Renewable and Sustainable Energy Reviews 82 (2018) 1149–1177

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Microwave-assisted conversion of biomass and waste materials to biofuels

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ARTICLE INFO

Keywords:
Microwave pre-treatment
Lignocellulosic biomass
Fermentation
Anaerobic digestion
Thermo-chemical conversion techniques
Biodiesel production

ABSTRACT

Lignocellulosic and waste materials represent a considerable potential for biofuel production. Currently, they are not fully utilised due to low biofuel yields from biological processes while thermo-chemical conversion technologies and transesterification processes suffer from certain drawbacks of conventional heating. Consequently, several technologies have been studied to improve biofuel production from lignocellulosic and waste materials, with microwave (MW) irradiation gaining increased interests over the years. This study reviewed the use of MW irradiation for assisting biofuel production from biological and thermo-chemical conversion processes as well as biodiesel production from the transesterification process. The principles underlying MW irradiation were initially described followed by the several benefits of MW over conventional heating and the different effects of MW irradiation on pre-treatment of lignocellulosic biomass and waste materials such as defragmentation of lignocellulosics, organic matter solubilisation and enhanced hydrolysis. Although MW irradiation generally enhanced biofuel production from biological processes, the extra biofuel (bio-ethanol, bio-methane or bio-hydrogen) produced could not compensate for the energy input due to MW irradiation, resulting in negative efficiencies for the pre-treatment technique. Regarding MW-assisted thermo-chemical conversion of biomass and waste materials to biofuels, it can be deduced that MW-heating is much more beneficial as opposed to conventional heating based on the products quality and yields obtained but the energy efficiency aspects of MW-heating are contradictory among studies. As for MW-assisted biodiesel production from the transesterification process, studies are almost unanimous as to the benefits of MW-heating over conventional heating such as reduced processing times or increased biodiesel yields. Finally, this article discussed some of the challenges of MW irradiation such as formation of inhibitors on biological processes, energy efficiency of the technology, technical aspects viz. poor dielectric properties of some substrates as well as difficulties for large-scale implementation of the technology before concluding on the future directions of MW-irradiation.

1. Introduction

Global energy demand remains heavily reliant on fossil fuels, with more than 81% of the world's primary energy supply being met through fossil fuels in 2014 [1]. However, due to the polluting nature of fossil fuels, their decreasing reserves as well as their volatile prices [2–5], considerable efforts have been made over the years to shift towards renewable energy. Among the different renewable energy sources, bio-energy is currently the main contributor, accounting for 10.3% of global primary energy requirement in 2014 [1]. Bio-energy refers to energy production from biomass or renewable waste materials through direct use of the biomass as fuel or the production of other biofuels from further processing of the biomass [1]. Biofuels, which can be either in the solid, liquid or gaseous form, are produced mainly through biochemical/biological and thermo-chemical routes [6–8] with mechanical extraction of oil from biomass for biodiesel production considered as another technique [6,9].

Biological technologies for biofuel production include anaerobic digestion for bio-methane production and fermentation processes for bio-ethanol and bio-hydrogen production [5,6]. Although lignocellulosic biomass represents a huge renewable energy resource [8,10], its use is not fully exploited for biofuel production due to the low yields of bio-ethanol, bio-methane or bio-hydrogen obtained. The low biofuel yield is often attributed to incomplete hydrolysis of cellulose molecules [11] which are protected inside the complex structure of lignocelluloses (by lignin and hemicellulose) and unavailable for fermentation into biofuels [12–15]. Besides lignin and hemicellulose content, other factors that have been reported to hinder hydrolysis of cellulose molecules include cellulose crystallinity and porosity as well as the extent of polymerisation [12,16]. To solve this problem, a wide range of pre-treatment technologies, classified as physical, physico-chemical, chemical and biological, has subsequently been investigated [13,17]. The goal of any pre-treatment is to break down the lignin protective barrier, remove hemicellulose and release cellulose

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http://dx.doi.org/10.1016/j.rser.2017.09.066
Received 22 December 2016; Received in revised form 20 May 2017; Accepted 17 September 2017
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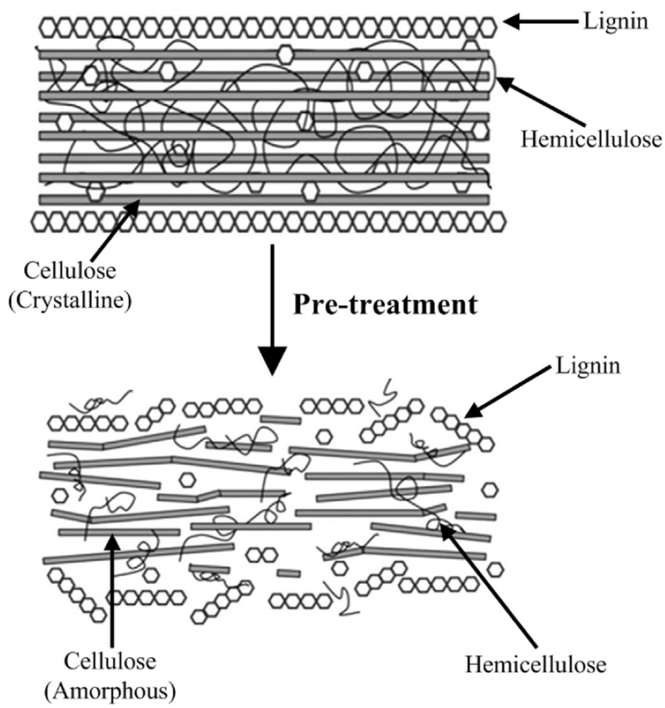

Fig. 1. Pre-treatment of lignocellulosic biomass and waste materials for enhanced biofuel production (Adapted from Ref. [22], with permission from Elsevier and under the Open Government Licence v3.0 from: http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/ and Ref. [23], with permission from Elsevier).

molecules followed by breakdown of their crystalline arrangement and depolymerisation so as to enhance biofuel production [13,14,17–22], as shown in Fig. 1.

Besides lignocellulosic biomass, other waste materials such as sewage sludge have also been subjected to pre-treatment with the aim of breaking down cell walls, rupturing of cells and assisting in the solubilisation of organics to provide a more digestible feed for enzymatic hydrolysis and subsequent conversion into biofuel [24,25]. Among the different techniques studied, microwave (MW) irradiation has been gaining increasing interests over the years for pre-treatment of lignocellulosic biomass and waste materials prior to biological conversion to biofuels, as illustrated in Fig. 2.

As for thermo-chemical conversion techniques for biofuel production, these include pyrolysis for biochar, bio-oil and fuel gas production, gasification for syngas production, hydrothermal liquefaction for bio-oil production and torrefaction and hydrothermal carbonization for a higher grade solid biofuel [6,9,26] as depicted in Fig. 2. Most of these thermo-chemical conversion technologies have long been carried out using conventional heating [27–32]. In recent years, there has been a growing interest towards the use of MW heating to drive these thermo-chemical processes owing to the benefits of MW heating such as non-contact and volumetric heating as well as being faster and possessing more control as opposed to conventional heating [27,33–40]. In the same line, MW heating has also been increasingly employed for assisting biodiesel production owing to enhanced reaction rates and biodiesel yields over conventional heating [41,42].

Several studies have reviewed the use of MW irradiation for biomass pre-treatment prior to biological conversion into biofuels [38,43–47], for assisting thermo-chemical techniques for enhanced biofuel production [27,36,37,39,48–55] and for promoting biodiesel production [40,41,56–59]. Similarly, Fang et al. [60] edited a book on MW irradiation with chapters focussing on MW-assisted biological conversion of biomass to biofuels [61], MW-assisted thermo-chemical conversion of biomass to biofuels [62–65] and MW-enhanced biodiesel production [66–68]. With regards to biomass pre-treatment prior to biological conversion to biofuels, none of the aforementioned reviews have provided an in-depth and critical understanding of the effects of the technology on lignocellulose pre-treatment such as delignification, cellulose solubilisation and breakdown of its crystalline arrangement. For thermo-chemical conversion of biomass to biofuels, most of the reviews have focused on MW-assisted pyrolysis while reviews on MW-assisted gasification, hydrothermal liquefaction, torrefaction and

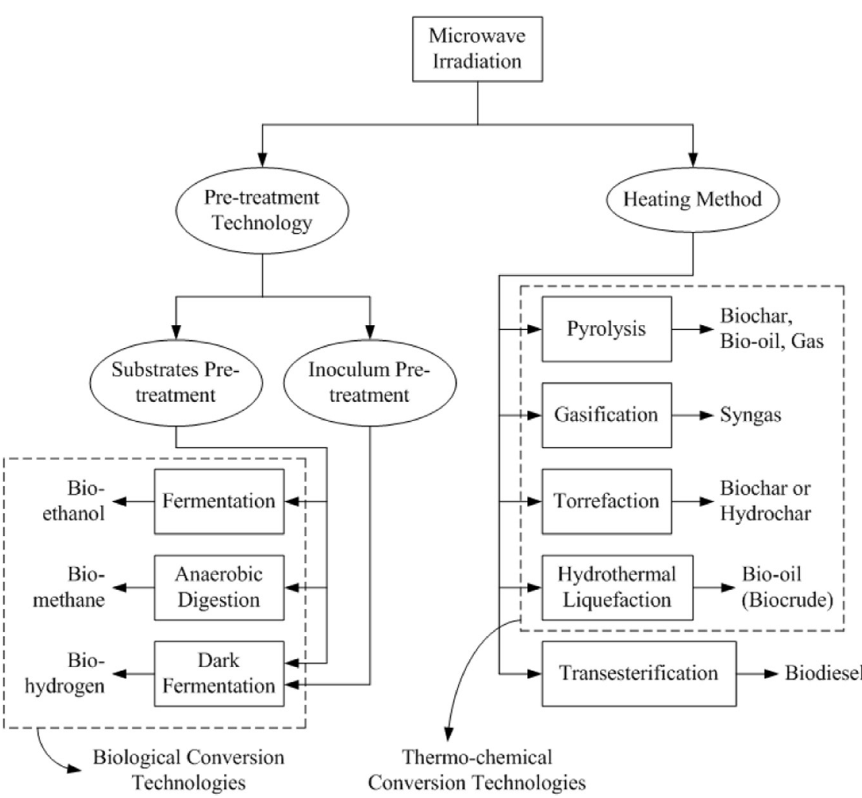

Fig. 2. Microwave irradiation as a pre-treatment technology and heating method for assisting biomass conversion to biofuels. Only main products are included.