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The effect of high power airborne ultrasound and microwaves on convective drying effectiveness and quality of green pepper

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ABSTRACT

The effectiveness of hybrid drying based on convective drying with application of ultrasound and microwave enhancement is the main subject of the studies. The drying kinetics, energy consumption as well as the quality aspect of green pepper is analysed. It was shown that hybrid drying methods shorten significantly the drying time, reduce the energy consumption and affect positively the quality factors. Each of the analysed aspects depend on combination of the convective-ultrasound-microwave drying programs. Besides, based on the drying model elaborated earlier by one of the authors, the effects of ultrasound on convective drying assessed by such phenomena as "heating effect", "vibration effect" and "synergistic effect" are presented.

1. Introduction

Evaporation of water from fruits and vegetables is a highly complex process associated with many negative consequences, such as changes in the internal structure and sensory properties (colour, flavour, aroma), chemical composition and changes in the content of bioactive components. In drying of foods, it is important to reduce the water content (water activity) while preserving the product quality [1,2]. The quality of dried biomaterial is one of the fundamental indicators in the assessment of the drying process effectiveness. The conventional drying techniques, especially hot air drying is still extensively employed as a preservation technique, however, it affects the final quality of dried product adversely. Convective drying is considered rather as highly destructive due to, e.g. shrinkage, discoloration and loss of nutrients, particularly for thermally sensitive materials like fruits and vegetables. Moreover, hot air drying is usually undesirable long-lasting and energy consuming process of food preservation [3].

One of the recommended ways to minimize these adverse features of convective drying is application of hybrid methods, where the energy is provided alternatively by combination of different energy sources, e.g. convection with ultrasound or microwave radiation, etc. By microwave radiation heat is provided to the entire material volume in a relatively short time, and not only to the surface as in convective drying. The increase of temperature in the material interior involves thermo-diffusion and pressure gradient that cause "pumping" of the moisture towards material surface. Thus, the moisture transport is more effective and results in shortening of drying time [4]. Kowalski and Mierzwa [5] showed that convective-microwave drying of beetroot increased the drying rate nearly four times compared with pure convective drying. Convective-microwave drying can be also favourable in terms of product quality. Prabhanjan et al. [6] proved that in microwave-assisted convective drying of carrot cubes the product revealed better reconstitution properties by rehydration than in pure convectively dried material. Moreover, Workneh et al. [7] showed that low temperature air ventilation with microwave assisted drying could be considered as an alternative drying method for tomato slices, as it maintains a superior quality in terms of colour. As presented Kowalski and Mierzwa [8], the convective-microwave drying of red bell pepper caused smaller shrinkage and deformation of this product, and reduced energy consumption by about 62%. Application of microwaves reduces also the degree of vitamin C degradation, i.e. by combined microwave–air–drying the ascorbic acid content was retained up to 98% [9].

Application of ultrasound in drying of foods is a relatively new item and one of the emerging technologies. High power ultrasound generates acoustic cavitation, and the absorption of the acoustic energy causes the so-called "heating effect" and micro-"vibration

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Nomenclature

A	surface [m^2]	m_{Rt}	sample mass during rehydration at time t [kg]
A_0	initial surface of sample [m^2]	m_s	mass of dry sample [kg]
AD_rE	ratio of drying rate enhancement [%]	m_t	mass of sample at time t [kg]
A_m	surface of mass exchange [m^2]	m_0	mass of sample before rehydration [kg]
A_T	surface of heat exchange [m^2]	P_{UD}	power of ultrasonic generator [W]
α	microwave energy absorbed by the skeleton [W]	p_{vs}	vapor partial pressure for the saturated state at given temperature [Pa]
a_{UD}	absorption coefficient of ultrasonic wave [−]	t	time [min]
a_w	water activity [−]	t_e	drying time at which the moisture content reaches equilibrium [min]
a^*	colour parameter from red to green [−]	T_a	air temperature [°C]
β	microwave energy absorbed by the moisture [W]	T_m	material temperature [°C]
b^*	colour parameter from yellow to blue [−]	UD	ultrasound
$CD_rE_{s,\ eff}$	contribution ratio of "vibration effect" [%]	v_a	air flow velocity [m/s]
$CD_rE_{T,\ eff}$	contribution ratio of "heating effect" [%]	$(\boldsymbol{x}\cdot\boldsymbol{n})$	distance of wave propagation [m]
$CD_rE_{v,\ eff}$	contribution ratio of "vibration effect" [%]	X	moisture content (dry basis) [kg/kg]
CV	convection	X_{eq}	equilibrium moisture content (dry basis) [kg/kg]
CVMW	convective-microwave drying	X_i	initial moisture content (dry basis) [kg/kg]
CVUD	convective-ultrasound drying	X_{cr}	critical moisture content (dry basis) [kg/kg]
CV	convective drying	α_V	volumetric shrinkage coefficient [−]
c_l	specific heat for liquid [J/kg·K]	ΔE	total colour change [−]
c_s	specific heat for liquid [J/kg·K]	ΔQ	heat source [W]
D_r	drying rate [g/h]	ΔQ_{MW}	microwave heat source [W]
D_rE	drying rate enhancement [g/h]	ΔQ_{UD}	ultrasound heat source [W]
EC	energy consumption [kWh]	δ_{MW}	decay factor of microwave energy [−]
h_m	mass transfer coefficient [kg/m^2 h]	φ_a	relative air humidity [%]
h_T	heat transfer coefficient [W/m^2·K]	$\varphi\|_{\partial B}$	relative air humidity near the material surface [%]
L^*	lightness [−]	χ_{UD}	working efficiency of the ultrasonic transducer [−]
l	latent heat of evaporation [J/kg]		
MW	microwave		

effect" in the material surface layer [10]. Therefore, ultrasound action changes the physical, mechanical or chemical/biochemical properties of biomaterials [11]. Riera-Franco de Sarabia et al. [12] showed that material vibrations induced by ultrasound accelerate notably the drying process and reduces the duration of the process three times. As presented by Rodríguez et al. [13], the ultrasound application in convective drying involved lower total polyphenol and flavonoid content losses in comparison to air dried apples. Gallego-Juárez et al. [14] showed that by dehydration of carrot with application of ultrasound the energy consumption was lower, and the sample rehydration was higher by about 70% than in processing without ultrasound. Deng and Zhao [15] observed that the water activity after the drying of apples with ultrasonic pre-treatment is lower as compared to pulsed vacuum pre-treatment. Ultrasound assisted drying can also leads to energy savings.

One can state a number of advantages while combining various drying techniques such as convection, microwave and ultrasound in an appropriate way. By combination of several energy sources in one drying process a significant improvement of drying efficiency can be achieved. Then, hybrid drying can be a very attractive and promising solution from the drying kinetics, energy consumption and as well as the product quality point of view. A number of reports in the literature allow to state that use of microwaves and ultrasound to enhance convective drying usually positively affects many properties of dried fruits and vegetables. Among some benefits of such an approach one can mention, e.g. elimination of shrinkage (higher porosity), retention of colour and aromas as well as bioactive components, while shortening processing time and reducing energy consumption [16,17]. As reported García-Pérez et al. [18], high-intensity ultrasound application in convective drying of orange peel reveals energy saving ranging from 12% to 20% in comparison with pure convective hot air drying.

Dried pepper has a lot of application. It is a rich source of valuable nutrients such as ascorbic acid, carotenoids and flavonoids. It is mainly used as a compound for soups, sauces and dry salad mixes [19]. Therefore, the main purpose of this study was to examine the effect of hybrid drying based on convection with ultrasound action and microwave radiation on drying kinetics, energy consumption and final quality of green pepper, i.e. total colour change, water activity, vitamin C retention and the ability to rehydration. In addition, the mathematical modelling is applied to assess the electiveness of ultrasound-convective drying, and to determine some positive effects followed from ultrasound action in drying processes.

2. Material and methods

2.1. Material and apparatus

Fresh green pepper (*Capsicum annuum* L.) imported from Spain were purchased at a local market. The biological material with an average initial water content of 13.19 kg/kg db was washed in tap water, drained with blotting paper and cut into 6 slices (45 mm length, 30 cm width, 2 mm thick), each about 7.5 g. The samples were placed on the pan in the form of ring, skin-side down to allow the most effective application of ultrasound in the focusing area. Then, the green pepper samples were dried to a final moisture content of 0.03 kg/kg db, on average. Seven different drying tests were carried out including convective drying (CV) as a reference, as presented in Table 1. For this purpose an innovative laboratory hybrid dryer (Promis–Tech, Poland), equipped with a microwave and airborne ultrasound generator (Pusonics, Spain) was used. The scheme and photo of the experimental set-up is presented in Figs. 1a and 1b.