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The application of microwave heating in bioenergy: A review on the microwave pre-treatment and upgrading technologies for biomass

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A R T I C L E I N F O

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A B S T R A C T

Bioenergy, derived from biomass and/or biological (or biomass-derived) waste residues, has been acknowledged as a sustainable and clean burning source of renewable energy with the potential to reduce our reliance on fossil fuels (such as oil and natural gas). However, many bioenergy processes require some form of pre-treatment and/or upgrading procedure for biomass to generate a modified residue with more suitable properties and render it more compatible with the specific energy conversion route chosen. Many of these pre-treatments (or upgrading procedures) involve some form of substantive heating of the biomass to achieve this modification. Microwave (MW) heating has attracted much attention in recent years due to the advantages associated with dielectric heating effects. These advantages include rapid and efficient heating in a controlled environment, increasing processing rates and substantially shortening reaction times by up to 80%. However, despite this interest, the growth of industrial MW heating applications for bioenergy production has been hindered by a lack of understanding of the fundamentals of the MW heating mechanism when applied to biomass and waste residues. This article presents a review of the current scientific literature associated with the application of microwave heating for both the pre-treatment and upgrading of various biomass feedstocks across different bioenergy conversion pathways including thermal and biochemical processes. The fundamentals behind microwave heating will be explained, as well as discussion of the imperative areas which require further research and development to bridge the gap between fundamental science in the laboratory and the successful application of this technology at a commercial scale.

1. Introduction

Biomass has the potential to become a major global energy source, with the ability to make a substantial contribution to the sustainable future energy demand [1]. Biomass resources can be considered as organic matter in which solar energy is stored in the chemical bonds of the molecules within the feedstock. When these bonds between adjacent carbon, hydrogen and oxygen atoms are broken this stored, chemical energy is released [2]. Furthermore, energy carrier sources, otherwise known as 'biofuels', that can be produced from such bio-based materials have the potential to reduce atmospheric CO_2 emissions. This is due to a balance in net CO_2, since the CO_2 which is released from the burning of the biofuel is proportional to the CO_2 that was fixed from the atmosphere by the plant during photosynthetic biosynthesis [3]. At present, biomass is the largest contributor towards renewable energy, as forestry, agricultural and municipal residues and waste have all been used as the principal feedstocks for the production of electricity and heat [4]. Within the European Union, biomass accounts for more than 62% of all renewables, with wood accounting for approximately 80% of the biomass used for renewable energy [5,6]. In the transport sector, biofuels are already widely deployed in several countries and are being produced on a commercial scale. This is mainly 1st generation bioethanol from corn and sugar cane in Brazil and 2nd generation bioethanol from straw and corn stover in the US [7].

There are a number of different bioenergy routes (processes) that can be applied to convert raw biomass feedstocks into final energy and chemical products which are typically divided into two main categories: thermochemical and biochemical conversion routes. Fig. 1 illustrates the main bioenergy conversion routes that have already been successfully employed or are currently the subject of further research and development for the production of renewable fuels. Other routes may require the inclusion of a biomass pre-treatment step (such as applied

Abbreviations: MW, Microwave; DT, Dry torrefaction; WT, Wet torrefaction; HHV, Higher Heating Value; AD, Anaerobic digestion; EPS, Extracellular Polymeric substance; WAS, Waste activate sludge; SCOD, Soluble chemical oxygen demand; TCOD, Total chemical oxygen demand; TS, Total Solids; AOP, Advanced oxidation process; •OH, Hydroxyl radicals; HRAP, High rate algal ponds; HRT, Hydraulic retention time; TEA, Techno-economic analysis; LCA, Life cycle analysis; IU, Units of enzyme activity

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Nomenclature

Pd	Power density [W/m^3]
f	Permitivity of free space [F/m]
ε_0	Permitivity of free space [F/m]
ε'	Dielectric constant
ε''	Dielectric loss factor
E	Electric field magnitude [V/m]
tan δ	Loss tangent

thermochemical pre-treatment prior to enzymatic saccharification in the case of bioethanol production) or biomass upgrading [8]. Each different route typically consists of a series of conversion steps that transform the raw biomass feedstock into an energy carrier such as heat, electricity or liquid or gas-based biofuel [1]. The preferred bioenergy conversion route often depends on many factors such as specific feedstock type and the quantity available, the desired form of the energy product, the current availability of the processing technology, environmental standards and the economic conditions [1,2]. However in most cases, it is ultimately the form in which the energy is required that is the main governing factor, followed by the availability and quantity of biomass feedstocks [2].

Although biomass has the potential to produce both cleaner-burning and also more sustainable sources of fuels compared to fossil fuels, there are disadvantages associated with the use of biomass feedstocks. For example, their lower energy densities and heterogeneity in physical nature make handling, transport and storage more complex and more expensive than fossil fuels [9]. Furthermore, there is a high degree of variation in the chemical composition, moisture and alkali contents across different biomass feedstocks. This requires some form of pre-treatment in order to meet the requirements for quality and homogeneity for the successful application of many conversion technologies [1]. Biomass upgrading and/or pre-treatment protocols are therefore key steps required for the efficient conversion of biomass into energy products and can significantly affect both the efficiency and choice of methodology of the subsequent energy process [10]. The primary goal of pre-treatment is to overcome the recalcitrant nature of the feedstock [11] and to modify its structure; making the feedstock more amenable for conversion into a final product. Pre-treatments also serve a purpose of increasing the surface area and pore volumes [12,13]. However to include such a step in a biomass conversion process is relatively expensive and in the case of bioethanol production for example, pre-treatments may contribute to ca. 18% of the total production cost [14–17]. Nevertheless, enhancing the final product yield (e.g. biofuel yield) through improved and optimised pre-treatment applications could significantly reduce the costs of prior process units; hence the overall cost of the production process can be reduced by increasing the pre-treatment efficiency [18]. Therefore, an ideal pre-treatment should be one that is suitably affordable with relatively low energy requirements, low resource consumption and limited waste streams to make the overall process environmentally friendly and sustainable. Above all, the pre-treatment and/or biomass upgrading process should aim to overcome the natural challenges imposed by notoriously recalcitrant and heterogeneous feedstock materials and generate a residue with a modified structure that may give it ideal properties that are more compatible with the chosen energy conversion route.

The development of microwave (MW) technology has gained an increasing amount of attention as an alternative non-conventional heating source that can be applied for the processing of biomass and wastes [19,20]; particularly for the pre-treatment and biomass upgrading steps.

The purpose of this review article is to identify and discuss the latest scientific literature associated with the application of MW heating to pre-treat and upgrade biomass. This review is structured in two main parts. The first part focusses on the latest research developments which use MW-based heating as a means to upgrade and pre-treat different feedstocks. The application of dielectric heating across different conversion routes within the sustainable energy spectrum are collated and will be discussed to establish the advances MW heating has had across the various areas of bioenergy and biochemical production. Particular attention will be devoted to explain how MW pre-treatment/upgrading has overcome hurdles involved with each bioenergy route. The second part discusses the technological challenges that currently exist with the technology and the future areas of research that need to be addressed if this form of heating is to become widely industrially applied. This review will be of benefit to those who are not experts with the use of MW technology and the understanding of electric field theory, yet utilise MW based systems to pre-treat and upgrade biomass.

2. Microwave heating – the fundamentals

Microwaves (MW) are a form of electromagnetic energy located on the electromagnetic spectrum between 300 and 300,000 MHz; a region that lies between infrared and radio frequencies and correspond to wavelengths of 1 cm to 1 m [21,22]. In order to avoid interference with telecommunications and mobile cellular phone frequencies, most microwave reactors (that are typically used for chemical synthesis reactions) and domestic microwave ovens operate at a frequency of

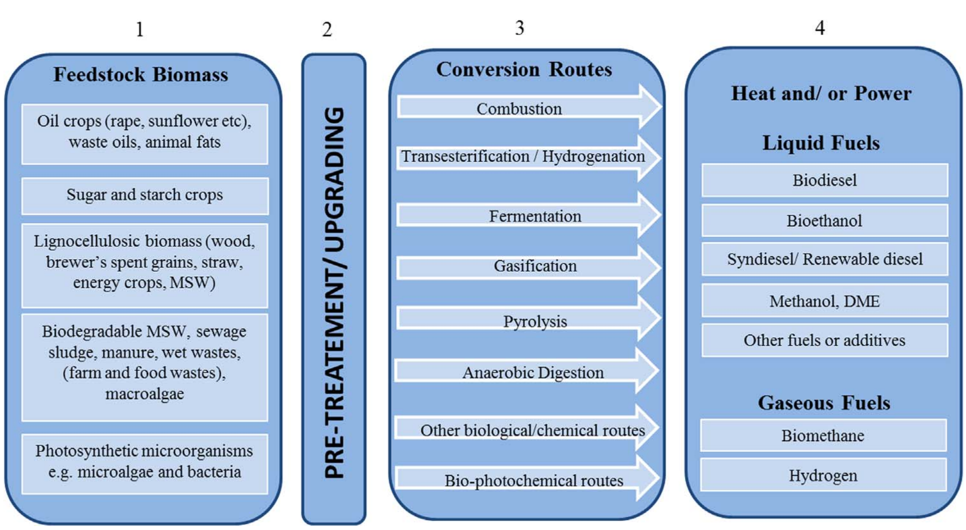

Fig. 1. Overview of current bioenergy routes which can be applied to different biomass feedstocks and the potential products of energy that can be produced (Adapted from [199]).