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A vital stage in the large-scale production of biofuels from spent coffee grounds: The drying kinetics

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ABSTRACT

Spent coffee grounds are being consolidated as one of the most abundant bioresources in the world for use as green energy. Biodiesel, bioethanol, bio-oil and fuel pellet are biofuels derived of this waste. To get them, spent coffee grounds need to be dried due to their high moisture content. This work analyzes their drying kinetics from isothermal drying experiments in a convective dryer at different temperatures: 100, 150, 200 and 250 °C, and sample thicknesses: 5, 10, 15 and 20 mm. Drying curves were fitted with the main mathematical models in the drying of agricultural products where the Two Term Gaussian model got the best results of fit. Drying rate was calculated and analyzed. Effective moisture diffusivities were calculated in a range between $1.29 \cdot 10^{-9}$ to $28.8 \cdot 10^{-9}$ m^2/s. Activation energies were 12.29, 12.78, 15.18 and 16.87 kJ/mol for each sample thickness: 5, 10, 15, and 20 mm, respectively.

1. Introduction

Coffee is one of the agricultural products intended mainly for beverage industry. Coffee plants are cultivated in more than 70 countries with an average annual production of 8 million tons in the world [1]. 50% of the world coffee production is destined for elaborating the instant coffee, while the other 50% is used in cafeterias, restaurant and homes to make directly beverages of the ground coffee [2]. Spent coffee grounds are the waste obtained in the coffee industry. This waste is an environmental problem due to its high biochemical oxygen demand (BOD) formed by toxic organic compounds such as: caffeine, polyphenols and tannins [3]. At present, spent coffee grounds are been used as horticultural production, animal feed, fertilizers, activated carbons and biochar [4].

However, in recent years spent coffee grounds are positioned as one of the biomass products more attractive due to the generation of waste in the coffee industry [5]. Four main types of biomass products are obtained from this residue: biodiesel, bioethanol, bio-oil and fuel pellet [6,7]. Biodiesel is produced using transesterification methods from oil contained in the spent coffee grounds, about 15% [8]. Defatted solid wastes are used to obtain bioethanol and bio-oil from processes like organic fermentation and slow pyrolysis, respectively. The leftover solid wastes (without lipids and sugars) are utilized to make fuel pellet, which is used as biofuel to generate electric and thermal energy. Fuel pellet has a net calorific value of 25 240 kJ/kg at 0% moisture content [9].

Spent coffee grounds have a high moisture content, between 55 and 80% depending on the process used. Generally, the instant coffee industry obtains moisture contents in the spent coffee grounds higher than those generated by the coffee bars from ground coffee. The drying process of the spent coffee grounds is necessary to make biofuels. First, in the production process of biodiesel, bio-oil and bioethanol, elimination of the moisture content is essential for the solvent becomes effective [10–12]. And second, when spent coffee grounds are directly utilized as fuel pellet, should be dried up to the equilibrium moisture content to improve the energetic characteristics as biofuel [13,14]. Furthermore, the drying makes possible to minimize the storage, packing and transport costs. Fig. 1 shows the process to obtain biofuels from spent coffee grounds.

Although there are some specific studies related to the drying and roasted of coffee [15,16], there are no works in the field of drying of the spent coffee grounds, where the nature of the particles is completely different from the coffee beans.

This paper presents a study about the drying kinetics of the spent coffee grounds in a convective dryer. Sixteen isothermal drying tests were carried out at different drying air temperatures and sample thicknesses with constant drying air velocity. Drying curves were fitted with the main mathematical models in the drying of agricultural

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Nomenclature

a, *b*, *c*, *d*, *e*, *f*, *n*	coefficients of the mathematical models
k, k_0, k_1	constants of the mathematical models (s^{-1})
D_{eff}	effective moisture diffusivity (m^2/s)
D_0	pre-exponential factor of the Arrhenius equation (m^2/s)
E_a	activation energy (kJ/mol)
L	thickness of the slab (m)
R	universal gas constant ($kJ \cdot mol^{-1} \cdot K^{-1}$)
R^2	coefficient of determination
RMSE	root mean square error
t	time (s)
T	temperature (°C, K)
v	velocity ($m \cdot s^{-1}$)
X_e	equilibrium moisture content (kg moisture/kg dry matter)
X_0	initial moisture content (kg moisture/kg dry matter)
X_t	moisture content at time *t* (kg moisture/kg dry matter)
XR	dimensionless moisture ratio
x_v	drying rate (s^{-1})

products. Two Term Gaussian model obtains the best results of fit. The experimental drying rate and its mathematical function of fit were analyzed and calculated. The effective moisture diffusivity values were found out for each test. Finally, the activation energies were found for each sample thickness.

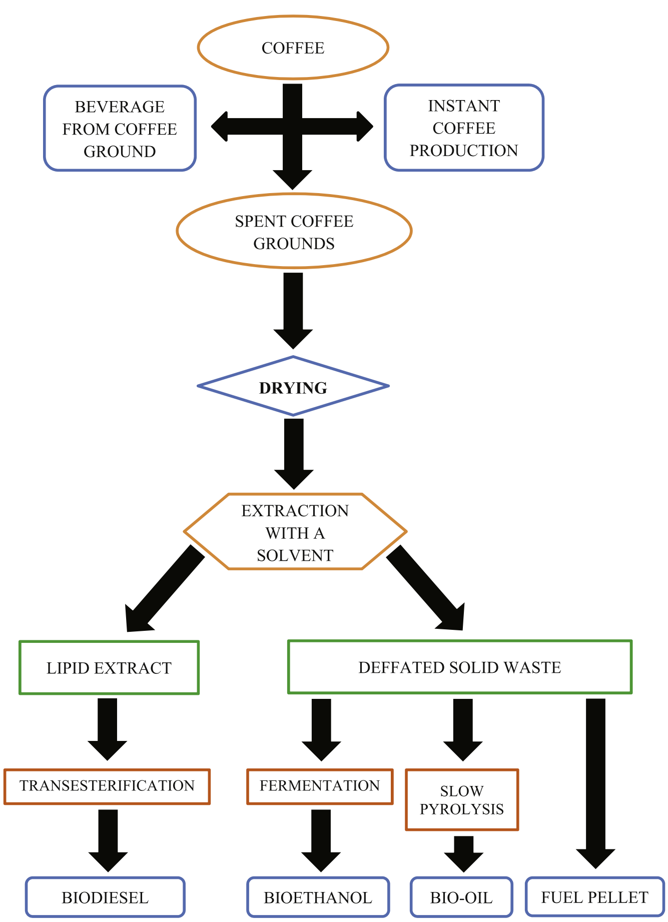

Fig. 1. Stages in the biofuel production from spent coffee grounds.

2. Materials and methods

2.1. Materials

Spent coffee ground samples (grounds obtained after brewing) were kindly provided by a cafeteria and a restaurant in the province of Jaen (Spain). To know the initial moisture content, the samples were dried in an oven (Memmert GmbH + Co.KG, SNB 167 Model 100, Germany) at 105 °C for 24 h. Drying samples were performed in triplicate. An average moisture content of 58.5 ± 1.5% (wet basis) was found. The same procedure was applied to obtain the equilibrium moisture content which was estimated at 7 ± 0.5% (wet basis) for a relative humidity of 50% and a temperature of 20 °C of surrounding air.

2.2. Experimental set-up and procedure

Drying experiments were carried out in a convective dryer (Fig. 2). The drying equipment consists of a blower, electric resistances and a tunnel of 2 m of length with thermal insulation and 0.15 m of square section. To achieve the desired temperature in each test, air was passed through a group of three independent resistances: 9 kW (first stage), 18 kW (second stage) and 18 kW (third stage), 45 kW in total. To control the constant temperature in each test, a PID (Proportional-Integral-Differential) controller acted on the resistances, measuring the temperature using a PT 100 sensor. The sensor was positioned just before the point of drying of samples. The air velocity of the blower was controlled by a Variable Frequency Drive (VFD) connected to an electric AC motor. Once the test conditions were correct, the sample was introduced (with the corresponding thickness in each test) into the tunnel in a steel basket of 7 cm of square section. The basket was placed over a precision balance (Blauscal AH1200) with an error of ±0.01 g. It was connected to personal computer by USB port. Software measured the variation of mass every second and stored the test information in files. Drying experiments were stopped when the equilibrium moisture content of the sample was approximately accomplished. However, to obtain the exact moisture content, when the experiments were finished, samples were dried until 0% moisture content in the oven at 105 °C for 24 h.

Sixteen experiments were performed. For each sample thickness: 5, 10, 15, 20 mm, four tests with constant drying air temperatures at 100, 150, 200 and 250 °C were carried out. The drying air velocity was established in 1 ± 0.1 m/s.

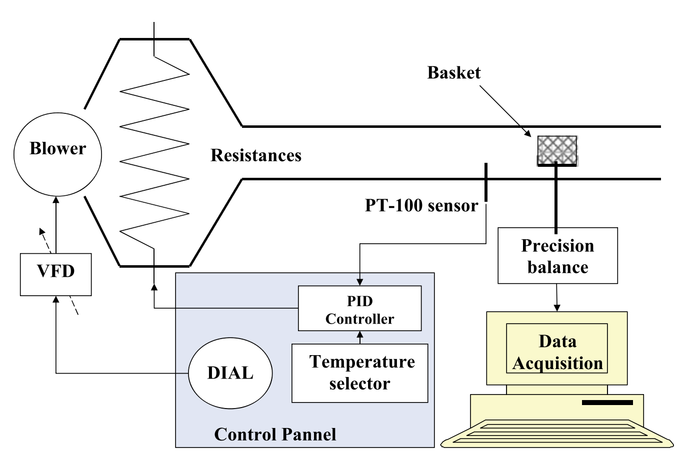

Fig. 2. Convective dryer scheme.