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Wet torrefaction of biomass for high quality solid fuel production: A review

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ABSTRACT

Wet torrefaction (WT) is a sustainable subcritical water pretreatment technology to upgrade moist biomass into hydrochar solid fuel with superior fuel properties with the avoidance of energy-intensive conventional thermal drying. In order to obtain a holistic understanding of WT processing system, this review has comprehensively discussed recent advances in WT of biomass to produce high quality solid fuel and its subsequent thermochemical applications. This review has not only summarized distinct advantages of WT over dry torrefaction of biomass with high moisture content but also clarified the similarities and differences between WT and hydrothermal carbonization. According to structures and chemical compositions of components therein, four representative categories of diverse biomass materials were selected to describe the influence of intrinsic nature of biomass on fuel quality of hydrochar derived from WT. Furthermore, this article has attempted to figure out the inherent relationship between WT conditions and fuel properties with respect to operating conditions (e.g. temperature, pressure, and residence time), biomass to water ratio, acids and additives, torrefaction atmosphere, and heating techniques. Three conventional thermochemical applications of wet-torrefied biomass have been extensively reviewed to reveal that WT could benefit energy recovery from wet biomass in terms of improved quality of ultimate energy carriers and obviously reduced pollutants emissions. Nevertheless, critical concerns associated with optimization of operating cost, minimization and controlling of pollutants emissions, re-design of industrially applicable reactor, and system integration with downstream applications have been pointed out in order to make WT technology more environmentally and commercially viable.

1. Introduction

Due to the rapid depletion and relatively high cost of non-renewable fossil fuels as well as induced severe environmental concerns, more efforts have been made to explore alternative inexpensive and renewable energy sources (RE) with less or no environmental impacts in order to meet dramatically increasing energy demand worldwide [1–3]. Biomass is currently becoming another primary energy source to reduce the dependence on fossil fuels (e.g. coal, oil and natural gas) [3,4]. To date, as one of the major globally applicable RE, the carbon-neutral biomass energy contributes nearly 10% to annual energy consumption [5]. Thus, biomass attracts remarkable attention to tackle with increasing sustainable energy demand in future [6]. Recently, based on current share of RE in gross final energy consumption in different EU member states, Proskurina et al. [2] have discussed the total biomass contribution (especially woody biomass) to heat and electricity production to achieve EU's RE targets by 2020. According to Fig. 1, RE (i.e. biomass, hydropower, geothermal energy, wind energy and solar energy) accounted for ca. 24.3% of total primary domestic production of energy (only 47% of gross inland energy consumption of 70 EJ), contributing approximately 8.2 EJ in the EU in 2013 [7]. More specifically, biomass energy contributed more than 62% among all RE and about

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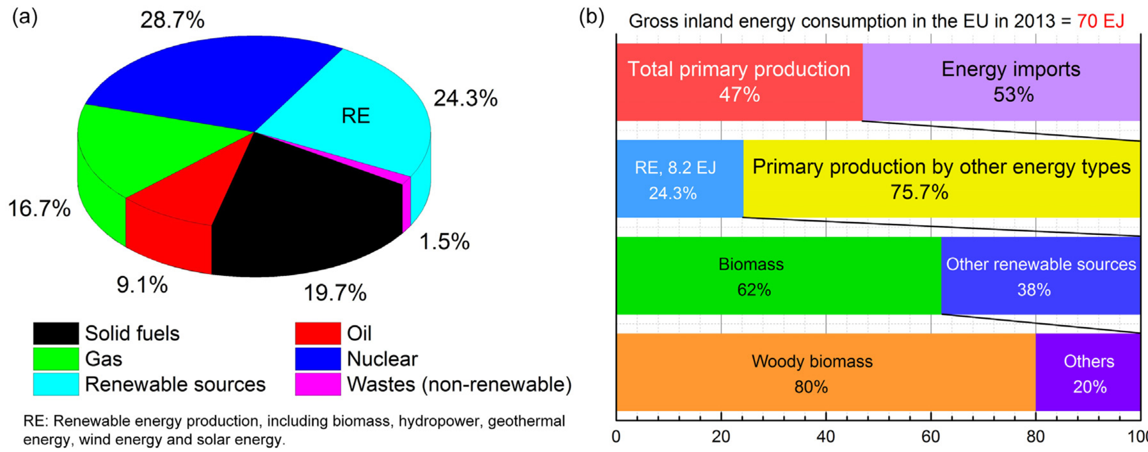

Fig. 1. Energy production and consumption of EU in 2013: (a) domestic energy production by different energy types; (b) gross inland energy consumption and contributions of renewable energy sources and/or biomass to EU domestic production of energy (Data are adapted from [2,7]).

80% of biomass feedstocks was woody biomass [2].

In order to avoid competition between food supply and bioenergy production [8], biomass sources limited by the finite agricultural land are proposed to be extended to abundant biomass waste streams [1], such as forest residues, agricultural/horticultural and food wastes, aquatic biomass waste, municipal solid waste (MSW), etc. However, these biomass feedstocks present distinct heterogeneity in structure and chemical composition which causes difficulties in conventional technologies for energy recovery, e.g. anaerobic digestion and combustion [9]. Furthermore, compared to fossil fuels, direct utilization of biomass as solid fuel exhibits critical disadvantages in terms of high moisture content, low bulk density, poor grindability, and inferior heating value [4,10]. Therefore, upgrading or pretreatment of biomass to biofuels with desired fuel quality is indispensable for efficient and successful energy conversion applications. So far, thermochemical pre-treatment is the most commonly applied technique both suitable for subsequent thermochemical and biochemical conversion routes.

In recent years, there are a lot of review articles on biomass pretreatment but hydrothermal treatment (HT) in hot compressed water turns out to be an attractive technology to upgrade wet biomass feedstocks just like their original existence in the nature [1,3,4,6,11–15]. For example, Pavlovič et al. [12] have mainly elaborated fundamental hydrothermal reaction chemistry of predominant components in agricultural and food wastes under sub- and supercritical water. Although effects of process parameters (e.g. feedstocks composition, reaction temperature and pressure, residence time, and catalyst) in hydrothermal carbonization (HTC) on mass/energy yield and physicochemical characteristic of biomass derived hydrochar have individually discussed [14,16,17], detailed linkage between processing conditions and hydrochar fuel quality for thermochemical applications was yet well illuminated. In addition, the importance of each parameter was not differentiated. Synthesis of functional nanostructured carbon materials via HTC has also attracted much attention because of cheap biomass based precursors but sustainable technique [18]. Initially, Titirici and Antonietti have discussed various applications of derived carbonaceous materials to facilitate novel design of HTC synthesis procedure [18]. Later, HTC of biomass materials to highly porous activated carbon has also been extensively reviewed [13]. As illustrated in Fig. 2, hydrochar derived from HTC could be further modified to make activated carbons with desired functions owing to their unique characteristics, i.e. high density of oxygenated functional groups (OFGs) and lower degree of condensation [13]. Actually, hydrochar is also strongly recommended for clean solid fuel utilization [1,5,14,19]. Previously, Zhao et al. [1] have systematically summarized the application of HT in conversion of some representative biomass wastes to clean solid fuel but they mainly emphasized the dewatering, dechlorination, denitrification and coalification reactions contributing to reduction of pollutants emissions in combustion. Then Bach and Skreiberg [5] have intensively reviewed biomass upgrading via wet torrefaction (WT) in subcritical water conditions. WT is somehow similar to HTC and specifically applied for upgrading and pretreatment of biomass, which will be discussed in details hereinafter. That review article focuses on comparison of physicochemical and fuel properties of solid fuel after WT and dry torrefaction (DT), but their results and discussion were only limited to woody biomass. It is therefore imperative to build a holistic knowledge system on WT of numerous biomass feedstocks. Complementarities of the entire processing system (i.e. from starting biomass feedstocks, hydrochar production, to ultimate energy utilization) and existing energy production technologies should be further analyzed.

Thus this article aims to render latest research advances and comprehensive overview of WT of various biomass feedstocks and downstream thermochemical applications. It is organized through four major sessions: (1) detailed introduction to WT in terms of its significant advantages over DT, clarification on similarities and differences between WT and HTC, and evaluation on mass and energy balances of WT; (2) effect of intrinsic nature of diverse biomass feedstocks (e.g. forest residues, agricultural and food wastes, aquatic biomass, and other contaminated MSW) on fuel quality of hydrochar as solid fuel after WT; (3) effect of WT conditions on mass and energy yields of hydrochar as well as its fuel quality; (4) effect of WT on conventional thermochemical conversion of wet-torrefied biomass. According to these fundamental data and analyses, specific perspectives are given to make WT more economically and industrially viable towards high quality clean solid fuel production and re-utilization.

2. Wet torrefaction of biomass

Torrefaction is a promising thermal pretreatment technology, which includes two distinct techniques, i.e. DT and WT. DT is a pyrolysis process which occurs at a mild temperature range of 200–300 °C in an inert environment under atmospheric pressure in the absence of water [10]. However, WT is generally defined as a hydrothermal pretreatment or upgrading in hot-compressed water or subcritical water under a mild temperature range of 180–260 °C with pressure up to 4.6 MPa within a residence time of 5–240 min [20,21]. It could lead to a predominant hydrochar with up to ca. 90% of mass and energy of raw biomass retained [5,10,22]. Moreover, the dewaterability of wet torrefied biomass and subsequent natural drying could be considerably enhanced by WT [23,24]. Since prior drying process can be avoided, WT extends the feedstocks for high quality solid fuel production to a wide variety of wet biomass wastes, mainly including forest residues, agricultural and food wastes, and aquatic energy crops or plants.