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Power ultrasound as a pretreatment to convective drying of mulberry (*Morus alba* L.) leaves: Impact on drying kinetics and selected quality properties

Yang Tao [a], Ping Wang [a], Yilin Wang [a], Shekhar U. Kadam [b], Yongbin Han [a,*], Jiandong Wang [a], Jianzhong Zhou [c]

[a] College of Food Science and Technology, Nanjing Agricultural University, Nanjing 210095, China
[b] UCD School of Biosystems and Food Engineering, University College Dublin, Belfield, Dublin 4, Ireland
[c] Institute of Agro-product Processing, Jiangsu Academy of Agricultural Sciences, Nanjing 210014, China

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ABSTRACT

The effect of ultrasound pretreatment prior to convective drying on drying kinetics and selected quality properties of mulberry leaves was investigated in this study. Ultrasound pretreatment was carried out at 25.2–117.6 W/L for 5–15 min in a continuous mode. After sonication, mulberry leaves were dried in a hot-air convective dryer at 60 °C. The results revealed that ultrasound pretreatment not only affected the weight of mulberry leaves, it also enhanced the convective drying kinetics and reduced total energy consumption. The drying kinetics was modeled using a diffusion model considering external resistance and effective diffusion coefficient D_e and mass transfer coefficient h_m were identified. Both D_e and h_m during convective drying increased with the increase of acoustic energy density (AED) and ultrasound duration. However, D_e and h_m increased slowly at high AED levels. Furthermore, ultrasound pretreatment had a more profound influence on internal mass transfer resistance than on external mass transfer resistance during drying according to Sherwood numbers. Regarding the quality properties, the color, antioxidant activity and contents of several bioactive compounds of dried mulberry leaves pretreated by ultrasound at 63.0 W/L for 10 min were similar to that of mulberry leaves without any pretreatments. Overall, ultrasound pretreatment is effective to shorten the subsequent drying time of mulberry leaves without damaging the quality of final product.

1. Introduction

Mulberry (*Morus alba* L.), belonging to the Moraceae family, is widely distributed in temperate, tropical and subtropical areas. The fruit, leaf, branch and bark of mulberry are good sources of bioactive compounds. Mulberry leaves are rich in chlorogenic acid, rutin, ferulic acid, catechin, isoquercitrin, polysaccharide, 1-deoxynojirimycin (DNJ), γ-aminobutyric acid (GABA) and many other bioactive compounds, which are related to various health-beneficial functions, including anti-oxidation, anti-obesity, anti-atherosclerosis, anti-inflammation and anti-diabetes [1–5]. In Chinese medicine, mulberry leaves are occasionally used for fever therapy and liver protection, while in Japan and Korea, mulberry leaves are consumed as a functional food by patients with diabetes mellitus [3]. In the last decade, the consumption of mulberry leaf tea has been increasing continuously in Asian countries, including Japan, China and Thailand [3,6].

Drying is an essential process to manufacture mulberry leaf tea. Traditionally, mulberry leaves are dehydrated by sun drying. Another common drying technology is hot-air convective drying. However, both technologies require longer duration for drying. Also, sun drying is climate-dependent, while convective drying requires a high amount of energy. Furthermore, high temperature during convective drying can be detrimental to the quality and bioactive compounds of food products [2]. Thus, convective drying has been combined with ultrasound, microwave and far-infrared radiation technologies to enhance the drying process and shorten the drying time [3,7,8]. On the other hand, researches have investigated various pretreatments, such as sonication, osmotic dehydration and mechanical dewatering, to improve the drying efficiency and reduce energy consumption [9,10].

Ultrasound has already been used as a pretreatment before convective drying of various food products, such as seaweed, apple,

* Corresponding author.
E-mail address: hanyongbin@njau.edu.cn (Y. Han).

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Nomenclature

a	regression coefficient in Eq. (11)
AED	acoustic energy density (W/L)
C_p	specific heat of water (4.18 kJ/kg °C)
D_e	effective diffusion coefficient (m^2/s)
DM	dry matter
E	mean relative deviation modulus (%)
h_m	external mass transfer coefficient (kg water/m^2 s)
L	characteristic dimension for water transport (m)
m	mass of water (kg)
m_0	initial mass of mulberry leaves before ultrasound pretreatment (kg)
m_{us}	mass of mulberry leaves after ultrasound pretreatment (kg)
m_{loss}	mass of solids lost into distilled water after ultrasound pretreatment (kg)
RMSE	root mean square error (kg water/kg DM)
P	ultrasound power (W)
R^2	coefficient of determination
Sh	Sherwood number
T	temperature (°C)
t	time (s)
W	moisture content (kg water/kg DM)
W_{ave}	average moisture content (kg water/kg DM)
W_{cal}	moisture content calculated from the diffusion model (kg water/kg DM)
W_{exp}	moisture content obtained experimentally (kg water/kg DM)
x	mass transport characteristic direction or independent variable
y	dependent variable
ρ_{DM}	dry matter density (kg DM/m^3)
φ_e	relative humidity of air at equilibrium (%)
φ_∞	relative humidity of drying air (%)

melon, parsley leaves, etc. [10–13]. All these published studies demonstrate that ultrasound pretreatment is effective to enhance the subsequent drying process and reduce the drying time. The basis of ultrasound as a pretreatment before drying is its mechanical effect and the accompanied ultrasonic cavitation phenomenon. Specifically, the propagation of ultrasound in liquid medium can cause a rapid series of alternative compression and expansion, as well as the formation of cavitation bubbles. Micro-streaming and local extremely high temperature and pressure are generated during the collapse of cavitation bubbles [14]. The mechanical force and the physical and chemical effects of ultrasound cavitation can remove the moisture strongly attached to food materials, deform porous food materials and create microscopic channels, thus enhancing the mass transfer during convective drying [11]. According to our best knowledge, ultrasound has not yet been used as a pretreatment before convective drying of mulberry leaves.

Furthermore, the construction of mathematical models with physical significance is helpful to understand the mass transfer mechanism during drying, as well as elucidate the effects of different pretreatments on subsequent drying kinetics. In many cases of simulation of convective drying, the diffusion model based on the Fick's second law was employed. For example, diffusion models with and without external resistance were proven to be accurate to model the drying kinetics of orange peel, apple and strawberry during convective drying in the presence of ultrasound irradiation [7,15,16]. However, there are few studies using physical models to explore the effect of ultrasound pretreatment on the subsequent drying kinetics of food products.

Therefore, the aim of this study was to investigate the feasibility of ultrasound as a pretreatment to enhance the convective drying of mulberry leaves. The effects of different parameters of ultrasound on weight gain, solid loss, moisture effective diffusion coefficient and external mass transfer coefficient calculated from diffusion model were studied. Moreover, several quality parameters of dried mulberry leaves with and without ultrasound pretreatment were also examined.

2. Materials and methods

2.1. Mulberry leaves

Fresh mulberry (*Morus alba* L.) leaves, cultivar Husang, were harvested from the mulberry plantation belonging to Jiujiu Silk Co. Ltd. (Suqian, China) in the end of May, 2015. All these leaves were young leaves (the third to the tenth leaves from the top of tree). Mulberry leaves were washed, drained, sliced into sections of approximately 1.5 × 1.5 cm, wrapped in plastic films and stored at 4 °C before experiments. The initial moisture content of mulberry leaves was determined using AOAC method by putting the leaves in a forced circulating air-drying oven at 105 °C for 24 h [17]. The initial moisture content of fresh mulberry leaves was 2.85 ± 0.08 kg water/kg DM (dry matter).

2.2. Ultrasound pretreatment

A 130 W ultrasound probe system (VCX130, Sonics and Materials Inc., Newtown, USA) with a diameter of 3 mm operating at 20 kHz was used for ultrasound pretreatment. The schematic diagram of the experimental setup is shown in Fig. 1. Specifically, 3.0 g of aforementioned mulberry leaves were placed in a 100-mL glass beaker and 50 mL of distilled water was added. This beaker was then positioned in a thermostatic water bath with an impeller (DC-0506, Fandilang Tech, Nanjing, China), so as to maintain the temperature inside the bath at 20 ± 0.5 °C during sonication. The ultrasound probe was submerged to a depth of 30 mm in the samples and the energy input was adjusted by setting the amplitude of probe. In this study, the amplitudes used included

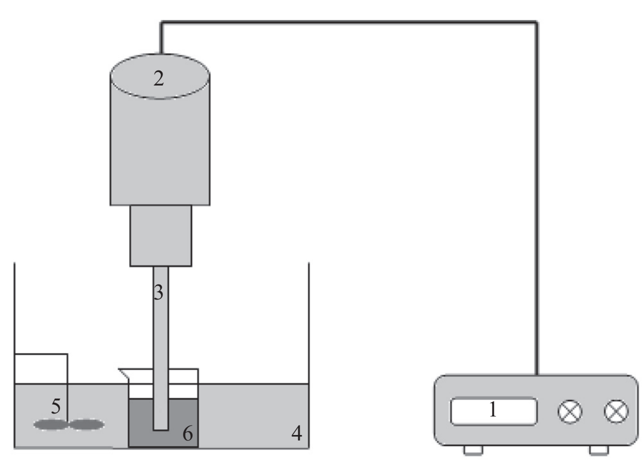

Fig. 1. Experimental setup of ultrasound pretreatment of mulberry leaves before drying. (1) ultrasound generator; (2) ultrasound transducer; (3) ultrasound cylinder probe; (4) thermostatic water bath; (5) impeller; (6) 100-mL glass beaker.