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Novel hybridized drying methods for processing of apple fruit: Energy conservation approach

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ABSTRACT

Strategic outlook of apple cultivation and its significant post-processing challenges have been the leading factors for energy and time saving research approaches in apple processing. In this research, apple slices were subjected to hot air flow, microwave radiation and combined microwave-hot air flow drying. Drying time, energy consumption and thermal efficiency at different microwave power levels (500 W, 1000 W, 1500 W and 2000 W), hot air temperatures (40 °C, 50 °C, 60 °C and 70 °C) and inlet air velocities (0.5 ms^{-1}, 1 ms^{-1}, 1.5 ms^{-1} and 2 ms^{-1}) were studied and compared. The minimum time of processing was 17 min when integrated hot air flow and microwave radiation was applied with 2000 W power at the temperature of 70 °C and air velocity of 2 ms^{-1}. Furthermore, the minimum value of total energy consumption during entire process of apple slices drying was 2684 kJ which belonged to microwave drying with 2000 W power.

1. Introduction

Apple is the fourth most important nutritional garden fruit in the world which is used as the raw material of different foods. Apple is the pomaceous fruit of the apple tree, species *Malus domestica* of the *rose* family (*Rosaceae*) [1]. Fresh apple, having a high level of moisture content is exposed to high risks of decaying and lower storage time. Man has always tried to increase the storage time of products and dry them to prevent them from decaying. This process is introduced by simultaneous transfer of temperature and mass, during which the water activity is minimized due to decreasing the moisture content to a desired level so the undesired microbial activity and chemical reactions are hindered [1–3]. Drying is known as a food processing method which aims at decreasing food moisture content in order to increase the storage time without any considerable changes in flavor, color and odor. Although drying inflicts undesirable effects on product quality, it seems to be an inevitable process in food industry since it increases storage time, and reduces costs of packaging, transportation and storage as well as ecological advantages [4].

Using sunlight and hot air flow are among the most common drying techniques due to their low-cost and availability. Sunlight drying is a traditional method in which obtaining homogeneous dried products is difficult since it is time-consuming, needs labor force, heavily depends on weather conditions and the product is exposed to environmental damages [4]. Thus, industrial methods have been recently applied to overcome these shortcomings.

Heated air flow is a typical and effective method used in the industry [1,3,5]. Yet, it suffers from some disadvantages such as adverse effects on color, flavor and nutrients, flow of soluble towards the surface as a result of high drying temperature and duration, product hardening and shrinkage. These features reflect not only transformations during the processing phase, but also lower product attraction and marketability [3,6]. Koyuncu et al. [7] dried two species of red and yellow azarole using hot air flow at various temperatures and constant air velocity. It is shown that temperature variation influences drying time and energy consumption. Drying tomatoes using hot air flow at various temperatures and constant air velocity was studied by Doymaz [8]. Air temperature affects the drying rate. The increase in the air temperature drastically increased the drying rate of tomatoes [8]. Inlet air velocity can alter the drying time, drying rate and energy consumption. Under this circumstance, manipulation of inlet air velocity, along with changes in temperature, contributes to obtaining a minimum level of energy consumption. However previous researches did not take into account the effect of air velocity. Koyuncu

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Nomenclature

E_1	Energy consumption of blower, (J)
E_2	Energy consumption of six heaters, (J)
W_1	Nominal power of blower, (70 W)
W_2	Nominal power of heater, (700 W)
t_1	Operating times of blower, (s)
t_2	Operating times of heaters, (s)
W_0	Initial weight of the sample (kg)
E_{T1}	Total energy consumption for producing hot air flow, (J)
E_{T2}	Total energy consumption for microwave radiation, (J)
E_{T3}	Total energy consumption for producing hot air flow and microwave radiation, (J)
E_{kg}	Specific energy consumption, (kJ/kg)
η	Thermal efficiency, (%)
L	Loading density, (kg/m^2)
Ad	Total drying area, (m^2)
λ	Latent heat of vaporization, (kJ/kg).
Mi	Initial moisture content, (% wet basis)
Mo	Final moisture content, (% wet basis)
P	Power of heating source, (kW)
t	Drying time, (s).

et al. [9] conducted a study on drying cherries at the temperatures of 50 °C, 60 °C, 70 °C and air velocity of 0.3 ms^{-1}, 0.6 ms^{-1}, 0.9 ms^{-1}. They found that both temperature and air velocity influence time and energy consumption. Moreover, they reported that in order to obtain minimum energy consumption in drying cherries, air velocity should not exceed 0.3 ms^{-1} for each temperature.

Considering the low heat conductivity of the agricultural products, penetration of heat into the flesh is regarded as a major concern increasing the drying period. Accordingly, researchers seek new technologies to optimize the drying process [1,10,11]. The drying process requires time and energy, so in recent years efforts have been directed at developing methods with lower time and energy consumption [1]. Infrared and microwave drying are examples of such methods [12]. Application of infrared radiation heating is gaining popularity in food processing because of its definite advantages over conventional heating. Faster and efficient heat transfer, lower processing cost and better organoleptic and nutritional value of processed material are some of the important features of infrared radiation drying [13,14].

Microwave food dehydration is a new way of drying agricultural products which has attracted researchers in the last decade because of availability of resources [1]. Microwaves are high-frequency electromagnetic waves with wavelengths ranges from 1 mm to 1 m and frequency ranging from 300 MHz to 300 GHz [2]. Microwave drying preserves the product quality while decreasing the drying duration. It also benefits from cost-effectiveness and potential for commercialism [3,4,11].

Infrared radiation affects only the surface of the food and heat transfer through the food takes place by conduction or convection. On the other hand, microwave heating occurs evenly throughout the food and produces volumetric heating [15]. Therefore microwave drying is more rapid, more uniform and more energy efficient than hot-air convection and infrared radiation drying [16]. A proof of this claim is reported by Sorour and Mesery [12] who dried onion slices with a moisture content of 7.3 g water/g dry matter using microwave and infrared radiation methods to a moisture content of 7% (wet basis). Results showed that microwave drying was more effective in shortening drying time when compared with infrared drying. Moreover, microwave dried onion slices were lighter in color and better in quality.

Microwaves are in the form of waves which turn into heat by bipolar rotation in reaction to substances. Water molecules are bipolar; that is, they have positive and negative poles. These molecules are exposed to electric field which its polarity changes quickly as a result of microwave radiation. Molecules rotate in line with changes in electric field polarity and continue to rotate randomly even when the electric filed vanishes. However, they rotate in line with the new electric field with an opposite polarity, i.e. approximately 2.45 billion per second and lead to transform electric energy into potential energy and potential energy to kinetic energy, which is finally transformed into thermal energy. Microwave energy is quickly absorbed by water molecules and accelerates water evaporation and drying rate. Consequently, energy consumed reduces considerably and product surface temperature remains low since drying duration is shortened by 50% [2]. Regarding time and energy consumption in the drying process and limited energy resources in the world, a bulk of studies have recently been directed at decreasing energy consumption while preserving the desired product quality. Since several studies have been published on microwave drying [4,17–20], it is already proved that drying process using microwave energy takes much less time in comparison to conventional drying methods. Therefore it is possible to hypothesize that energy consumed will be reduced due to reduced drying time. Using an electronic microscope to observe results of drying process with microwaves reveals that big holes appear on product tissues and make the dried product look porous, which facilitates dehydration. However, in heated-air flow process, the dried product is stiff with strong bonds between cells, within which moisture can hardly escape [21].

This process is advantageous to previously established methods [10,11] because of,

- Fast and volumetric heating
- High drying rate
- Short drying duration
- High Product quality
- Reduced energy consumption
- Cost-effectiveness

Nevertheless, this method is not all inclusive and impeccable and, apart from aforementioned advantages, it may induce non-uniform heating, depending on thermal and dielectric properties of the product [22]. Moreover, due to rapid mass transfer in this method, desorption of moisture expelled from the product is difficult and leads to condensation of vapor in the chamber, increasing relative air moisture in the dryer chamber and decreasing drying rate [23]. To overcome these shortcomings, a combination of different systems such as combined microwave-hot air flow, or microwave–vacuum combination can be used in the drying process [11]. In the combined microwave-hot air flow method, energy of microwaves pushes water in the product towards the surface which is then vaporized by hot air flow [5]. Considering the above mentioned advantages, some literature has been published on combined microwave-hot air flow drying [5,6,10,11,23,24].

Briefly speaking, in spite of numerous experimentations reported, the simultaneous effect of all influencing parameters including air temperature, air velocity and microwave power on the drying time and energy consumption is not discussed while slight changes in any of them contribute to large variations of time and energy consumption.