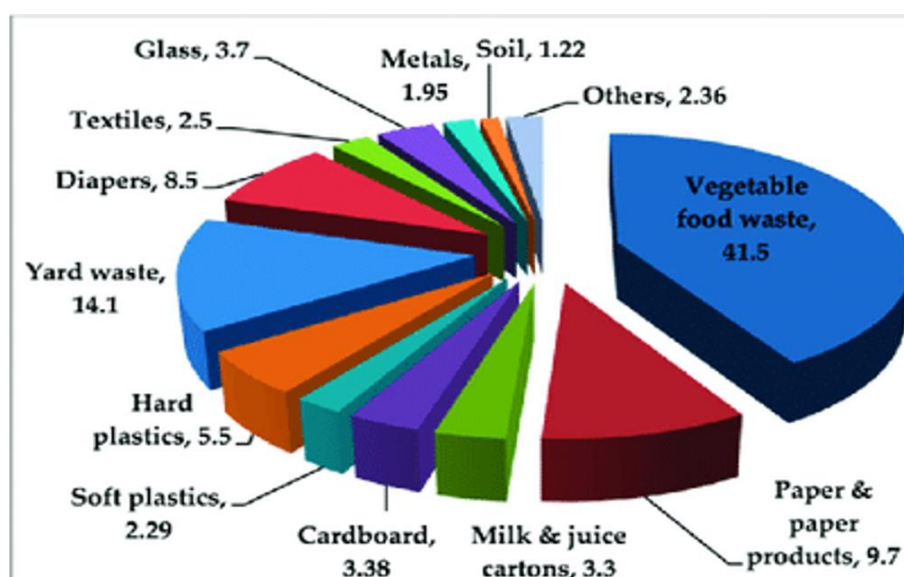


Production of biochar from Municipal Solid Waste via torrefaction and pyrolysis

The generation of Municipal Solid Waste is increasing at a rate of 8 -10% annually and it is estimated that more than 150 million tons of MSW is produced annually. Municipal solid waste (MSW) is waste material produced by households and businesses in cities and include paper, food waste, leather, plastics/rubbers and fabrics etc. All these are source of biomass. There are many different types of municipal solid waste, and these are now divided into three main types: Such waste categories include; food waste, municipal solid waste mixtures and recyclable waste.

Global generation rate of municipal solid waste is approximately 4 billion tonnes per year; with both food waste/rotting matter contributing to approximately 30–45% of the total based on the geographic location and country. Based on experiments, food waste sampling can be divided into seven types: Noxious food particles including meat and bones, starchy staples, vegetables, nut shells, fruit peels soya bean residues and tea leaves.



Composition of Solid Waste generated from households

Pyrolysis involves the process where biomass undergoes decomposition in the lack of oxidizing agents. This is generally at 300-650°C and can go beyond this point for certain types of biomass feedstock. In the Pyrolysis Process, the body of biomass is heat to the pyrolysis temperature and retained at that temperature for a certain period. The biomass degrades into 3

constituent yields: 1) Coarse ashes- Char or Carbon 2) Naphtha, Heavy oil and Water 3) Gaseous product – CO₂, H₂O, CO, C₂H₂, C₂H₄, C₂H₆, C₆H₆ & etc. During pyrolysis, heat is transferred to the product mainly by electricity and convection, although some heating processes use conventional methods. The main known heat transfer processes are: - Heat conduction in particles - Convection in particle pores - Convection and heat from particle surfaces. Pyrolysis therefore is a non-oxidative form of thermal decomposition process. It results in the formation of three unique product fractions: Solid residue is known as biochar; Liquid, which can be condensed is called bio-oil; Gaseous which does not condense is referred to as syn-gas. Combustion is impossible when oxygen is taken out from the mixture; what takes place is pyrolysis. Thus, with moderate temperatures and short residence time there is more of the liquid produced. Char generation is usually prompted by intramolecular and / or intermolecular rearrangement events and leave behind a residue that will have superior thermal stability. This route is thus determined by the synthesis of benzene rings as well as the linking of these rings to create an aromatic polycyclic system. In most of the cases, these rearrangement reactions accompanied by the evolution of liquid or gases.

Torrefaction is a less severe type of pyrolysis that is performed at temperatures of about 200-300 °C. It is mainly applied as a precondition for feeding biomass through the process of enhancement of the energy to density ratio by drying. During the process the biomass gets dry and undergoes partial de-volatilization in such a way that the Biomass weight is highly reduced but the energy value is retained. Biomass turns black increases its density, and becomes dry and hard (due to the breakdown of Hemicellulose molecules of the biomass). Since it makes the biomass easily manipulated and easy to mill it cuts down on the handling cost. In short, it will enable a tough strand structure to weaken like coal so as to be crushed for application in a boiler or any other reactor. Reduces the Biomass mass to 62%-69% of their initial weight although, the energy density can rise by 29%-33%. This process will transform the Biomass in a way that it will have lesser inclination towards absorbing moisture when it is stacked than normal Biomass.

METHODS –

MSW collection and pre-treatment

The components of the MSW were then separately picked up from the markets and households then stored accordingly in their respective bins. Individual samples of the MSW

components were sun –dried whilst other portions were oven-dried at 60°C for 48 hrs after which the whole mass of the fully dried components of the MSW were crushed using a hammer mill and a multi-purpose shredder. After drying the MSW samples, each was ground and then kept in an airtight container to inhibit moisture from seeping into it.

MSW characterization

Then the collected waste is gone through proximate and elemental analysis.

Pyrolysis

Depending on which crop residue feedstock is to be converted into biochar through pyrolysis, relevant pyrolysis technology needs to be chosen for the best biochar output in terms of (for instance, process efficiency, cost, with reference to the environment, etc.). This review focuses on six major types of pyrolysis technologies: fast, slow, flash, vacuum, and hydro pyrolysis as the conditions of operation permit.

In **slow pyrolysis**, heating rate ranges between 0.1 and 1°C/s with residence time varying between 300 to 7200 seconds while its temperature ranges from 300 to 600 degree Celsius. The low heating rate minimizes secondary pyrolysis and thermal cracking of biomass in the pyrolysis process, which leads to the production of biochar as the dominant product. Mineral-rich biomass produces less biochar. Due to the systematic development of secondary reactions, slow pyrolysis could be exothermic.

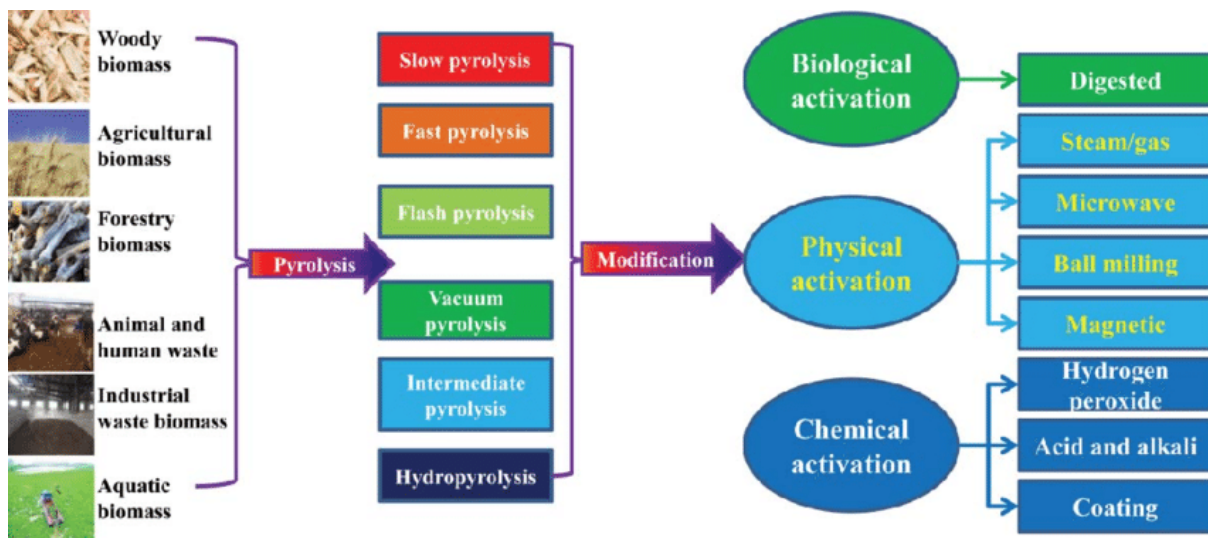
Fast pyrolysis is performed at high temperatures, high heat rate of 10-1000°C per second and with a short residence time of 0.5 to 2 seconds. Thus, fast pyrolysis works to prevent secondary reactions by minimizing the time during which the vapours are held and by ensuring that the biomass is heated rapidly. This is because yields from fast pyrolysis processes contain only primary carbon and are therefore usually lacking in biochar yields. The main reactions are rapid pyrolysis reactions, whereby, because the secondary reactions are unavailable, the whole process becomes endothermic. Low moisture content also prevents the formation of large particles which would make it difficult to heat and undergo pyrolysis quickly.

Flash pyrolysis aims to optimize biofuel production. High temperature is characterized by high speed ($> 1000^{\circ}\text{C/s}$) and short contact time ($< 0.5\text{s}$). Flash pyrolysis produces essentially the same product as fast pyrolysis. It occurs between 800 and 1000°C. Generally good biomass feed pellets ($< 0.2\text{mm}$) are needed.

Vacuum pyrolysis uses reactors operating at sub-atmospheric pressure to thermally crack feedstocks in the absence of oxygen. The pyrolysis temperature and heating rate are 300~700°C and 0.1~1°C/s, respectively. The vacuum pyrolysis reaction leads to a high yield of bio-oil due to the effect of secondary destruction required for biochar production. For vacuum pyrolysis, increasing the pyrolysis temperature reduces the biochar yield, which is synergistic with other types of pyrolysis.

In **intermediate pyrolysis**, the reaction is faster than in slow pyrolysis and slower than in fast pyrolysis. It occurs between 450 and 550 °C, is faster than slow pyrolysis, takes 10-30 seconds to complete, and produces less electricity than slow pyrolysis. Intermediate pyrolytic chemical synthesis at appropriate temperature prevents the formation of high molecular weight tars and leads to the formation of many products (biochar, bio-oil and oil). The size and shape of biomass particles are not as important in intermediate pyrolysis as in fast pyrolysis. It can process a wide range of biomass, from larger pieces to pellets and chips, and data is close to 40%.

Hydropyrolysis is with hydrogen with a high pressure in the atmospheric condition inside the reactor for the process. The process parameters for hydro-pyrolysis are generally in the following ranges: pressure ranges from 10 to 17 MPa, pyrolysis temperature ranges between 350 and 600°C, heating rate is between 10 and 300°C/sec and residence time of more than 60 seconds and H₂ has a synergistic effect in enhancing the biochar conversion while minimizing the formation of tar and light aromatics secondary reactions.



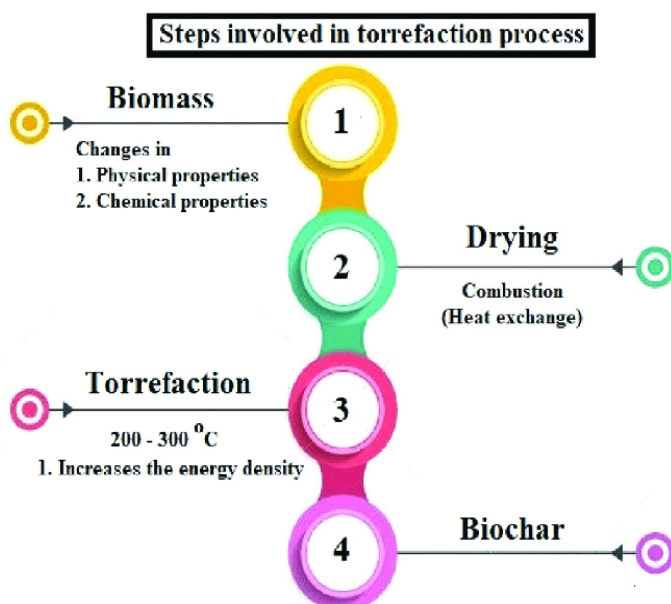
Pyrolysis processes

Biochar characterization

Economic analysis, ingredient composition, high heating value (HHV), surface area and morphology were used to evaluate the properties of biochar obtained under suitable conditions. Composition and HHV analysis followed the MSW characterization process. Nitrogen adsorption analysis was used to determine the area, while field emission scanning electron microscopy was used to analyse the shape of the biochar.

Torrefaction

Dry torrefaction is normally carried out at temperature of 200-300°C which is a mild form of thermal degradation. Biomass reactions involved in dry torrefaction include hemicellulose, lignin, and cellulose devolatilization and depolymerisation, and carbonization. In dry torrefaction, the reaction atmosphere has also evolved from inert gases to non-inert gas atmospheres including CO₂, O₂, and NH₃. In conventional dry torrefaction, the carrier gas of



choice is nitrogen, which is energy-intensive and costly due to separation and production. On the other hand, the oxidative torrefaction use a specific amount of air as the carrier gas hence avoiding the use of inert gases and energy. It is assumed that the, and the feasibility of using oxygen-containing flue gas as the carrier gas for oil palm biomass torrefaction, proposed a reaction mechanism for oxidative

torrefaction including two consecutive reactions or two parallel reactions, with the first stage of the torrefaction reaction and the second stage of the oxidation reaction. The main process of oxidative torrefaction is surface oxidation, which can help to mitigate heat and mass transfer constraints in the inert gas environments. It was observed that oxidative torrefaction produces biochar with higher ash yield than non-oxidative torrefaction.

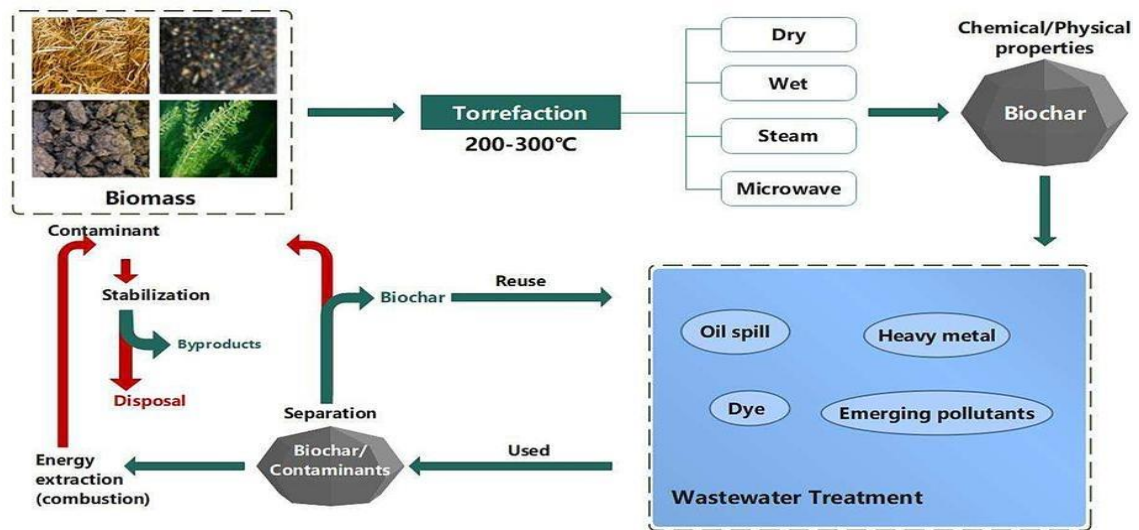
Wet torrefaction sometimes called hydrothermal carbonization (HTC) or Hydrothermal torrefaction (HTT) is a process that involves the use of hot compressed water and thermal liquid media at temperatures between 180°C and 260°C. They include: a] Loading and preparation of water and biomass; b] Pressurization and heating; c] Torrefaction proper; d]

Cooling and depressurization; e] Product collection. The first step is hydrolysis during which hemicelluloses and cellulose are degraded into oligomers and monomers while lignin does not experience extensive degradation at this stage. It has the ability to work on relatively wet, or even highly moist biomass feedstock including algae (micro and macro), sludge, cattle and pig dung etc. as it doesn't require the energy intensive pre-condition of dewatering very wet feedstock. There are three main advantages of wet torrefaction compared to dry torrefaction: This is due to the ability of the gasification process to accept a wider variety of biomass feedstocks, high energy density, heating value, and fixed carbon as well as low inorganic metals.

Steam torrefaction is a process where biomass is subjected to high temperature and high pressure, then treated with steam explosion. The application of steam torrefaction primarily only alters the heat transfer medium. Superheated steam provides a larger heat capacity and higher heat transfer rate as compared to N₂ or air and does not have mass transfer limitations. With steam torrefaction, past research was focused on pressurization, while high-pressure reactors had to be developed to enhance the performance and cost-effectiveness of the process. Greater pressure leads to an increase in the rate of thermodegradation. Subcritical steam torrefaction is significant, which utilizes pressure beneath the vapour pressure. Superheated steam as the only heat source and the carrier gas at atmospheric pressure obtains torrefied carbon with the same characteristics as slow pyrolysis carbon fuel at 350 °C within 15 minutes, while steam torrefaction does not require the preliminary removal of water from the biomass and results in increased elasticity and mechanical properties of the particles. Steam torrefaction needs much less water to heat the steam than the wet torrefaction, and even the moisture of the wet substance itself is adequate. However, its energy yield is still poorer than torrefied charcoal derived from untreated feedstock and steam torrefaction needs more energy to expel the particles from the mold.

Microwave torrefaction utilizes a microwave reactor to control the electromagnetic wave for biomass torrefaction, which provides a longer penetration depth as well as an even distribution of temperature, both of which are beneficial for the uniform preparation of biochar. Some of the advantages of employing microwave radiation in heating are the duration of heating, enhanced internal thermal conductivity, control of heating and more balanced heating. Microwave torrefaction is also found to have a shorter reaction time as well as a higher heating value of the biochar, but with a lesser biochar mass yield as compared to conventional torrefaction. Conventional torrefaction in feeds from waste coffee and microalgae residues

used in torrefaction treatments require between 15-60 min while the microwave torrefaction ranges from 2-10 min. Since, microwave and volumetric heating selective in nature in the



Torrefaction processes

context of drying process, whereas more effective degradation at comparatively low activation energies.

Process	Process temperature	Residence time	Solid product yield on a dry wood feedstock basis (mass %)	Carbon content of the solid product (mass %)	Carbon yield ($\text{mass}_{\text{carbon, product}}/\text{mass}_{\text{carbon feedstock}}$)
Slow pyrolysis	~400	Minute to days	~30	95	~0.58
Fast pyrolysis	~500	~1 s	12–26	74	0.2–0.26
Gasification	~800	~10–20 s	~10	—	—
HTC	~180–250	1–12 h	< 66%	< 70%	~0.88
Flash carbonization	~300–600	< 30 min	37	~85	~0.65
Torrefaction	~290	10–60 min	61–84	51–55	0.67–0.85

Comparison of typical operating conditions and product properties of various biochar production processes