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Recent developments in microwave-assisted thermal conversion of biomass for fuels and chemicals

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ABSTRACT

Increasing energy demand coupled with greater consumer awareness of sustainability in meeting that demand has made the need to find renewable alternatives to fossil-derived products more pressing today than it has ever been. Biomass has long been identified as the renewable resource best suited for being converted through various processing techniques into products that can supplement and ultimately replace fossil derived fuels and chemicals. The thermal conversion of biomass to renewable fuels and chemicals has been the subject of research for several decades with some commercial success. One of the limitations of current thermal biomass conversion platforms is process efficiency due to the nature of heat transfer. Microwave-assisted thermal conversion of biomass has received significant attention in recent years as it is capable of improving the process efficiency and product quality. The objective of this work was to perform a review of the recent developments in the microwave-assisted thermal conversion of biomass for fuels and chemicals. Specifically, we review the fundamentals of microwave dielectric heating and microwave-matter interactions in light of the factors that influence this interaction; the studies related to the use of microwave dielectric heating in the pyrolysis of biomass, with emphasis on the advances made in recent years; and the challenges that affect the commercial deployment of pyrolysis of microwave assisted biomass and future direction. The available literature shows significant progress has been made in understanding the microwave-assisted thermal conversion of biomass. However, additional efforts and research are still needed to fully translate the technology from research to commercialization.

1. Introduction

The world's energy demand has been rising since the industrial revolution and is projected to continue rising for the foreseeable future, driven largely by emerging economies as a result of strong long-term economic growth and ever expanding populations [1–4]. The global energy demand has been projected to increase significantly by 48–56% by the year 2040 [1,2]. The vast majority of the current global energy is supplied by non-renewable resources in the form of petroleum, natural gas and coal, together accounting for more than 75% of the current energy needs [5]. Petroleum derived fractions currently supply over 95% of the total energy needs of the transportation sector [6]. As well, petroleum serves as an important source of raw material for several chemical industries producing essential products such as solvents, lubricants, plastics and polymers [7]. The current dependence on petroleum was fueled by the relative ease of its discovery, transportation, processing and utilization [7].

Despite the importance of petroleum or fossil derived fuels in today's economy, there are several issues associated with its use and our overdependence on them. One of the major issues associated with petroleum use is its finite reserves and non-renewability. With a current total consumption of nearly 97 million barrels per day, the current confirmed reserves are expected to be depleted in about 50 years [8]. Another major issue with petroleum use is exhaust emissions from transportation vehicles, which result in environmental pollution and greenhouse gas emissions that have been implicated in global warming [9]. Furthermore, there are geographic concerns associated with petroleum use, with over 50% of the current proven reserves located in some of the most politically unstable countries/regions of the world. Additionally, petroleum suffers from price fluctuations and uncertainty as well as increasing environmental awareness. As a result of these issues, a considerable effort into research and development of renewable alternatives to petroleum has been made over the last several decades. There is also currently renewed interest in the development of

Abbreviation: CO, carbon monoxide; CO_2, carbon dioxide; C_2H_4, ethylene; CH_4, methane; FCC, Federal Communication Commission; H_2, hydrogen; ISM, industrial, scientific and medical; N_2, nitrogen; NOx, nitrogen oxides; SiC, silicon carbide; SOx, sulfur oxides

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alternative renewable fuels and chemicals, especially in the European Union, spurred by regulations and incentives from several governments mandating and promoting the development and use of renewable fuels and chemical.

Several alternative and renewable energy technologies are being developed including solar power, wind power, wave power, geothermal energy, and biomass (including biofuels). The various alternative and renewable energy technologies have their advantages and drawbacks, which affects their large-scale deployment and utilization. Biomass represents a renewable and alternative energy source that can meet our demand for carbon-based liquid transportation fuels and chemicals being that it is the only renewable energy source that can yield solid, liquid and gaseous fuels [10–13]. Additionally the exploitation of biomass also has the potential to return value to the agricultural and forestry sectors, both of which are seeking value-added opportunities in North America. The utilization of biomass will therefore play an important role in meeting our energy demands sustainably in the future.

2. Biomass and biomass conversion

2.1. Biomass resources

Biomass is a very broad term covering a wide variety of materials. The term biomass, broadly defined, encompasses all living and non-living biological material and can include a variety of natural and derived materials [7,14–16]. As the only renewable organic carbon resource, biomass is intrinsically a storehouse of chemical energy. Dead biomass or biological waste can be used as a direct source of energy (e.g. heat and electricity) or as an indirect source of energy through biorefining conversions to various types of fuels. Living biomass such as bacteria, yeasts and algae, or components thereof (e.g. enzymes), can be used to convert one form of biomass into another, usually of higher value. A good example of this is the well-established conversion of sugars to ethanol through yeast fermentation or the conversion of sugars and glycerol to lipids by oleaginous yeast and algae [17,18].

Sources and availability of biomass vary widely and is influenced by several factors the most important of which is geographic location. As depicted in Fig. 1, there is a wide range of potential biomass sources for utilization in renewable fuels and chemical generation. However, concerns over the use of food and/or arable land for the production of fuels [19,20] have led to a general shift in focus from using food grade biomass to utilizing wastes and residues, which does not directly compete with food and feed uses [21,22]. The use of non-food and waste biomass sources such as agricultural and forestry residues, industrial wastes, municipal solid waste, and sewage sludge has been identified as necessary to minimize the impact of the use of biomass for fuel generation on the global food and feed supply [23–26]. In addition, the utilization of municipal solid waste as a source of biomass for the production of renewable fuels and chemicals has the added benefit of significantly reducing the amount that will end up in landfills, thereby minimizing the potential negative environmental impact associated with landfills [27–29]. Since municipal solid waste, industrial waste and residues, and sewage sludge are readily available in most municipalities, the use of these sources of renewable feedstock for chemicals and fuels will be important as new and low cost feedstocks are researched.

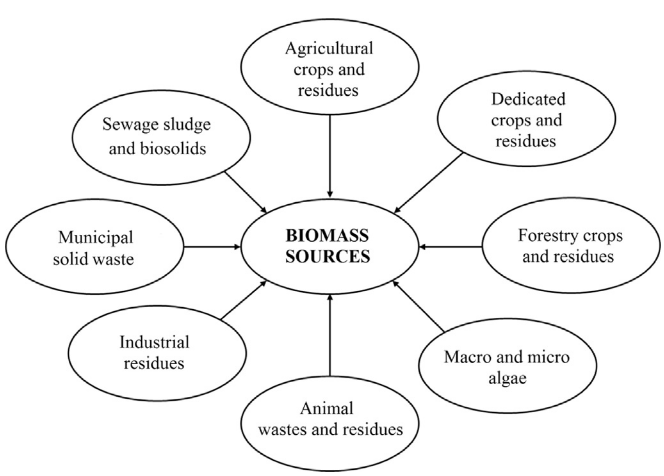

Fig. 1. Sources of biomass for energy conversion (adapted from [14] reused with permission).

2.2. Biomass conversion technologies

Biomass contains a variety of components, some of which are readily accessible and others that are much more difficult and costly to extract. The composition of the biomass feedstock determines the ease with which the biomass can be converted to useful products or intermediates, and influences the functionality of the final product [30]. There are several biomass conversion technologies that can be applied to convert biomass from one form to more valuable forms including thermochemical, biochemical, mechanical or physical, and chemical [10,30]. The conversion technology employed is dependent on various factors, one of the most important of which is the type of biomass. Fig. 2 shows a simplified summary of conversion technologies employed for converting different biomass into valuable products.

The thermal (thermochemical) conversion of biomass is one of the most studied biomass conversion platforms/technologies as it has the advantage of producing liquid, solid and gaseous products similar to those from the oil and gas industry, depending on the conditions employed. In addition, the products of thermal conversion of biomass can be directly integrated into the well-established existing petroleum infrastructure with little or no modification [31,32]. The use of microwave-assisted heating of biomass for thermal conversion into valuable products has gained a lot of interest in recent years due to several advantages microwave heating has over conventional heating. Specifically, compared to conventional electric resistance heating commonly used in thermal conversion of biomass, microwave heating has the advantage of being more efficient through rapid volumetric heating [33–35].

3. Microwave technology principles

Microwave radiation consists of electromagnetic waves, an electric and a magnetic field component; hence it is categorized as electromagnetic radiation. The position of microwaves within the electromagnetic spectrum is characterized by a frequency range of 300 MHz–300 GHz and wavelengths from 0.001 m to 1 m. The microwave region of the electromagnetic spectrum lies between infrared and radio frequencies.

Within the electromagnetic spectrum, a portion of frequencies are used for cellular phones, radar and television satellite communications. Industrial heating is performed at five reserved electromagnetic frequencies (0.433, 0.915, 2.45, 4.0 and 5.8 GHz) in order to avoid any interference [36]. These frequencies were allocated by the Federal Communications Commission (FCC) for industrial, scientific, and medical (ISM) purposes [37].

There are three potential ways by which microwaves and matter interact: absorption, transmission and reflection (with regard to heat generation by the electrical component of the microwave field) or any combination of these three interactions [38,39]. This is depicted in Fig. 3. Accordingly, material may be categorized in the following way:

(1) Absorbers, where the microwaves can be absorbed by the material (e.g. water, methanol) leading to rapid heating of the medium
(2) Microwave-transparent material, where microwaves pass through or transmit without any losses (e.g. quartz, teflon) and