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Ohmic and conventional drying of citrus products: energy efficiency, greenhouse gas emissions and nutritional properties

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Abstract

The use of energy efficient technologies for dehydration of food materials without compromising final food product quality is gaining increased interest in the food industry. A promising dehydration-enhancing process step that has been applied in the food industry mainly for pasteurisation operations is Ohmic heating. This study investigated the use of Ohmic and conventional thermal heating for dewatering of two citrus products, orange and grapefruit. A number of analyses including electrical thermal conductivity (ETC), energy consumption, cost, greenhouse gas (GHG) emissions, moisture content, PH and Vitamin C levels were performed. The results revealed that there was a positive increase of the ETC over time in both samples, resulting in higher values of 70^{0}C for the orange samples and 100^{0}C for the grapefruit samples. The moisture content of the samples was significantly ($P<0.05$) reduced during Ohmic and thermal dehydration over time while no significant difference was detected in terms of pH and Vitamin C level. The analysis of energy consumption showed that thermal dehydration was between 3.5 and 5 times higher than Ohmic dehydration. Similar trend was observed in terms of cost and GHG emissions.

Keywords: Ohmic heating; thermal drying; citrus products; energy efficiency; GHG emissions; Vitamin C

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1. Introduction

Industrial energy intensive manufacturing processes are responsible for over 30 % of global GHG emissions [1], while the food and drink sector in the European Union is responsible for 18 %. One of the most intensive processes in the industry is dehydration, which accounts for 12-20 % of the energy consumption [2]. The majority of dehydration processes in the food industry are based on hot air drying where air is heated by the combustion of fossil fuels, which requires high energy consumption [2]. There is an increased pressure from the government on the food industry to maximise process efficiency whilst reducing energy consumption and GHG emissions and providing at the same time high quality products with minimal increase in cost. This has been stimulated by numerous international agreements on climate change.

The European Union Emissions Trading System (EU ETS), whose third phase began in January 2013, has put into force the 2020 Climate and Energy Package which aims to reduce the UK's GHG emissions below 1900 levels by at least 35%, by the year 2020. The EU has now taken this one step further by introducing "The 2030 European Climate and Energy Framework" that builds on the 2020 Climate and Energy Package by doubling the reduction in GHG to 40% and increasing energy from renewables and energy efficiency to at least 27% [3]. In the last decade the UK government has introduced the Climate Change Act with the aim to reduce the UK's GHG emissions by at least 80% from the 1990 baseline by 2050 and also provided a system of carbon budgeting and financial incentives to improve sustainability. The Climate Change Umbrella Agreement is a voluntary agreement between the Environment agency and the food and drink sector association, referred as FDF1 that influenced the food industry even more to seek sustainable approaches and find out how much energy can be exempted from the Climate Change Levy discount via energy bills [4]. All this legislation and environmental policies require the food industry to evaluate its energy use and GHG emissions. One of the ways to improve energy efficiency in the food industry is the use of more energy efficient technologies. The choice of these technologies depends on various factors such as type of product, availability, energy consumption, time and cost of dehydration process and final quality of the dehydrated product. One of the promising alternative dehydration processes is Ohmic heating treatment. It is an emerging food heating technology with a great ability to heat food materials rapidly and uniformly and has a wide application for blanching, evaporation, fermentation, extraction, sterilization, pasteurization and heating. During Ohmic heating the food is directly exposed to electric current where electrical energy is converted into thermal energy [5, 6]. One of the advantages of using this process is the high energy conversion efficiency. In comparison to the conventional heating, it offers energy saving of 82–97% and reduction of heating times by 90–95% [7]. The other advantage is the tendency of maintaining high nutritional retention, colour and sensory attributes. The success of this process depends on a number of factors such as electrical, thermophysical and rheological properties of the food and the process parameters such as current frequency, electrode material, geometry of the treatment chamber, electrical field strength, residence time and electrical conductivity [6, 8]. The Ohmic dehydration could be also used as a pre-treatment for further drying methods such as hot air drying, solar and microwave drying resulting in a better structure and volume of the final food products, improved taste, colour and reduced water activity [9, 10]. The application of osmotic dewatering prior to an expensive drying technique also makes the process more energy and cost efficient.

During food heating a significant amount of the valued components such as proteins, phytochemicals and vitamins could be affected. Vitamin C is considered as a natural antioxidant and very important nutrient that is used by the food industry for various purposes e.g. extension of the shelf life. A number of factors such as temperature, time and concentration of the oxygen during processing could affect the vitamin C degradation rate [7, 10, 11].

To the authors knowledge there is very little evidence in the literature if Ohmic heating could be used as an energy efficient method for drying of food materials and preservation of their nutritional properties, Therefore, the main objective of this work was to investigate the effect of Ohmic and conventional thermal drying on a number of parameters such as energy efficency, GHG emissions, cost, moisture content, pH and Vitamin C levels.

2. Experimental Investigations

2.1. Food Materials

Two citrus products, orange and grapefruit, were purchased from a local retailer in the UK. The samples were blended using a Russell Hobbs blender (Russell Hobbs, Greater Manchester, England, the UK) at the speed 2 for 10 min. The samples were collected in foil tin then exposed to the Ohmic and thermal heating over 30 minutes at two different temperatures of 70^0C and 100^0C. A number of analyses were conducted including electrical thermal conductivity (ETC), moisture content, pH and Vitamin C levels and energy consumption, cost and GHG emissions calculated.

2.2. Ohmic heating

Ohmic heating experiments were conducted using Ohmic heater (CTech Innovation, Capenhurst, Chester, UK) operating at atmospheric pressure. The Ohmic dehydration apparatus comprised a polypropylene product container with an electrode at each end, located in a bunded tray with an interlocked cover and free-standing control panel (housing the power supply unit with a proportional-integral-derivative PID controller for voltage control), and attached to the heater. 250 g of the orange and grapefruit samples were fed into a product container with 10-kW batch heater over half an hour. The polypropylene product container internally measures 9 0 mm x 95mm high, with a variable length between 80 mm and 300 mm, adjustable between the two end electrode housings via 80 mm and 220 mm long spacer sections, fitted with tie rods. The maximum operating voltage is the mains supply voltage (~240V), controllable via the PID controller between 0 and maximum voltage to achieve desired product temperatures. In this work, only the 80 mm option, corresponding to a maximum voltage gradient of ~30 V/cm was used. The material was heated from ambient to the temperature of 70 or 100°C with a holding time of 26 s, just like the microwave system. The heating-up time was in the range 50-70 s. Electrical energy consumption data was collected at two levels. Data was obtained for the total power input to the heater (which determines the total energy input), as has been done in various previous works. In addition, data was collected specifically between the electrode terminals, via the control panel, by measuring the electrode terminal voltages via a voltmeter, and the current through it, using a clamp-on ammeter. This approach enables the actual electrode control voltage signal and hence, voltage gradient dynamics to be determined. Fig.1 (A) shows a schematic of the Ohmic heating system with the electrical energy instrumentation connections while Fig. 1 (B) shows the A2 and V2 connections in the control panel. The samples were cooled down and sent for further analyses as explained below.

2.3. Thermal processing

The thermal drying was performed on 250 grams of orange and grapefruit samples at 700 ^{o}C and 1000 ^{o}C over 30 minutes using Opus Combi Dryer (Lincat Limited, UK). The dryer was allowed to pre-heat for approximately 30 min prior to operation and the fan assisted heating option was switched off for all drying operations. The samples were cooled down and sent for further analyses as explained below.

2.4. Electrical conductivity

Electrical conductivity (S/m) was calculated using Ohmic heating voltage and current data as $\sigma = L/AR$, where:

σ - electrical conductivity (Sm^{-1})
A – inner cross sectional area of Ohmic heater (m^2);
L - interval between electrodes (m);
R - resistance (Ω); [R= V/I ; V - voltage and I – current]

2.5. Energy profile, costs and GHG emissions

The energy consumption of Ohmic heating was recorded as indicated in section 3.2 while energy consumption of thermal drying was measured during drying of the samples using a high quality power meter (LUKE 435-II Power Quality Analyser, Fluke Industrial). The cost of the energy was calculated using average industrial electricity cost of 8.83 Pence per kWh while GHG emissions using CO_2 emissions factor for UK electricity grid generation of 205 gCO_2e/kWh.

2.6. Moisture content and PH level

The pH of the citrus samples were recorded using a pH electrode HI-1612D (Hanna® instruments, UK.) before and after the heating. The meter was connected to a DrDAq USB data logger (Pico Technology, UK) and recorded for each experimental test. Picolog Beta 8 software (Cambridge, UK) software was used in the computer to measure the changes in pH. Moisture content of the samples were analysed before and after the heating using Ohaus MB 25 (Ohaus Corp.,USA), at 160°C in auto setting until the bone dry weights were achieved.

2.7. Vitamin C level

A reliable and sensitive high-performance liquid chromatographic (HPLC) method as described by [12] was used for the determination of total vitamin C (L-ascorbic acid, AA, plus dehydro-1-ascorbic acid, DHAA). After extraction AA was oxidized enzymatically to DHAA with the aid of ascorbate oxidase. The latter compound is condensed with ophenylenediamine (OPDA) to its highly fluorescent quinoxaline derivative. This derivative was separated on a reversed-phase HPLC column and detected fluorometrically. Total vitamin C was determined in concentrations as low as 0.2pg/g. The amounts of DHAA was determined separately by the same procedure with omission of the enzymatic oxidation.

2.8. Statistical analyses

The statistical programme SPSS (SPSS Inc, the USA) was used to preform one-way ANOVA and post hoc comparison at $P< 0.05$ statistical analyses for the following parameters: moisture content, pH and Vitamin C levels. The results were reported as an average of three replicates.

3. Results and discussion

3.1. Electrical conductivity

The most important parameter in Ohmic heating is electrical conductivity (EC). Figure 2 presents the results of the EC of the citrus products (orange and grapefruit) over 30 minutes at two different temperature of 70^0C and 100^0C. The results revealed that there was a positive increase of the EC over time resulting with the higher values at 70^0C for the orange and 100^0C for the grapefruit samples. The range of the electric thermal conductivity for orange and grapefruit samples in this study varied between 0.5 and 6.5 [S/m], which are comparable to the reported values of 0.05 - 1.2 [S/m] for different samples such as apple, pineapple, pear, strawberry, pomegranate and peach [1, 7, 13] . It has been extensively accepted that the EC is strongly dependent on the type of the food used for heating, electric field intensity [7], increased concentration of solids as a result of water evaporation [13], different ionic mobility [1], temperature and voltage gradient [14].

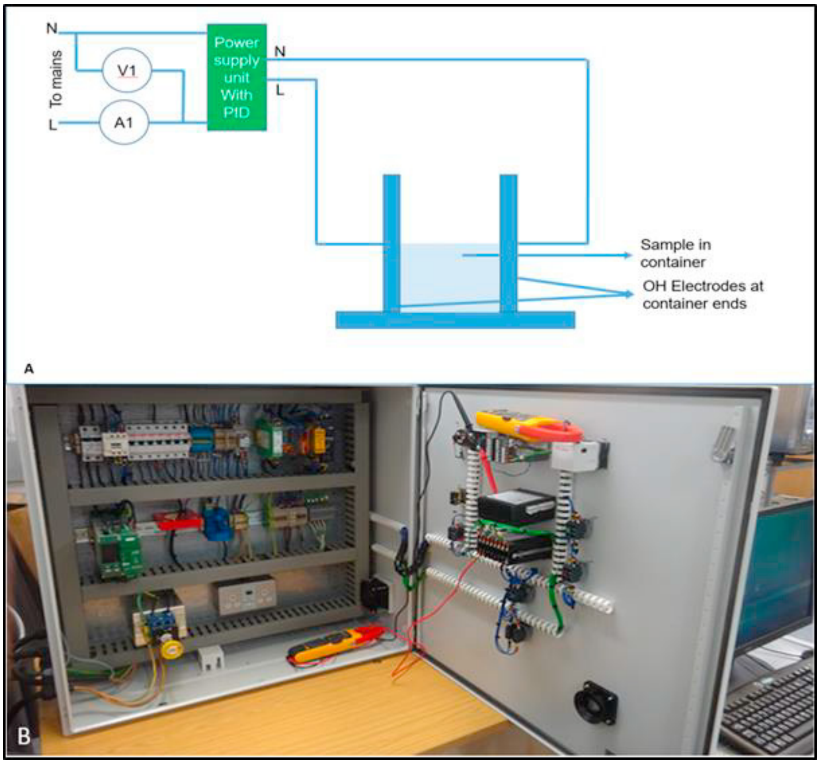

Fig. 1. (a) A schematic of the Ohmic heating system with the electrical energy instrumentation connections (A1 and V1) (b) Power control panel of Ohmic heating system.

3.2. Energy profile, costs and GHG emissions

Figure 3, presents the Ohmic energy profile of the samples at two different temperatures of 70 °C and 100 °C over 30 min. It can be seen that there was an increase of the energy consumption at both temperatures over time, resulting in a maximum energy consumption of 237.15 KJ and 216.08 KJ for grapefruit and citrus samples, respectively, which was achieved at 100 °C. Figure 4 presents the thermal energy profile of the samples at two different temperatures of 70 °C and 100 °C over 30 min. It can be seen that there was an increase in the energy consumption at both temperatures over the time resulting in a maximum energy consumption of 580 KJ for 70 °C and 880 KJ for 100 °C. Figure 5 presents the comparison of the energy consumption, energy cost and GHG emissions of thermal and Ohmic heating. It can be seen that the energy consumption of conventional thermal drying was about 3.5 to 5 times higher than Ohmic drying. Consequently, the similar trends were obtained for the cost of energy and the GHG emissions. It has been reported that energy in the industry could account for about 10% or more of the total operational cost. With Ohmic dehydration, significant energy savings can be achieved with a short payback period of about 18 months [15].

3.3. Moisture content and PH level

Table 1 presents the moisture content and pH of the samples before and after Ohmic and conventional drying. It can be seen that the initial moisture content of the two samples was very similar. There was a significant ($P<0.05$) difference found between the control samples and samples exposed in both, Ohmic and thermal drying, at 100 °C but no difference was seen at 70 °C. In terms of the pH there was no significant difference found between the two drying methods. The only significant difference ($P<0.05$) was seen for the orange sample exposed to Ohmic heating at 70 °C. It seems that the pH value could be affected by the type of sample and temperature. Darvishi et al. (2013) reported that the pH of pomegranate juice in Ohmic heating was significantly affected by the applied voltage. The reported values for the pH of the pomegranate juice after Ohmic heating were in the range of 3.22–3.35, which were similar to our values of 2.67 – 3.60.

3.4. Vitamin C level

Table 2 presents the Vitamin C level of the samples dried at 100 ^{0}C. Although, there was some variation seen between the samples using different drying methods, the statistical analyses revealed that there was no significant difference detected. Those findings were very similar to other published results. Mercali et. Al. [11] and Lima et. al. [16] studied the Ohmic thermal stability of ascorbic acid in ground cashew apples and acerola pulp, respectively. It was observed that during 120 min at 100 °C, the ascorbic acid content in ground cashew apples was decreased by 30% while in acerola pulp showed very low decrease. There was a nonlinear relationship reported between ascorbic acid degradation and frequency but the impact of temperature was very low [11]. In our study, a constant frequency of 80 Hz was used and there was no possibility to estimate the relationship to the ascorbic acid degradation. Castro e.al. [7] used conventional and Ohmic heating to assess ascorbic acid degradation kinetics in strawberry pulps at the temperature of 60 – 97 °C and found that an electric field of 20 V/cm does not affect the degradation of ascorbic acid. Santos and Silva [10] studied the degradation of ascorbic acid in different drying processes and found that the most important parameters that affect Vitamin C retention are time and temperature, which occurs mainly as a result of the acid diffusion to the solution and chemical deterioration. Erle and Helmar [9] used Ohmic dehydration in combination with microwave heating for apples and strawberries and found that Vitamin C retention was around 60% and preserved volume of the samples between 50 % and 60 %.

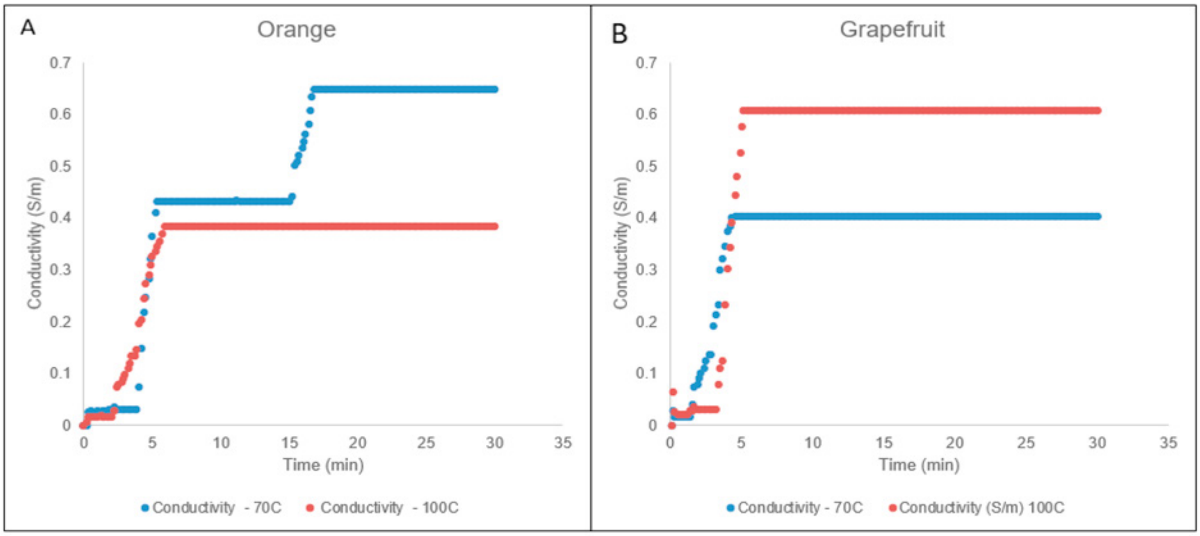

Fig. 2. (A) Conductivity profile of orange pulp samples processed with Ohmic drying at 70 ºC and 100 ºC over 30 min; (B) Conductivity profile of grapefruit pulp samples processed with Ohmic drying at 70 ºC and 100 ºC over 30 min.

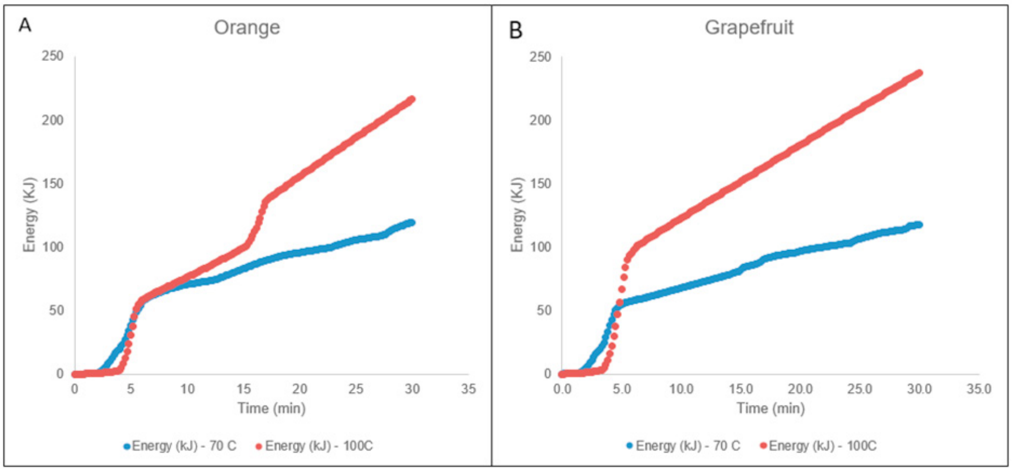

Fig. 3. (A) Energy profile of orange pulp samples processed with Ohmic drying at 70 ^{o}C and 100 ^{0}C over 30 min; (b) Energy profile of grapefruit pulp samples processed with Ohmic drying at 70^{0}C and 100^{0}C over 30 min.

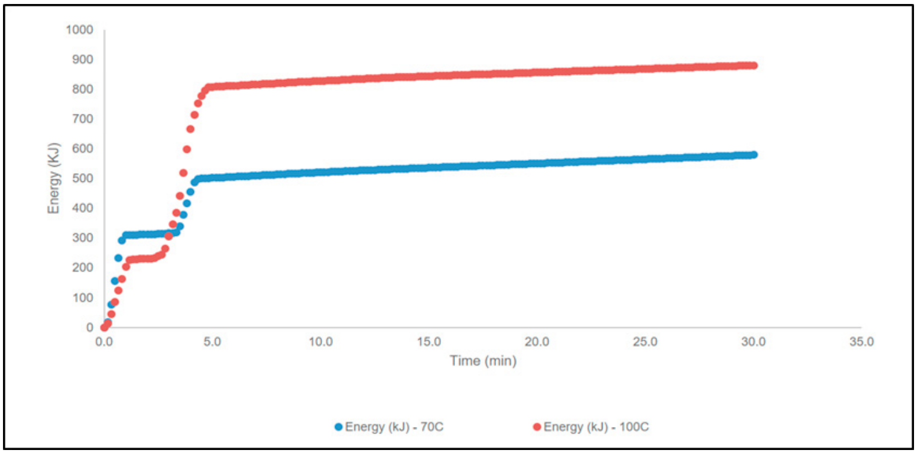

Fig. 4. Energy profile of the samples processed with thermal drying at 70 ^{o}C and 100 ^{o}C over 30 min.

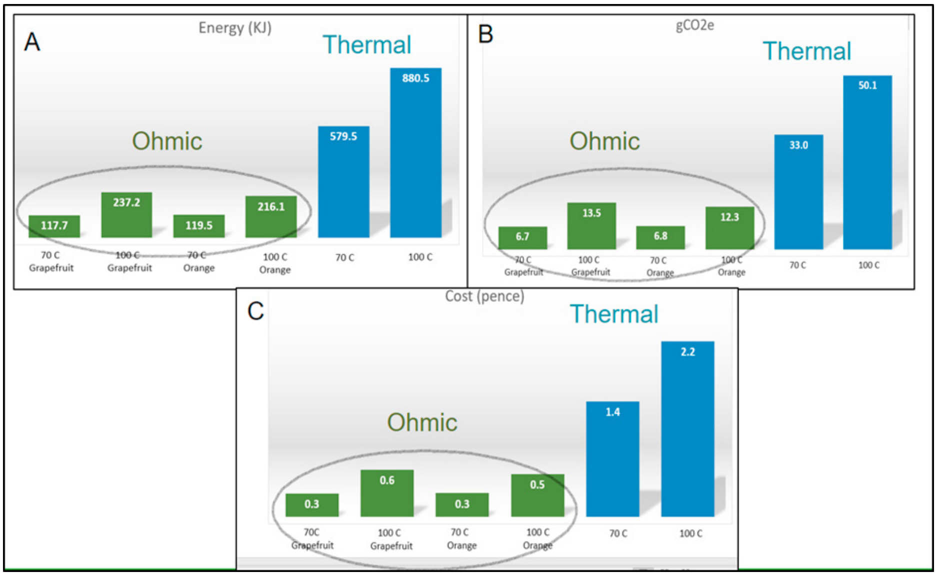

Fig. 5. (A) Energy profile of orange pulp samples processed with Ohmic drying at 70 ºC and 100 ºC over 30 min; (b) Energy profile of grapefruit pulp samples processed with Ohmic drying at 70 ºC and 100 ºC over 30 min.

Table 1. Moisture and pH variation of the samples using thermal and Ohmic heating at temperatures of 70ºC and 100ºC.

	Samples	Moisture content (%)	pH
Grapefruit pulp	Control	65^{a}	2.8^{a}
	Ohmic – 100^{0}C	$45^{b,c}$	2.67^{a}
	Thermal – 100^{0}C	44^{c}	$3.40^{a,d}$
	Ohmic – 70^{0}C	59^{a}	2.9^{a}
	Thermal - 70^{0}C	58^{a}	$3.7^{b,c,d}$
Orange pulp	Control	62^{a}	$3.50^{b,d}$
	Ohmic – 100^{0}C	$43^{b,c}$	$3.46^{b,d}$
	Thermal – 100^{0}C	$42^{b,c}$	$4.17^{b,c}$
	Ohmic – 70^{0}C	55^{b}	$3.60^{b,c,d}$
	Thermal - 70^{0}C	56^{a}	4.24^{c}

Values bearing the same letters within the same column are not significantly different from each other ($P < 0.05$)

Table 2. Vitamin C variation of the samples using thermal and Ohmic heating at the temperatures of 70 ºC and 100 ºC

	Samples	Vitamin C (%)
Grapefruit pulp	Control	48.2
	Ohmic 100ºC	49.2
	Thermal 100ºC	44.4
Orange pulp	Control	53.4
	Ohmic 100ºC	49.9
	Thermal 100ºC	54.5

4. Conclusion

This article presents a comparative study of Ohmic and thermal heating for dewatering of citrus products (orange and grapefruit). The obtained data demonstrated that Ohmic heating could be used as an alternative for dewatering and in comparison to the conventional treatment, it could be more beneficial in terms of energy efficiency, cost and GHG emissions. Additional advantages have been seen in the significant amount of water removal and retention of the Vitamin C level. However, further research is needed to clarify the effect of Ohmic heating on the nutritional properties of the food products using different times and process conditions.

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