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Review

Microwave pyrolysis of biomass for bio-oil production: Scalable processing concepts

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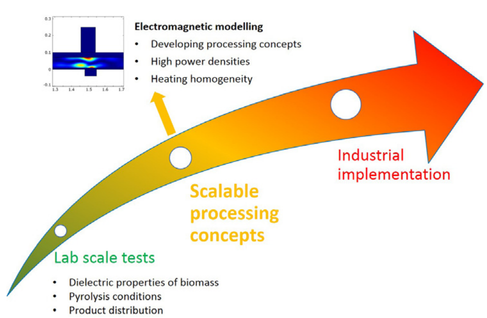
HIGHLIGHTS

- Several large-scale configurations are analysed for microwave pyrolysis.
- Rotary kilns, conveyor belts, fluidised beds and extrusion systems are evaluated.
- Any attempt of microwave pyrolysis scaling-up should be based on continuous mode.
- High power densities are required to induce pyrolysis without using susceptors.
- Electromagnetic modelling as an extremely helpful tool to sustain the scalability.

GRAPHICAL ABSTRACT



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ABSTRACT

The pursuit of sustainable hydrocarbon alternatives to fossil fuels has prompted an acceleration in the development of new technologies for biomass processing. Microwave pyrolysis of biomass has long been recognised to provide better quality bio-products in shorter timescales compared to conventional pyrolysis. Although this topic has been widely assessed and many investigations are currently ongoing, this article gives an overview beyond the physico-chemical pyrolysis process and covers engineering aspects and the limitations of microwave heating technology. Herein, we provide innovative scalable concepts to perform the microwave pyrolysis of biomass on a large scale, including essential energy and material handling requirements. Furthermore, some of the possible socio-economic and environmental implications derived from the use of this technology in our society are discussed. Such potential concepts are expected to assist the needs of the industrial bioenergy community to move this largely studied process upwards in scale.

Contents

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1. Introduction

The growing demand for energy, depletion of viable petroleum reserves and environmental and socio-political concerns have accelerated the need for the development of sustainable technologies for utilization of biomass. The European Commission recently set a long-term goal to develop a competitive, resource efficient and low carbon bioeconomy by 2050 [1]. Its central vision is the use of renewable raw materials and industrial biotechnology in sectors such as paper and pulp, food and biofuels production, while detecting new growth opportunities considering global challenges and resource constraints [2,3]. The bioeconomy has already been reported to be one of the most important components of the EU economy and in 2012, was worth €2 trillion in annual turnover [4]; with the bioenergy and bio-based industries representing €100 billion [5]. Approximately 78 million tonnes of biomass feedstock has been projected to be used for biofuel production in the EU by 2020, which is almost twice that used in 2012 [5]. Furthermore, up to 30% of oil-based chemicals and materials are expected to be replaced with bio-based alternatives by 2030 [6]. Such factors have contributed towards a growing focus in the bioenergy research sector over the last few years.

1.1. Biofuels production

Biofuels can be broadly defined as fuels that are derived from biomass (biological material derived from living, or recently living organisms). The most common biofuels are biodiesel and bioalcohols, which include bioethanol and biobutanol [7], otherwise known as 1st generation biofuels. However, such biofuels are produced mainly from food-based crops (sugar and starch based crops [corn and sugarcane] for bioethanol and oil crops [mainly rapeseed oil] for biodiesel [5]). However, issues associated with the impact 1st generation biofuels have on the sources of feedstocks, including the impact they have on biodiversity, water conservation, land use and competition with food crops have raised concerns and implement many challenges that need to be addressed [8]. Furthermore, it is claimed that biodiesel is not a cost efficient abatement for GHG emissions [9].

On the contrary, second generation biofuels are derived from non-food and the non-edible parts of crops (such as wood, agricultural residues) which are usually self-seeding crops that require no fertiliser input and are suitable for growth on marginal lands [10]. As a consequence 2nd generation biofuels may have the potential to overcome the problems associated with 1st generation biofuels as the need for food crops, deforestation and threats to biodiversity are hence reduced. Second generation biofuels have been identified to supply a larger proportion of fuel in a more sustainable manner and with greater environmental benefits [7]. A recent European Council decision restricted the use of 1st generation biofuels to 7% of the energy use in transport for 2020; with the remainder of the target coming from 2nd generation lignocellulosic biofuels [11].

Although the political prospects for 2nd generation biofuels are promising, major developments on available technologies to sustain their production are still needed. Research efforts have focused on the development of different production techniques; for instance, biological, chemical and thermochemical conversion pathways. Biofuels produced by biological conversion (bioethanol, biogas and biohydrogen) generally involve the use of several microorganisms (*e.g. Saccharomyces cerevisiae*, *Methanogenic archae* or *Pyrococcus furiosus*). In the specific case of bioethanol production, the development of an efficiently optimised biomass pre-treatment process is imperative in order to maximise sugar liberation yields, whilst simultaneously reducing the overall cost of the process and minimalising waste production. Moreover, efforts are needed to develop efficient microorganisms with enhanced abilities to ferment hemicellulose-derived pentose sugars [7]. Biogas (i.e., $CO_2 + CH_4$) is a suitable fuel for both the generation of electricity and for transportation [12]. Biohydrogen may be a viable longer-term biofuel, but research is still primitive and has not progressed beyond laboratory scale [13].

Biofuels that are generated by chemical conversion methods include the production of biodiesel from microalgae and oil-based crops *via* transesterification with the co-production of glycerol. The major drawback faced with this approach is the economic feasibility due to the complexity of the primary recovery of bio-oil from algae [14].

Thermochemical conversion technologies involve the thermal degradation of biomass (Fig. 1) [15–17]. Biomass can be heated in the absence of oxygen (fast pyrolysis) to ultimately produce an intermediate liquid product known as bio-oil (which may serve as raw material for producing biofuel), or in the presence of an oxidising gas (gasification) to induce the production of an intermediate synthesis gas. Both routes need an additional stage to refine the intermediates for further production of biofuels. For instance, biomass-to-liquid processes have been trialled as a plausible alternative, making use of molecular sieves or transition metal-based catalysts to produce synthetic fuels from syngas [18].

1.2. Fast pyrolysis of biomass for bio-oil production

Fast pyrolysis of biomass is a form of pyrolysis technology, and can be used to valorise a broad range of feedstocks ranging from organic wastes to plastics [19] (see Fig. 2). Typically, fast pyrolysis involves heating the biomass (previously grinded and dried) up to ca. 500 °C in an oxygen-free atmosphere in very short timescales (~1 s) [20]. As a result of the rapid quenching of the released volatiles during the pyrolysis, a carbonaceous solid residue (char), and a liquid fraction containing high value-added compounds (bio-oils) are obtained. A fraction of non-condensable gases, such as H_2, CO_2, CO and light hydrocarbons are produced. Bio-oils can be co-utilised