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Evaluation of infrared techniques for the assessment of biomass and biofuel quality parameters and conversion technology processes: A review

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ABSTRACT

Rapid methods to characterise biomass for energy are needed due to the increasing use of biomass in the energy system and the expanding varieties of biomasses available. Chemical information on biomasses can be utilised in integrated management systems, allowing for the appropriate selection and optimum use of biomass to energy conversion techniques. Composition of biomass has important implications for optimisation of conversion processes such as pelletising/briquetting, combustion, gasification, pyrolysis and anaerobic digestion. There are opportunities to develop rapid spectroscopic techniques for both biomass to biofuel and biofuel to bioenergy process control. Rapid spectroscopic techniques and chemometrics may also be used to predict the key biomass and biofuel parameter calorific value and could be used to improve energy crop growing programmes. This review brings together the reported uses of infrared spectroscopic analysis coupled with chemometric techniques which have been applied to optimising biomass to biofuel and bioenergy conversion processes.

Contents

Abbreviations: EU, European Union; IEA, International Energy Association; Mtoe, million tonnes of oil equivalent; GHG, greenhouse gas; MC, moisture content; AC, ash content; CV, calorific value; AD, anaerobic digestion; PAT, process analytical technology; NIR, near infrared; PLS, partial least squares; BPLS, bi-orthogonal partial least squares; FTIR, Fourier transform infrared; PCA, principal component analysis; TG-FTIR, thermogravimetric Fourier transform infrared; OPD, optimal population density

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1. Introduction

1.1. Biomass for energy production

Economies worldwide face two central energy challenges: securing the supply of reliable and affordable energy, and achieving the transformation to a low-carbon, high-efficiency and sustainable energy system [1]. An important step in decreasing the levels of greenhouse gases in the atmosphere is to increase the contribution of renewable energy in the energy mix [2]. In the European Union (EU) wood pellet demand grew to about 11 million tonnes in 2010, an increase of 7% on the previous year [3]. In 2013, the International Energy Association (IEA) estimated the global primary energy consumption for the year 2012 at 12476.6 Mtoe (Million tonnes of oil equivalent) [4]. Fossil fuel sources amounted to 87 (10,847.7 Mtoe) of this total with oil having the biggest share (33.1%), followed by coal (29.9%) and gas (24%). Nuclear and hydroelectric sources amounted to 4.5% and 6.7%, respectively [4]. Given that sources of fossil fuel reserves are being depleted and the greenhouse gases emitted through their combustion is leading to an accelerated change in global climatic conditions [5,6], alternative sources of energy will be needed in the medium to long term. Legislative requirements such as the Kyoto Protocol, the Irish Government's Energy White Paper and the EU Climate and Energy Legislative Package all call for a reduction in greenhouse gases (GHG's) and more emphasis to be placed on the use of renewable forms of energy [1,7]. Of the alternative sources available biomass plays an important role as it can be utilised in existing power generation facilities by co-firing the feedstocks alongside fossil fuels to reduce emission levels of major pollutants such as carbon dioxide, nitrous oxides and sulphur oxides [8–10].

It has been recognised that dedicated energy crops could provide a significant contribution as a major global primary energy source [11–13]. The dedicated bioenergy crops that have been widely investigated are switchgrass (*Panicum virgatum*), *Miscanthus* × *Giganteus* species, and short rotation woody crops i.e. willow (*Salix* species.) and poplar (*Populus* species) [14–17], while microalgae has emerged recently as a potential new bioenergy resource [18]. Switchgrass, which is native to North America, is a C_4 perennial grass which can be harvested twice a year. Biomass yield has been reported to range from 4.5, on marginal land, to 23 dry t ha^{-1} year^{-1} in Alabama alone and an overall US average of 11.2 dry t ha^{-1} year^{-1} [19]. Numerous factors can affect switchgrass productivity, including soil texture, nutrients, pH, and slope [20]. Economic analysis of switchgrass production in the USA indicate that production costs may be halved if the yield could be increased from 10 to 30 Mg ha^{-1} through genetic improvement, intensive crop management, and/or optimised inputs [21].

Miscanthus × *Giganteus* is also a C_4 perennial grass which can grow to over 3.5 m in height. *Miscanthus* × *Giganteus* is native to East Asia and was introduced to Europe from Japan in the 1930s [22]. Research has indicated successful *Miscanthus* × *Giganteus* establishment is related to an adequate soil moisture content (MC) and appropriate rhizome storage [23]. Indeed care must be taken to ensure that rhizomes do not dry out during harvest, transport or planting as this has been linked to poor establishment rates [22,23]. Willow is a perennial woody crop native to northern temperate zones. It grows up to 8 m in height and is usually harvested on a two to three year cycle. Some of the major contributing factors in poor establishment or yield include poor weed control and diseases such as *Melampora* rusts [24]. But it is not just woody biomass and grasses that can be used as energy crops. The use of microalgal cultivation for energy purposes is another emerging sector [18,25]. Microalgae are unicellular organisms that are typically photosynthetic and found in marine and freshwater environments. They have a high growth rate with higher biomass productivity and oil yield compared with other oil crops, which demonstrates its potential for production for energy purposes [25].

Variability in crop establishment and yield on a commercial scale will affect the economic return growers can expect and hence can be a barrier to the increased use of dedicated bioenergy crops. Therefore technologies which can assist producers in ensuring good crop establishment and achieving high productivity will be one critical tool to assist in the wide spread success of dedicated bioenergy crops. Remote sensing technologies can provide timely and accurate information which can be employed for crop management and to assess actual crop conditions [26]. Numerous vegetative indices have been developed using spectral remote sensing to quantify various agronomic parameters, e.g., leaf area, crop cover, biomass, crop type, nutrient status and yield [27]. Provision of important crop parameters is critical for optimising crop management and harvesting processes. Ehlert et al. [28] stated that sensors for measuring such parameters with an acceptable accuracy, high reliability and in a cost effective manner are essential. Rapid sensing techniques which can provide valuable information for crop management can include remote sensing and vehicle based methods. Such approaches take into account in-field spatial variability, thereby offering the potential to reduce input costs, optimise the use of inputs and reduce environmental impacts [29]. The compositional variances within many crops can often be difficult to control [30]. However if the composition of a given feedstock can be measured in real time that information could be used to adjust process conditions for optimal conversion of the biomass to energy.

Utilisation of sustainable agricultural crops and residues as sources of renewable energy can be further optimised using infrared spectroscopy within the ‘biomass to bioenergy’ chain. The conversion of biomass to energy is influenced by the type of feedstock, its physical characteristics and chemical composition [31,32]. Chemical composition of biomass fuels influences the choice of conversion technology suitable and process control in the selected conversion technology [33].

1.2. Biomass to biofuel conversion

1.2.1. Pelleting/briquetting

There has been increasing interest in biofuel pellet production for both domestic and industrial use in recent years [31]. Biofuel pellet production has grown rapidly in Europe, Northern America and China in the last few years [34,35]. There is a growing market for biofuel briquettes and pellets since biomass pellets offer advantages such as easy storage and transport, as well as lower pollution, lower dust levels and higher heating values than previously attainable [36]. Rhen et al. [37] reported that pellets offer the same advantages for automation and optimisation as the petroleum-derived fuels, with comparatively high combustion efficiency and low levels of combustion residues compared to traditional firewood. With this growth in pellet production and increasing varieties of biomass used in their production there is a need for rapid quality control techniques. Tabares et al. [38] reported the densification of biomass would help improve its behaviour as a fuel by increasing its homogeneity and allowing a wider range of lignocellulosic materials to be used as fuel.

MC is considered the principal parameter of importance in biomass chips and pellets for a number of reasons [39]. High MC in biomass chip piles can result in self-combustion of the pile due to elevated temperatures caused by increased microbial activity [40]. If the MC of the chips being fed into the pellet press is too low the friction between the particles and the die will increase the required energy to expel the material from the die or cause blockages