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Research Paper

# Influence of mode stirrer and air renewal on controlled microwave drying of sliced zucchini

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An on-line temperature-controlled microwave (MW) system, based on infrared thermography, was developed for drying zucchini slices. Moreover, the effects of different configurations, including turntable rotation, mode stirrer and air renewal, alone or in combination, on drying kinetics and quality of dried product were evaluated. The combination of stirrer and air renewal reduced the drying time of zucchini slices by about 48% with respect to the basic configuration and by 22% with respect to air renewal only. The lowest oscillation of temperatures about the fixed level (65 °C) was found when operating with the stirrer mode, because of the improved uniformity of the MW distribution. The samples treated by stirrer and air renewal configurations showed less variation in colour: the decrease of brightness was about 19% with respect to fresh samples and the value of global variation of colour, ΔE, was 18. It is important to note that air renewal in MW processing is an almost zero energy-cost option.



## 1. Introduction

The use of microwaves (MWs) could be successful to enhance heat transfer rates realised in conventional hot air drying process. In fact, in MW-assisted drying heat is not transferred from the surface but it is generated in the bulk of the material by absorption of electromagnetic (EM) energy from the MW field. Volumetric heating develops internal pressure gradients that drive water flow from the interior to the surface of the material thus realising fast drying. On the other hand, during the MW drying process, highly non-uniform temperature fields can be established inside the MW oven because of the non-uniformity of the EM field. Energy density changes both in space and in time are emphasised by the strong temperature-dependent MW absorption and by the decrease in volume of the material, as moisture is lost during the process. Therefore, quality loss for the final product is often observed, and a controlled MW power delivery is required to avoid or limit over-heating. The latter is not an easy task to realise because of well-known difficulties in measuring and controlling process temperatures. As a result, a wide and generalised expansion of MW industrial applications for drying has been slow.

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**Abbreviations**

| | |
|---|---|
| MW | microwave |
| IR | infrared |
| EM | electromagnetic |
| i.d. | internal diameter |
| o.d. | outside diameter |
| w.m. | wet matter |
| rpm | revolutions for minute |
| RH | relative humidity |
| MR | moisture ratio |
| $M_{water}(t)$ | moisture content at time t |
| $M_{water}(t=0)$ | moisture content at time 0 |
| $M_d$ | moisture content on dry basis |
| $L^*$ | brightness |
| $a^*$ | red index |
| $b^*$ | yellow index |
| ΔE | colour differences |
| LSD | least significance difference |
| NDR | normalised drying rates |
| $m_w(t)$ | sample weight at time t |
| $t_c$ | critical time: beginning of falling rate period |
| $R^2$ | coefficient of determination |
| SD | standard deviation |

In response to such critical issues, several techniques have been proposed to improve temperature uniformity in fruits and vegetables during MW drying process (Clary, Wang, & Petrucci, 2005; Cui, Xu, Sun, & Chen, 2005; Püschner, 2005), e.g. rotating supports (Calín-Sánchez, Figiel, Wojdylo, Szaryez, & Carbonell-Barrachina, 2014; Geedipalli, Rakesh, & Datta, 2007; Sutar & Prasad, 2007), as well as rotating stirrers (Zhenfeng, Raghavan, & Orsat, 2010). In this way, it is possible to shorten drying times and improve product quality, while achieving high nutritional and sensory quality (Zhang, Tang, Mujumdar, & Wang, 2006).

In this framework, the present study aims to show how different operational devices could be effective to improve the uniformity of the MW drying treatment, which obviously affects the final product quality and process speed. In particular, turning table, air renewal and stirrer mode were used and their effects evaluated individually or in combination during the drying of zucchini slices at 65 °C. The MW plant used was able to adapt the delivered MW power to keep the zucchini slices temperature at a fixed level while drying.

## 2. Materials and method

### 2.1. Microwave prototype

Drying experiments were carried out using a lab scale MW plant (Fig. 1), which houses a magnetron with a nominal power output of 2 kW operating at a frequency of 2.45 GHz; the generated MWs were fed to a metallic cubic chamber (1 $m^3$) equipped with a fan placed on the bottom of the cavity for air renewal. A stirrer was placed inside the oven to improve heating uniformity. Since stirrer performance can be improved by increasing size and asymmetry (Wu & Chang, 1989), a fan with three blades 19 cm long, each with a different tilt angle and coated with aluminium tape, was installed inside the chamber. Helix rotation modifies the EM boundary conditions within the MW heating applicator, resulting in a non-stationary electric field pattern over the processed materials.

A Teflon rotating annulus (500 mm i.d, 55 mm o.d.) held a high-density polyethylene squared grid (10 mm × 10 mm), which supported the samples to be tested. The grid was suspended under a technical balance (Gibertini EU-C 1200 RS, Novate Milanese, Italy) located on the top of the oven for measuring moisture loss during drying experiments. An infrared (IR) thermometry system (ThermaCAM Flir P65, Canada) looked at the surface temperatures of the samples through a square hole (70 mm × 70 mm) at the top of the oven.

The hole was properly shielded with a metallic grid, which allowed the IR radiation from the detected scene to escape but held back the long wavelength (about 12 cm) EM radiation produced by the magnetron (Cuccurullo, Giordano, & Viccione, 2016). The IR equipment produced a feedback signal every 0.9 s, which allowed an on/off control to set up for the magnetron delivered power around a preset target temperature. The control was set inside a freely specified nominal differential bandwidth over the target temperature using LabView software.

### 2.2. Sample preparation

Fresh zucchini (*Cucurbita pepo* L.) were purchased at a local market in Salerno, Italy, and stored at 4 °C before drying, when the samples were cut into 15 ± 0.5 mm slices with 30 ± 0.5 mm diameter, before placing them on the grid suspended in the MW oven (Fig. 1).

The zucchini initial moisture content (91.8% w.m.) had been previously determined by drying selected samples in a convection oven. The moisture content was determined according to oven drying method at 105 °C until a constant weight was reached (AACC, 2000).

### 2.3. Experimental setup

Different configurations for the experimental setup were considered, each one employing different techniques for carrying out the drying process. For each device, the ability to perform fast drying and/or to improve the final product quality, were checked. The configurations were:

- Turning table: it was the basic arrangement, which allowed MW drying assisted by IR based control system while the turntable rotated at 7 rpm. The zucchini slices were placed on the rotating plate in one layer for dehydration, with air initially at room conditions (24 ± 1 °C; 50 ± 5% RH).
- Air renewal: similar to the turntable arrangement with, in addition, circulation of forced external dry air for fast moisture removal. The fan created an ascending airflow, with an average speed of 1.1 ± 0.1 m $s^{-1}$ at the level of the zucchini, as measured by hot wire digital anemometer.