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Microwave dielectric characterization of Saudi Arabian date palm biomass during pyrolysis and at industrial frequencies

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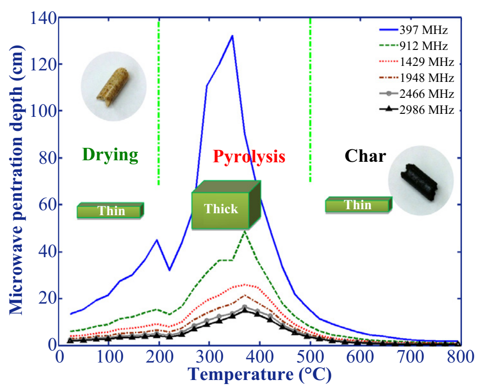
HIGHLIGHTS

- Dielectric properties of date palm biomass were measured during pyrolysis.
- Temperature was the major factor determining the profile of dielectric properties.
- The influence of frequencies was seen in char stage only.
- Penetration depth was much higher in pyrolysis stage but dropped in char stage.
- Knowledge on drastic change in dielectric properties of the biomass was important.

GRAPHICAL ABSTRACT



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ABSTRACT

The knowledge of the dielectric property is essential to design and develop microwave technology for processing biomass materials. This paper focuses on the measurement of dielectric properties of three different Saudi Arabian date palm biomass (seed, leaf and stem) from room temperature to ~800 °C and at six different frequencies (397–2986 MHz) using a cavity perturbation method. The result showed that all date palm biomass samples were poor microwave absorbers from room temperature till 500 °C. The dielectric constant and loss factor dropped slightly in the drying region due to removal of moisture and was almost constant in pyrolysis region. However, a significant increase in dielectric constant and loss factor occurred in temperature between 500 and 750 °C, except for leaf biomass. Penetration depth and tangent loss had an opposite behavior with the rise in temperature. In conclusion, the dielectric properties might not only depend on the temperature and frequency but also on the physical and chemical characteristics of the biomass material. For instance, it was interesting to know that date leaf showed a sharp decrease in loss factor from temperature 475 °C, which was opposite to that observed in case of date seed and stem. The data can be very useful in designing, modeling and simulation of microwave processing system for date palm biomass.

1. Introduction

Date palm tree is perhaps one of the oldest trees in the world. Statistics shows that Saudi Arabia has about 23 million palm trees, which produce approximately 0.78 million tons of dates per year

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[1]. These dates are consumed in abundant quantity as a dietary because of its high nutrition values [2]. Therefore, a huge amount of date palm biomass waste is generated annually while processing date palm fruit, which is true for the surrounding date producing regions. However, very little attention is paid for its utilization. These quantities have great potential to produce sustainable industrial product in terms of bioenergy and bioproducts which will be environmental friendly and can partially replace the existing fossil fuels. Further, excess amount of date palm leaves which are left over the land causes environmental hazards such as fire, bait for insects and other diseases [3]. Interestingly, date seeds represent about one third of the date weight. These date seeds are not fully utilized and hence can serve as a potential source of energy or it can be converted into value-added chemical products. Joardder et al. [4] produced bio-oil and activated carbon from date palm seeds in a fixed bed reactor using pyrolysis technique.

In recent years, microwave has become one of the emerging technologies to process biomass materials [5–7]. However, prior to processing any material in the microwave, the fundamental understanding of dielectric properties is very important. These properties provide some crucial information such as the change in microwave absorption characteristics of the material during processing, the penetration depth, the best choice of frequency for heating biomass under microwave, and whether the material will absorb or reflect microwave power at a particular temperature? Dielectric properties are also considered as the most important factors for designing large scale microwave systems [8]. They have also stated that lack of proper understanding of dielectric properties may lead to restriction in development of microwave technology.

Microwave absorption of wood and biomass material is known to be dependent on its dielectric properties. It was demonstrated that the biomass are low loss dielectric material, and are essentially transparent to microwaves from room temperature to 450 °C [9–11]. They also stated that the microwave absorption by biomass materials can be significantly affected due to the heating temperature. Although, most published works have reported the dielectric properties of a wide range of materials including inorganic and organics [12], food and biological substances [13] and some common industrial materials [14], but limited data is available on biomass materials. The published articles on dielectric properties of switchgrass [9], hay [10], corn stover [11], oat and barley straw [15], sweet sorghum biomass [16], oil palm shell [17], and seeds of invasive Chinese tallow tree [18] are very recent. Similarly, Peng et al. [19] investigated dielectric properties of coal during pyrolysis. Others have performed at relatively narrow or at room temperature for example, oil palm biomass [20], peanut hull pellets [21], woody biomass [22,23], hardwood [24], Aleppo pine, Holm oak and Thuja burl woods [25], and empty fruit bunch [26]. A detailed study on the dielectric characterization of date palm biomass at high temperature and during pyrolysis is clearly lacking in the literature.

Therefore, to our knowledge, the microwave dielectric properties of three types of date palm biomass (seed, stem and leaf) were measured for the first time. The dielectric properties consisted of dielectric constant, loss factor, tangent loss and microwave penetration depth. The dielectric properties were determined from room temperature to ~800 °C and at six different frequencies including that used for industrial heating applications (912 and 2466 MHz).

2. Dielectric properties

The dielectric properties data will be certainly helpful in evaluating the microwave absorption characteristics of the material as well as in designing the microwave processing system [14]. The dielectric response of a substance is commonly presented as complex permittivity (ε^*), which can be given by:

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \tag{1}$$

where (ε') is the real part which is generally known as dielectric constant and it is a measure of the ability of the dielectrics to store electrical energy, (ε'') is the imaginary part which is called dielectric loss factor and it represents the ability of the material to absorb or dissipate the electric energy, and j is imaginary unit. For common nonmagnetic materials, only ε_r'' and ε_r' are needed to determine the heating rate under microwave irradiation [27]. The significance of this loss factor is that it determines the ability of a material to heat up in a microwave oven and dielectric constant shows the influence on the distribution of electric fields [28]. The ratio of loss factor to the dielectric constant is quantified as loss tangent ($\tan\delta$) which is an estimate of a material's ability to convert electromagnetic energy into heat at a specific temperature and frequency. The penetration depth (D_p) is one of the important factor in the design and scale-up of a microwave heating system. It is defined as the depth in the material at which the power carried by a forward-traveling electromagnetic wave of the specified frequency falls to $1/e$ of the value just at the surface. The penetration depth is calculated using the following equation [29] (λ_0 is the microwave wavelength in free space):

$$D_p = \frac{\lambda_0}{2\pi(2\varepsilon')^{0.5}}\left\{\left[1+(\tan\delta)^2\right]^{0.5}-1\right\}^{-0.5} \tag{2}$$

Several techniques are used to measure the dielectric properties [12,30,31]. This includes open coaxial probe, transmission line, free space and resonant cavity or cavity perturbation method [32]. Typically, the choice of dielectric property measuring technique depends on the nature of material (solid, liquid, powder), accuracy, material properties, sample size, contact or non-contact, frequency and temperature [32,33]. Cavity perturbation technique is able to measure the dielectric properties for the most commonly used industrial frequencies (400–3000 MHz), in the temperature range from room to about 1400 °C [31], the size of the sample is small, and can handle low loss material [14] such as biomass, and therefore it was selected in this study. The merits and demerits of this method have been detailed in the literature [14,29,31,34] and hence not discussed herein. The procedure to measure the dielectric property using cavity perturbation method is described in further section.

3. Methodology

3.1. Materials

In this study the dielectric properties of three different parts of date palm tree namely seed, leaf and stem were measured. The sample was produced by grinding in a Wiley mill to particle size less than 2 mm, then the powder was dried at 105 °C for 15 h in an oven. The moisture content of the grinded date palm biomass was determined according to the ASTM standard no. D4442 – 07 (Method B—Secondary oven-drying method) and it was 11.05 wt %, 10.10 wt%, and 10.93 wt% for date seed, leaf and stem, respectively. These values are the average of two replicates. The dielectric properties were investigated on pelletized samples which were formed by uniaxial press in a die lined with tungsten carbide at ~140 MPa. The initial and final physical parameters of date palm biomass during measurement of dielectric properties with their proximate and ultimate analysis are provided in Table 1. The initial dimensions shown in the table were measured just a few minutes before the measurements. Three pellets of each date palm biomass