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Easy Digital Control of Refractance Window and Microwave Heating Drying for Sustainable Valorization of Orange Residuals

Ahmad Adeel Arshad [a*], Cristian Ramirez[b], Francesca Colicigno[c], Francesco Marra[c]

[a] Department of Science, Technology and Society, University School for Advanced Studies IUSS Pavia, Pavia (PV), Italy
[b] Departamento de Ingeniería Química y Ambiental, Universidad Técnica Federico Santa María, Valparaíso, Chile
[c] Dipartimento di Ingegneria Industriale, Università degli studi di Salerno, Fisciano (SA), Italy
arshad.ahmad@iusspavia.it

This study explores the stabilization of orange pomace with digitally controlled drying system that combines Refractance Window™ (RW) and Microwave (MW) technology, to obtain a sustainable pomace powder, a by-product of orange processing. The setup includes a microwave cavity, a water-filled glass container, Mylar film, and orange pomace spread over the film. Controlling MW-assisted heat transfer is challenging due to high heating rates and limitations in using thermal probes, which may interfere with the electromagnetic field. The dehydration process was optimized by controlling the drying time through a system that followed the time-evaluation of the temperature of the RW water and the orange pomace. Under optimal conditions, the RW-MW system reduced the water activity (Aw) of orange pomace below 0.3 within 40 minutes, ensuring microbial stability and suitability for long-term storage while preserving product quality. Compared to conventional drying methods like freeze-drying or hot-air drying, the RW-MW system offers faster drying with energy consumption (~4.8 kWh/kg). This approach offers a sustainable solution for agro-industrial waste valorization, supporting circular economy principles and reducing environmental impact.

1. Introduction

Orange global market size grows from $3.64 billion in 2024 to $3.87 billion in 2025 at a compound annual growth rate (CAGR) of 6.3% (The Business Research Company, 2025). In 2024, the gross production value of oranges in Italy was 559.84 million US dollars PPP (ReportLinker, 2024). Spain and Italy represent the leading EU citrus producers, followed by Greece, Portugal, and Cyprus. Additionally, Sicily and Calabria together produce about 86% of Italy's citrus crop (USDA, 2024) (U.S. Department of Agriculture, Foreign Agricultural Service, 2024).

A large portion of the yield is used in the production of orange juices, marmalades, candies, and jams, generating a good deal of residuals annually, including peels and segment membranes (Mahato et al., 2019). These residuals require appropriate and innovative handling (Li et al., 2023) due to their high content of fermentable organic matter and high-water activity, which make them prone to rapid microbial degradation and unsuitable for direct environmental disposal (Santagata et al., 2021). This leads to significant environmental issues, including soil and water pollution, if not properly managed (Mahato et al., 2019; Santagata et al., 2021). Additionally, the disposal of these residues represents a substantial economic burden for agro-food companies and local communities (Ferrara et al., 2023). Therefore, it is essential to develop effective recovery and valorization techniques that reduce environmental impact and improve the overall sustainability of the agro-industrial sector.

The most widely adopted stabilization method is based on the drying and the grinding of fresh residuals immediately after processing, which can stabilise them and extend their shelf life, avoiding further waste and reducing environmental pollution. However, food drying is a complex process that involves mass and heat transfer phenomena and structural changes coupled with the physical and chemical transformations of various compounds present in the food matrix (Morais et al., 2018). These transformations can significantly affect the nutritional quality, flavour, and texture of the food product. Therefore, understanding the underlying mechanisms

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of drying and grinding is crucial for optimising these processes and ensuring the production of high-quality stabilised food items.

In recent years, non-conventional methods like freeze-drying, microwave (MW) drying and radio frequency (RF) drying are being applied to dry and stabilize the orange pomace (Elik et al., 2023). Freeze drying is more effective in preserving antioxidants but has some disadvantages, such as long drying times and high operational cost (Phuon et al., 2022). Microwave (MW) drying has been proved to be a fast-drying method by dielectric heating but at the same time this technology requires ad-hoc control design since it may lead to uneven heating distribution during the process. Nevertheless, MW-assisted processes are recognized to contribute to the sustainability goals (Marra, 2023).

Refractance Window™ (RW) drying, also known as hydro-conductive drying (Baeghbali et al., 2016), has gained attention in recent years as an effective method for dehydrating pulps and fruits while preserving food quality (Mahanti et al., 2021). It is a drying technique based on the use of hot water as a heating medium, which is in contact with a plastic film (mylar). The sample is placed on top of the plastic film and is primarily heated by conduction and infrared radiation, which promotes faster water vaporization and allows the samples to dry in a short drying time (Franco et al., 2019).

Recent studies have demonstrated that RW drying, when combined with microwave energy, can accelerate moisture removal and improve the nutritional retention of the dried material (Ramírez et al., 2025). However, existing literature has not yet extensively explored the drying of orange pomace with RW-MW technology and also the integration of digital control strategies to dynamically manage the drying endpoint based on real-time feedback a novel contribution of the present work.

Previous studies underlined that when the biomass sample reaches the water activity (Aw) lower than 0.3, its temperature shows a rapid increase of increased time-derivative up to the temperature of the RW water (Núñez et al., 2023). So, this particular characteristic observed in the process can be used to alert a control system that the drying process has been completed, which can be a milestone in the RW-MW drying process upscaling.

This work aimed to study the drying of orange pomace using RW coupled with MW and digital control for precise drying time.

2. Material and methods

2.1 Sample preparation

Fresh oranges (Citrus sinensis) were purchased from a local market and stored at ambient temperature until use. The orange pomace (peel, pulp and albedo) was obtained by DICTROLUX's juice extractor with 500W power and 1800 rpm.

2.2 Drying with RW Coupled to Microwave (RW-MW)

The RW-MW drying system (Figure 1) used in this study is based on an RW system inside a modified microwave oven. For this, a glass container (21 x 15 x 6 cm^3) filled with (300 ml) water and 50 grams of orange pomace on plastic mylar film (thickness of 0.1 mm) on the surface in contact with the water was placed inside the microwave chamber. The microwave cavity (Whirlpool Europe, Cassinetta, Italy) was modified with a power generator that controlled the microwave power, which was provided continuously. The microwave oven of 2450 MHz has variable power output settings ranging from 0 W to 900 W. Orange pomace was dried in the lab-scale RW-MW dryer system with an exhaust system to avoid moisture in the microwave chamber, as shown in Figure 1.

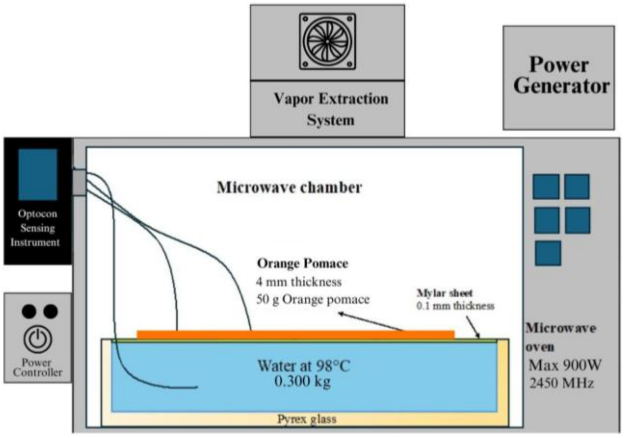

Figure 1: Refractance window - Microwave system

Refractance window water temperature and orange pomace temperature were monitored during RW-MW drying by Optocon (Weidmann, Germany) with fiber optics (TS2 type). RW-MW was operated at an output power level of 360 W in order to keep the water temperature near boiling (~98 °C) during all the experiments. For this case, the microwave power density used was 8 W/g.

Drying time was dynamically controlled by a system following the time-evaluation of the water used in the refractive window because the moisture content of 3 g water/100 g of sample (wet basis) to ensure Aw <0.3 the sample attained as the sample temperature increased from the water, as supported by previous studies (Núñez et al., 2023).Figure 2 shows the different transformation forms of oranges in the experiment. The drying experiment was performed in triplicate (n=3) under the same process conditions, and the results of the Aw were expressed as the mean ± standard deviation.

Figure 2: Orange transformation to orange pomace powder

2.3 Determination of Water Activity

Water activity of all the samples was determined using the AquaLab Per Water Activity Meter (Decagon Devices, Pullman, WA, USA) with ± 0.01 Aw accuracy.

3. Results and Discussion

The RW-MW combined drying system demonstrated a highly efficient and rapid approach for reducing the Aw of orange pomace as shown in Figure 3 while maintaining its functional and nutritional properties.

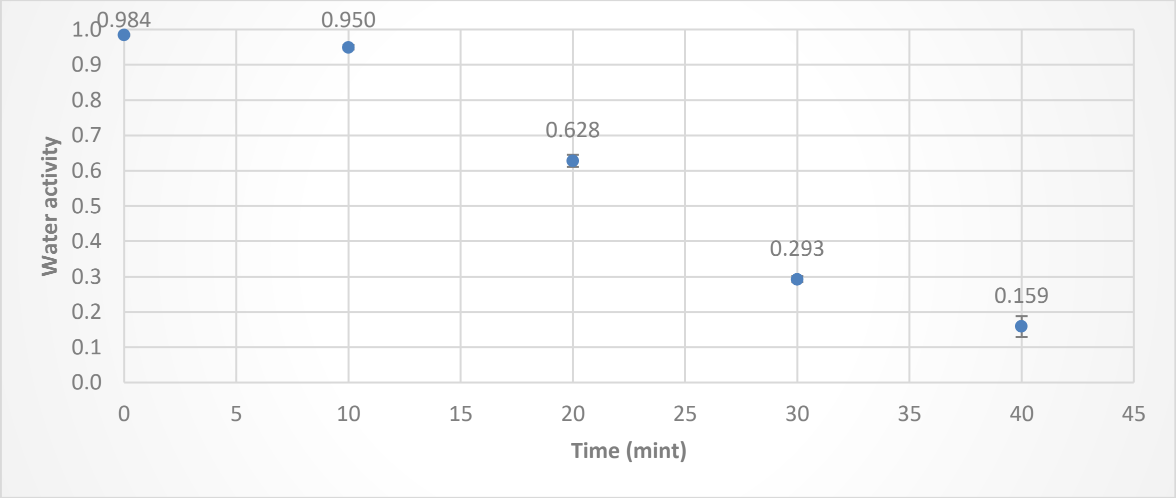

Figure 3: Change in Water Activity over Time

Initially (t = 0 min), the orange pomace exhibited a high Aw of 0.984 ± 0.00252, reflecting the presence of abundant free water. The presence of this unbound moisture predisposes the substrate to microbial proliferation and biochemical reactions, highlighting the necessity for rapid and efficient drying techniques.

During the initial drying phase (t = 0–10 minutes), dielectric heating from microwave energy initiated the oscillation of polar water molecules within the pomace matrix. This phenomenon created localized thermal energy, enhancing moisture migration from the interior of the material toward the surface. Simultaneously, the Refractance Window layer facilitated heat transfer to promote surface evaporation. The cooling effect due to evaporative cooling prevented thermal degradation while supporting the removal of loosely bound surface water. This phase showed a reduction in Aw to 0.950 ± 0.00611, marking the initiation of capillary-driven moisture transport.In the intermediate drying phase (t = 10–20 minutes), the system exhibited a significant decline in Aw, reaching 0.628 ± 0.01735, attributed to Fickian diffusion mechanisms. The generation of internal vapor pressure gradients by microwave energy accelerated moisture transport within the material, while infrared radiation through the RW layer further supported surface evaporation. The effective water diffusivity during this phase was enhanced due to structural modifications such as pore formation, which facilitated moisture migration, while ensuring the retention of structural integrity as in Figure 4.

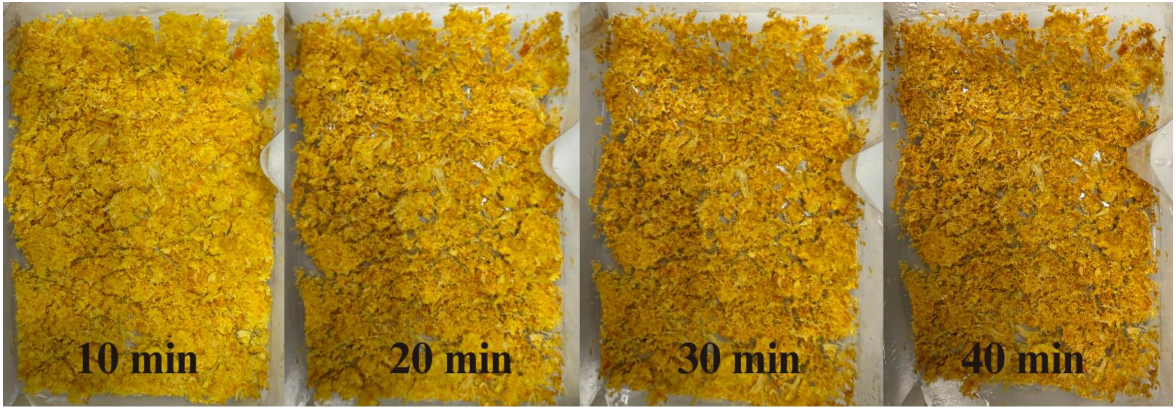

Figure 4: Different stages of orange pomace while drying

At t = 30 minutes, the Aw decreased to 0.293 ± 0.00862, indicating the removal of tightly bound water. This phase involved the dominance of monolayer water interactions, where molecular mobility is increasingly restricted. The system maintained a balance between heat transfer and moisture removal, ensuring minimal damage to the material's biochemical attributes. Notably, pore formation in this phase enhanced moisture diffusion, while capillary collapse began to influence structural changes as bound water content diminished, as in Figure 4.

In the final drying phase (t = 40 minutes), Aw stabilized at 0.159 ± 0.02914, below the microbial stability threshold (Aw < 0.4). During this stage, heat transfer mechanisms shifted predominantly to conduction due to reduced moisture content. The structural adjustments, such as capillary collapse, further limited moisture pathways, yet the system preserved the overall structural integrity of the pomace. The precision of the RW-MW system ensured temperature control, mitigating the risks of excessive thermal degradation and preserving the product's bioactive compounds.

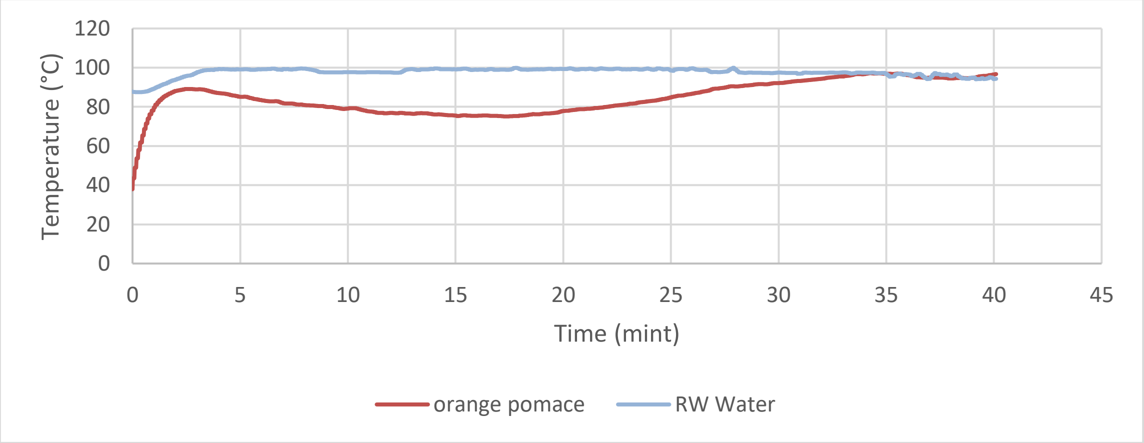

Figure 5: Temperature profiles of orange pomace and Refractance Window (RW) water during drying.

Figure 5 shows the temperature profiles of the orange pomace and RW water. The RW water rapidly stabilized near 98 °C, while the orange pomace initially showed a plateau due to evaporative cooling. After ~30–35 minutes, the pomace temperature rose sharply, approaching the water temperature, signaling the exhaustion of

free water. This inflection point was used as a digital endpoint trigger by the fiber-optic sensing system, eliminating reliance on fixed drying times. This approach aligns with the findings of Núñez et al. (2023), who reported similar temperature-derived criteria for process control in RW systems.
The digitally controlled RW-MW system used in this study achieved effective drying of orange pomace in just 40 minutes, significantly reducing water activity below 0.3, while maintaining product quality and minimizing thermal degradation, in line with the benefits reported in prior RW-MW systems (Ramírez et al., 2025). Compared to conventional drying methods, it offers significantly better product quality. Table 1 provides a comparative analysis with established techniques.

Table 1. Comparative analysis of RW-MW and conventional drying methods for orange pomace stabilization.

Method	Time	Nutrient Retention	Limitations
RW-MW (this study) (Ramírez et al., 2025).	40 min	High (no browning)	50g batch; MW-safe sensor integration
Freeze Drying *(Phuon et al., 2022)*	12–20 h	Very High	High CAPEX; slow throughput
Spray Drying *(Mahato et al., 2019)*	Minutes	Medium	Not viable for fibrous pomace
RF-Hot Air *(Elik et al., 2023)*	1.5–3 h	Moderate	Thermal degradation
Hot-Air Drying	3–6 h	Low (oxidation)	Long time; reduced bioactive preservation

In this method, the energy consumption (~4.8 kWh/kg) based on MW power 360 W over 40 min drying time and 50 g sample mass, is relatively high due to the small batch size and significant heat losses; however, these losses can be minimized through improved system design and process control. The RW-MW system demonstrated a 65–90% reduction in drying time compared to freeze drying and hot-air methods. Spray drying, while fast and energy-efficient, is not feasible for solid pomace without pre-filtration or juice extraction (Mahato et al., 2019). Similarly, RF-assisted drying has limitations in nutrient retention and system complexity (Elik et al., 2023).Although the current system processes 50 g per batch, its modular flat-bed configuration allows scalability through multi-tray or conveyor designs. The integration of fiber-optic sensors supports automated endpoint detection and aligns with industrial IoT infrastructure. Nevertheless, challenges remain, such as the high initial cost of microwave-compatible control systems, difficulties in process monitoring within electromagnetic fields, and safety protocols required for microwave operation.

4. Conclusion

The study demonstrates that a hybrid Refractance Window–Microwave (RW-MW) system, enhanced with real-time temperature monitoring, can effectively reduce orange pomace water activity to <0.3 within 40 minutes while preserving structural integrity and minimizing thermal degradation.
Compared to freeze-drying and conventional hot-air methods, the RW-MW system provides significant reductions in drying time. The integration of fiber-optic sensing for dynamic endpoint detection eliminates the need for fixed time cycles and enables process automation. While promising, the current setup is limited to small-scale use and requires further research on industrial feasibility, including equipment costs, process safety in electromagnetic environments, and long-term operational stability. These aspects will be central to future upscaling efforts. Future research should address these limitations to advance the industrial adoption of RW-MW drying for sustainable food waste valorization.

Nomenclature

Aw – Water Activity
MW – Microwave
RW – Refractance Window
RW Water – Water used in Refractance Window

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