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Effect of thermosonic pretreatment on drying kinetics and energy consumption of microwave vacuum dried *Agaricus bisporus* slices

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ABSTRACT

This study was conducted to evaluate the drying kinetics and energy consumption of microwave vacuum dried *Agaricus bisporus* slices using various thermosonic pretreatment procedures. All the considered thermosonic pretreatment procedures involved complete inactivation of the PPO in *A. bisporus* slices. It was found that thermosonic pretreatment removed approximately 40%–45% of water in *A. bisporus* slices. The experimental data of the followed microwave vacuum drying process was fitted and Page model showed excellent for explaining the drying characteristics of microwave vacuum dried *A. bisporus* slices both untreated and thermosonically treated. A simplified and modified form of Fick's second law was primarily used to calculate the moisture diffusivity during microwave vacuum drying, which was observed to vary between 3.68×10^{-8} and 1.52×10^{-7} m^2/s, with the activation energy varying between 41.87 and 49.52 kJ/mol. In addition, the input energy and specific energy requirements for drying of the thermosonically pretreated *A. bisporus* samples were respectively determined to be within 0.30–0.54 kWh and 4.97–9.97 kWh/kg for power supplies ranging between 481 and 865 W and a constant vacuum degree of 70 kPa. Thermosonic pretreatment not only improved the product color of the microwave-vacuum-dried *A. bisporus* slices, but also reduced the energy consumption of the drying process.

1. Introduction

Agaricus bisporus is the most widely cultivated and produced edible fungus and is of great commercial importance globally. The desirability of the fungus stems from its favorable characteristics, which include a low calorific value, high vitamin B and mineral content, and almost no fat or cholesterol (Walde et al., 2006). However, *A. bisporus* is extremely perishable and, in its fresh form, can only be kept for 24 h at room temperature (Giri and Prasad, 2007a, b). Drying is a relatively inexpensive method for prolonging the shelf life of the fungus (Rama and Jacob John, 2000). Microwave vacuum drying (MVD), which combines the advantages of microwave heating and vacuum drying, is a potential method for obtaining high-quality dried foods. Some researchers have reported microwave vacuum drying of *A. bisporus* slices to be superior to conventional drying methods owing to the reduction of the amount of nutrients lost during the drying process, shortening of the drying time (Li et al., 2010), improvement of the rehydration ratio of the dried materials (Giri and Prasad, 2007a, b; Li et al., 2010; Motevali et al., 2011), and reduced energy consumption (Argyropoulos et al., 2011). Nevertheless, most previous studies on microwave vacuum drying of *A. bisporus* slices did not take full consider into inactivation of polyphenol oxidase (Rodríguez et al., 2005; Giri and Prasad, 2007a, b).

Polyphenol oxidase (PPO) is an enzyme commonly found in

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Nomenclature

C_p	heat capacity of the water (4.187 kJ/kg·K)
dT/dt	rate of temperature increase (K/h)
D_{eff}	effective moisture diffusivity (m^2/s)
D_0	pre-exponential factor (m^2/s)
E_a	energy of activation (kJ/mol)
E_{kg}	specific energy requirement (kWh/kg)
E_t	total energy needed (kWh)
$E_{t'}$	energy consumed by thermosonic pretreatment (kWh)
$E_{t''}$	energy consumed by microwave vacuum drying (kWh)
E_1	energy consumed by the ultrasonic process (kWh)
E_2	energy consumed during each microwave vacuum drying cycle (kWh)
E_3	energy consumed by the vacuum pump (kWh)
K_1, K_2	slope of straight line
L	half of the slab thickness (m)
m	mass of the sample for drying (g)
M_e	equilibrium moisture content of sample (kg water/kgdry solid)
M_0	the initial moisture content (kg water/kg dry solid)
M_t	the moisture content at any time (kg water/kg dry solid)
MR	moisture ratio (dimensionless)
M_1, M_2, M_3	mass of the water (kg)
P_m	useful microwave power (kJ/h)
P_p	peristaltic pump power (kW)
P_u	ultrasonic power (kW)
P_v	nominal vacuum pump power (kW)
Q_1	energy used to heat the water (kWh)
W_0	initial weight of the sample (g)
t	time of drying (s)
t_0	microwave heating time (h)
t_1	ultrasonic processing time (h)
ΔT_1, ΔT_2	increase in temperature (K)
R^2	correlation coefficient
L^*	whiteness/brightness
a^*	redness/greenness
b^*	yellowness/blueness

A. bisporus and considered to be principally responsible for the browning of the fungus (Devece et al., 1999). Under the catalysis of PPO, which contains copper, the monophenolic compounds in *A. bisporus* are hydroxylated to o-diphenols, and the o-dihydroxy compounds are oxided to o-quinones (Van Loey et al., 2001). Slicing treatment may destroy the cell tissue and the balance of phenolic compounds and o-quinones in *A. bisporus* with the entry of large amount of oxygen, leading to accumulation of o-quinones. The further polymerization of the o-quinones results in the formation of dark-colored pigments. During drying, due to the heating and the increase of dry matter concentration, the enzyme action is more intense. The enzymatic browning may alter both the appearance and flavor of the product, ultimately lowering the nutritional and market values. The inhibition of enzymatic browning is thus of great importance in the food industry (Mcevily, 1992).

Ultrasound is a mechanical wave that is capable of propagating through solid, liquid, and gaseous materials. The frequencies of ultrasound waves range from 20 kHz to 100 MHz (Nowacka et al., 2014). The physical and chemical properties of food products can be altered by high-intensity ultrasound (power ultrasound) processing using a low frequency (kHz) (Mcclements, 1995; Zheng and Sun, 2006). The ultrasound technology currently utilized in food processing is quite appealing, and its combined use with heat, known as thermosonication (TS), is a good alternative to conventional heat treatment. Indeed, thermosonication has been reported to enhance the enzyme inactivation of microorganisms (Sala et al., 1995), watercress peroxidase (Cruz et al., 2006), lemon pectinesterase (Kuldiloke et al., 2007), and tomato juice pectin methylesterase (Terefe et al., 2009). Comparing to traditional blanching, ultrasound could help reduce processing time and increase efficiency, and the inactivation effect of the combined use of ultrasound and heat has also been found to synergistically improve the inactivation kinetics of PPO in *A. bisporus* (Cheng et al., 2013). Thermosonic processing is thus a potential method for treating *A. bisporus* slices before microwave vacuum drying, to inhibit enzymatic browning. However, the “sponge effect” of power ultrasound on a solid–liquid system may induce compression and expansion of the material. This is believed to cause a double effect on the internal micro-structure of the material. On one hand, microscopic channels are created in the tissue, and on the other hand, the expansion and escape of the gas trapped in the pores are eased. Both effects would impact the subsequent drying process (Fernandes and Rodrigues, 2007; Knorr et al., 2004; Rastogi, 2010). Furthermore, the occurrence of blanching may also soften the tissue (Tunde-Akintunde and Ogunlakin, 2011). Hence, the economic viability of thermosonic technology and its combination with MVD for the treatment of *A. bisporus* slices requires investigation.

The aim of the present study was to evaluate the use of thermosonic pretreatment for microwave vacuum drying of *A. bisporus* slices. This involved investigation of the drying kinetics, energy consumption, and color of the dried *A. bisporus* slices.

2. Materials and methods

2.1. Raw materials

Fresh *A. bisporus* was obtained from a local supermarket in Nanjing, China. All the *A. bisporus* samples were thoroughly cleaned to remove adherent soil, and then graded based on the exposed surface area. The diameter of the cap and stipe of the samples were set to about 50 and 30 mm, respectively. The middle sections of the samples were cut longitudinally into slices of thickness 5 ± 0.16 mm using an electric vegetable slicer. The AOAC method was used to determine the moisture content of the samples. The process was performed in a vacuum oven at 70 °C for 14–16 h (AOAC, 1984).

2.2. Thermosonic pretreatment

The *A. bisporus* slices were thermosonically treated in a water bath using a frequency of 25 kHz and 80% of the maximum equipment power. The ultrasound generator (KQ-300GVDV; Kunshan Ultrasonic Instrument Co. Ltd., Kunshan, China) had internal dimensions of 300 × 240 × 180 mm. The calorimetrical method was used to determine the acoustic intensity of the sonication process. The temperature increase with respect to the time of application of the ultrasound was recorded. The ultrasonic power was calculated using the following formul (Raso et al., 1999; Cárcel et al., 2007):