Chapter

Economics, Sustainability, and Reaction Kinetics of Biomass Torrefaction

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Abstract

Biomass torrefaction is capable of significantly improving the quality and properties of solid biofuels. It is often referred to as complex reactions involving the decomposition of lignin, cellulose, and hemicellulose as well as moisture evaporation due to several reactions involved. To evaluate the efficiency of the torrefaction process as well as the reactor performance, considering the economics of biomass torrefaction including the total production cost and capital investment, production capacity, feedstock input, feedstock type, pre-treatment, procurement and transportation costs is of high importance. In this Chapter, the economics of torrefaction process will be discussed. In addition, ways to ensure competitiveness of torrefaction technology will be explained provided factors including the use of plant with larger capacity, integrated system features such as pelletization, and moisture content of the feedstock, are properly considered. Thereafter, the concept of sustainability of biomass torrefaction in relation with the environmental factor (sustainable forest management), social factor (revitalization of rural areas), and economic factor (fossil fuels dependence and renewable energy consumption) will be presented.

Keywords: biomass, fuels, torrefaction, renewable energy, lignocellulosic, lignin, briquettes

1. Introduction

Biomass has been widely recognized as an important source of renewable energy due to its inherent properties such as availability, abundant supply, carbon stability, organic nature, etc. Unlike non-renewable resources such as oil and coal, biomass is a renewable natural resource and organic material mostly derived from animals and plants for the production of fuels at local and commercial scales, which is the dream of many biofuel producers and energy experts over the years. Interest in biomass as a renewable resource is increasing with time thanks to its ability to be burned directly for heat or converted to renewable fuels via several thermal decomposition methods including torrefaction, gasification, hydrotreating, carbonization, and pyrolysis [1–4].

It is important to know that biomass which can be crops, wood, landfill gas, alcohol fuels, and garbage contribute the largest percentage of energy used in many sectors including the electric power, commercial, residential, commercial, transportation, and industrial. For instance, wastes derived from biomass and woods are used to produce electricity in electric power sector, renewable natural gas derived from municipal solid waste (MSW) are consumed and sold in commercial sector whereas the wood pellets and firewood are mostly consumed in residential sector. In addition, the plant and animal-based biomass are used to generate liquid biofuels including biomass-based diesel and ethanol which finds major application in most transportation and industrial sectors.

Biomass can be converted to energy via several methods such as biological conversion for the production of fuels (gaseous and liquid), chemical conversion for producing liquid fuels, thermochemical conversion for the production of liquid, gaseous, and solid fuels; and direct combustion to generate heat. In biological conversion process, biomass can be converted into renewable natural gas or biogas [5] through anaerobic digestion method or ethanol through fermentation process. Meanwhile, in chemical conversion process, greases, animal fats, and plant-based biomass such as vegetable oils can be converted into fatty acid methyl esters (FAME) which are mostly utilized for the production of biodiesel through trans-esterification method. On the other hand, through thermal decomposition methods including torrefaction, gasification and pyrolysis, biomass can be thermochemically converted to produce bio-oil (hydrotreating), hydrogen, methane, renewable diesel (pyrolysis), or synthesis gas and carbon monoxide (CO) (gasification) [1, 2, 4]. Furthermore, biomass can be converted to energy in direct combustion method such as the generation of electricity in steam turbines, industrial process heat, and heating buildings.

Generally, biomass sources for energy include but not limited to human sewage and animal manure, biogenic materials in MSW (wood wastes, yard, food, wool products, cotton, paper), waste materials and agricultural crops (woody plants, switchgrass, sugar cane, soybeans, corn, etc.), and wood processing wastes (paper mills, sawdust, wood chips, wood pellets, firewood) [6–11]. For easy storage and transportation, biomass can be interestingly made or densified into briquettes for producing fuels and biogas [5]. Briquettes are the solid biofuels with compact shape and size for producing renewable energy which can be made with binders [6, 8–11] or without the use of binders [7]. Biomass has been densified into solid briquettes in the past using the same or different materials including corncob, rice bran [8–10], mesocarp fiber (MF), fruit fresh bunches (FFB), palm kernel shell (PKS) [8–11], bagasse, tea waste, cotton stalk, sugarcane bagasse (SCB), empty fruit bunches (EFB), etc. Most of the performance related problems such as low yield and energy content are linked to the effectiveness of the binder materials, type and compositions [6].

As a form of thermal decomposition processes of converting biomass to energy, torrefaction is presently receiving wide attentions for producing high grade solid biofuels with greater energy density/high heating value (HHV). Torrefaction process is capable of significantly improving the quality and properties of solid biofuels. It improves the physicochemical properties of biomass for a long-term storage. In addition, torrefied biomass can serve as a good replacement for coal in the generation of heat and electricity. The three common types of torrefaction types are the dry torrefaction (DT), wet torrefaction (WT), and ionic-liquid assisted torrefaction (ILA) [6]. The DT is usually carried out in a gas-phase environment, while the WT is often performed under pressure of a liquid-phase environment. Meanwhile, the ILA is a combination of a typical torrefaction and a pretreatment process, which is aimed at improving the reaction rate. The ionic-liquid assisted torrefaction (ILA) usually involves the use of ionic liquids which is often referred to as green solvents due to their ability to dissolve lignocellulosic biomass under normal conditions due to their special properties such as recyclability and high thermal stability [4].

However, an in-depth understanding on the economics and sustainability of the torrefaction process is lacking. With the aim of giving new insight into further study, a comprehensive overview on the reactor design for commercialization purposes, reaction kinetics and mechanism, economics, as well as the sustainability of biomass torrefaction is presented in the next section of this chapter.

2. Biomass torrefaction: A general overview

Biomass torrefaction is the process of producing high-quality and attractive solid biofuels from several sources of ordinary agro residues or woody biomass, with the sole aim of improving biomass properties and performance for gasification [1–3] and combustion applications via thermal decomposition at temperature ranging from 200–300°C [12] under atmospheric pressure. Through torrefaction, a coal-like material can be generated from biomass with superior fuel properties and quality when compared with the parent materials. Torrefaction is a mild pyrolysis process where biomass is thermally treated in a controlled environment (in a non-fluidized bed reactor or fluidized bed) with low or no traces of air or oxygen [13] resulting in the production of torrefied biomass which is water resistant, brittle and stable with less energy intensive and easy grindability. During torrefaction, drying of biomass and partial devolatilization occurs leading to mass reduction without losing or decreasing the energy content. Heating biomass at typical temperatures between 200°C and 300°C often lead to the evaporation of moisture or unbound water (H_2O) through thermo-condensation process (at temperature above 160°C) and the removal of volatiles (low-calorific parts), resulting in the decomposition of hemicellulose in the biomass hence the transformation of biomass from a low-quality fuel into an excellent high-quality fuel. In a bid to improve the biochemical, chemical, and physical properties of biomass, the basic principle behind the biomass torrefaction process can thus be summarized as the removal of volatiles via several decomposition reactions. With torrefaction, there is no biological activity, hydrophobicity and higher durability can be obtained, excellent grindability and higher bulk density can be achieved. In addition, more homogenous product and a fuel comparable to coal can be produced with higher calorific value as compared with original feedstock.

It should be noted that the torrefaction processing parameters such as the residence time and torrefaction temperature have significant effects on the overall properties and performance of torrefied biomass. In other words, there is a direct relationship between the torrefaction processing parameters and the physicochemical properties of torrefied biomass. For instance, high torrefaction temperature and short residence time tend to optimize the material flow via the torrefaction reactors thereby producing a cost-efficient torrefied biomass on a large scale. By increasing the torrefaction temperature, the fixed carbon and ash contents in biomass can be markedly increased with a decrease in volatile contents. This can lead to a decrease in atomic ratios of oxygen-carbon (O/C) and hydrogen-Carbon (H/C), as well as decreasing the oxygen content resulting in improved calorific value, which ultimately enhance the overall fuel features and performance of the biomass products. Moreover, the acid content in biomass materials can be significantly reduced with increasing the torrefaction temperature. The decrease in the acidity of the biomass say bio-oil for example [14] can be attributed to the fact that the acetic acid solely originates from the deacetylation reaction and decomposition of hemicellulose component of the biomass. In addition, increasing the torrefaction temperature can reduce the moisture content of the biomass, hence improving the quality of the biomass. By this, it can be said that torrefaction can increase the carbon yield of aromatic hydrocarbon and decrease the number of compounds containing oxygen in the biomass such as furans, sugars, and acids [15]. Furthermore, an increase in the residence time and torrefaction temperature can improve the hydrophobicity and the calorific value and lignin contents can be increased by decreasing the contents of hemicellulose and cellulose [16]. While studying the influence of torrefaction temperature on the production composition, physicochemical properties, structure, and yield of bio-oil [14], an increase in torrefaction temperature reportedly reduce the crystallinity index as a result of recrystallization and degradation, increase the pore volume and the residual carbon contents, decrease the pyrolysis peak temperature and increases the carbon-carbon contents.

The residence time during torrefaction process can also directly influences the biomass properties including the energy density, surface area, and grindability. For instance, increasing the residence time tends to increase the energy density and grindability, leading to the production of biomass with fine and small particle sizes thereby resulting in larger surface area. In addition, due to the disintegration of the fiber structure of biomass, increasing the residence time can increase the fixed carbon and volatile matter compositions. In other words, the higher the residence time, the better the properties and compositions of biomass materials. Heating value can also be increased with an increase in residence time and the disintegration of fiber structure continues with increasing the residence time, thereby enhancing the grindability and improving the energy density of the biomass products. Meanwhile, grindability is an important property in biomass torrefaction which is the resistance of biomass materials to be ground.

In terms of composition, biomass can be broadly categorized as non-lignocellulosic (mostly rich in fatty acids and protein) with animal manure and fat, and sewage sludge as the main components; or lignocellulosic with hemicellulose, cellulose, and lignin as the major components, together with small amounts of minerals, proteins, and pectins [17–21]. As indicated in **Figure 1**, torrefaction process involve several stages ranging from the initial to the solids cooling [22–25].

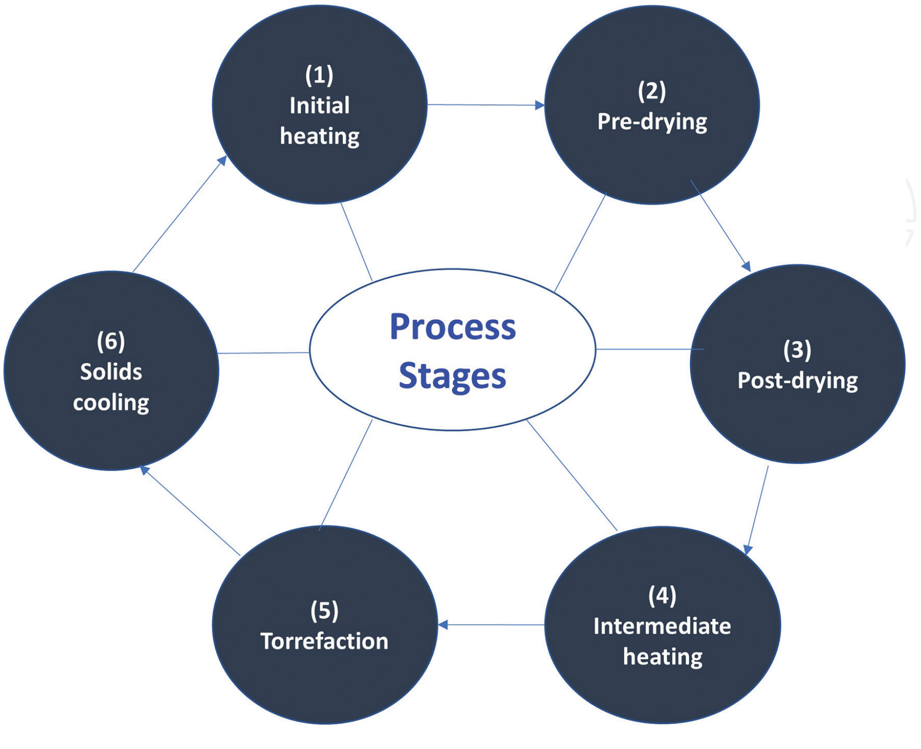

Figure 1.
The main stages in the total torrefaction process.

Figure 2 presents the mechanism of the thermal treatment during dry torrefaction, from decarboxylation to aromatization chemical reactions. During the thermal conversion in dry torrefaction, an improvement in the fungal resistance [26–34], dimensional stability, absorption, water vapor, and durability can be achieved. As illustrated in **Figure 3**, the binderless briquetting technology can be summarized into several theorems including capillary, adhesion molecule, bituminous, humic acid, colloid, and denser water.

As compared with the original biomass, torrefied biomass offers many advantages including homogeneity, increased density in briquettes, reduced grinding

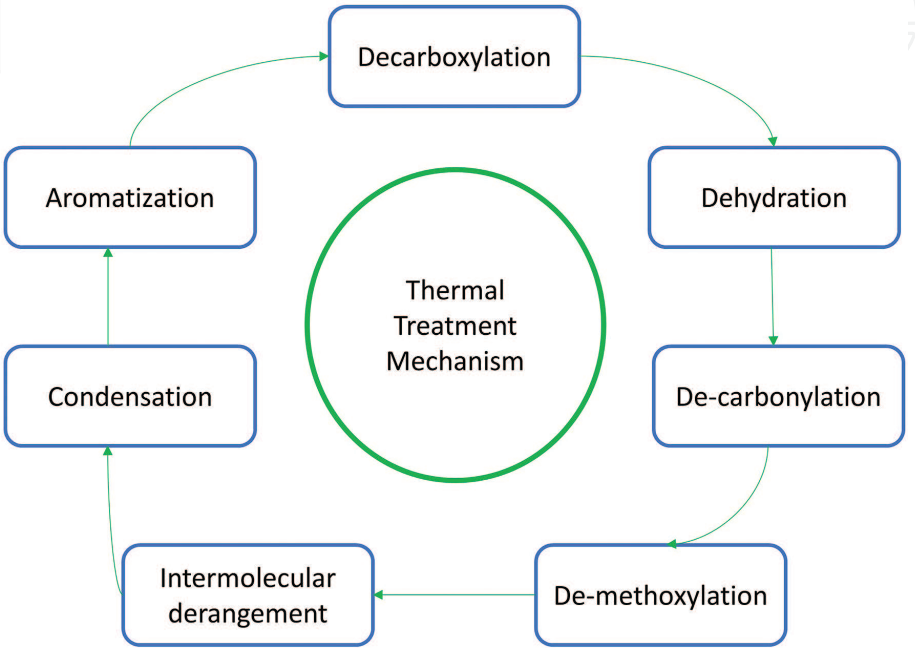

Figure 2.
Mechanism of the thermal treatment during dry torrefaction.

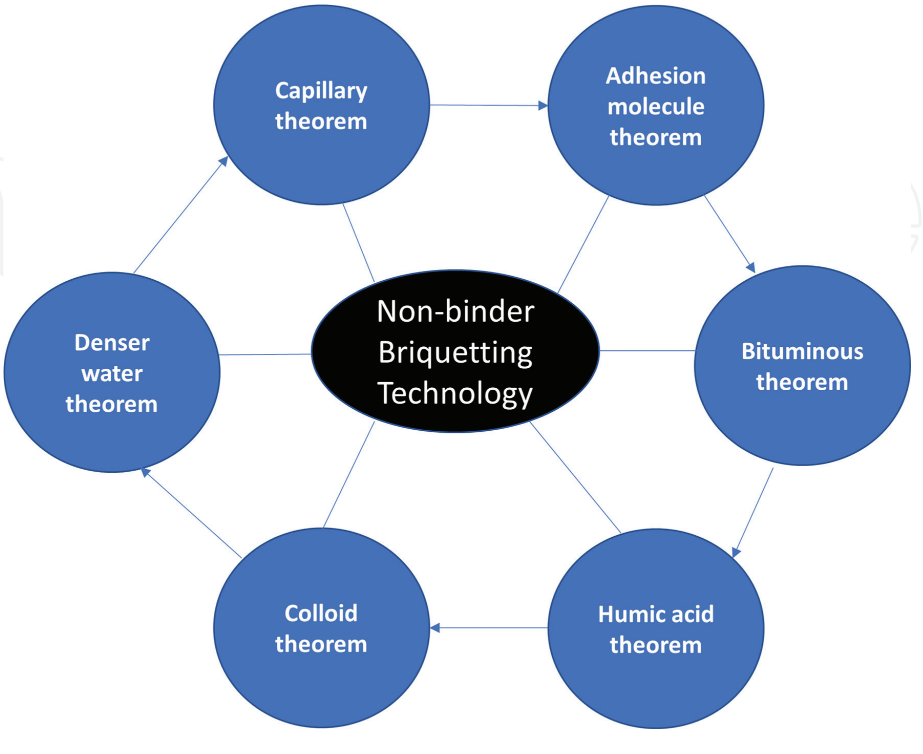

Figure 3.
Binderless briquetting technology.

energy, hydrophobicity, increased energy density, and lower moisture content. As a source of a power source, with torrefied biomass, low net carbon energy source and renewable fuel for baseload power can be achieved.

3. Economics of biomass torrefaction

While ensuring the conversion of biomass into renewable energy for the benefits of mankind, it is necessary to consider the economics aspect of biomass torrefaction. That is, the costs of generating high-grade fuel should be affordable. The economic features of the torrefaction process covers the total production cost, total capital investment, production capacity, feedstock input, feedstock type, procurement costs, transportation costs, pre-treatment, etc. [4].

For effective economy analysis, economic optimization of the system, including the extended fuel supply to application system, and integrated process between torrefaction and gasification as well as torrefaction and gasification should be properly looked into. The cost of the torrefaction process which is higher than that of coal at times can be greatly reduced by improving the empirical cumulation and torrefaction plant equipment size and as well as the utilization of carbon credits market. The total costs during the torrefaction process is often influenced by the important sensitivity parameters including the torrefaction plant CAPEX and torrefaction mass yield, drying technology, biomass moisture content, logistics equipment, biomass premium, and the quantity of the available biomass [2, 3]. Meanwhile, the depreciation, biomass delivery costs, energy consumption, labor, capital expenditure, biomass delivered costs are the common influencing factors for production with CAPEX.

Biomass torrefaction is widely regarded as a breakthrough technology accounting for the world largest renewable energy which reduces the investment for co-firing application as well as decreasing the storage and handling costs thereby making the process economically viable and serving as a potential way of replacing coal in power plants.

4. Sustainability of biomass torrefaction

Biomass torrefaction involves the conversion of biomass into a coal-like material with improved fuel properties as compared with the original biomass. It is presently a vital tool for the sustainable development in many developed and developing countries with the aim of supporting large scale utilization of bioenergy through the reduction of carbon dioxide (CO_2) at source and other emissions which may be harmful to the community. That is, the production of solid sustainable energy can be obtained through biomass torrefaction. It is important to note that biomass torrefaction can pose threats to humanity since some harmful toxins and greenhouse gases are usually generated and released into the atmosphere during biomass combustion resulting into environmental problem. Carbon dioxide (CO_2) remain the greenhouse gas with the largest volume and percentage released into the atmosphere when compared to other greenhouse gases. Biomass as a renewable energy which has some similar features with fossil fuels still have some environmental challenges. It can cause deforestation and it is not entirely clean.

Sustainability concept of biomass torrefaction can be properly broadly categorized into three factors; (1) economic factor, (2) environmental factor, and (3) social factor [4]. Generally speaking, the economic factor is majorly related to the fossil fuels dependence and renewable energy consumption whereas the environmental factor is associated with the sustainable forest management. On the other hand, the social factor is linked with the regeneration of rural areas and more jobs.

5. Reaction kinetics of biomass torrefaction

To a large extent, torrefaction process can influence the overall kinetics and mechanism [35] as well as the reactivity, reaction behavior, and thermal conversion performance of biomass which is often estimated through thermogravimetric analysis (TGA). Through TGA, the reaction kinetics parameters including the mechanism function, pre-exponential factor, and activation energy [36, 37], as well as the thermal features including temperature at peak value, reaction period, peak value, and thermogravimetric (TG) data can be determined. In addition, biomass torrefaction is often regarded as a complex mechanism due to the several reactions involved including the decomposition of the common biomass components including lignin, cellulose, and hemicellulose as well as moisture evaporation.

The decomposition of the biomass components depends to some extent on the temperature at which the torrefaction process is carried out. For instance, at the temperature range of 160–900°C, lignin slowly decomposes, cellulose decomposes at 315–400°C, while the hemicellulose decomposes at the lowest temperature ranging from 220–315°C [38]. For instance, while the torrefaction of hemicellulose leads to more devolatilization and carbonization, the depolymerization of cellulose plays a vital role in the decomposition mechanism. The study on the kinetics of biomass torrefaction is very important because it represents the torrefaction reaction thereby predicting the optimum thermal degradation conditions which can ultimately enhance the process control for continuous torrefaction reactor [39, 40]. Meanwhile, at the temperature range of 230–300°C [41], the kinetics of torrefaction reactions can be best described by a two-step mechanism; cellulose and hemicellulose decomposition.

6. Conclusions

Biomass upgrading for the production of high-grade solid fuels with greater energy density, excellent grindability, and enhanced durability can be achieved by subjecting the original raw biomass to thermal mild pretreatment process under inert atmosphere without the presence of air or oxygen. This process is commonly referred to as torrefaction. The major aim is to improve the chemical, thermal, and physical properties of biomass for a long-term storage through the elimination of oxygen, reduction of moisture content and change of chemical compositions. After torrefaction, some challenges pertaining to technological applications of biomass such as difficulty to obtain a small particle size and high oxygen–carbon ratio, can be properly addressed.

Upon the mild thermal pyrolysis of raw biomass in oxygen-free or N_2 atmosphere at moderate temperatures over a period of time, the biomass fiber structure tends to break down which makes the biomass easy to grind, hence an enhanced energy density. By this process, the properties of raw biomass including low calorific value, grindability, hydrogen-carbon and, hygroscopicity, can be greatly improved. At first, torrefaction process can reduce the weight of the biomass to about 30%, but the final solid biofuel produced can retain about 90% of the original biomass energy content.

As compared to the original raw biomass, torrefied biomass can serve as a good replacement for coal in the generation of heat and electricity, as well as input for gasification, densification, and iron making processes, with many positive attributes, like grinding and burning like coal, lower ash and sulfur content, lower transport and shipping costs, lower feedstock costs, and the ability to produce non-intermittent renewable energy. Hence, further studies to understand the mechanism behind the torrefaction process in producing more uniform biomass products and the influence of torrefaction process parameters on the biomass feedstock upgrading is necessary to open the market for the mass production of high-grade solid biofuels with enhanced energy density and hydrophobicity for a long-term storage.

Attributed to the several reactions involved, biomass torrefaction is sometimes referred to as the complex reactions including the decomposition of the common biomass components including lignin, cellulose, and hemicellulose as well as moisture evaporation. The economic, environmental, and social factors are the three major concepts of sustainability as regards the biomass torrefaction. While the economic factor is majorly related to the renewable energy consumption, the environmental factor focused more on the sustainable forest management while the regeneration of rural areas and more jobs is related to social factor. The economics of biomass torrefaction including the total production cost, total capital investment, production capacity, feedstock input, feedstock type, pre-treatment, and procurement costs, transportation costs are necessary to evaluate the efficiency of the torrefaction process as well as the reactor performance.

Nomenclature

MSW	municipal solid waste
FAME	fatty acid methyl esters
CO	carbon monoxide
CO_2	carbon dioxide
O_2	oxygen
H_2O	water
HHV	high heating value
PKS	palm kernel shell
MF	mesocarp fiber
FFB	fruit fresh bunches
EFB	empty fruit bunches
DT	dry torrefaction
WT	wet torrefaction
ILA	ionic-liquid assisted torrefaction
TGA	thermogravimetric analysis
SCB	sugarcane bagasse
CAPEX	capital expenditures
O/C	oxygen–carbon
H/C	hydrogen-carbon
TG	thermogravimetric

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