrochar. Lastly, the challenges during scale-up design especially in terms of technical, economic and environment are discussed. This review would provide a comprehensive overview of MAHTC, which positioning a way forward for the energy and power sector.

1. Introduction

The emission of carbon dioxide (CO_2) and other greenhouse gases (GHGs) into the atmosphere from coal usage in the power generation industry has been identified as the leading cause of global climate change (Lobell et al., 2008, Lobell et al., 2007, Lobell et al., 2011). Renewable energy, specifically solid biofuel, is an attractive option to reduce these power plants' emissions and transition towards an utterly carbon-free power sector. Aside from power plant application or energy production (Larkum, 2010), biomass can also be used for carbon sequestration (Pratt and Moran, 2010, Mathews, 2008, Whitman and Lehmann, 2009) and soil fertility. In the past decades, biomass as an essential renewable energy source, attracting more attention from researchers and companies (Hesam et al., 2020). However, the application of biomass in a large scale is not a feasible solution as it can lead to depletion of soil nutrients and less forest pools (Schulze et al., 2012). All possible renewable energy sources must be utilized at the minimum possible rate and also overall energy consumption must be reduced (De Blasio, 2019).

As an alternative for coal, solid char has been widely researched and preferred due to its high energy density, low fibrous structure and high carbon content (Nizamuddin et al., 2016). Generally, solid biochar is generated from biomass and biomass is renewable and abundant globally which is the opposite of fossil fuel that is limited. Moreover, the combustion of coal is usually accompanied by the emission of green-house gases and it remains a global issue. The application of carbon-neutral solid biofuel is the main solution for this problem. Furthermore, the low sulfur and nitrogen contents in solid biofuel is also a huge advantage to reduce pollutions (Mohammed et al., 2017). Ash content is among the environmental issue for a plant and it can increase particle emissions (Hartmann, 2012). However, solid biofuel has lower ash content thus lowering the cost for handling and disposal of ash and maintenance of heat exchanger (Hartmann, 2012, Reza et al., 2013).

There are two standard processes or techniques in preparing a solid biofuel: pyrolysis and hydrothermal carbonization (HTC) (Yan et al., 2017, Kim et al., 2017). Pyrolysis is a commonly used thermochemical conversion process to produce solid biofuel (Surenderan et al., 2018). It is a process of heating the raw material or feedstock at a moderate temperature (200-400°C) without or with minimal existence of oxygen (Vieira et al., 2020). Meanwhile, hydrothermal carbonization (HTC) occurs at a medium temperature ranging from 150-300 °C with subcritical water (Román et al., 2012). The feedstock is treated by heating it in a confined atmosphere under autogenous pressure (Peng et al., 2017). The major challenge with pyrolysis is the high energy required as the feedstock's moisture content is high (Zhao et al., 2014). Moreover, most researchers have shown great interest in hydrothermal conversion as it is more cost-effective than conventional drying (Zhao et al., 2014). Thus, HTC is seen as a more favorable conversion method than pyrolysis in producing a solid biofuel.

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* Corresponding author.
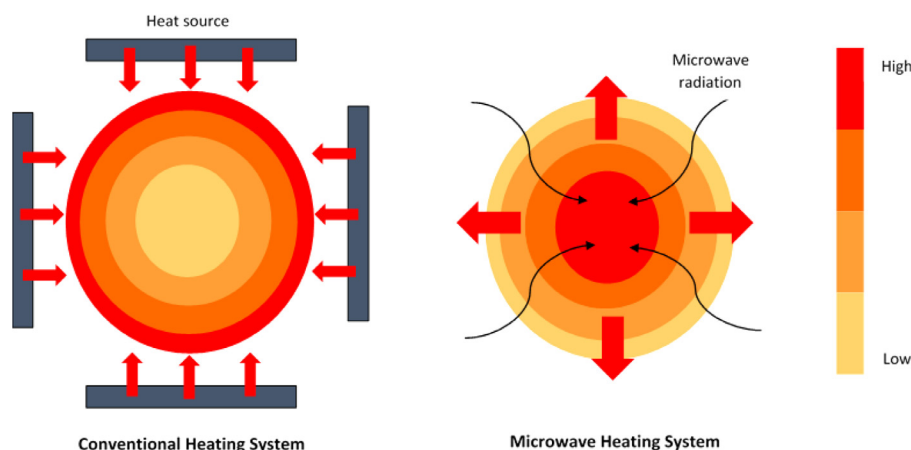 *E-mail address:* abdhalim@uniten.edu.my (A.H. Shamsuddin).

Figure 1. Comparison between conventional and microwave heating systems

Microwave heating is the preferred type of heating compared to conventional heating. Microwave heating will indeed help in the HTC process, especially in terms of residence time. However, there are some disadvantages of microwave such as hotspots and thermal runaways. Currently, there is barely any review on the HTC process using microwave heating. Moreover, the study on solid biofuel application for microwave-assisted HTC hydrochar is also limited due to the challenges in applying the overall system in larger scale.

In this paper, the process of microwave-assisted hydrothermal carbonization (HTC) is highlighted and critically reviewed in terms of lignocellulosic biomass as the feedstock and the process parameter's effect on the hydrochar quality. The kinetic model and parameters of hydrochar are also reviewed. The application of hydrochar as an alternative solid biofuel to replace coal is discussed. Lastly, challenges in applying the MAHTC on a bigger scale are explicitly reviewed on the technical, economic, and environmental sides.

2. Microwave-assisted Hydrothermal Carbonization (MAHTC)

In recent years, microwave-assisted heating system has become a trend compared to conventional heating systems as microwave has its strengths and advantages from conventional heating (Peng et al., 2017, Rillig et al., 2010, Kleinert and Wittmann, 2009). Conventional heating has several flaws: lower yield from unnecessary side processes, heat losses, and longer residence time (Meyer et al., 2011, Tsubaki et al., 2012, Yin, 2012, Tripathi et al., 2015). The molecular heating level is increased in the microwave heating and, at the same time can lead to homogeneous temperature elevation. Cost and energy-efficient have been the advantages of microwave heating, in addition, to be more controllable (Chen et al., 2012, Elaigwu and Greenway, 2019). Thus, microwave heating has a high processing rate, leading to lower residence time while consuming lower energy (Kleinert and Wittmann, 2009, Kharisov et al., 2012, Xia et al., 2020, Guangzhi et al., 2017). Furthermore, the calorific value (CV) or the (HHV) of the hydrochar from microwave heating is also higher compared to conventional heating (Yao et al., 2016, Silitonga et al., 2020).

The significant difference between the microwave heating system and the conventional heating system is the heat generation mode (CO et al., 2005). The heat source location is outside of the bed in conventional heating and applies the convection and/or conduction principles. In other words, heat will move from the outside to the inside core. If it once achieved a steady-state condition, then the temperature gradient occurs. Meanwhile, in microwave heating, microwave radiation will penetrate the material and convert microwave energy into internal energy, or in other words, the heat s transferred inside-out (Mujawar et al., 2016). The microwave system has an overall frequency of 80-85% (RJ, 1998). Figure 1 shows the comparison between the conventional and microwave heating system in terms of heat generation mode.

Microwave energy comprises electromagnetic radiation that occurs at around 0.3 to 300 GHz frequency waves and it is also considered part of the electromagnetic spectrum (Kalla and R., 2017, Gong and Bassi, 2016). Higher frequency electromagnetic waves have shorter wavelengths and higher energy (Nomanbhay and Ong, 2017). Generally, microwaves are non-ionizing radiation that will trigger molecular motion by ions movement and dipoles rotation yet does not affect the molecular structure (Abdul Latif et al., 2019). The microwave heats the target object by applying the electromagnetic field while conventional heating applies the interfacial heat transfer. Polar substances are the main element that will help a substance to be heated during the microwave heating process. Higher content polar substances will increase the heating rate.

The dipolar features, dispersive qualities, and imaginary permittivity part of water make it an important medium in microwave heating (Silva Santos and Rodriguez-Esquerre, 2020). Water comprises of a negatively charged oxygen atom and two positively charged hydrogen atoms. The negatively charged end of the microwave attracts the positively charged end of water and vice versa. Thus, as microwaves oscillate, water molecules will rotate. Intermolecular collisions occur as a result of these events, resulting in friction force. The heat generated from friction force is transferred through the substance by convection, conduction, or radiation (Kalla and R., 2017). Moreover, biomass has poor microwave absorbency due to its lower dielectric characteristics (Yin, 2012). Water on the other hand has high dielectric properties therefore able to assist in the penetration of microwave energy (De Sousa et al., 2017). Thus, HTC, a water-based conversion technique, is preferred for application in microwave energy.

A comparison between conventional and microwave hydrothermal carbonization has also been done to prove the advantages of microwaves heating. Zhang et al has concluded that a hydrochar that is comparable in terms of energy properties can be obtained by 5-10 times decrement in reaction time with the help of microwave heating compared to conventional heating (Zhang et al., 2018). Moreover, the study on orange peel waste also shows that the hydrochar produced by MHTC of orange peel was on par as regards to the physicochemical properties, to that of hydrochar obtained from conventional HTC process (Lei, 2018). These studies suggest that MHTC has the potential to provide a more efficient approach to produce hydrochar from lignocellulosic biomass compared to conventional heating.

The requirements for industrial use of hydrochar for solid biofuel are defined in the Standard ISO 17225-8 (ISO 2016). Table 1 shows the limits for industrial use of hydrochars. These limits must be considered in producing hydrochars for industrial use as they can affect the emissions of NO_x, SO_x and chlorinated species such as HCl, PCBs ad PCDD/F.

Table 1
Limits for industrial use of hydrochar

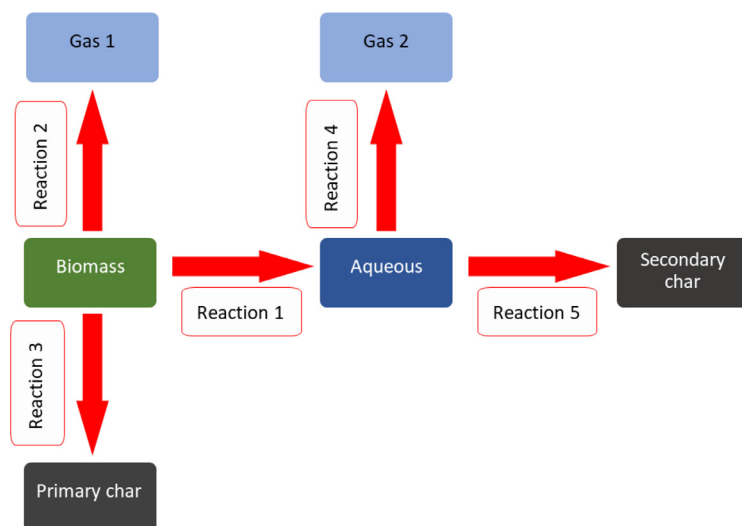| Feedstock	N (%)	S (%)	Cl (%)	Ash (%)	VM (%)	HHV (MJ/kg)
Lignocellulosic biomass and digestate	1.5	0.2	0.15	10	<75	>18
Biowaste and sewage sludge	3	0.5	0.2	To be stated	<75	>17

Figure 2. Model of reaction mechanism for MAHTC

These are also important to minimise slagging and corrosion problems and avoid the risk of explosion in the combustion chamber (Khan et al., 2009).

The current study by Sharma et al has reported that digestate from anaerobic digestion can be further processes via hydrothermal treatment to produce hydrochar (Sharma et al., 2020). This is in line with the concept of circular economy to improve efficiency and optimise the waste disposal. The biogas produced from anaerobic digestion process is used to generate electricity while hydrochar produced from MHTC can be used as adsorbent, soil amendment and solid biofuel (Fang et al., 2018). Thus, it is that it is possible to apply the regenerative circular economy which ensure that the resources and materials are continuously recycled and minimise the waste produced (Sharma et al., 2020). This will be an eye opener for policy makers and authorities to integrate the anaerobic digestion system with hydrothermal treatment for organic waste processes.

A study by Lucian et al has reported that plant efficiency is highly dependent on the moisture content and ratio of biomass to water (Lucian and Fiori, 2017). The study reported that at the best conditions, the plant efficiency of 78% is obtained, specific electric energy consumption is equal to 0.16 kWh/kg$_{hydrochar}$ (0.04 kWh/kg$_{feedstock}$) and specific thermal energy consumption was equal to 1.17 kWh/kg$_{hydrochar}$ (0.31 kWh/kg$_{feedstock}$). The industrial and laboratory scales study for sewage sludge has shown positive result which are the reduction of the total energy input for dewatering to 61-62% of heat demand and 65-69% of electricity demand if the thermal drying is dismissed (Escala et al., 2013, Stucki et al., 2015). Moreover, the overall energy balance could be negative if the heat from slurry cooling process of hydrochar and the excess exothermic heat of reactions are recoverable (Wang et al., 2014).

In term of reaction mechanism, MAHTC undergone hydrolysis, dehydration, decarboxylation, polymerization, and aromatization (Zhang et al., 2018, Guiotoku et al., 2009, Dai et al., 2018, Liu et al., 2021). Figure 2 shows the model of MAHTC reaction. Reaction 1 or hydrolysis produces aqueous or liquid substances made up of intermediate molecules from biomass structural components such as cellulose, hemicellulose, lignin) (Libra et al., 2011). Hemicellulose are among the substituent that is known to be affected at low temperatures (Lei et al., 2016). Concurrently, hydrolysis also leads to forma-

tion of monomers and oligomers in the aqueous substances while a part of cellulose and lignin disintegrated into smaller molecules such as 5-Hydroxymethylfurfural (5-HMF) and phenolic derivatives (Funke and Ziegler, 2010, Ulbrich et al., 2017). The aqueous substances are very reactive and could go through polymerization and condensation leading to a formation of solid substances called Secondary Char (Reaction 5). At the same time, decarboxylation and decarbonylation reaction occurred leading to formation of Gas 2 consisting of carbon dioxide and carbon monoxide (Reaction 4). Throughout the process, there are non-dissolved cellulose and lignin that will gone through dehydration and decarboxylation/decarbonylation reactions leading to formation of Primary Char (Reaction 3) and Gas 1 (Reaction 2) (Titirici, 2013).

2.1. Lignocellulosic Biomass as Feedstock

Many types of feedstock are available to produce bioenergy such as agriculture wastes, forestry residues, manures, energy crops and municipal wastes (Biswas et al., 2017, Williams and Nugranad, 2000, Mulligan et al., 2009). Lignocellulosic biomass is the sole carbon-neutral energy resource that includes variety of feedstock such as forestry residues, energy crops and agriculture wastes (Özbay et al., 2001, Mani et al., 2011, Ruiz-Gómez et al., 2017). Excessive development in energy crop leads to a reduction in arable land and disposal of forestry and agricultural residues is becoming a dilemma for the industry (Wang et al., 2019). However, direct application of these feedstock is not applicable due to its low energy density, high transportation cost and high moisture content (Hu et al., 2015). Thus, a proper pre-treatment technique is required to enhance the quality of the feedstock.

Lignocellulosic biomass comprises of mainly cellulose, hemicellulose, lignin, a small amount of water extractive, and ash (Heidari et al., 2019). Most of these biomass comprises 20-40% hemicellulose, 40-60% cellulose, and 10-25% lignin, depending on the maturity, type, and climate condition (Acharya et al., 2015). However, there are some challenges in utilizing the lignocellulosic biomass. One of the major obstacles is the recalcitrance of the plant cell wall due to the integral structural complexity of lignocellulosic fractions and substantial hindrance from the inhibitors and by-products generated during processes

(Kumar and Sharma, 2017). To reduce these, thermochemical processing strongly recommended decomposing the hemicellulose, cellulose, and lignin. At atmospheric pressure, hemicellulose decomposes at 200-300 °C and around 160 °C while in subcritical water. For cellulose and lignin, it will start decomposing at 180-200 °C and above 220 °C in subcritical water, and 300-400 °C and above 600 °C in ambient conditions, respectively (Grønli et al., 2002).

In the MAHTC process, water is added as the solvent for the reaction. To obtain an improved quality of hydrochar, subcritical water is the preferred option as the solvent compared to ambient water. Water, as a solvent, is critical in acting as a transfer medium for ions and it travels from one bond to another. Furthermore, water also constantly tears the inactive bonds and connects them to another compound while also rearranging the biomass structure (Mahoney, 2005). Meanwhile, lignocellulosic biomass has a high chance of breaking the lower molecular organic compound as it comprises of solid and polymeric organic compounds. Moreover, a high value of the ionization constant is also advantageous for subcritical water. A high amount of H^+ and OH^- ions can accelerate the hydrolysis process for lignocellulosic material due to in-situ acid or base-catalyzed reactions (Kruse, 2008).

Currently, the study on MHTC using lignocellulosic biomass is blooming with interest such as rice straw, sugarcane, coconut shell, pine sawdust and rice husk (Guiotoku et al., 2009, Nizamuddin et al., 2019, Chen et al., 2012, Elaigwu and Greenway, 2019, Nizamuddin et al., 2018). Coconut shell study via MHTC process indicated that at higher temperature and time, the hydrochar produced has higher high heating value (15.06 MJ/kg to 19.76 MJ/kg) (Elaigwu and Greenway, 2019). The study concluded that the hydrochar has potential to be used at solid biofuel due to its high energy content. Moreover, prolonged residence time was seen to be more favorable for acetyls dissociation compared to increased temperature (Dai et al., 2018). The hydrochar produced shows better thermal stability as peaks in thermogravimetric (TG) and derivative thermogravimetric (DTG) curves shifted to higher temperature region under more severe conditions (higher temperature and time) (Dai et al., 2018). Under more severe condition, the Py-GC/MS analysis indicated that sugars content increased while acids content decreased.

Catalyst is proven to be effective in increasing the solid or liquid yield of the hydrochar depending on the properties of the catalyst. A study on sugarcane bagasse via MHTC by Chen et al has concluded that addition of catalyst (sulfuric acid) can enhance the carbonizing effect of the biomass (Chen et al., 2012). In addition, the result also suggests that when the energy density of bagasse is increased by 20%, the temperature of MHTC can be lower than that of dry torrefaction around 100 °C. This indicates that a hydrochar produced from MHTC is preferred to be used compared to biochar obtained from dry torrefaction. The result from a study by Chen et al also implies that an addition of catalyst (H_2SO_4) can increase the solid yield while increasing the acid concentration will increase the HHV and energy densification (ED) of the hydrochar (Cao et al., 2019).

Nizamuddin et al has done an optimization study on rice straw via MHTC process to study the effect of temperature, time, particle size and biomass to liquid ratio (Nizamuddin et al., 2019). The result exhibits an increase in fixed carbon values, carbon content and higher heating value (HHV) from 14.37%, 37.19% and 12.3 MJ/kg for rice straw to 35.4%, 48.8% and 17.6 MJ/kg for hydrochar. Furthermore, crystallinity, porosity and thermal stability of the hydrochar were greatly improved compared to raw rice straw (Nizamuddin et al., 2019). The fuel properties of rice straw hydrochar such as proximate analysis, ultimate analysis, HHV and energy density were also comparable to lignite coal thus proven its potential to be utilized as solid biofuel (Nizamuddin et al., 2019). Kang et al on the other hand has done the optimization of corn stalk using MHTC process and concluded that temperature is the dominant parameter in determining the solid yield, heating value and fuel quality (Kang et al., 2019). Table 2 shows some other studies carried out for lignocellulosic biomass using MHTC process.

2.2. Effect of Temperature

Temperature is considered the most important and common parameter used in applying the HTC process. Leilei Dai et al (Dai et al., 2018) has done a test on bamboo sawdust by varying the temperature to 150, 180, 210, and 230 °C via microwave-assisted HTC. The solid yield shows decreasing value (19.1%, 17.3%, 16.2%, 10.6%) as the temperature is increased (150, 180, 210, 230 °C). Research by Chen et al (Chen et al., 2012) by applying MAHTC to sugarcane bagasse also shows the same trend as decreasing solid yield percentage when the temperature is increased. Qian Lei et al (Lei, 2018) has done MAHTC to orange peel waste and show the same result as manipulating the temperature.

Figure 3 illustrates the effect of temperature on solid yield and HHV for various feedstocks (Lei, 2018, Guiotoku et al., 2009, Dai et al., 2018, Elaigwu and Greenway, 2019, Shao et al., 2019, Knappe et al., 2018). The solid yield percentage decreases as the temperature are increased or inversely proportional to each other. This may occur as feedstock underwent more carbonization process at a higher temperature and lowering the solid yield. It may also due to hydrogen and oxygen loss as liquefaction and gasification process occurs at higher temperature (Möller et al., 2011, Kruse and Gawlik, 2003, Falco et al., 2011). It is important to note that the maximum temperature for HTC is around 350 °C. At higher temperatures, the product will comprise more of liquid yield and is called HTL (Hydrothermal Liquefaction) process. As the temperature increases higher or in a supercritical state, the product will mostly comprise gas yield because of the enhancement of radical reactions and called HTG (Hydrothermal Gasification) process (Safari et al., 2018). At supercritical condition, water has lower density, higher specific heat capacity and lower viscosity (De Blasio, 2019).

Higher temperature will also increase the carbon content and reduce the oxygen and hydrogen content in the hydrochar (Elaigwu and Greenway, 2016). Higher carbon and lower oxygen are good to boost the hydrochar combustion properties (Sevilla et al., 2011). This occurs as deoxygenation, dehydration, and decarboxylation reactions taking place in the process (Kang et al., 2012, Liu et al., 2013). The pH value of hydrochar will decrease as the higher temperature is used because organic acid accumulates and increase the ionic product. Thus, inorganic ions will be dissolved and mineral content is reduced in the hydrochar formed (Reza et al., 2013).

A decrease in H/C and O/C ratios occur as higher temperature is applied in the heating process. These ratios are used to generate a Van Krevelen diagram (graph of H/C against O/C) to study atomic composition differences. These ratios suggest that transformation emerged from dehydrogenation, decarboxylation, deoxygenation, and dehydration reactions (Erdogan et al., 2015, Elaigwu and Greenway, 2016). A lower H/C and O/C ratios are suitable to be used as biofuel (Nizamuddin et al., 2019).

Nizamuddin et al has studied the characteristic of rice straw hydrochar via microwave HTC and discovered that higher temperature would increase the HHV (Nizamuddin et al., 2019). Rice husk also shows the same trend (Nizamuddin et al., 2018). The possible cause for the result may be because at low temperatures, the only hemicellulose is degraded and as the temperature rises, cellulose and lignin will start to degrade. The change in HHV may have the same reason because as the temperature rises, most of the hemicellulose will degrade mainly leaving cellulose and lignin. The HHV will increase as lignin has the highest HHV, followed by cellulose and hemicellulose (Sheng and Azevedo, 2005).

2.3. Effect of Residence Time

Residence time is also considered a crucial factor in the HTC process even though it may not be a crucial factor in the HTC process even though it may not be as significant as temperature. Generally, the residence time is quite the same as temperature with the temperature being the more dominant factor. As the residence time is increased, the solid yield will decrease while carbon content and HHV increase (Zhang et al.,

Table 2
Studies of microwave-assisted HTC for lignocellulosic biomass

| Biomass	Conditions	Findings	Refs
Green waste	130-190 °C, 30-120 min, :1:7-1:10 solid to liquid ratio	- Hydrochar with the highest calorific value is obtained at 190 °C, 60 min, and 1:8 solid to liquid ratio - The energy output is greater than energy input at 190 °C - Suitable application of green waste hydrochar for adsorbent and fuel	(Shao et al., 2019)
Pine sawdust	60-240 min	- Volatile matter decrease while fixed carbon increase as the residence time is increased - Gross calorific value of produced hydrochar is comparable to coal, charcoal, and ethanol	(Guiotoku et al., 2011)
Assai (Amazonian fruit waste)	145-200°C, 14 min	- Narrower porosity product can be achieved with CO_2 activation yet not affecting the spherical morphology - The product has good overall bulk density and potential for methane storage	(Cruz et al., 2018)
Brewer spent grain	180-250°C, 0-2h	- Higher severity of condition decreases the yield yet increase the calorific value - The hydrochar produced was more mesoporous, hydrophilic, rough material, containing several cavities and oxygen functionalities on the surface - Has potential for bioadsorbent material	(Lorente et al., 2020)
Willow wood	150-185°C	- At 170 °C, most efficient combination of energy input, pH drops, increasing heating value and decreasing mineral content was obtained - The possibility of applying MAHTC to enhance low quality biofuel by reducing emission precursors	(Knappe et al., 2018)
Corn stalk	122.7-257.3 °C, 4.8-55.2 min, 0.98-6.02 g/50mL H2O	- Statistical analysis shows that the temperature is the dominant parameter in evaluating the solid yield, heating value and quality of hydrochar - The software expected that highest energy yield of 80.55% was achieved at 181.9°C, 39.7 min and 3.8 g/50 mL H2O - At 230°C, 45 min and 2 g/50 mL H2O, the higher heating value of 22.82MJ/kg was produced	(Kang et al., 2019)
Phoenix tree leaves	130-220°C	- At higher severity of condition, higher heating value increase from 17.7 to 22.42MJ/kg while solid yield decrease -Microwave heating can economize more than 50% of time compared to conventional heating - Morphological analysis result indicated that OH^- can boost the decomposition of wood structure and reduce the time for cellulose to make contact with reaction medium	(Xu et al., 2020)
Coconut shell	150-200°C, 5-30min	- Recorded an increase in energy properties after MHTC process. - The HHV increased from 15.06 MJ/kg in the feedstock to 19.76 MJ/kg after MHTC process - MHTC as promising technique to produce high value product from waste coconut shell	(Elaigwu and Greenway, 2019)
Bamboo sawdust	150-230°C, 5-35min	- HHV and fixed carbon content gradually increased with increased pretreatment severity - Dissociation of acetyls was more favorable under prolonged residence time, unlike hydroxyl group, - Acid content was decreased but sugars increased with increased MHT severity based on Py-GC/MS analysis	(Dai et al., 2018)
Red seaweed	160–200°C, 1–40min, 0–0.6 M, 1%–10% w/v	- Highest levulinic acid yield of 16.3 wt% was produced at 5% (w/v) biomass loading, 0.2M H_2SO_4, 180 °C, and 20 min - The energy efficiency was comparable to the conventional hydrothermal treatment with shorter reaction time and higher carbon recovery	(Cao et al., 2019)
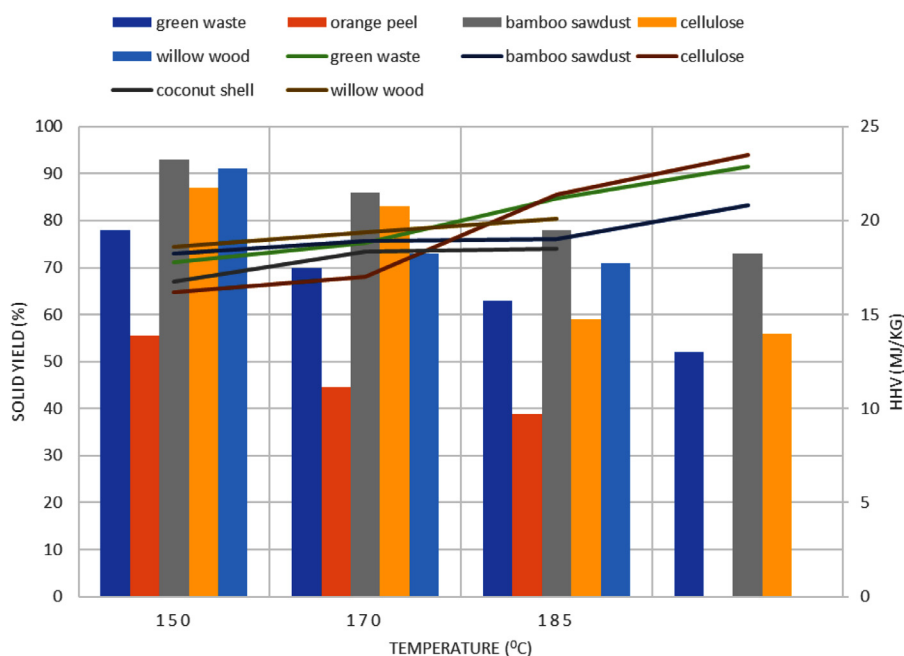
Figure 3. Solid yield and HHV against temperature for various feedstocks (Lei, 2018, Guiotoku et al., 2009, Dai et al., 2018, Elaigwu and Greenway, 2019, Shao et al., 2019, Knappe et al., 2018)
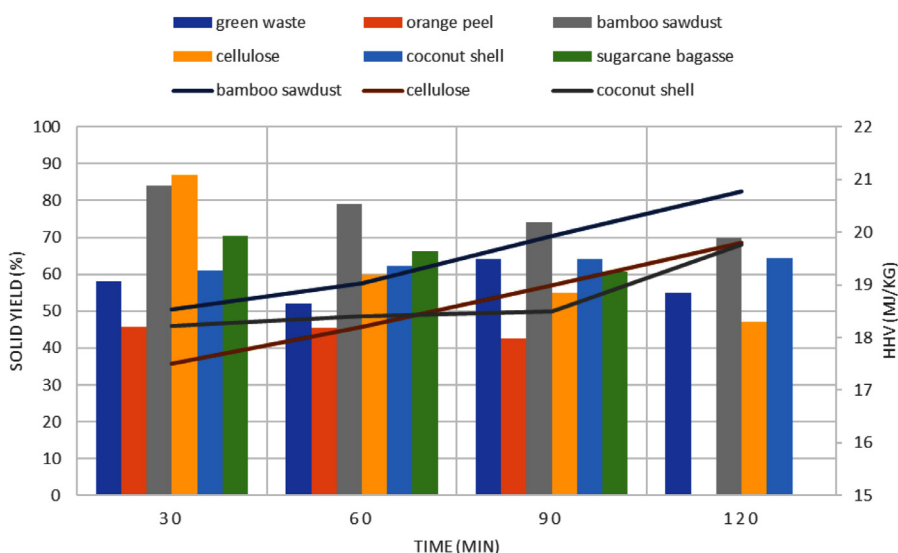
2018). Figure 4 shows the effect of residence time against solid yield and HHV (Lei, 2018, Guiotoku et al., 2009, Dai et al., 2018, Chen et al., 2012, Elaigwu and Greenway, 2019, Shao et al., 2019). However, Shao et al have done a study on green waste by varying the residence time between 0.5h to 2h and found out that the HHV decreases at 1-2h residence time while solid yield increases between 1-1.5h residence time (Shao et al., 2019). This may occur due to the recombining of organic matter in the liquid phase into hydrochar. Thus, optimization of residence time is crucial to produce hydrochar with high HHV.

Elaigwu et al (Elaigwu and Greenway, 2016) has used *Prosopis Africana* shell as a biomass resource and manipulating the residence time to 5-20 min and the result has shown a decrease in solid yield as the residence time is increased. They also compared the two types of heating, conventional, and microwave, for the *Prosopis Africana* shell and the result for solid yield does not change significantly when a heating time of 5-20 min was used for microwave and 120-240 min for conventional heating respectively. This shows the advantage of microwave heating as a lower time of microwave heating can produce the same amount of yield.

As reaction time is extended too much, it may not significantly affect hydrochar carbon enrichment because the carbonization reaction is already completed. Thus, the highest carbon content indicated that it had become a pure hydrochar product (Jatzwauck and Schumpe, 2015). Zhang et al have discovered that the highest carbon content can be achieved within 120 min for microwave HTC while conventional HTC takes 6.8 h and 20 h to obtain the highest carbon content (Zhang et al., 2018, Kang et al., 2012, Álvarez-Murillo et al., 2016). This shows another example of how microwave heating can increase the quality of hydrochar within a shorter time. Moreover, microwave heating also can increase the HHV of produced hydrochar compared to conventional heating. Within 96 h residence time, an average HHV of 25 MJ/kg can be achieved for conventional heating (Lu et al., 2013). However, HHV of 26.31 MJ/kg can be obtained within 120 min for microwave HTC, a 50% increment compared to conventional HTC at similar conditions (Zhang et al., 2018, Álvarez-Murillo et al., 2016).

2.4. Effect of Solid to Liquid Ratio

Solid to liquid ratio or the minimum amount of water to ensure complete diffusion of biomass in the reaction medium in the HTC process is critical. It can affect the efficiency of hydrothermal reactions. Despite that, it must be noted that higher water to biomass ratio will result in a higher amount of water consumption and the required energy for heating (Heidari et al., 2019). Water is critical in the hydrothermal reaction

and at the same time in ensuring the mass and heat transfer are sufficient. The hydrothermal reaction is also dependant on the hydrophobicity, structure, and density of biomass used. A lower hydrophobicity and more porous structure biomass need lower water amount and vice versa. Moreover, higher density biomass will need a higher amount of water for the hydrothermal reaction.

Kang et al has reported that a higher solid to liquid ratio will increase the solid yield for corn stalk (Kang et al., 2019). A study by Leichang et al is also in agreement with the finding (Cao et al., 2019). This is due to the limited hydrolysis process of mass transfer and substrate accessibility. The contact of substrate water molecules may also lessen due to substrate swelling and agglomeration (Kang et al., 2018). In the microwave process specifically, biomass decomposition happened due to microwave irradiation, increasing the temperature and pressure. Nonetheless, microwave energy has low penetration ability and a higher solid to liquid ratio will make penetration harder (Budarin et al., 2015, Bundhoo, 2018).

Moreover, HHV also increased as the solid to liquid ratio increased until a certain point and decreased after that (Cao et al., 2019, Shao et al., 2019). This may imply that further carbonization became less effective at a higher solid to liquid ratio. Despite that, the effect of liquid to solid ratio is inferior compared to temperature and residence time in terms of solid yield and energy densification (Shao et al., 2019).

2.5. Effect of Catalyst

The catalyst used and its concentration can also affect the overall characteristic of hydrochar produced. The usage of catalysts is dependent on the desired hydrochar characteristic. For instance, an acid catalyst will help in the hydrolysis process, thus increasing the formation of solid yield, thus increasing the formation of solid yield. A basic catalyst is applied to increase the liquid yield. A favorable catalyst is cost-effective, thermally stable, and high selectivity towards the required yield (Westermann et al., 2007). Catalyst can also reduce NO_x as it is converted into nitrogen and water via catalytic chemical reactions (Nizamuddin et al., 2017). Figure 5 shows the catalyst types with their advantages and disadvantages.

Leichang et al (Cao et al., 2019) has done a study on red seaweed via microwave heating of HTC by manipulating the acid concentration. They have concluded that acid (H_2SO_4) can enhance the formation of solid yield yet the different concentration of acid does not significantly affect the solid yield. This result implies that an acidic environment can enhance the degradation speed of material. Meanwhile, the HHV and energy densification increases as a higher concentration of acid are used.
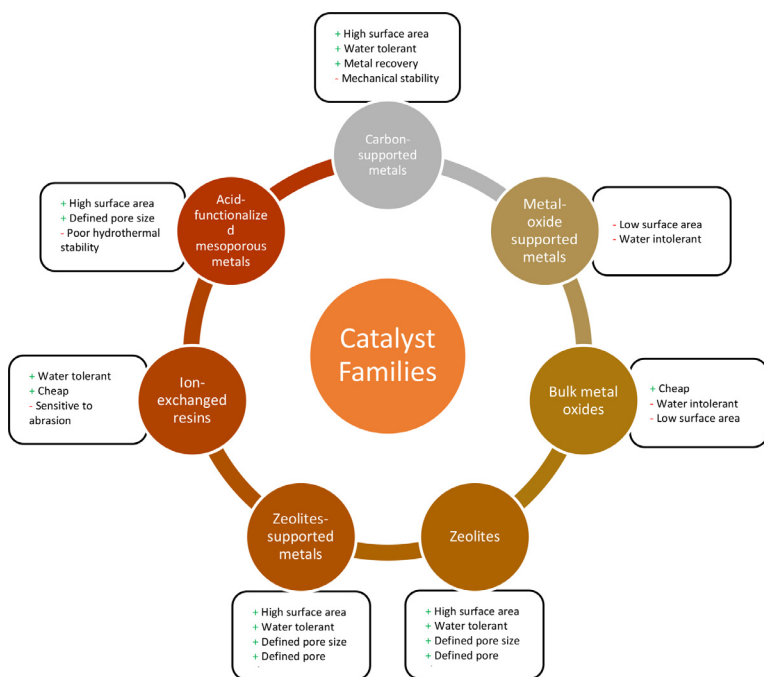
Figure 5. Types of catalyst

This conclusion is in line with the study done by Chen et al (Chen et al., 2012).

Meanwhile, Wang et al have added a different catalyst (H_2SO_4 & CaO) to pig feces for MAHTC (xin et al., 2020). The addition of H_2SO_4 decreases the solid yield while CaO increases the solid yield. The addition of H_2SO_4 decreases the pH value of hydrochar produced while CaO addition increases the pH value of hydrochar obtained, making it more suitable for soil improvement/remediation. However, both catalyst addition increases the carbon content leading to higher HHV in hydrochar formed.

Liu et al has reported that H_3PO_4 will decrease the solid yield and increase the liquid yield (Liu et al., 2021). This indicates that acidic catalyst enhances the degradation of lignin, hemicellulose, and cellulose, and microwave heating, on the other hand, it improves hydrolysis, dehydration, and decarboxylation (Jain et al., 2016). The addition of H_3PO_4 will increase the HHV, however, it can decrease the energy conversion rate due to a decrease in solid yield.

2.6. Effect of Particle Size

The study for particle size is scarce and limited not only to the HTC process but also to other thermochemical processes such as pyrolysis (Demirbas, 2004) and gasification (Hernández et al., 2010). For microwave heating, Nizamuddin et al (Nizamuddin et al., 2019) has done a study on rice straw and they found that as the particle size is increased, the solid yield produced will also increase. The result is in line with a recent study (Nizamuddin et al., 2018). This is due to the reduction of volatile's diffusion rate through char and secondary reactions will produce higher char yield (Várhegyi et al., 1998, Di Blasi et al., 1999, Manyà et al., 2007).

It is known that hemicellulose degrades the easiest compared to cellulose and lignin. Meehnian et al (Meehnian et al., 2016) has proved that as particle size increases, lignin's degradation will be lowered. The crystallinity characteristic of the product will be improved as the size is increased. An increase in crystallinity will lead to a decrease in mass transfer characteristics. As most of the lignocellulosic biomass comprises cellulose and lignin rather than hemicellulose, cellulose and lignin conversion will be more effective if the particle size is smaller.

2.7. Effect of pH

A neutral to acidic condition is favorable for the enhancement of the coalification process (Funke and Ziegler, 2010). Drop in pH was recorded after the MHTC process in previous studies due to the formation of organic acids such as formic, acetic, levulinic and lactic acids (Pauline and Joseph, 2020, Berl and Schmidt, 1928, Orem et al., 1996, Watanabe et al., 2004). These acids could help in decomposition of biomacromolecules thus affecting the characteristics of the hydrochar (Titirici et al., 2012, Jain et al., 2016). The initial pH of feedwater is usually between 2 to 12. However, the pH will decrease between 2.8 and 4.2 due to the formed organic acids. The HHV will increase at lower pH (Yang et al., 2015). Moreover, lower pH helps in increasing the surface area thus enhancing the recovered solids energy and carbon content (Lu et al., 2014).

Elaigwu et al had reported that after MHTC process, the pH value of the hydrochar decreased from 6.87 to 4.35 (Elaigwu and Greenway, 2019). The HHV and carbon content also increase in the lower pH hydrochar. The pH values decreased due to formation of organic water during MHTC process as well as high oxygenated functional groups and supported by previous studies (Elaigwu and Greenway, 2016, Elaigwu et al., 2014).

3. Kinetic Model of Hydrohar

Kinetic analysis of solid state decomposition is mainly based on a one-step kinetic equation and the general equation is as follows (Islam et al., 2015);

$$\frac{d\alpha}{dt} = k(T)f(\alpha) \tag{1}$$

Where $k(T)$ is temperature dependant rate constant can be replaced by Arrhenius equation and α is the thermal conversion of combustible material expressed as the following;

$$\alpha = \frac{m_i - m}{m_i - m_f} \tag{2}$$

Where m, m_i and m_f are the instantaneous, initial and final mass of the sample respectively. By substituting Arrhenius equation in the general equation and considering non-isothermal conditions, the time dependence of conversion is replaced through temperature-time relation thus

the following equation is formed

$$\frac{d\alpha}{dt} = \frac{A}{\beta}\exp\left(\frac{-E_a}{RT}\right)f(\alpha) \tag{3}$$

Where β is constant heating rate and is expressed as $\beta = dT/dt$. Further process of integration of $d\alpha/f(\alpha)$ will produce the following equation

$$g(\alpha) = \int_0^\alpha \frac{d\alpha}{f(\alpha)} = \frac{AE_a}{R\beta} I\left(\frac{E_a}{RT}\right) \tag{4}$$

E_a/RT has no definite solution and numerical approximations is used as in literature (White et al., 2011). Generally, there are two general different mathematical schemes to evaluate kinetic parameters for thermal decomposition of biomass samples which are model-free methods (iso-conversional technique) and model-based method (Dhaundiyal et al., 2018).

3.1. Model-free Method

The model-free methods or also known as isoconversional are used on determining the Arrhenius parameters without depending on the reaction order (Ravi et al., 2012). Isoconversional methods can be used to evaluate isothermal and non-isothermal process and various isoconversional methods were proposed as follows

a Kissinger Method

The Kissinger method is used in estimating the activation energy (E$_a$) from plotting of Kissinger $\ln(\beta/T_m^2)$ against $1/T_m$, where T_m is the temperature at maximum of $d\alpha/dT$ (Kissinger, 1957). A pre-exponential factor is to be calculated under the assumption of first-order reaction from the following equation for non-isothermal and isothermal condition;

$$A = \frac{\beta E}{RT_m^2}\exp\left(\frac{E}{RT_m}\right) \tag{5}$$

The following equation is then considered

$$\ln\left(\frac{\beta}{T_m^2}\right) = \ln\left(\frac{AR}{E_\alpha}\right) - \left(\frac{E_\alpha}{RT_m}\right) \tag{6}$$

The activation energy is then calculated from the slope of the graph and is equal to $-E_a/R$. The T_m value can be calculated from the derivative of conversion over temperature. As of now, there is still no study conducted on MHTC that applies Kissinger method to calculate the activation energy.

a Flynn-Wall-Ozawa Method (FWO)

Approximation of Doyle is used in the integrated equation of $d\alpha/f(\alpha)$ to produce Flynn-Wall-Ozawa (FWO) method.

$$\ln\left(\beta_i\right) = \ln\left(\frac{AE_{\alpha_i}}{Rg(\alpha_i)}\right) - 5.331 - 1.052\left(\frac{E_{\alpha_i}}{RT}\right) \tag{7}$$

α_i is the fixed conversion at different heating rates. The plot from the equation is a straight line with the slope of $-1.052E_{\alpha_i}/RT$. Currently, there is no recorded study on MHTC applying this method to calculate the kinetic parameters. Lang et al on the other hand, has study the combustion behaviour of hydrochar from co-HTC of corn stalk and swine manure using Flynn-Wall-Ozawa (FWO) and Kissinger-Akahira-Sunose (KAS) method (Lang et al., 2019). It is recorded that increasing the corn stalk percentage will increase the activation energy from 141.53–171.23 and 138.35–169.66 KJ/mol via FWO and KAS respectively.

a Kissinger-Akahira-Sunose Method (KAS)

The approximation of $I(\frac{E_a}{RT}) \cong \frac{exp(\frac{-E_a}{RT})}{(\frac{E_a}{RT})^2}$ is used to derive the Kissinger-Akahira-Sunose method thus forming the following the equation

$$\ln\left(\frac{\beta_i}{T_{\alpha_i}^2}\right) = ln\left(\frac{A_\alpha R}{g(\alpha)E_\alpha}\right) - \left(\frac{E_\alpha}{RT_{\alpha_i}}\right) \tag{8}$$

The activation energy can then be estimated from a plot of $\ln(\beta_i/T_{\alpha_i}^2)$ against $1000/T_{\alpha_i}$ for a fixed value of conversion α and the slope is equal to $-E_\alpha/R$.

Liang et al has used KAS method to study the combustion kinetic of tobacco residues (Liang et al., 2020). The result indicated that the activation energy is in range of 117.1-290.7 at 0.1-0.8 conversion degree. The activation energy is higher at 0.3 and 0.7 conversion degree compared to others suggested that the initial thermal degradation of hemicellulose and lignin respectively. Furthermore, the increasing activation energy from 194.8 kJ/mol at 292.6 kJ/mol at more severe condition suggested an increased difficulty to start the reaction at more severe condition. Moreover, addition of graphene oxide can act as a catalyst and decrease the activation energy and proven the effect of catalyst on the combustion behavior and kinetic parameters (Liang et al., 2020).

3.2. Model-based Method (Coats-Redfern Method)

The asymptotic technique is applied in Coats-Redfern method for approximating the exponential integral $g(\alpha)$ as follows;

$$ln\left(\frac{g(\alpha)}{T^2}\right) = \ln\left(\frac{AR}{\beta E_\alpha}\left(1 - \frac{2RT}{E_\alpha}\right) - \frac{E_\alpha}{RT}\right) \tag{9}$$

Where $2RT/E_\alpha$ is usually negligible and T is the mean temperature. The graph of $ln(g(\alpha)/T^2)$ against $1/T$ is then plotted. Activation energy (E_α) and pre=exponential factor (A) is obtained from the slope and intercept of the graph respectively.

A study on fuel properties and kinetic combustion of corn straw via HHTC was done by Xing et la (Xing et al., 2016). Corn straw hydrochar prepared at 230 °C and 30 min was analysed using Thermogravimetric analysis at three different heating rates (10°C/min, 20 °C/min and 40 °C/min). The result that the activation energy of raw corn stalk in lower compared to corn straw hydrochar due to decomposition of cellulose and hemicellulose during the MHTC process (Xing et al., 2016). Moreover, as the heating rate is increased from 10°C/min to 40 °C/min, the activation energy decreased from 41.6 kJ/mol to 34.2 kJ/mol.

3.3. Other Methods

Yang et al has highlighted the usage of the following equations (Yang et al., 2016);

$$ln\left(\frac{-1(w_o - w_f)dw}{dt}\right) = \ln A - \frac{E}{RT} + n \, ln\left(\frac{w_t - w_f}{w_o - w_f}\right) \tag{10}$$

$$y = B + Cx + Dz \tag{11}$$

Where,

$$y = ln\left(\frac{-1(w_o - w_f)dw}{dt}\right)$$

$$B = \ln A$$

$$C = -E$$

$$x = \frac{1}{RT}$$

$$D = n$$

$$z = ln\left(\frac{w_t - w_f}{w_o - w_f}\right)$$

The constant B, C and D were then calculated using multilinear regression from TGA data in each zone using Linest function in Microsoft Excel sheet. The result shows that a hydrochar prepared at 180 °C has a higher activation energy compared to raw bamboo and other hydrochar

prepared at 220 °C and 260 °C due to the decomposition of cellulose and hemicellulose throughout carbonization process (Yang et al., 2016). Furthermore, the result also shows higher value compared to meso bamboo biochar prepared using pyrolysis and Coat and Redfern method of estimation. Despite that, the result was still lower than cellulose and hemicellulose extracted from bamboo using modified three-parallel-reaction model model (Yu et al., 2015). The difference in the activation energy value may be due to different heating rates used, biomass type and air used as oxygen could reduce the diffusion layer thus enhancing the volatile mass losses compared to nitrogen (Chen et al., 2014, Islam et al., 2015).

Meanwhile, Zhang et al has introduced the carbon concentration into calculation as all carbon concentrations in the products (hydrochar, liquid and gases) came from the initial carbon of cellulose (Zhang et al., 2018). The general formula used was as follows;

$$\frac{d_C}{d_t} = kC \tag{12}$$

Where k was defined as the Arrhenius equation while C represent the carbon concentration. The carbon concentration equation of the initial cellulose (A), soluble path (B) and solid pathway (C) were as follows;

$$C_A = 0.431(1-Y) \times Solid\ yield \times \frac{m_o}{v_o} \times 10^3 \tag{13}$$

$$C_B = 0.431 \times \frac{m_o}{v_o} \times 10^3 - C_A - C_C \tag{14}$$

$$C_C = 0.725Y \times Solid\ yield \times \frac{m_o}{v_o} \times 10^3 \tag{15}$$

Where Y represent carbo content of hydrochar and m_o/v_o represent initial solid concentration. The Rynge-Kutta-Method using ode45 function of MATLAB software was used to calculate the activation energy. The calculated activation energy of 'soluble pathways' in the study (53 kJ/mol) is lower compared to others studies (90.1 kJ/mol and 77 kJ/mol) and the possible explanations may be due to the ignorance of hydrochar formation under 'soluble pathway' as well as the advantages of microwave in enhancing hydrolysis efficiency (Álvarez-Murillo et al., 2016, Reza et al., 2013, Fan et al., 2013). Meanwhile, the solid pathway recorded an activation energy of 198.1 kJ/mol which is higher than soluble pathways (53 kJ/mol) indicates that it prefers higher reaction temperature. However, it is still lower compared to biochar prepared from pyrolysis due to less stable structure of hydrochar from MHTC compared to biochar from pyrolysis (Lédé, 2012).

4. Application of MAHTC Derived Hydrochar as Solid Biofuel

Even though biomass is known as one of the promising alternatives as an energy source, its application as a solid biofuel is limited due to low bulk density, high moisture content, low HHV, and high volatile content. Via MAHTC, hydrochar that is comparable to coal or lignite can produce high carbon content, high HHV, and high energy density (Pauline and Joseph, 2020, Sharma et al., 2020). Apart from that, the grindability of hydrochar is also enhanced because the microstructure is being altered thus decreasing the fibrous clinging nature. This happened due to decomposition, depolymerization and softening of hemicellulose, cellulose, and lignin respectively that facilitate the breaking down of lignocellulosic structure (Funke and Ziegler, 2010). Furthermore, the hydroxyl group present in biomass can contribute to the hygroscopic characteristic of biomass. Via MAHTC, the hydroxyl group will be terminated by dehydration reaction thus making biomass hydrophobic and more convenient for transportation and storage purposes (Yan et al., 2009).

4.1. Co-combustion With Coal

Co-combustion with coal is among the future outlook for hydrochar produced via MAHTC. The limitation in blending biomass with coal for co-combustion is the fuel segregation in the boiler, leading to lower efficiency of steam generation, fouling, and burnout at a lower temperature. Hydrochar with lower volatile matter and higher fixed carbon can be produced before co-combustion to ensure it is comparable to coal (Gao et al., 2019). Moreover, raw biomass is more significant compared to coal because of its fibrous nature making it difficult for co-combustion (Jenkins et al., 1998, Baxter, 2005). Despite that, hydrochar has a high grindability ability and easier to grind, making the problem solvable (Kambo and Dutta, 2015).

Study on co-combustion of hydrochar with coal is scarce as of now. Due to its more disordered carbon microcrystalline structure and more developed pore structure, increment of hydrochar in mixture blend will enhance the reaction condition of the mixture, leading to faster combustion reaction (Zhang et al., 2020). The combustion reaction can be enhanced until a certain point however the promotion effect will not be the same due to different structure and properties of hydrochar. Moreover, the activation energy obtained from Coats-Redfern method is also reduced as more hydrochar is mixed with coal (Zhang et al., 2020).

A hydrochar usually has higher volatile matter compared to coal thus making it easier to ignites (Li et al., 2011). Parshetti et al has co-combust EFB hydrochar with low rank Indonesian coal and it is discovered that an increased in blending ratios will reduce the ignition temperature (Parshetti et al., 2013). However, too much blending ratio with coal can lead to fire hazard. Thus, it is important to ensure that the reduction in ignition temperature is within the range (Muthuraman et al., 2010).

Furthermore, higher burnout temperature leads to higher temperature and longer time for complete combustion. It is proven that an addition of hydrochar in coal combustion can reduce the burnout temperature compared to sole coal combustion according to Liu et al (Liu et al., 2012). Additionally, the total burnout is also increased from 91.3% to 92.6% and 95.2% as 50% of eucalyptus leaves and coconut fibre are added to lignite respectively.

4.2. Co-MHTC with Other Biomasses

Another outlook is on co-MAHTC or by blending two different biomasses instead of only one and applying the MAHTC process on it. Animal manure and sludge are among the biomass types that have higher ash content and lower carbon content. Co-MAHTC with lignocellulosic biomass can increase the quality of the hydrochar by reducing the ash content and raise the carbon content (Lang et al., 2019, Zhang et al., 2017). Moreover, food waste and animal manure have lower lignin which leads to lower mechanical properties. Co-MAHTC with woody biomass better inter-particle bonding can improve the mechanical properties of the hydrochar making it more durable (Wang et al., 2018, Ul Saqib et al., 2019).

5. Challenges of Applying MAHTC

As of now, it is known that microwave heating has a variety of advantages with its dominant advantages in shortening the residence time. However, there is still limited study on the triple bottom approach which are technical, economic, and environmental aspects (Arowoshegbe, 2016). These aspects must be thoroughly reviewed to increase efficiency and enhance the hydrochar quality.

5.1. Technical Challenges

The result of experiment may contradict with different study by different researchers due to lack of standard for operation of instruments and detection techniques. Besides, the occurrences of metal discharge, microplasma and other special phenomena at random leads to difficulty in figuring the mechanism of microwave energy on chemical reactions (Guo et al., 2020). Thus, the fundamental mechanism and the effect of microwave energy on chemical reactions in HTC process have not been

established and effort from multidisciplinary energy field are needed to elevate the understanding and knowledge on this technology.

Moreover, the dielectric properties of biomass are a crucial factor for MW heating (Kostas et al., 2017). Biomass generally is a poor microwave absorber and there is limited study on the dielectric properties of biomass (Kostas et al., 2017). These properties must be fully understood because they can affect the permittivity of a microwave. Microwave permittivity is also dependant on temperature and frequency. These factors must be considered in designing a reactor to avoid any failure in the reactor to reach the desired temperature (Mitani, 2018). Moreover, MW absorbers are also necessary to deal with biomass's low dielectric properties (Yin, 2012, Li et al., 2016).

"Thermal runaways" and "hotspots" also may occur in MW heating due to heterogeneous electrical fields and non-uniform heating. Currently, the study on electromagnetic field distribution in MW heating is scarce, making it a great challenge in applying this system on large scale (Huang et al., 2016). Some studies have proposed solving it by continuously stirring and mixing the material while being carbonized (Wu, 2008). Moreover, the difference in domestic and industrial MW frequency is also a challenge as MW frequency can affect the product quality (Bundhoo, 2018). The knowledge of the interaction between MW and material is also lacking, making it difficult for scaling up.

5.2. Economic and Environmental Challenges

There is a limited study on the energy efficiency, energy balance, and MW heating economics for any biofuel conversion method (Arpia et al., 2021). A recent study has concluded that the MW system's energy efficiency is unfavorable as product yield is insufficient to counteract the energy input (Treichel et al., 2020). Techno-economic analysis (TEA) is among the analysis to determine the feasibility and viability of a system. The information needed to run the analysis is investment, feedstock type, capacity, product options, operation cost, and revenue (Wang et al., 2015). However, there is still limited study on the information needed, especially for MAHTC.

Impact on the environment is crucial in ensuring that an alternative has minimum effect on the environment. A study by Benavente et al has indicated that HTC has an excellent overall environmental impact except for freshwater eco-toxicity and freshwater eutrophication due to liquid discharge and gas emission (Benavente et al., 2017). Proper management of liquid discharge and gases emission can significantly improve the environmental impact (Berge et al., 2015). Additionally, capturing the heat generated to produce power can be implemented to increase environmental saving further.

In spite of all the challenges described, the development of microwave energy shows promising potential to be utilized for conversion of biomass into energy. By utilizing the microwave radiation and its special phenomenon such as metal discharge and plasma generated throughout the process, an enhanced selectivity of chemical reactions and higher efficiency process could be achieved (Guo et al., 2020). More efficient and cleaner biomass to energy conversion is achievable via the microwave application due to its characteristics and advantages. Thus, with better understanding on microwave principles and continued research and development, an industrial scale production of hydrochar via MHTC is within reach.

6. Conclusion

Currently, GHG and CO_2 emission has been significant challenges globally. One of the major contributors is the application of fossil and natural gas for power and electrical plant. To cater to these, biomass has been one of the promising alternatives, specifically solid biofuel. HTC is preferred to produce a sold biofuel as it is more cost and energy-efficient than pyrolysis. Water as a solvent in the HTC process also has its advantages. Besides, the microwave heating system is preferred compared to a conventional heating system. It can significantly reduce

the reaction time, decrease power consumption, en-hance the HHV, and improve energy efficiency.

The study of kinetics for the hydrochar produced via MAHTC is still limited and should be studied. The hydrochar obtained from MAHTC is comparable to coal or lignite as it has high carbon content, high HHV, and high energy density. Moreover, high grindability can help in the co-combustion of hydrochar with coal to reduce fuel segrega-tion in the boiler, thus increasing efficiency and preventing fouling. Co-MAHTC is another study to be considered as it can offset the weakness of individual biomass properties.

The lack of knowledge in the technical aspect of microwave heating is a challenge to apply on a bigger scale. The dielectric properties of biomass and "hotspot" occurrences in microwave heating are among the technical side challenges. Furthermore, the lack of information on the economic side makes it difficult to employ the Techno-economic Analysis (TEA). The environmental side has an excellent overall environmental impact except for freshwater eco-toxicity and freshwater eutrophication. This can be prevented by having proper management of liquid discharge and gases emission

Declaration of interests

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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